SYMPOSIUM ON PETROLEUM GEOLOGY OF TARIM BASIN IN CHINA AND SIBERIA PLATFORM IN RUSSIA

Jia Chengzao and N.V. Sennikov *et al.*

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Preface

Based on the great success made in oil and gas exploration in Mesozoic and Cenozoic continental basins in the past decades, China produces 160 million tons of crude oil annually. However, to keep the country's oil production and reserves stable and rising steadily, China needs to step up the efforts for oil and gas exploration of Paleozoic marine carbonate rock that is extensively distributed in China. The purpose is to help the country obtain the strategic substitute areas for oil and gas resources. There are three characteristics extensively existing in China's marine carbonate rock tableland. 1. The era of the strata is very old, usually Lower Paleozoic and Proterozoic, with a long history. The period for hydrocarbon is very early. 2. Evolution of organic matter is extensively of high degree and usually under a stage from wet gas to dry gas. 3. The abundance of organic matter in carbonate rock is extensively low, formed mainly in shallow water and shallow water environment represented by epicontinental sea. For example, North China area (including Ordos basin) is an epicontinental sea environment at Cambrian–Early Ordovician era. The remaining organic carbon content of old carbonate rock is usually about 0.20 percent in China. This bears great influence on assessment of marine carbonate rock resources volume and principles for oil and gas exploration in the country.

On the contrary, Russia has made tremendous achievements in old marine carbonate rock oil and gas exploration. For example, the proven and controlled oil and gas resources volumes are currently 3.2 billion tons of equivalent oil and gas in Timan–Pechyora basin and the prospect resources volumes are 17 billion tons. West Siberia is a famous oil and gas basin in Russia. In addition to some large and giant oil and gas fields of Mesozoic-Cenozoic Jurassic and Cretaceous such as Qiuming Oil Field and Urengoy Gas Field, Paleozoic has become more and more important target horizons for exploration. A total of four Ordovician oil and gas reservoirs have been discovered. Kovikgin Condensate Gas Field and Verchon Gas Field have been discovered in the central southern part of the East Siberia platform. The producing layers of Koviktin Condensate Gas Field are of the second formation of Vendian. The oil and gas flow is found in 22 wells with the production reaching 300,000 m^3/d.

In 1999, Academician Dai Jin at China's Academy of Sciences sponsored a research project for cooperative comparison of "Chinese-Russian marine carbonate rock and oil and gas " in an attempt to promote bilateral academic exchange in this field and borrow each other's experience. It is important for the Chinese side to borrow experience from marine carbonate rock oil and gas exploration from the Russian side. In addition, the research project can promote exchange of samples of hydrocarbon source rock and crude oil for common analysis and study and solve some issues of mutual concerns.

Basedon the scheduleof Chinese-Russian marine carbinate rock and oil and gas project an

eight-member delegation headed by Dr Jia Chengzao visited Russia for technical exchange between December 10 and 29, 1999. The Chinese researchers visited Geophysical Chemistry & Analytical Chemistry Research Institute under Russia's Academy of Sciences (from December 10 to 18, 1999), VNIGRI (from December 19 to 22), GAZPROM (on December 21) and Petroleum Geological Research Institute of Russia's Academy of Sciences (from December 23 to 28). The bilateral sides exchanged geophysical chemical samples from Tarim basin and Timan–Pechyora basin as well as some preliminary research results on these two basins. During the course of technical discussion, the Chinese side briefed about the oil geological conditions of Tarim basin while the Russian side reciprocated by briefing about the oil geological conditions of Timan–Pechra basin, East Siberia tableland and West Siberia basin.

The Chinese researchers discussed in detail with their counterparts at Petroleum Geological Research Institute under Russia's Academy of Sciences about the oil geological conditions of Tarim basin and Siberia tableland. The two sides have highly evaluated each other's research fruit and shared an identical view on such scientific exchange. They proposed to publish the result of their academic exchange in English in China and in Russian in Russia.

This book is an English version of the theses submitted for Chinese-Russian academic exchange concerning the oil geological conditions of Tarim basin and Siberia platform. This book collects 19 academic papers in total, six ones from the Chinese side and 12 ones from the Russia side. Those papers cover the structure, sedimentation, oil generation and oil and gas reservoirs of Tarim basin, West Siberia basin and East Siberia tableland. Those papers are also focused on the comprehensive oil geological conditions and the oil economic conditions in Russian. Publication of this collection partially reflects the exchanged results of the "Chinese-Russian marine carbonate rock and oil and gas research project." Meanwhile, I hope that this collection of papers can help the Chinese and Russian researchers borrow each other's experience in oil and gas research and exploration.

The papers in this book have been examined and determined by Dr. Jia Chengzao and Dr. Sennikov N. V. Thank Academician A.E.Kontorovich for offering good conditions for academic exchange. Thank Academician Dai Jinxing and Academician A.E.Kontorovich for their instructions on publication of this book.

Dr. Jia Chengzao and Dr. N.V.Sennikov
April 20, 2000

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The Exploration Achievements and the Prospect for Natural Gas in Tarim Basin, China

Jia Chengzao & Xiao Zhongyao

(*PetroChina Company Limited, China*)



Jia Chengzao, born in 1948, received a B. S. Degree in geology from Xinjiang Engineering College, and a Science Dr. from Nangjing University. He is a chief geologist in PetroChina.

Abstract: In recent years, a great progress has been made in the gas exploration by Tarim Oilfield Corporation. A total of 15 giant and medium-size oil and gas fields are proved, with the proven and probable geological reserves being 9.03×10^8 tons oil equivalence including proven geological gas reserves of $5050\times10^8m^3$, and a total $11010\times10^8m^3$ of proven, probable and predicted gas geological reserves. So this is the base switching on the project of "western natural gas delivered eastward". Kela-2 gas field is the largest sized gas field proved in China, with gas-bearing area 47.1 km^2 and proven gas geological reserves $2506.1\times10^8m^3$. Tarim Basin is a large superposed composite basin made by Palaeozoic cratonic basin and Meso-Cenozoic foreland basin, with the two types of gas resources of cracking gas from marine strata and pyrolysis gas from measure strata. The tectonic position of the Tarim Basin belongs to basin group at the north margin of Tethys and belongs to a part of gas-rich province of Middle Asian. The basin has good condition forming giant–medium sized gas fields, developed with 4 sets of source rocks including main gas source rocks of Cambro–Lower Ordovician and Trassic–Jurassic, and 5 good reservoir-seal assemblages for gas accumulation. Several petroleum systems such as Kuqa, Mangl, Awati, Southwestern Tarim, Tanggu, Southeastern Tarim and Yingjisu are composed of by the 4 sets of source rocks and 3 oil-gas regions can be classified obviously, which are Kuqa–Tabei gas region, Mangal oil-gas region and Bachu–Southwest Tarim gas region. At present, the focal exploration area is in Kuqa petroleum system. At the same time, seismic reconnaissance and comprehensive research are under way for Southwest Depression, which will be a very important strategic prepared area for gas exploration.

Key words: Gas-oil field, Petroleum system, Gas exploration, Tarim Basin

1 Introduction

Tarim Basin, surrounded by Tianshan Mountains and Kunlun Mountains, is located in the southern part of Xingjiang Uygur Autonomous Region and is the largest sedimentary basin in China, covering $56\times10^4km^2$. The central part of the basin is Taklamakan desert, the largest moving desert called "death Sea" in the world, is, with an extent of $33\times10^4km^2$.

From April 1989 to April 2000, 2D seismic survey of 19.4×10^4km and 3D seismic survey

of 10460 km^2 were accomplished, 369 explosive wells were finished by Tarim Oilfield Corporation, with a total footage of 187.37x10^{4}m, and the commercial oil and gas flow came out in 151 of 369 explosive wells. The average success ratio for exploration well is 41% and the average success ratio for exploration trap is 34%. 15 giant-medium sized oil and gas fields were proved, which include 7 oil fields, i.e. Lunnan, Sangtamu, Jiefangqudong, Donghetang, Hade 4, Tazhong 4 and Tazhong 16, and 8 gas fields i.e. Kela-2, Yaha, Yingmai 7, Yangtake, Yudong 2, Jilake, Hetianhe and Tazhong 6 ^{1}. Therefore, obviously, 3 oil-gas regions could be divided, i.e. Kuqa–Tabei gas region, Mangal oil-gas region and Bachu–Southwest Tarim gas region (Fig. 1).

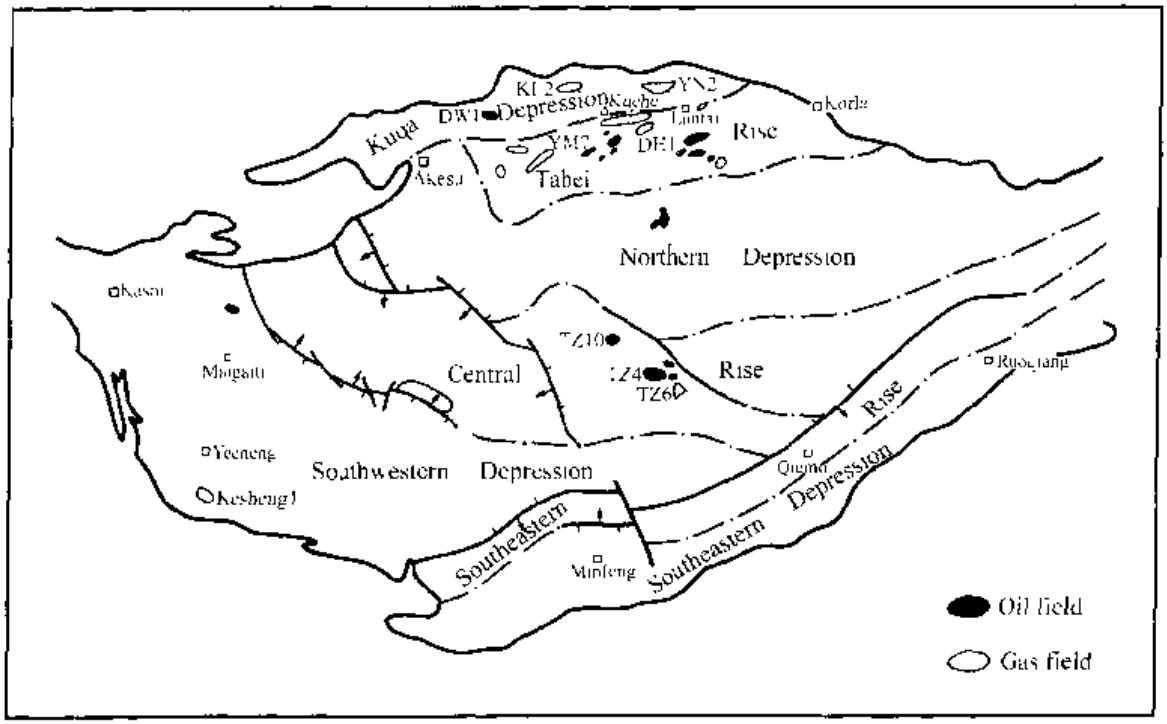


Fig. 1 The oil and gas field distribution in Tarim basin.

Till the end of the April 2000, the total geologica reserves of proven 3.25×10^8 tons of oil (0.95×108 tons recoverable) and 4700x10^{8}m^3 of gas (3248×10^{8}m^3 of gas recoverable), probable 0.67×10^8 tons of oil and 760×10^{8}m^3 of gas and predicted 1.26×10^8 tons of oil and 4208×10^{8}m^3 of gas, had been obtained by Tarim Oilfield Corporation for the 11 years' exploration.

For 3 years from 1997 to 1999, a very important progress had been made in the gas exploration. Hetianhe gas field was discovered and proved in Mazatage structural belt of the south margin of Bachu Uplift, with proven reserves of 616×10^{8}m^3. Kela-2 gas field in Kelasu structural belt and Yinan-2 in Yiqikelike structural belt were discovered, and then several gas fields such as Dabei-1 and Tuzi-1 etc. had been found in Kuqa Depression. The proven gas geological reserves of Kela-2 was 2506×10^{8}m^3 and the total predicted gas geological reserves of Dabei-1, Tuzi-1, Ynan-2, Yishen-4 and Kela-3 gas fields was 3543x10^{8}m^3 (Fig. 2).

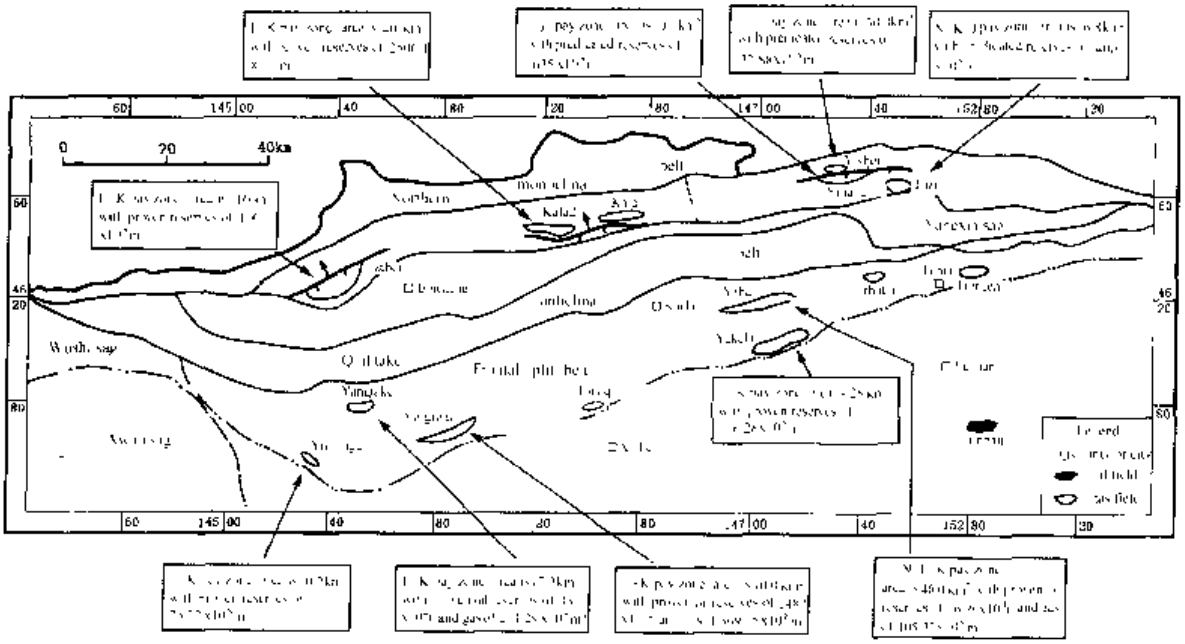


Fig. 2 The distribution of the gas fields in Kuqa–Tabei gas region.

Up to now, Tarim Oilfield Corporation has acquired 9.03×10^8 tons of oil equivalence of proven and probable geological reserves including $5050\times10^8 m^3$ of proven gas geological reserves, and a total $11010\times10^8 m^3$ of 3 grade gas geological reserves. So Tarim Basin has already been a basin with the largest remnant recoverable gas reserves. It costs 0.73 dollar for a recoverable barrel of oil equivalence lower than the average level of the oil companies in the world.

2 Petroleum Geology and Gas Resources

2.1 Tectonics

(1) Tarim Basin is a large superposed composite basin made from Palaeozoic cratonic basin and Meso–Cenozoic foreland basin, with the two types of gas resources of cracking gas from marine strata and pyrolysis gas from measure strata and with the two kinds of exploration targets in Palaeozoic cratonic basin and Meso–Cenozoic foreland basin [2].

The main body of the Tarim Basin is Palaeozoic cratonic basin developed upon the old continental crust and basement, superposed by the two Meso–Cenozoic foreland basins in the northern part and in the southern part of the basin in late period. These two basins have their own sediments, tectonic characters and petroleum accumulation regularities (Fig.3). The hydrocarbon accumulation is under the control of paleo-uplift and its slope in Palaeozoic cratonic basin and thrust belt of Himalayan orogeny in Meso–Cenozoic foreland basin [3]. The natural gas in Palaeozoic cratonic basin is mainly the cracking gas from Cambro–Ordovician and the natural gas in Meso–Cenozoic foreland basin is mainly the pyrolysis gas from meas-

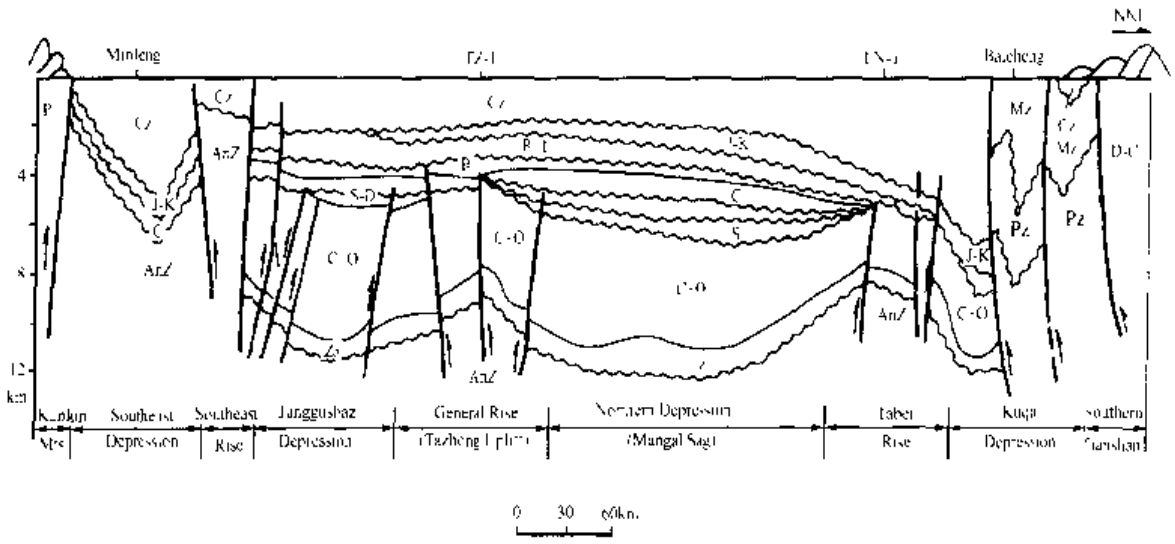


Fig. 3 Structural cross section of Tarim Basin.

ure strata of Triassic and Jurassic.

The Palaeozoic cratonic basin has a huge thickness of carbonate and clastic sediments, involving cratonic marginal aulacogen stage from Sinian to Ordovician, marginal foreland basin stage from Silurian to Devonian and cratonic margin and intracratonic rift stages from Carboniferous to Permian[2]. The paleo uplifts are the main hydrocarbon accumulation area and can be divided into 3 types or 5 kinds, including Tazhong stable paleo uplift, Tabei and Tadong residual paleo uplifts and Bachu and Tanan active paleo uplifts. In Palaeozoic cratonic basin, Hetianhe gas field has been discovered at the south margin of Bachu paleo uplift.

Kuqa Depression and Southwest Depression are marine sediment depression from Mesozoic to Cenozoic in the front of Tianshan Mountains and Kunlun Mountains, respectively. In the two depressions, Lacustrine to swamp deposit was developed in Triassic and Jurassic with coal-bearing strata, and fluvial–delta deposit was mainly developed in Creataceous and Tertiary with shallow sea facies and lagoon facies developed in the western part of the basin. Thus, the good source–reservoir–seal assemblages were formed. At the end of the Tertiary, the strong thrust belts, being the most favorable gas accumulation area, were taken shape in Kuqa Depression and Southwest Depression, caused by Himalayan orogeny and formed a lot of fault-folded local structures and traps. Some giant to supergiant anticlinal gas fields such as Kela-2, etc., had been found in the foreland basins.

Therefore, there are two types of gas resources of the cracking gas from marine strata and the phyrolysis gas from measure strata and two kinds of exploration targets in Palaeozoic cratonic and Meso–Cenozoic foreland of the large superposed composite basin.

(2) The tectonic position of the Tarim Basin is situtated in the basin group at the north margin of Tethys and belongs to a part of gas-rich province of Middle Asian

The basin group is located at the northern margin of paleo Tethys structural belt, including Tarim Basin, Fergana Basin, Sirduya

Basin, Kala–Kum Basin and Tadzhikistan–Afghanistan Basin etc. These basins are always under the active continental marginal tectonic setting of the north side of paleo Tethys Sea and neo Tethys Sea from Mesozoic Era, and involved retroarc foreland basin from Permian to Triassic, retoarc expanding rift-subsidence basin from Jurassic to Palaeogene and regenerative forland basin (Fig.4).

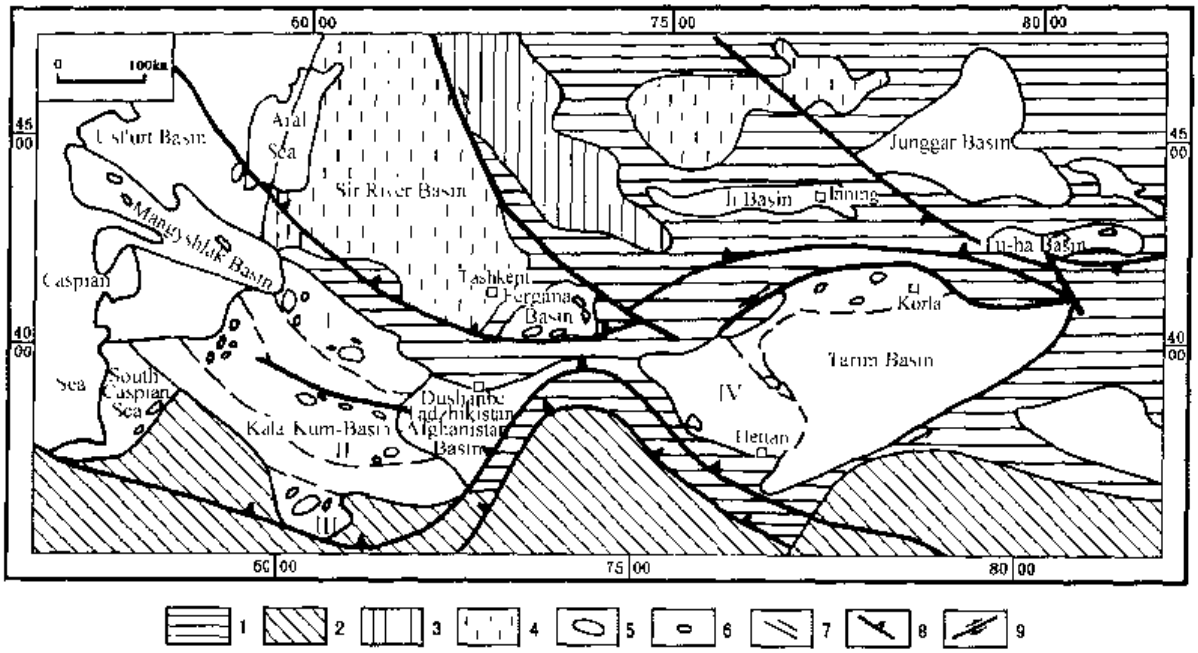


Fig. 4 The gas field distribution of Jurassic basin in the northern Tethys.

1. Fold belt of Palaeozic; 2. Fold belt of Meso–Cenozoic; 3. Sedimentary basin of Palaeozoic; 4. Sedimentary basin of Meso–Cenozoic; 5. Jurassic basin; 6. Gas field; 7. Fault; 8. Plate stylolitic structural belt or subductition orogenic belt; 9. Strike-slip fault; I. Buhar-Karzov Step Block, II. Kala Uplift, III Budhzi–Kalar Uplift, IV. The Cresent Zone of Western Tarim

The tectonic setting of the northern margin of Tethys determines that the organic matters in the basins are mainly humic type (the kerogen of type II and III) generating mainly natural gas. It is well known that these basins are much rich in gas, for example. Kala–Kum basin with gas reserves of 67000×10^8.

The hydrocarbon-bearing basins of the north margin of Tethys are much similar in the conditions of petroleum geology as follows.

Tectonic setting: All basins were always under the active continental marginal tectonic setting of the north side of paleo-Tethys and neo-Tethys from Mesozoic Era.

Evolution history: These basins involved the basement developing stage in Triassic, the subsidence stage from Jurassic to the end of Paleocene and the molasse developing stage from the end of Eogene.

Organic matter: The main hydrocarbon source rock is Jurassic coal-bearing strata, in which the organic matter is humic type (type III) or humic sapropellic type (type II) and humic organic matter is dominant, which mainly generates natural gas.

The trap formation is closely related with the fold thrust belt of the foreland, and the dynamic background is related with continued impingement between Indian plate and Eurasian plate.

So the conclusions can be obtained as follows through the analysis of tectonic setting and petroleum geological conditions of the Tarim Basin.

(1) Tarim Basin is one part of the gas-rich province of Middle Asia and has probably been an entirty with Kala–Kum Basin and Tadzhikistan–Afghanistan Basin, which were separated by Pamir Arch developed in Miocene and formed the present tectonic framework.

(2) Tarim Basin has the petroleum geological conditions to form huge sized natural gas fields, especially in the western Tarim Basin where stratigraphic sequences are much similar to the basins of Middle Asia and also the main gas-enriched area.

2.2 Source Petroleum System

4 sets of main source rocks including Cambro–Lower Ordovician, Middle and Upper Ordovician, Carboniferous and Trassic–Jurassic, are developed in Tarim Basin. But the gas source rocks are mainly Cambro–Lower Ordovician and Triassic–Jurassic. Analysing by sedimentary facies and organic matter source, the source rocks of Palaeozoic are marine strata developed in cratonic basin and the ones of Mesozoic are terrestrial strata developed in foreland basins. The 4 sets of source rocks grouped seven petroleum systems, such as Kuqa petroleum system, Mange petroleum system, Awati petroleum system, Southwestern Tarim petroleum system, Tanggu petroleum system, Southeastern Tarim petroleum system and Yingjisu petroleum system (Fig.5).

2.2.1 Gas source rock of Cambro–Lower Ordovician

The source rock of Cambro–Lower Ordovician is distributed most widely, with higher organic abundance, the largest amount of resources composed and the multiple stages of thermal evolution and hydrocarbon generating. According to sedimentary environment, the source rock can be divided into 2 types of starved basin facies of margional cratonic and endogenous platform facies of inner cratonic.

The high quality source rock of starved basin facies of marginal cratonic is mainly distributed in the eastern part of the Mangl Sag. The lithology of the source rock is black shaly micritic marl and siliceous or calcareous mudstone, with average TOC from 1.24% to 2.28% and the maximum TOC 5.52%. The organic precursor of the source rock is mainly planktonic algae, constituting type I organic matter. The source organic matter of the starved basins facies are at the stage of over-maturation, with converted Ro from 1.91% to 3.61% for Middle and Lower Cambrian strata, from 1.88% to 2.13% for Upper Cambrian strata.

The source rock of endogenous platform facies was developed in Middle and Lower Cambrian strata and was distributed in the western part of the basin with average TOC from 0.91% to 1.24%. The organic matter of the source rock belonged to type I and is at higher thermal evolution, equivalent to vitrinite reflectance Ro from 1.44% to 2.06%, showing the source rock being at the stage of high maturation to over-maturation.

The distribution of the oil and gas derived from the source rock is very complicated because of multiple thermal evolution stages. The dstribution of gas field in cratonic area is

under the control of the source rock. The dry gas in Hetinhe gas field and in Jilake gas field found at present were derived from high-quality and effective source kitchen of Cambrian in Southwest Depression and in the eastern part of Mangl Sag, respectively. Moreover, the central and western part of Awati Sag is a potential dry gas-rich area generating from Cambrian. The Cambro–Lower Ordovician petroleum system can be regionally classified into 2 confirmed petroleum systems and a guessed petroleum system, which are Mangl, Southwest Tarim and Awati petroleum systems.

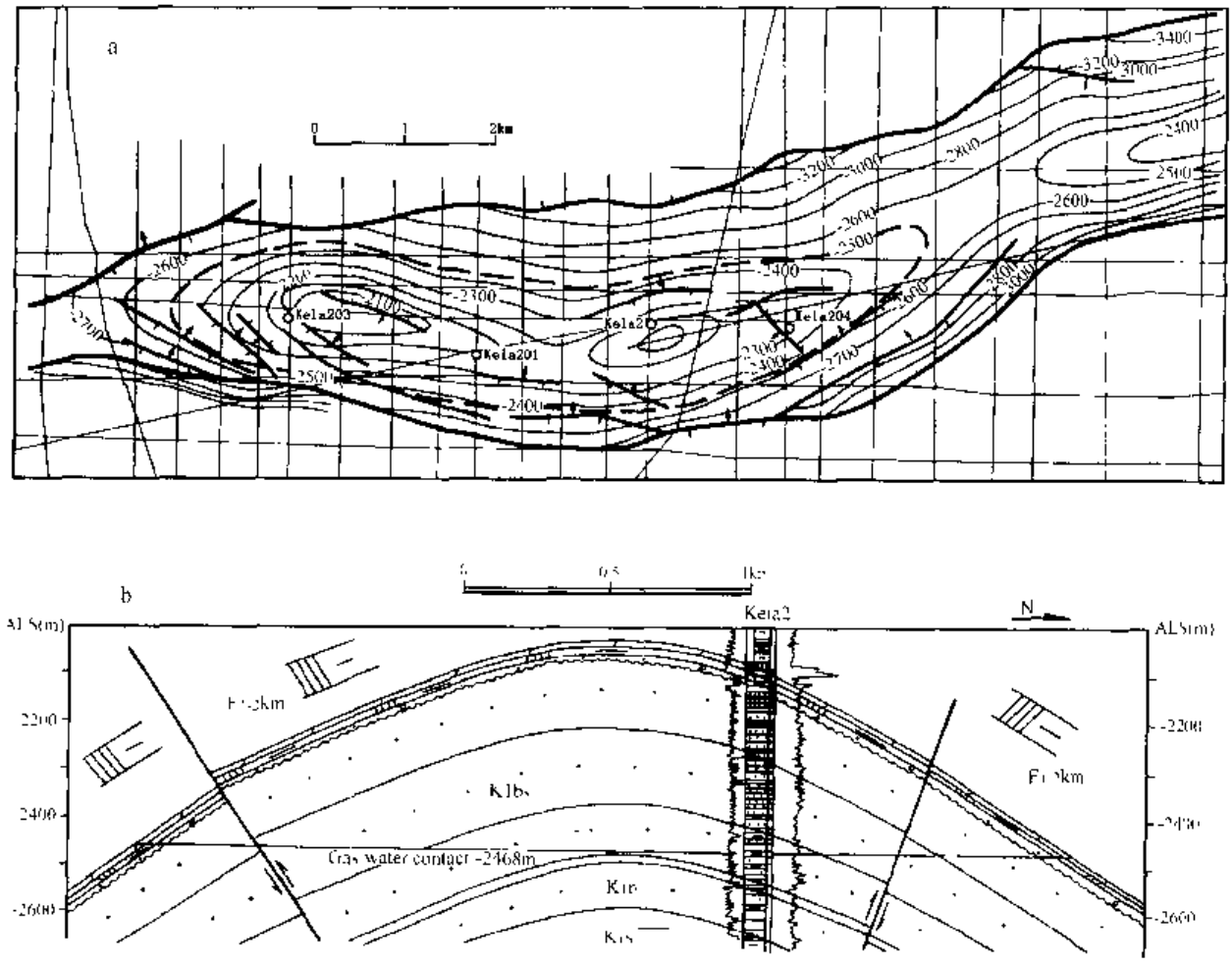


Fig. 5 (a) The gas bearing area of Kela-2 gas field;
(b) The cross section of Kela2 gas field along BC95-230 line through well Kela-2.

2.2.2 Middle–Upper Ordovician source rock

The high-quality Middle–Upper Ordovician source rock is mainly distributed in Tazhong Uplift, Tabei Uplift and its south slope and the central and western part of Awati Sag.

The source rock in Tazhong area is widely

distributed in the main uplift and its northern slope, with average thickness of 80m, TOC from 0.5% to 5.54%. The organic matter of the source rock is type I or mixed type II$_1$ to III, and is at the peak of hydrocarbon generation of oil prone, with organic maturation R_o from 0.81% to 1.30%.

The Middle–Upper Ordovician source rock in Tabei Uplift is distributed in the central and eastern part of the Uplift, with TOC from 0.2% to 0.96% and *Ro* from 0.89% to 1.45% being at the peak of hydrocarbon generation and the end of oil-generating window.

The Middle Upper Ordovician source rock distributed in cratonic area, with higher organic abundance, moderate maturation and oil-prone mixed organic type, is a reality and effective marine oil source rock. Now, the distribution of marine oil field is under the control of the source rock in cratonic area, and most of the marine oil is derived from the Middle–Upper Ordovician source rock.

2.2.3 Carboniferous source rock

The Carboniferous source rock of high organic abundance is mainly distributed in the western part of the basin, and developed vertically in Kalashayi Formation and Bachu Formation.

The mudstone of Kalashayi Formation belongs to littoral lagoon facies and offshore fluvial–paludal facies with maximum thickness 97m, maximum TOC=7.09% and hydrocarbon source potential 37.78mg/g of the coal-bearing source rock. The organic matter of the source rock is mainly from type II$_2$ to III, being at the lower mature stage with *Ro* generally less than 0.7%.

The biomicritite of Bachu Formation belongs to the sediment in marginal platform slope with the thickness 30m, average TOC - 0.62% and the maximum TOC=1.93% of the source rock. The mixed type is characteristic of the organic matter of the source rock , with *Ro* 0.80% or so. The Carboniferous petroleum system is distributed in Southwest Depression, in which the oil and gas commercial flow from Carboniferous has not been found except oil and gas indications and low oil flow in Well.Qun-4 and Well.Qu-1, and Well.Ma-4 in Mazatage structural belt.

2.2.4 Triassic and Jurassic source rock

The source rock of Triassic and Jurassic source rock, being mainly lacustrine mudstone and coal-bearing mudstone, is distributed in Kuqa Depression and Sothwest Depression.

(1) Triassic and Jurassic source rock in Kuqa Depression.

Triassic and Jurassic source rock in Kuqa Depression includes coal-bearing mudstone and lacustrine mudstone, with their sedimentary facies belonging to palludal facies and lacustrine facies, respectively. The coal-bearing source rock is widely distributed in the whole depression and vertically distributed mainly in Middle–Lower Jurassic and secondly in Upper Triassic. The lacustrine source rock is distributed in Jurassic and Triassic and is mainly developed in Qiakemake Formation of Jurassic and in the main body of Triassic.

Five source beds can be distinguished. They are Qiakemake Formation, Kezilenuer Formation and Yangxia Formation of Jurassic and Taliqike Formation and Huangshanjie Formation of Triassic, with the source thickness of Jurassic ranging from 0 to 1704m and the source thickness of Triassic from 0 to 980m. The maximum thickness of Jurassic and Triassic is located in Baicheng Sag, and the source rock of Jurassic is wider in distribution than that of Triassic because of overlying measure in Mesozoic. Some known

structural belts such as Kelasu, Yiqikelike, Qiulitake and Gumuzibieke etc are in or near the hydrocarbon-generating center.

The source rock in Kuqa Depression has higher organic abuncance with TOC from 0.01% to 39.98% and averages 3.68% for Jurassic mudstone and carbargillite, and from 0.01% to 24.52% and averages 3.68% for Triassic mudstone and carbargillite.

The source rock of Jurassic and Triassic is enrichment in vitrinite with the average content 52.07% and lower hydrogen index in a large pyrolysis data. The terrigeneous source kerogen in the whole depression is from −19.43‰ to −28.10‰ with main body from −22.8‰ to −28.1‰ showing terrigeneous plants for the organic precusor.

The vitrinite flectance of the Mesozoic source rock is generally more than 0.7%. In the direction from north to south, the main body of the depression, Baicheng Sag and Yangxia Sag of the central part of the depression, is higher in source maturation, while the northern part and the southern part of the depression are in lower mature stage. The bottom of Jurassic is at over-maturation stage with Ro more than 2.0%, in Baicheng Sag and at high-maturation stage with Ro 1.5% or so in Yangxia Sag. So, Kuqa foreland area is rich in gas because of the organic matter and maturation of Mesozoic source rock.

The peak of gas generation occurred in late Himalaya and the main period of gas accumulation began from 5 Ma, matched with the formation of traps and all these things were favorable for oil and gas accumulation with main dry gas and condensate gas phase.

(2) Jurassic source rock in Southwest Depression.

The source rock of Mesozoic in Southwest Depression is mainly measure strata of Middle–Lower Jurassic with fluvial, palludal and lacustrine facies, and is mainly distributed along Kashi Sag and Yecheng Sag near range-front. A total thickness of the source rock is more than 300m and the maximum 700m in Kashi Sag with dark lacustrine mudstone over 80m. The oil and gas in Kekeya gas field were generated by the source rock.

The organic abundance of the source rock of Middle–Lower Jurassic is higher than the other in the southwest of Tarim Basin. The value is TOC from 1.10% to 3.73% and hydrocarbon content from 539 ppm to 2789 ppm in Kashi Sag, and TOC from 0.70% to 1.10%, hydrocarbon content from 37 ppm to 285 ppm in Yecheng Sag. The organic matter of the source rock is mainly type II_2 or type III, with maturation from premature and early mature stage near Maigaiti Slope to mature and highly mature stage in central part of Yecheng Sag and Kashi Sag. The source rock of Jurassic entered the threshold of hydrocarbon generation in Miocene and was at the peak of oil generation or even at the stage of condensate gas and wet gas generation at present.

According to the analysis above, there are 2 sets of important gas source rocks, which are Cambro–Lower Ordovician source rock and Triassic–Jurassic source rock respectively. The natural gas generated by the former is the cracking gas from old oil reservoir with an example of Hetianhe gas field, and the one generated by the latter is pyrolysis gas from kerogen of type III with an example of Kela-2 gas field.

2.3 Reservoir–seal Assemblages

Five good reservoir–seal assemblages for gas accumulation are developed in Tarim Basin as follows:

(1) The assemblage of Cretaceous sandstone and Eogene saltay and gypseous mudstone is the best assemblage of the basin, of which Kela-2 gas field has been found, and is distributed in Kelasu and Qiulitake structural belts and Tabei area.

(2) The assemblage of Jurassic coal-bearing mudstone and its underlying sandstone, of which Yinan 2 gas field has been found, is distributed in monocline zone in the northern part of Kuqa Depression and Yiqikelike structural belt.

(3) The assemblage of interbeds of limestone and sandstone–shale of Carboniferous and buried hill in Ordovician weathering crust, of which Hetianhe gas field has been found, is mainly distributed from Selibuya to Mazatage structural belt.

(4) The assemblages of sandstone and mudstone in Neogene and gypseous mudstone and dolomite, sandstone in Eogene and Cretaceous, of which Kekeya gas field has been found, is distributed on the south margin of Southwest Depression.

(5) The assemblage of Cambrian salty and gypseous strata and the underlying dolomite are to be exploded further.

Moreover, the gypseous mudstone and gypseous salty mudstone of Jidike Formation and its underlying sandstone at bottom together construct composed of another high-quality assemblage.

2.4 The Resources of Natural Gas

(1) According to resource assessment of the whole nation in 1994, the resources of natural gas is $8.39\times10^{12}m^3$ in Tarim Basin, which is one of the richest basins in China.

(2) The resources of natural gas in Kuqa Depression

The range of Kuqa petroleum system is equivalent to Kuqa–Tabei gas region including its main body of Kuqa Depression and the northern part of Tabei Uplift, with a total area of 42700 km^2

The reassessment of hydrocarbon resources to Kuqa Depression shows that the hydrocarbon resources is 26.5×10^8 tons of oil ecuivalents including 4.1×10^8 tons of oil and $2.23\times10^{12}m^3$ of gas. The oil and gas abundance reaches 9.43×10^4 tons of oil equivalents per square kilometers and gas to oil ratio is 5.4:1, indicating Kuqa petroleum system is rich in gas. The gas resources in the known structural belts is above $2\times10^{12}m^3$ in Kuqa petroleum system.

Comparing it with gas-rich province of Middle Asia, we anticipate that the big-sized gas field with gas reserves from $3000\times10^8m^3$ to $4000\times10^8m^3$ could be possibly found. According to G.P.Zipf rule explaining a relationship of power function between the rank and the size of oil and gas reservoir, 6–8 gas fields with gas reserves from $500\times10^8m^3$ to $1500\times10^8m^3$ and a total gas reserves near $7000\times10^8m^3$ could be found later.

(3) The resources of natural gas in Southwest petroleum system.

The resources of natural gas in Southwest petroleum system is $2.089\times10^{12}m^3$, and 2 gas fields of Hetianhe and Kekeya has been found, with proven geological reserves $967\times10^8m^3$ and probable geological reserves $436\times10^8m^3$. The petroleum system, with very poor exploration at present, is an important strategic prepared area for gas exploration in Tarim Basin.

(4) The cresent gas-rich zone in the western part of Tarim Basin.

The cresent gas-rich zone in the western part of Tarim Basin, composed of Kuqa, Southwest Tarim and Awati petroleum sys-

tems, includes Kuqa Foreland Depression, Southwest Foreland Depression, Bachu Uplift and Awati Sag, with a total area of $18\times10^4 km^2$. The resources of natural gas of the zone is $4.485\times10^{12}m^3$, occupying 54% of the whole basin. So far, the total gained geological reserves is $8806\times10^8m^3$ including $4567\times10^8m^3$ of proven reserves, $463\times10^8m^3$ probable reserves and $3776\times10^8m^3$ of predicted reserves in the zone.

On the basis of the analysis of the regional tectonic setting, Tarim Basin is one of the basins in the north margin of Tethys such as Kala–Kum Basin and Tadzhikistan–Afghanistan Basin, and a part of gas-rich province of Middle Asia. It is needed to indicate that the western part of Tarim Basin is more comparable with gas-rich basins, such as Kala–Kum Basin in conditions of gas accumulation.

As a result, the cresent gas-rich zone in the western Tarim Basin has the prospect obtaining gas geological reserves from $2\times10^{12}m^3$ to $3\times10^{12}m^3$ and the capacity forming gas-rich province as larger as the ones in the world.

3 The Proved Gas Fields

Till to April 2000, 9 giant or medium sized gas fields (Table 1) had been proved and some examples were as follows.

Table 1 Nine giant–medium sized gas proved by Tarim Oilfield Corporation

No.	Oil & gas fields	Pay zones	Oil & gas-bearing area	Proven geological reserves	
				Crude oil ($\times10^4$tons)	Natural gas ($\times10^8m^3$)
1	Kela-2 gas field	E, K	47.1 km^2		2506.1
2	Yaha oil & gas field	N, E, O	48.9km^2	4442.9	405.37
3	Kekeya gas field	N	27.5km^2	3065.5	343.55
4	Hetianhe gas field	C, O	145km^2		616.94
5	Yingmai 7 gas field	E, K	48.3km^2	1950.1	309.75
6	Yangtake gas field	E, K	18.3km^2	567.5	274.29
7	Jilake gas field	T, C	52.5km^2	782	136.8
8	Tazhong 6 gas field	C	58km^2	73.4	85.26
9	Yudong 2 gas field	E, K	10.2km^2	142.5	73.32
Total			455.8km^2	11023.9	4751.38

3.1 Kela-2 Gas Field

Kela-2 gas field is located at the eastern part of Kelasu structural belt, found in January 1998 by the first discovery Well Kela-2. The assessment exploration of the field was completed in March 2000, and the field had been proved based on 2D seismic survey (1.0km x 0.75km), 4 exploration wells and high-level technology of early reservoir description. The proven gas geological reserves is $2506.1\times10^8m^3$ with the gas-bearing area 47.1 km^2 (Fig.6, Table 2).

Kela-2 gas field is the largest sized gas field in China, with super high gas abundance, high to super high yield and super high voltage, and is one of the important discoveries of oil and gas exploration in China. The discovery and verify of Kela-2 gas field will help facilitate the national huge engineering project of "western natural gas delivered eastward" and Kela-2 gas field will be the main gas field in the project. So, it is determined that Tarim Basin is the main gas production base in the project of "western natural gas delivered eastward".

Table 2 The calculation sheet for the proven gas geological reserves of Kela-2 gas field

Calculation beds	Gas-bearing area (km^2)	Average effective thickness (m)	Por. (%)	Gas-bearing saturation (%)	Formation temperature (K)	Formation pressure (MPa)	Original gas deviation factor	Proven geological reserves ($x10^8m^3$)
E_1-K_{m_2}	47.1	5.6	12.4	89	374	74.41	1.489	113.96
E_1-Km_3-K_1bs_1	43.5	78.4	12.5	67				1118.21
K_1bs_2	29.8	103.1	13.6	71				1161.46
K_1bs_2-K_1b	11.9	42.1	9.4	61				112.47
Total	47.1	154.1	12.7	69	374	74.41	1.489	2506.1

The anticlinal area of Kela-2 gas field is 48.1 km^2, with closed magnitude 455m. The main payzones are the sandstone of Cretaceous and the bottom sandstone of Eogene, with interconnection in vertical. All the pay zones are in the same temperature and pressure system, with high formation pressure coefficient from 1.95 to 2.20. The gas field has unite gas water contact (of 2468m under the seal level), with gas column of 448m and higher fullness coefficient. The gas field is anticlinal block gas field of edge water and basal water, with its buried depth from 3500m to 4050m (Fig.7).

The high-quality sandstone of Cretaceous is steadily distributed, averaging from 350m to 400m thick, and has good reservoir property. The average effective thickness of the gas-bearing zones is 154.1m, with average porosity 12.7% and average gas-bearing satu-ration 69%. 95.5% of the gas reserves concentrates in the sandstone of the gas field. There were 16 pay zones producing high yield in the bottom sandstone of Cretaceous and Eogene in wells of Kela-2, -201, -203 and -204, with their daily gas production of single zone from 23.8 $x10^4m^3$ to 104.6$x10^4m^3$ after well completing test. The maximum daily gas production reached 104.6$x10^4m^3$ in interval from 3770 to 3795m in Well.Kela-201 after isochronol testing, with only 4 MPa pressure differential. The maximum daily gas production of interval from 3698.5m to 3916.5m in Well.Kela-203 was over 200$x10^4m^3$ through pilot development.

The natural gas of Kela-2 gas field is very good in quality which is very favorable to develop, with much simple components of methane content over 95%, very dry gas with less condensate and water and without H_2S.

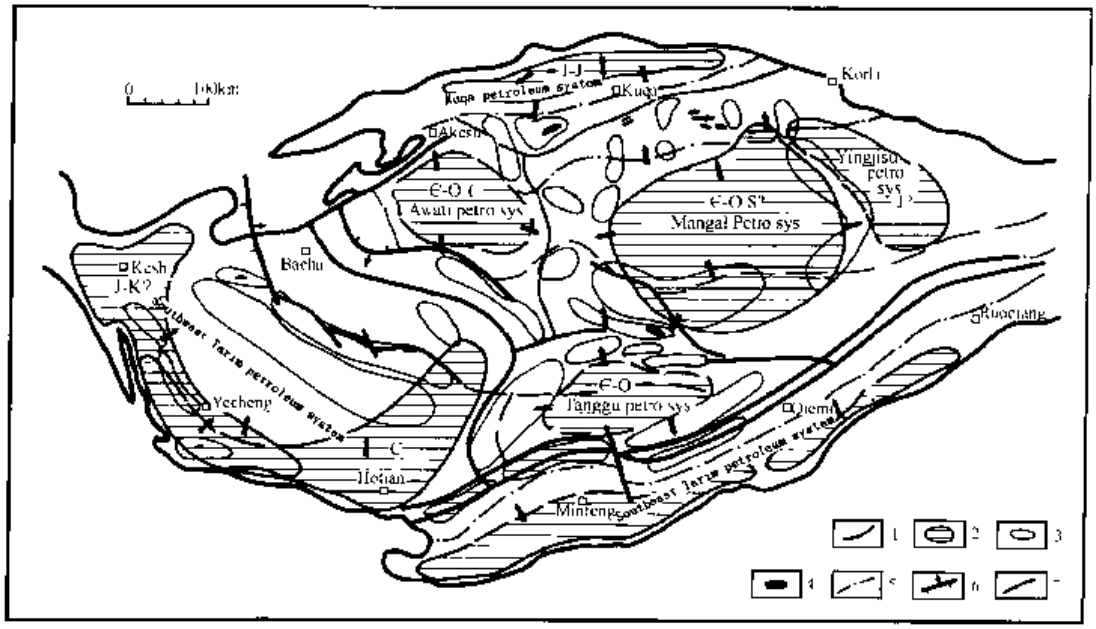


Fig. 6 The division petroleum system and distribution of source rocks in Tarim basin.

1. Boundary of petroleum system 2. Source rocks area 3.play 4. Major oil and gas fields and their number,

5. Boundary of tectonic elements. 6. Fault 7 Basin boundary

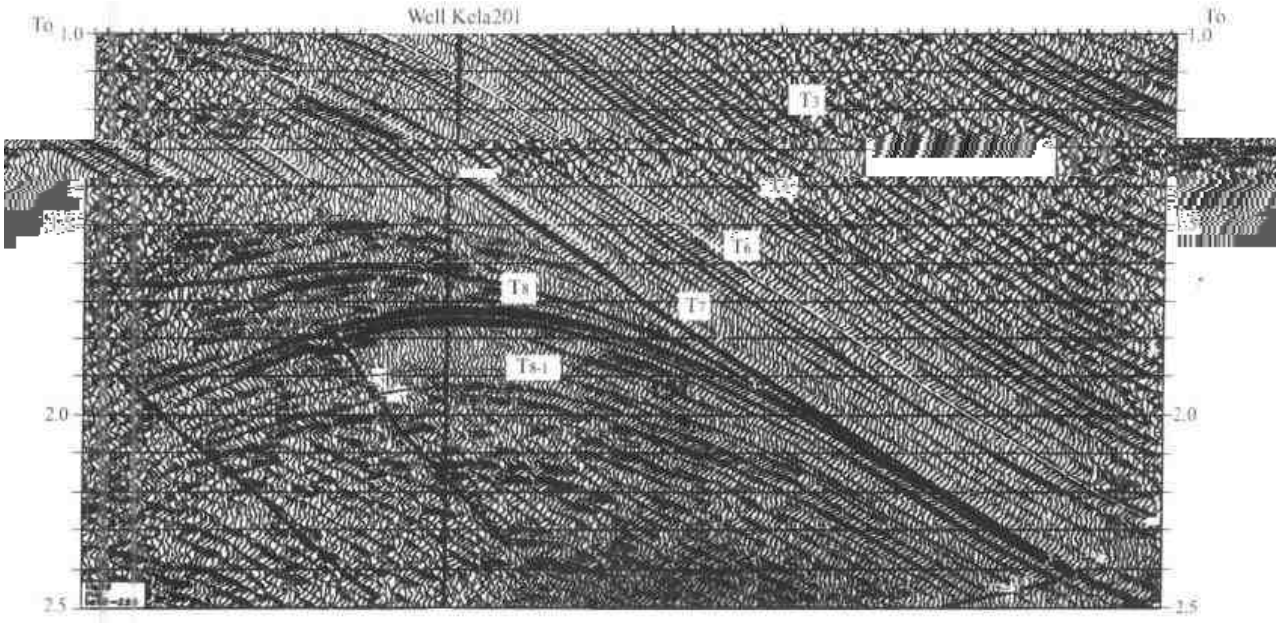


Fig. 7 BC95-230 migrated section through Kela-2 gas field.

3.2 Hetianhe Gas Field

Hetianhe gas field is located at Mazatage structural belt of the south margin of Bachu Uplift. The structural belt is about 90km long from east to west. developed with the traps of No.Ma-2 and No.Ma-4, composed of 5 local highs. Hetianhe gas field was found in 1997 by the first discovery of Well.Ma-4, and was proved in 1998, with the gas-bearing area 143.4km^2 and the gas geological reserves 616.94x10^{8}m^3 (including nitrogen gas

$87.22\times10^8m^3$). The main payzones are bioclastic limestone and glutenite of Carboniferous and carbonate of Ordovicion buried hill. The buried depth of the gas field is from 1546m to 2272m, with the thickness of gas bearing column from 11.5m to 47.8m. The gas field belongs to layered gas reservoir with edge water and block gas reservoir with bottom water. The natural gas is dry gas with nitrogen content over 14%. The formation temperature is from 56 to 72 C and the formation pressure from 13.6 MPa to 24.8MPa. with the pressure coefficient from 0.9 to 1.15. The reserve abundance is $4.3\times10^8m^3$ per square kilometer with single zone's daily production from 5 $\times10^8m^3$ to $17.3\times10^8m^3$ in a well.

3.3 Yaha Oil and Gas Field

Yaha oil and gas field is located at Yaha fault structural belt in the central part of Luntai faulted upfold in Tabei Rise. The structural belt is about 80 km long from east to west and composed of oil and gas-bearing drag anticlines or faulted anticlines under the control of normal fault such as Yaha-1, Yaha-5, Yaha-7, Yaha-2, -3, Yaha-6 and Yaha-4. Yaha oil and gas field was found in December 1993 by the first discovery of Well.Yaha-3. The main payzones are the bottom sandstone of Neogene, the bottom sandstone of Eogene and the sandstone of Cretaceous, with average porosity from 9% to 18% and permeability from 22 $\times10^{-3}$ μ m^2 to 340×10^{-3} μ m^2. The buried depth of the field is from 4900m to 5400m, and the eastern part of the field is 370m higher than the western part. The field belongs to normal density oil field in the western part of the structural belt, condensate gas field with oil ring in the central part and condensate gas field in the eastern part. The maximum thickness of the 2 oil and gas-bearing zones is 30m and 80m, respectively, with daily oil production from 100 m^3 to $300m^3$ of oil and gas production from 10 $\times10^4m^3$ to $30\times10^4m^3$ in most wells by testing of single zone. The proved oil and gas-bearing area is $60.2km^2$, with the proven geological reserves being 4442.9×10^4 tons of oil including 2826.9×10^4 tons of condensate oil and $405.37\times10^8m^3$ of gas including $47.59\times10^8m^3$ of solution gas.

3.4 Yingmai-7 gas field

Yingmai 7 gas field is located at Yingmai 7structural belt about 30km long in the western part of Luntai faulted upfold in Tabei Rise, composed of oil and gas-bearing anticlines under the control of normal south-dipping fault including Yingmai-7– -19. Yingmai-17, Yingmai-23 and Yingmai-21. The gas field was found in 1992 by the first discovery of Well.Yingmai-9. The main payzones are the bottom sandstone of Eogene and the sandstone of Cretaceous, which is mainly composed of feldspathi detritus quartzose sandstone, with average porosity from 16% to 19% and permeability from 160 $\times10^{-3}$ μ m^2 to 338×10^{-3} μ m^2. The buried depth of the field is from 4400m to 4600m, and the oil water contact in the western part of the field is 230m higher than the one in the eastern part. The field belongs to condensate gas field with oil ring, with daily production from 37 m^3 to $105m^3$ of oil and from 18 $\times10^4m^3$ to $26\times10^4m^3$ of gas by testing of single zone. The proved oil and gas-bearing area is $48.3km^2$, with the proven geological reserves being 1950×10^4 tons of oil including 463×10^4 tons of condensate oil and $310\times10^8m^3$ of gas including $14\times10^8m^3$ of solution gas.

4 Conclusion and gas explosive prospect

A great progress has been made in the gas exploration by Tarim Oilfield Corporation. 15 giant–medium sized oil and gas fields are proved. A total proven and probable geological reserves is 9.03×10^8 tons of oil equivalence including proven gas geological reserves $5050\times10^8 m^3$. Gas geological reserve of 3 grade reaches $11010\times10^8 m^3$. So this is the base switching on the project of "western natural gas delivered eastward". Kela-2 gas field is the largest sized gas field proved in China, with gas-bearing area 47.1 km^2 and proven gas geological reserves $2506.1\times10^8 m^3$.

Tarim Basin is a large superposed composite basin made by Palaeozoic cratonic basin and Meso–Cenozoic foreland basin, with the two types of gas resources of cracking gas from marine strata and pyrolysis gas from measure strata. The tectonic position of the Tarim Basin belongs both to basin group at the north margin of Tethys and to a part of gas-rich province of Middle Asian. The basin has good condition forming giant–medium sized gas fields, developed with 4 sets of source rocks including main gas source rocks of Cambro–Lower Ordovician and Trassic–Jurassic, and 5 good reservoir–seal assemblages for gas accumulation. The 4 sets of source rocks grouped as several petroleum systems such as Kuqa, Mangl, Awati, Southwestern Tarim, Tanggu, Southeastern Tarim and Yingjisu and 3 oil-gas regions can be classified obviously. They are Kuqa–Tabei gas region, Mangal oil-gas region and Bachu–Southwest Tarim gas region.

Now, the extensive gas exploration has been being done in Tarim Basin. According to the plan of CNPC, China, a total $1\times10^{12} m^3$ of the proven and probable gas geological reserves will be achieved in Kuqa–Tabei gas-rich region before 2005, which is the base of delivering eastward $120\times10^8 m^3$ of gas. This will promote economic development and environment protection in western and eastern China.

The focal exploration area is in Kuqa petroleum system by Tarim Oilfield Corporation, which has good condition of petroleum geology and great potential forming large gas-rich region. At present, seismic reconnaissance is being done and lots of explosive wells are being drilled. Several new discovered gas pools such as Dabei-1 etc are being evaluated. At the same time, seismic reconnaissance and comprehensive research are being done in Southwest Depression, there will be a very important strategic prepared area for gas exploration. It is expected that the gas exploration in Tarim Basin will get into a new great developing period.

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The Characteristics of High-Quality Clastic Reservoir and the Genetic Analysis in Tarim Basin

Gu Jiayu, Ning Congqian and Jia Jinhua

(Research Institute of Petroleum Exploration and Development, Beijing, China 100083)



Gu Jiayu, a deputy chief geologist, is a council member of China Association of Geology. He has published 58 articles both at home and abroad, and written 4 works about sedimentation and oil and gas reservoir researches.

Abstract: Clastic reservoirs are well developed in the Tarim Basin and are distributed predominantly in the basal Donghetang sandstone of the Carboniferous, the Triassic, the Jurassic basal sandstone, Cretaceous and the Paleogene basal sandstone. The reservoir spaces of the clastic rocks are dominated by pores, with minor fractures. The pores fall into two types, predominantly original pores in the Mesozoic and the overlying sediments, and secondary pores in the Paleozoic sediments. The secondary pores are predominantly of intergranular and intragranular pores, and the diagenesis diversifies in type, with supergene leaching, dissolution by acid derived from lowly matured organic matters and dissolution and precipitation by acid from deep-seated thermo-chemical sulfate reduction being the most important factors influencing the reservoir properties. In the article, the authors make an approach to the genesis of the deep buried high-quality clastic reservoirs in the Tarim basin. The article proposes that the special geological conditions in the Tarim basin, including low geothermal gradient, rapid subsidence and short-term deep burial after Neogene, dissolution of the rock grains and matrixes by acid formational water and unconformities and fault systems formed during multiple tectonic events greatly improved the quality of the reservoirs and that the favorable sedimentary facies created good material bases for the development of the high-quality clasitic reservoirs.

Key words: Clastic Reservoir, Intergranular Pores, Geothermal Gradient, Unconformity, Sedimentary Facies.

Introduction

The Tarim basin covers an area of 560,000 km^2, with the sediments ranging from Pre-Cambrian Sinian through Quaternary in age. So far, hydrocarbons have been discovered in 9 of the 13 formational sequences from Sinian through Quaternary. Most of the hydrocarbon reservoirs are over 3500 m in burial depth, being of deep reservoirs. Since most of the reservoirs remain good properties even at large depth, the diagenetic series, pore type and evolution, and the forming and preservation conditions of the high-quality reservoirs as well as the factors influencing reservoir quality drew quite a great deal of interests and attentions of the geologists.

1 Characteristics of the Clastic Reservoirs in the Tarim Basin

The oil and gas pools found so far in clastic reservoirs make up approximately 82% of the total number of oil and gas pools in Tarim basin, with the proven reserves accounting for 99.7%. The clastic reservoirs are distributed predominantly in the Carboniferous, Triassic, Jurassic, Cretaceous, Paleogene and Neogene, among which the former three ones are currently the major reservoirs.

1.1 Petrologic Features of the Clasitic Reservoirs

The Carboniferous is one of the major reservoirs of the Tarim basin, which can be subdivided vertically into two sets of clastic reservoirs. The basal one is of littoral facies sandstone and is composed predominantly of gray fine sands, silty fine sands and minor medium-grained sands, with a quartz content of 69%–94%, with the thickness ranging 50–200 m, distributed predominantly around paleohighs and generally called Donghetang sandstone. The upper one is of deltaic sandstone consisting predominantly of feldspar quartzite, lithic quartzite and part of sub-feldsub-feldspathic lithic sandstone and sub-lithic arkose. The lithic fragments consist predominantly of lowly metamorphic rocks and mudstone.

Reservoir is well developed in the Cretaceous of the basin, in which sandstone and siltstone account for 65%–75% of the total sediments, predominantly being of siltsone and litnic sandstone. The Tertiary sandstone consists predominantly of lime siltstone and medium-fine grained lithic sandstone, high in quartz content (37%–65%).

Both the texture and composition maturities of the clastic reservoirs are higher in marine sandstone than in nonmarine sandstone, with the order from high to low being Carboniferous, Jurassic (Middle), Triassic, Cretaceous and Tertiary.

1.2 Reservoir Spaces of the Clastic Rocks

The reservoir spaces of the clastic rocks are predominantly of pores with minor fractures. According to the pore classification, the pores can be subdivided into original pores and secondary pores.

1.2.1 Original pores

Reservoirs of the Cretaceous and Tertiary

The Silurian sandstone also kept a certain original pore percent.

1.2.2 Secondary pores

Secondary pores were formed by dissolution and replacement of the rock grains, matrixes and cements or formed after reworking of the original pores. They are often seen with remained clastic grains, matrixes or cements within them. The edge of the remained clastic grains within the secondary pores was often dissolved into irregular, estuary-like and even floating shape. Distribution of the pores is uneven. Such secondary pores play a very significant role in the reservoirs of the Silurian and Carboniferous and also play a certain role in the Triassic and Jurassic. The major characteristics and classification of the secondary pores are described as follows:

Intergranular solution pores: They are the pores among grains, which were formed after the matrix, carbonate cements or grain edges and angles were dissolved or replaced. Such secondary pores are quite ununiform in distribution, size and shape.

Intragranular solution pores: Such a kind of solution pores was formed partly or completely due to the dissolution or replacement of some internal compositions of the original clastic grains. The dissolution often occurs within the relatively unstable grains, such as feldspar grains and lithic fragments, or occurs along week texture lineaments, such as joints and microfractures. The intragranular solution pores are commonly distributed celularly or irregularly and are often connected with the intergranular solution pores.

Moldic super-large pores: When some of the clastic grains were completely dissolved or replaced, there will form moldic pores at the original grain locations. Such pores will keep the shape of their original grains. If the pore space is larger than the original grains, making the grains take a floating shape, the pores can be classified as super-large moldic pores.

Solution fissures: Strictly speaking, such spaces can not be classified as secondary pores. However, since they were formed by dissolution along some weak lineaments, such as structural fractures and joints, we still classified them as secondary pores. The solution fissures are often 0.05–1.0 mm in width. They can act as conduits for fluids and can also provide fluids for the development of other pores.

1.3 Diagenesis and Pore Evolution

1.3.1 Dissolution in the diagenesis

The diagenesis in the Tarim basin includes compaction, cementation, replacement, dissolution and recrystallization etc. In the article, the author will focus on discussing the dissolution, of 3 types, which are the major factor controlling the development of the secondary pores.

(1) Supergene leaching. Multiple tectonic movements in the Tarim basin made the sediments, especially the unconformity and its underlying sediments, uplifted and emerged, suffering leaching and weathering by meteoric water. Degypsification, dedolomitization and dissolution occurring during the process improved the reservoir quality of the sediments. For example, the reservoirs along the unconformities of top Silurian/Carboniferous and top Carboniferous/Jurassic obviously improved in porosity. This is just a result of the leaching of meteoric water.

(2) Dissolution by organic acid from lowly matured organic matters.

The kerogen of the hydrocarbon source

rocks produced large amount of organic acid through pyrolysis and oxidative pyrolysis during lowly mature stage, which dissolved into formational water. The salinity of the formational water in the Tarim basin is high, 21.64×10^4–23.08×10^4mg/l in the Tarim North area (Tabei), and 18.04×10^4 mg/l (the highest) in the Central Tarim area (Tazhong). The Cl^- concentration of the formational water also is very high, about 2–7.5 times higher than that of the other Chinese basins. The pH value of the formational water ranges 5–7, occasionally 3–4, reflecting the formational water is sour. For example, the Carboniferous formational water in the Donghetang area has a pH value ranging 5–6.5, in which the water from authigenic kaolinite ranges 5–7. The sour water dissolved aluminosilicate, resulting in authigenic kaolinite. The acid is predominantly of organic acid or carbonic acid derived from lowly matured kerogen. Therefore, the kaolinite content in the Carboniferous sandstone is high, up to 60%–90%.

$$2KAlSi_3O_8 + 2CH_3COOH + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2 + 3H_2O + 2CH_3COO^-$$

$$2KAlSi_3O_8 + 2H_2CO_3 + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2 + 8H_2O + 2HCO_3^-$$

Study of the organic acid reflects that the organic acid concentration is controlled predominantly by temperature, age of the formation and unconformity. The organic acid consists of formate, ethanoic acid, benzoic acic, lactic acid, propionic acid and butyrate, dominated by ethanoic acid. The releasing peak of organic acid is within a geotemperature range of 85–135°C, and the concentration of organic acid reached the highest at the unconformity and within a 50m range below the unconformity. For example, in the Lunnan area, the organic acid concentration reached up to 1852×10^{-6} and 1700×10^{-6} at the unconformities of Carboniferous/Ordovician and Carboniferous/Silurian and within the range of 50m below the unconformities, respectively. The younger the unconformities, the lower the organic acid concentration, e.g. the organic acid concentration being 873×10^{-6} at the Jurassic/Carboniferous unconformity whereas being 104×10^{-6} at the Cretaceous/Jurassic unconformity. This presents a positive correlation to the secondary pore development.

(3) Dissolution and precipitation caused by acid from deep-seated thermal chemical sulfate reduction.

The sulfate reduction occurred predominantly within a depth range of 5400–6000m (with the temperature reaching 130–135 °C) in the Donghetang area. The gypsum in sediments provided enough SO^{2-}_4 for the formational water, as is evidenced by the pseudomorphic gypsum crystals and dissolution phenomena seen in cores. Additionally, it might be seen that clastic grains and carbonate were replaced into clottedly cemented pyrite or grained pyrite so long as there were hydrocarbon in reservoirs.

$$SO^{2-}_4 + 2C + 2H_2O \rightarrow 2HCO^-_3 + H_2S$$

$$Fe^{2+} + H_2S \rightarrow FeS + 2H^+$$

1.3.2 Pore evolution

The pore evolution of the clastic rocks in the Tarim basin was influenced by many factors, such as sedimentary environment, tectonic events, burial history, tectonic stress field, geotemperature field and thermal evolution of organic matters. Therefore, it differs largely in or at different places, different horizons and different depths. Generally, the section above 3600m is original pore developed zone, from 3600m to 4300m is

original and secondary pore mixed zone and from 4300 to 6000m is secondary pore zone. Now, let's take the Carboniferous of Donghetang area as an example to discuss briefly the pore evolution history (Fig.1).

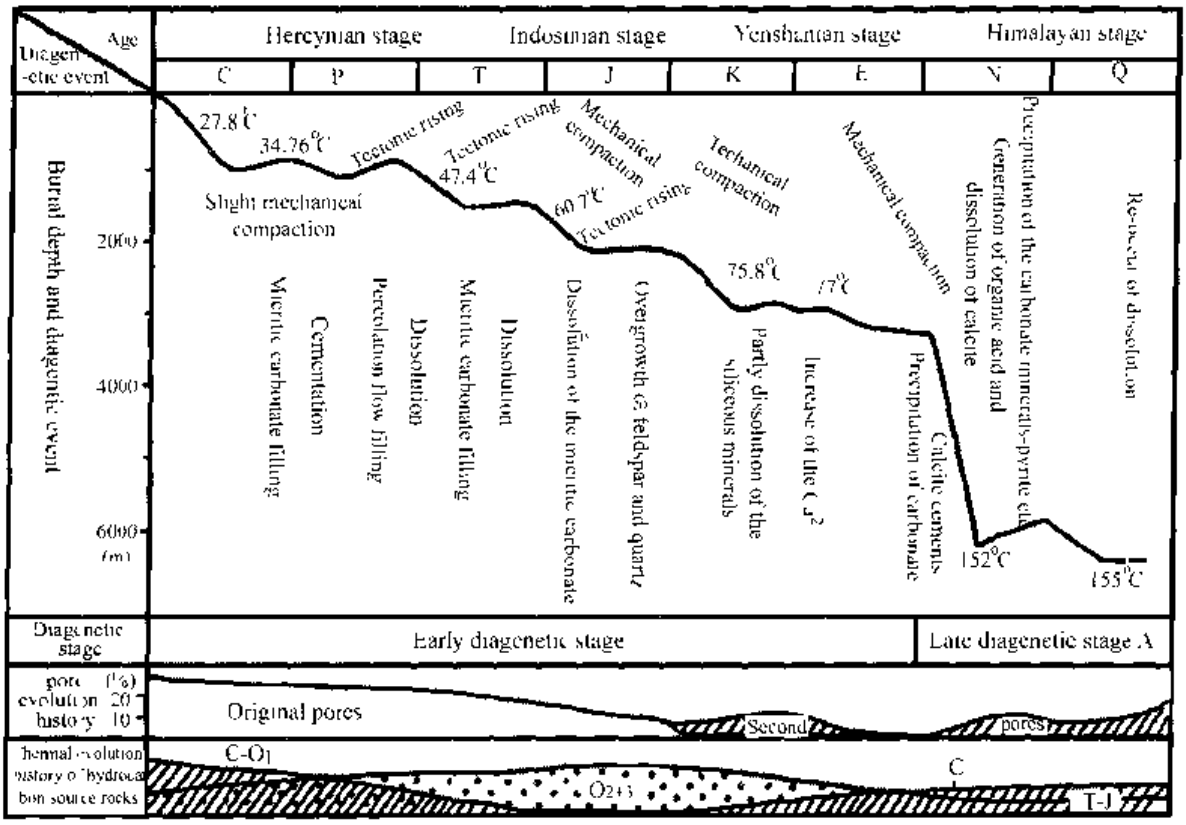


Fig. 1 Pore evolution of the Carboniferous in Donghetang area, the Tarim basin.

The pore evolution of the Carboniferous clastic rocks in Donghetang area has undergone three stages.

(1) Stage with original pores gradually decreasing.

The Carboniferous sediments remained within a depth range of 0 to 1900m till the end of the Jurassic, while the pores underwent only a slight mechanical compaction, cementation and infilling by micritic carbonate, percolation flow infilling and part dissolution, with only clay films formed over the grains. During this stage, the pores are predominantly of original pores, with the porosity gradually decreased from 30% down to 20%, with part of secondary pores formed.

(2) The first development stage of second pore.

At the end of the Jurassic through the Early Tertiary, with the depth ranging from 1900m to 2600m, the original pores decreased since mechanical compaction increased. But, however, the original pores still dominated. During this stage, the geotemperature reached 80 °C with the depth increase, and the hydrocarbon source rocks of the Middle and Lower Ordovician entered initial maturation, releasing a certain amount of carbonic acid and organic acid. As a result, while the feldspar and quartz occurred initial overgrowth, part of

the silicate minerals were dissolved by acid, forming some secondary pores and leading to co-existing of original pores and secondary pores. Now, the porosity of the rocks reduced to about 18% in average, but still with the original pores dominated.

(3) The second development stage of secondary pore.

From Early Tertiary to the present, the burial depth of the sediments greatly increased from 2600m to 5000–6000m due to rapid subsidence, while the temperature increased from 80 °C up to 135 °C. On one hand, the greatly enhanced mechanical compaction led to the rapid decrease of original pores, and on the other hand, organic acid and carbonic acid were produced since the Middle and Upper Ordovician source rock continued to expulse hydrocarbon and the Carboniferous source rock began maturation. Although some ferruginous sulfate minerals, pyrite and kaolinite began participation during this stage, the acid caused part of the aluminoscorodite grains and calcite cements occur disso.ution, leading to formation of secondary pores. During this stage, the secondary pores dominated, with the total porosity being around 15%.

2 Discussion on the Deep-buried High-quality Clastic Reservoirs

Although all the current hydrocarbon reservoirs in the Tarim basin are at burial depth over 3500m, occasionally reaching approximately 6000m (the Carboniferous Donghetang sandstone in the Donghetang area), the quality of the reservoirs remained very good and can be classified as high-quality reservoirs. For example, the Carboniferous Donghetang sandstone at 6000m depth has an average porosity of 15%, the highest reaching 24%, and an average permeability of 64.04×10^{-3} um^2, the highest being 1911×10^{-3} um^2 (according to 178 samples). It is a rare thing in the world petroleum geology history that so good reservoirs can be kept at such a large burial depth.

Discussion on the issue will be of important theoretic and practical value.

(1) The low geothermal gradient enables preservation of original pores and meanwhile causes the deep-buried reservoirs still at peak secondary pore developing stage.

It is widely accepted that the Tarim basin is a low geothermal gradient basin, with the average geotemperature gradient ranging 1.8 —2.0 °C/100m, being 0.5 —1.0 °C/100m lower than the other basins of China. Due to the low thermal gradient and the high anti-compaction capacity of the quartzite sandstone, the quartz grains underwent a very weak pressure solution and still kept being point contacted each other even at so deep a burial depth over 5700m. This enables preservation of original pores in the reservoirs. On the other hand, due to the low thermal gradient, the organic matters remained at the maturation stage although the burial depth had reached over 5000m. A large volume of organic acid and carbon dioxide generated from the organic matters can dissolve part of the early-formed cements, matrixes or even mineral grains, forming some secondary pores and keeping the rocks a high porosity.

(2) Long-time shallow burial and rapid short-time deep burial enable preservation of original pores.

Since the Cambrian, the uplift areas of the Tarim basin had undergone several times of tectonic rising, and the rapid deep burial did not occur until the Neogene, about 23.3 Ma.

For example, the Carboniferous sediments of the Lunnan area kept a burial depth of 1400–1800m during the 257 Ma from deposition to the end of the Paleogene. They were deeply buried over 5000 m after the 3300 to 3600 m thick sediments of the Neogene was deposited during the 23.3 Ma from Neogene to the present. Because the deep burial time is short and the geothermal gradient is low, the original pores can be kept within the high maturity rocks.

(3) Dissolution of part of the cements or mineral grains by sour formational water increases the porosity: In the terrigenous clastic sediments, the carbonate rocks or carbonate grains moving in from outside met dissolution after the water media changed, and when the formational water reached carbonate saturation, the carbonate began precipitation, forming syngenetic micritic carbonate cements. With the increase of the burial depth, and when the formational temperature reached 85–135 °C, corresponding to early diagenesis stage B—late diagenesis stage A, a great amount of organic acid generated made the aluminoscoroditic feldspar strongly dissolved, with the Ca^{2-} and Al^{3-} moving away in complex solution. This led to the porosity increase by 12.6% and 12.5% with the development of secondary pores. On the other hand, the authigenic kaolinite dispersed among the rock grains, with less influence on the porosity and permeability, and formed a clay film over the quartz grains, prohibiting the quartz grains from overgrowth. This is good to preserve reservoir pores.

(4) Modification of the diagenetic system by unconformity and structural faults improves the reservoir property.

The Tarim basin has undergone several tectonic movements, leading to 7 large unconformities and several fault systems of different ages. The unconformities and fault systems acted as oil and gas migration pathways, and meanwhile, the unconformities underwent long time weathering and leaching. Therefore, the organic acid concentration reaches the highest along the unconformities and faults. For example, in the Donghe-2 well, the organic acid concentration reaches 873×10^{-6} at the unconformity between Jurassic and Carboniferous. Meanwhile, along the unconformities, kaolinite obviously increased due to dissolution of the feldspar, and leaching caused carbonate dissolved and moved. And as a result, the reservoirs along the unconformities and the neighboring intervals were obviously improved. Generally, the unconformities are 2%–5% higher in porosity than the original rocks or the original non-fractured rocks.

(5) Favorable sedimentary facies provided a basis for the deep buried high-quality reservoirs to develop.

The study shows that the sedimentary facies is a basis controlling the high-quality reservoirs development. In the marine sediments, the beach subfacies and subtidal high-energy microfacies, and in the non-marine sediments, the delta front facies, the fan delta front sub-water braided facies and the shallow beach facies of the lacustrine sediments are all of high energy during sedimentation and are long lasting, and as a result, the sediments in these facies are high in both composition maturity and texture maturity, with low matrix content. The quartz grains within the sediments have a high anti-compaction capacity and are difficult to dissolve, and thus favorable for original pores to preserve. The pure sandstone has very less

1 Contents of Natural Gas

Natural gas is composed of hydrocarbon gas and non-hydrocarbon gas, and the latter includes CO_2, N_2, H_2S and rare gases. Natural gas in Tarim Basin is dominated by hydrocarbon gas, with a small part of CO_2 and N_2.

1.1 Composition of Hydrocarbon Gas

Methane is the major content in hydrocarbon in natural gas from Tarim Basin, it covers 70–95% of the whole contents in different samples (Zhou et al., 1998) with a main distribution percentage of 80–90%. Methane covers generally 80–95% of total hydrocarbon gas thus the natural gases in Tarim Basin are mainly of wet gas. The maturation and type of organic matter in the source rock determine whether natural gas is dry or wet. Cracking gas from oil during overmature is drier than that from kerogen during mature period; while gas from humic OM is drier than that from saprolific OM. Natural gas with high dry-coefficient (the ratio of methane in total hydrocarbon gases) includes the highly-mature humic-type gas from the Kela-2 well in the Kuqa Depression (its dry-coefficient is about 0.988 to 1.00) and highly-mature saprolific gas in the southern part of the North Uplift.

Table 1 Geochemical characteristics of natural gas from main gas fields in Tarim Basin

Structural Unit	Gas Field	Producing Bed	Gas Content(%)					$\delta^{13}C$(‰)			Genetic Type
			CH_4	C_2H_6	C_3H_8	CO_2	N_2	CH_4	C_2H_6	C_3H_8	
Kuqa Depression	Kela-2	K	98.05	0.40	0.40	0.94	0.60	-27.3	-19.4		
Northern Depression	Yingmai-7	E	86.63	8.01	1.38			-33.5	-22.0	-23.9	Humic
	Yaha	E	76.55	14.91	4.88			-32.9	-24.7	-21.2	
	Yangtake	E	77.88	8.08	3.06		7.86	-38.7	-24.1	-24.3	
	Jilake	I	76.15	6.52	4.73	0.04	7.17	-36.1	-34.6	-32.1	
	Yakela	O	84.51	5.01	2.00	2.88	3.85	-39.9	-32.0	-30.9	Saprolific
Southwest Depression	Hetianhe	C	83.22	2.05	0.65	1.55	12.11	-41.8	-34.6	-35.8	
	Kekeya	N	82.41	8.75	2.29	0.11	5.39	-38.0	-26.0	-25.3	Humic

1.2 Composition of Non-hydrocarbon Gas

1.2.1 Nitrogen

Nitrogen concentration in natural gas in Tarim Basin varies largely from 0 to 40%. Natural gas with high nitrogen content is mainly distributed in the Tazhong Area, and some is also found in the southern part of the North Uplift. Nitrogen content in natural gas from the Kuqa, and the Southwest Depression is generally below 4%.

1.2.2 Carbon dioxide

Carbon dioxide contents in 90% of natural gas samples from Tarim Basin is lower than 6%, most of them is less than 2%. However, a small part of samples from the southern part of the North Uplift have CO_2 content of as high as over 20%.

2 Carbon Isotope Composition and Genetic Type of Natural Gas

2.1 Carbon Isotope Composition of Alkanes

Carbon isotope composition of alkanes is an important parameter to distinguish the genetic type of natural gas, which depends on the maturation and type of organic matter in the source rock. Maturation degree influences carbon isotopic composition of methane to a large degree. $\delta^{13}C$ of Methane formed during biochemical period can be lighter than −60‰. During mature to over-mature period, methane from humic OM is much richer in ^{13}C than that from saprolific OM: $\delta^{13}C$ of the former is generally −52‰– −24‰ while $\delta^{13}C$ of the latter is generally −58‰– −30‰. So a sample of natural gas from saprolific OM of higher evolution degree can have $\delta^{13}C$ value as heavy as that from humic OM of lower evolution degree. Compared with $\delta^{13}C$ of methane, $\delta^{13}C$ of other alkanes is less influenced by maturation and migration and can provide more accurate information of source rock. Study on natural gas samples from large and medium gas fields in China showed that $\delta^{13}C$ of ethane from humic OM is generally heavier than −27‰ while that from saprolific OM is generally lighter than −25‰; while natural gas with $\delta^{13}C$ of ethane between −25‰ and −27‰ can be either from humic OM or from saprolific OM, or the mixture of these two types of gas (Song, 1998). Since methane is the dominate component in natural gas, it's more efficient to correlate gas and source rock combining $\delta^{13}C$ values of both methane and ethane. $\delta^{13}C$ of alkanes in natural gas from Tarim Basin varies largely. $\delta^{13}C$ of methane varies from −45‰ to −25‰ while that of ethane varies from −43‰ to −18‰. In the $\delta^{13}C_1$–$\delta^{13}C_2$ relation chart there are four regions representing four different types of natural gas (Fig. 1).

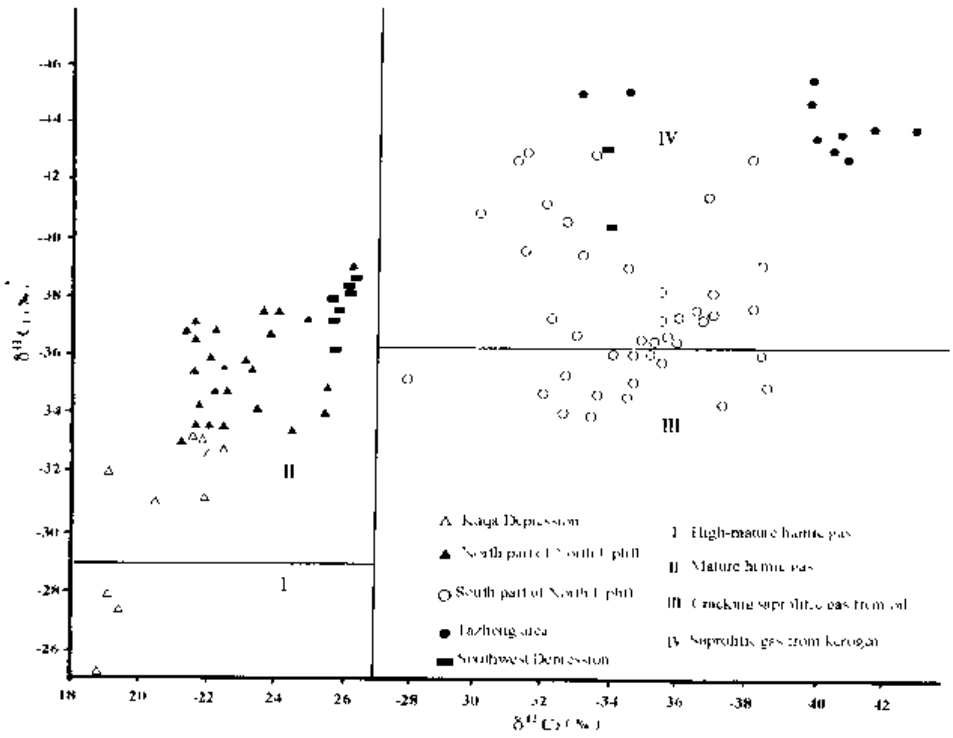


Fig. 1 Genetic types of natural gas from Tarim Basin.

(1) In region I is plotted the samples of over-mature gas from humic OM, with $\delta^{13}C_1$ of −27.8‰ - −25.1‰ and $\delta^{13}C_2$ of −19.4‰ - −18.8‰, the heaviest values appeared in the whole basin. These samples are from the Kela-2 Gas Field in the Kuqa Depression, the source rock is the Jurassic coal measure and the producing bed is Cretaceous sandstone.

(2) Plots in region II represents mature gas from humic OM, with $\delta^{13}C_1$ of −39‰ - −29‰ and $\delta^{13}C_2$ of heavier than −27‰. These samples are mainly from the gas fields in the Kuqa Depression, the north slope of the North Uplift, and the Southwest Depression. Their source rock is also Jurassic coal measure and the producing beds are Cretaceous and Eocene sandstone.

(3) Samples of cracking gas from saprolific oil is plotted in region III of Fig. 1, with $\delta^{13}C_1$ of −36‰ - −33‰ and $\delta^{13}C_2$ of lighter than −27‰. These samples are from the Santamu and Jilake area in the south part of the North Uplift, and their source rock is the Lower Paleozoic marine mudstone or marl.

(4) Samples plotted in region IV are gas from saprolific kerogen, and their $\delta^{13}C_1$ values are less than −36‰ and $\delta^{13}C_2$ values are less than −27‰. Natural gas from Paleozoic in the Yakela, Donghetang and South Yingmaili areas belongs to this type.

Considering the minimum $\delta^{13}C$ values of natural gas of each type, it can be seen that the difference between the $\delta^{13}C_1$ values of mature humic gas and mature saprolific gas is about 7‰, while the difference between the $\delta^{13}C_2$ is about 16‰; the difference between the $\delta^{13}C_1$ values of over-mature humic gas and over-mature saprolific gas is about 8‰, while the difference between the $\delta^{13}C_2$ is about 19‰. Thus we can conclude that the overlapped scope of $\delta^{13}C_2$ values of humic gas and saprolific gas is more narrow than that of $\delta^{13}C_1$.

The distributive pattern of carbon isotopic composition of methane, ethane, propane and butane can help to determine the mixture of humic gas and saprolific gas. The above mentioned pattern for a biogenic natural gas from a single source rock should be a line showing a more heavy $\delta^{13}C$ with the increase of carbon number in an alkane molecule, i. e., $\delta^{13}C_1<\delta^{13}C_2<\delta^{13}C_3<\delta^{13}C_4$; however, some samples from Tarim Basin do not accord with this regularity. This might be caused by the following reasons:

(1) The mixture of natural gas from different OM. For example, Some humic gas samples from the Kuqa Depression and the North Uplift have lighter $\delta^{13}C$ values of propane or butane. This phenomenon can be explained by the mixture of Jurassic humic gas with gas from Jurassic and Triassic mudstone with saprolific OM, which generated more propane and butane with lighter $\delta^{13}C$ values.

(2) The mixture of natural gas generated in different maturation period of source rock. This mechanism can help to explain the reverse order between the $\delta^{13}C_1$ and $\delta^{13}C_2$ of natural gas from the Lunnan and Caohu areas. The entrapment of over-mature saprolific dry gas derived from cracking-oil with methane rich of ^{12}C into a previously formed mature gas reservoir made the $\delta^{13}C_1$ value heavier than $\delta^{13}C_2$.

(3) Fractionation during dissipation. There appeared a reverse order of $\delta^{13}C$ values in the gas sample from the segment of 2391–2394m in Well Dawan-1 in the Kuqa Depression, i. e., $\delta^{13}C_1>\delta^{13}C_2>\delta^{13}C_3>\delta^{13}C_4$ (their values are −17.9‰, −21.4‰, −26.2‰ and −27.5 ‰ respectively). Since there is no magmatic

activities and helium isotope also indicate a crustal origin of this natural gas, the possibility of abiogenic (or called inorganic) origin of this gas can be ruled out. From the character of this reservoir, the reverse order of alkane carbon isotope composition might be caused by dissipation due to the insufficient gas supplement. An alkane molecule with a ^{13}C atom is heavier than that consists of only ^{12}C atoms (and hydrogen atoms) and migrate more slowly; this fractionation effect is most obvious for the lightest alkane molecule of methane. So, in a reservoir with more dissipation and less supplement, a reverse order of $\delta^{13}C$ values of alkanes can be met. Since the difference between $\delta^{13}C_2$, $\delta^{13}C_3$ and $\delta^{13}C_4$ is less than that between $\delta^{13}C_1$ and $\delta^{13}C_2$, the phenomena of $\delta^{13}C_2>\delta^{13}C_3$ or $\delta^{13}C_3>\delta^{13}C_4$ is more common than $\delta^{13}C_1>\delta^{13}C_2$.

2.2 Carbon Isotopic Composition of Carbon Dioxide

From Table 2 it can be seen that $\delta^{13}C$ values of CO_2 in natural gas from Tarim Basin vary between −7.8‰ and −22.6‰. $\delta^{13}C$ values of CO_2 from most parts in the basin is lower than −10‰; only those of some Paleozoic natural gas from the North Uplift are as heavy as −7.8‰ to −9.9‰.

There two types of carbon dioxide from their generation, one is organic type, formed from deposited organic matter; the other is inorganic type formed from carbonates or derived from mental. Our previous study on over 200 natural gas samples from China indicated that there is obvious difference between $\delta^{13}C$ values of organic and inorganic CO_2. $\delta^{13}C$ values of organic CO_2 in natural gas vary between −8‰ and −39‰, generally between −12‰ and −17‰; while $\delta^{13}C$ values of inorganic CO_2 vary between +7‰ and −10‰ and mostly between −3‰ and −8‰. Usually a $\delta^{13}C$ value heavier than −8‰ indicates inorganic origin of CO_2 and a $\delta^{13}C$ value lighter than −10‰ indicates organic origin (Dai et al., 1995). From this standard, CO_2 of most samples in Table 2 are of organic origin; only $\delta^{13}C$ values of CO_2 in Paleozoic gas samples from wells Yaha-7X-1 and Donghe-11 may partly be of inorganic origin. Inorganic-origined CO_2 is formed either from the chemical reaction of carbonates or from volcanic-magmatic activities. CO_2 in these two samples should be a mixture of CO_2 from organic origin and carbonates owing to the following reasons:

(1) Neither obvious volcanic and magmatic activities nor large deep rift is observed in the region of the above-mentioned two wells; these two samples are produced from Paleozoic carbonate strata, so carbonate is a more reasonable source of CO_2.

(2) Helium isotope is an important evidence to distinguish mental and crustal gas. Helium isotope composition is usually expressed as R/Ra, the ratio of $^3He/^4He$ of sample to $^3He/^4He$ of air. Helium from the crust is characterized by R/Ra much lower than 1, while helium from the mental is characterized by R/Ra higher than 1. R/Ra values in natural gas from Tarim Basin are commonly lower than 0.15, the mean value of R/Ra values in natural gas from the Kuqa Depression is 0.05, so CO_2 accompanying with helium should also derived from the crust.

(3) $\delta^{13}C$ values of CO_2 from reaction of carbonates should be heavier than those from magma. Shangguan (1990) pointed out that $\delta^{13}C$ value of CO_2 from metamorphism of rocks is about +1‰– −3‰. $\delta^{13}C$ values of

CO_2 in Paleozoic natural gas from wells Donghe-23 and Yaha-7X-1 are much lighter than typical $\delta^{13}C$ values of CO_2 from metamorphism of rocks, indicating the mixture of organic and inorganic CO_2.

Table 2. Carbon Isotopic Composition of CO_2 in Natural Gas from Tarim Basin

Region	Well	Producing Bed	Depth (m)	$\delta^{13}C_{CO_2}$ (‰)	Genetic Type
Kuqa Depression	Kela-3	E	3540–3550	-10.8	Organic type
	Kela-201	K_2	3770–3745	-22.6	
	Yinan-2	E	1472–1481	-15.4	
	Yinan-4	J	4578–4758	-11.7	
	Dabei-1	J	3619–3677	-12.0	
North Uplift	Yangta-5	F	5568–5620	-18.0	
	Yingmai-9	E	5294–5321	-15.9	
	Yingmai-2	K	4945–4949	-11.0	
	Donghe-2	O	5759–6050	-21.8	
	Donghe-23	J	5405–5445	-15.1	
	Yaha-7X-1	Cam.–O	5877–5898	-9.9	Mixed type
	Donghe-11	Carb.	5780–5790	-7.8	
Tazhong Uplift	Tazhong-4	Carb	3566–3670	-13.1	Organic type

3 Light Hydrocarbons in Natural Gas

3.1 C_6 Hydrocarbons

It's very obvious in the gas samples from Tarim Basin that C_6 hydrocarbons in humic gas are rich of benzene (Zhou, 1998). Benzene covers 11.0% to 33.9% of the sum of hexane, cyclohexane and benzene in humic gas, while it covers lower than 5% of that in saprolific gas.

3.2 C_7 Hydrocarbons

Composition of C_7 hydrocarbons is often applied to study the origin of natural gas. Different C_7 compounds have different precursors: methylcyclohexane derives mainly from lignin of higher plants, it is abundant in humic gas; dimethylcyclopantane compounds come mainly from lipoid of aquatic biomass, normal heptane comes mainly from algae and bacteria, they indicates saprolific origin. In Tarim Basin, natural gas from the structural belts of Yaha, Yingmai-7, Tiergen and Yangtake in the Kuqa Depression and the North Uplift is relatively rich in

methylcyclohexane, methylcyclohexane covers generally 40% to 60% in the sum of normal heptane, dimethylcyclopantane and methylcyclohexane, which is characteristic for humic gas. Meanwhile, since the OM type in source rocks differs in the above area, the composition of C_7 hydrocarbons also varies largely: methylcyclohexane is a bit lower in gas from terrestrial lacustrine OM than that in gas from coal measure. Normal heptane is abundant in gas from the Tazhong Uplift and North Uplift, indicating a saprolific origin

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Organic Geochemistry of Middle–Upper Ordovician Source Rocks in Tarim Basin, Northwest China

S.C. Zhang [1,2] B.M. Zhang[2] M.J. Zhao [2] F.Y. Wang [3]
L.Z. Bian[4] D.R. Wang [1,2] Z.H. He [1,2]

(1 Key Laboratory of Petroleum Geochemistry, China National Petroleum Corporation (CNPC), Beijing 100083, P.R. China. 2 Research Institute of Petroleum Exploration & Development, CNPC, Beijing 100083, P. R. China; 3 Petroleum University, Beijing 102249, P. R. China; 4 Department of Geologic Sciences, Nanjing University, Nanjing 210093, P.R.China)



Zhang Shuichang received a B.S degree in petroleum geology from Chengdu College of Geology in 1983, a M.S. degree from the Lanzhou Institute of Geology, the Chinese Academy of Sciences, in 1986, and a Ph.D. from China University of Geosciences in 1991. He has worked as a senior geolcgist at RIPED. CNPC since 1991 or applications of organic geochemistry in understanding petroleum systems and exploration problems.

Abstract: Tarim Basin is the only area where commercial oil pools formed by the marine Low Paleozoic strata have been discovered in China continent. The application of age- and environment-related biomarks such as triaromatic dinosteranes, 24-norcholestanes and C_{28}steranes indicates that almost commercial oils come from the argillaceous limestone and marl of the Middle–Upper Ordovician System. These source rocks with a thickness of 80–300m and TOC content of 0.5%–5.54% are widely distributed along the northern slope of the Tazhong (Central Tarim Basin) and the southern slope of the Tabei (Northern of the Tarim) lifts. In the Keping area and the Awati depression, shale of open bay or gulf facies was deposited, whose TOC ranges from 0.5% to 2.78% and the thickness is about 110m. This set of source rocks has reached major liquid hydrocarbon generating stage since 200Ma. The sedimentary facies and high organic productivity chiefly control the developments of the source rocks.

Key words: Ordovician; slope facies; triaromatic dinosteranes; 24-norcholestanes; C_{28}steranes; history of hydrocarbon-generating; Tazhong; Tarim basin.

Introduction

Tarim Basin, located in northwest China, is a huge-scale composite basin containing many sets of hydrocarbon source rocks[1-4], where have undergone several phase of tectonic movements and multiple periods of hydrocarbon generation, migration and accumulation. The resultant complexity of the basin makes the petroleum geology difficult[5]. It is contro-

versial in the confirmation of the oil and gas source rocks, especially in confirming the marine source rocks that were deposited within the platform-basin region. The previous research suggests that the major source rock in Tarim Basin should compost Cambro-Ordovician marine sediments [1]. However, it remained unclear for so many years that if the Cambro–Ordovician systems with 5km~7km thick are all source rocks and how much the source rocks have contributed to the commercial hydrocarbons.

Based on the geological and geochemical investigation and data interpretations of the rock samples taken from 200 wells in Tarim Basin, two sets of efficient Cambrian and Middle–Upper Ordovician hydrocarbon source rocks are found in the basin. Potential Cambrian source rocks deposited in starved basins and lagoonal facies has extensive distribution and a thickness of 120–415m. Average TOC values within individual wells generally range from 1.24% to 2.28% but reach a maximum of 5.52%[5]. This source rocks, however, are overmature (VRE>2.0%) in the eastern Manjaer depression and highly mature(VRE values of 1.65% to 1.70%) in the western part of the basin based upon vitrinite reflectance equivalence (VRE), which suggest that the remaining oil-generative potential of these source rocks must be low at least since the Hercynian, but may be effective for gas generation. Middle–Upper Ordovician, however, is probably the most practical hydrocarbon source rock of the basin. In this study, the probability of regarding Middle–Ordovician as the principle oil source stratum of the basin is demonstrated in detail from facts such as the source rock distributions, the oil-source rock correlation and the hydrocarbon-generating history.

1 The development of the oil source rocks of Middle–Upper Ordovician in Tarim Basin

The tectonic and sedimentary palaeo-geographic framework of Tarim Basin in Middle–Late Ordovician age is at the stage of marine flysch construction of foredeep basin evolution under background of kinetic continent margin. It has the divergence of the starved basin, platform and gulf. The hydrocarbon source rocks were only developed in the later two sedimentary facies (Table 1 and Fig.1). High organic abundance and moderate degree of maturity characterize the source rocks. Moreover, the rocks bearing higher organic matter moved from the margin of the Craton platform to its center during Middl–late Ordovician age as the ascending of the sea level and the movement of the active continent margin. Middle–Upper Ordovician source rocks can be divided into three sections vertically, including the Yijianfang formation (upper section of middle Ordovician, O_2y), the Tumxiuke formation (top of middle Ordovician and bottom of upper Ordovician, $O_{2-3}t$), the Yingan (O_3y) and the Lianglitage (O_3l) formation, in which the source rocks of the Yingan and the Lianglitage formations are the most significant discovery of Tarim basin.

The source rock of the Yingan formation, the shale bind of mudstone sediment in open bay or gulf facies, occurs in the Keping area and the Awati depression. Whose TOC is 0.5%–2.25% in a thickness of 97m, and VRE values are 1.1% to 1.3 %. Potential source rock of the Lianglitage formation (O_3l) are widely distributed along the northern slope and the crest of the Tazhong (middle part of the basin) uplift with a thickness of about 80–100m (Fig.2). These are mainly muddy micrite limestone, marls and lime mudstone

deposited in shelf edge and slope settings. The content of TOC ranges from 0.5% to 5.54% and asphalt "A" from 100ppm to 1395ppm. VRE values are between 0.81% and 1.30% that are just at the peak of hydrocarbon generating. Similar rocks exist in some Lunan wells in North Tarim, as well as in some wells near the Hotian River on the Bachu uplift. Both of the organic abundance and the thickness of the source rocks, however, are less than those of the Tazhong. The reason for that is related to the fact that the developing of carbonate is prohibited because of the low terrain and the relative deep and nepheloid water and the fact that the barrier interaction of lacking margin of platform (submarine).

Table 1 The organic characters in various sedimentary facies of Middle–Upper Ordovician in Tarim Basin

	Tazhong N. slope	He3 well	Tabei S. slope	Keping area	Tazhong 28 well	Tazhong 32 well	Tadong 1 well	Qunkel well
TOC %	0.05–5.43/ 0.43	0.21–1.99/ 0.93	0.20–0.85/ 0.42	0.56–2.87/ 1.56	0.02–0.48/ 0.23	0.01–0.53/ 0.21	0.10–0.37/ 0.24	0.06–0.53/ 0.21
Asphalt "A",ppm	100–1395			470–2090				
Thickness, m	80–300	33		40–110				
Facies	*1	*1	*1	*2	*3	*3	*3	*3

*1– Platform-edge slope facies; *2–gulf facies; *3–Super compensated basin facies.

The source rocks of Lower Ordovician developed only within the eastern part of Manjar depression. The distribution and thickness of the source rocks are very limited and appear to be highly- and over-mature based on VRE data, so the suggested remaining generative potential of the source rocks must be low and thus they will be not discussed here.

1 Oil and Source Rock Correlation

The relationship between oil and source rocks should be identified and verified depending on the correlation between them. The correlation is based on the conception that the migrated oil and residual asphalt of the source rocks have no distinct differences in some parameters. Detailed correlation can provide information of the generating of the oil and possible migrating channels. For the correlation, one of the crucial technologies is the biomarker compounds analysis and it is an important way to prospect and identify the source rocks.

Terpanes and steranes are two common kinds of compound of biomarkers. Terpanes come chiefly from the cell wall lipids of bacteria (prokaryote) [6]. Almost all oil contains terpanes because bacteria exist widely in the sediment. The oil generated from different sources rocks deposited under the similar conditions often has the analogous tepane

fingerprints [7], so distinguishing the crude oil types and correlating the oil and source by the relative concentration of terpanes is sometimes not so useful. Steranes come mainly from eucaryote (mostly algae and higher plants). They ordinarily reflect the characteristics of the marine organism of the plankton or benthic algae [8]. Thus, we consider it more efficient to use steranes for the oil-source correlation of such a Paleozoic marine basin as the Tarim than terpanes. Especially, some age- and environment-related steranoid compounds, such as dinosterane, triaromatic dinosteroids (derived from dinoflagellate [9-13]), 24–norcholestane (C_{26}, ocean algae such as diatoms [14-15]) and C_{28}–starene (generated from plankton), have shown favorable application in distinguishing the source rocks and generated hydrocarbons of the Cambrian and Ordovician in the basin.

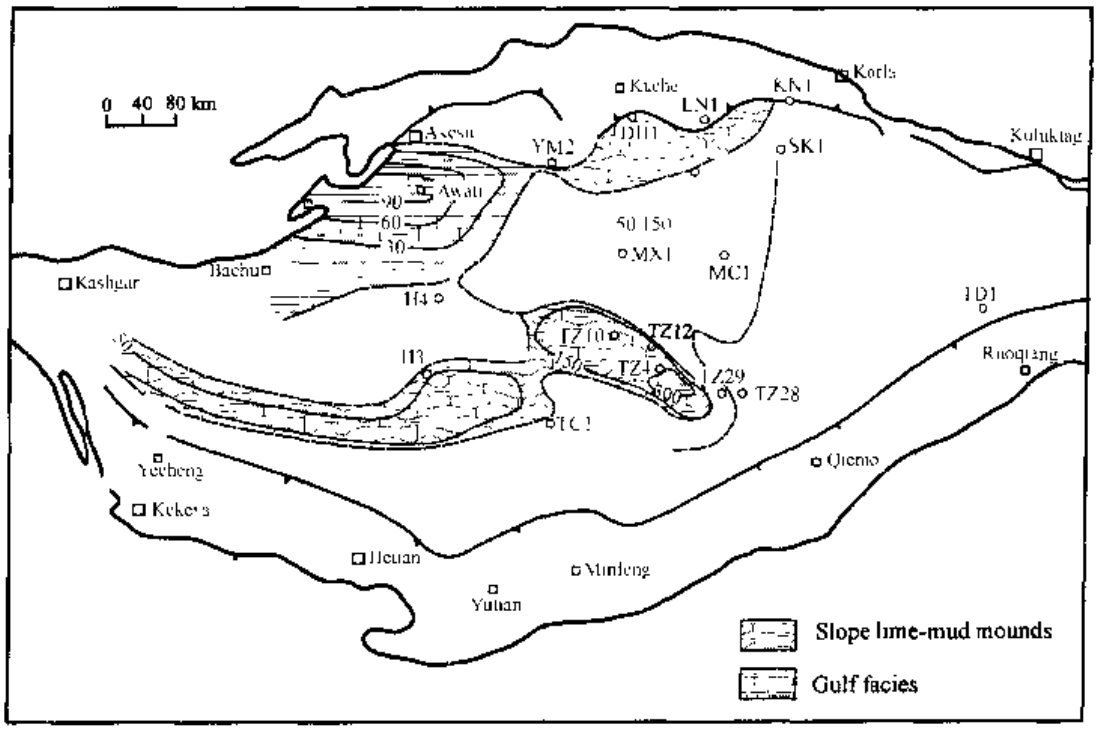


Fig. 1 The distribution of Middle and Upper Ordovician source rocks in Tarim Basin.

The distributions of methylsteranes, triaromtic dinosteroid hydrocarbons and norcholestanes of the marine oils and the rock extracts from the Cambrian and the Ordovician of the basin are shown in Fig 3. It is easily found from this Fig. that the extracts of rocks of the Cambrian are characteristic of the higher abundance dinosterane, 4 α –methyl–24–ethyl cholestane (peak 1 and 2 in the Fig.3), triaromatic dinosteroid (peak 7) and 24–norcholestane (peak 14). But those of the Middle–Upper Ordovician are characteristic of higher abundance 2 α –and 3 α –methyl–24–ethyl cholestane (peak 3 and 4 in Fig. 3b), 3 α –methyl–24–ethyl triaromatic sterane (peak 9), and 27- and 21–norcholestane (peak 15 and 16), while dinosterane and aromatic dinosterane almost can not be detected. The two sets of the source rocks have remarkable differences in the molecular compound composition. Constrasting the crude oils and these rock extracts, we can easily find that the compound distribution (Fig.3 c) of the marine oil are greatly similar to those of the rock

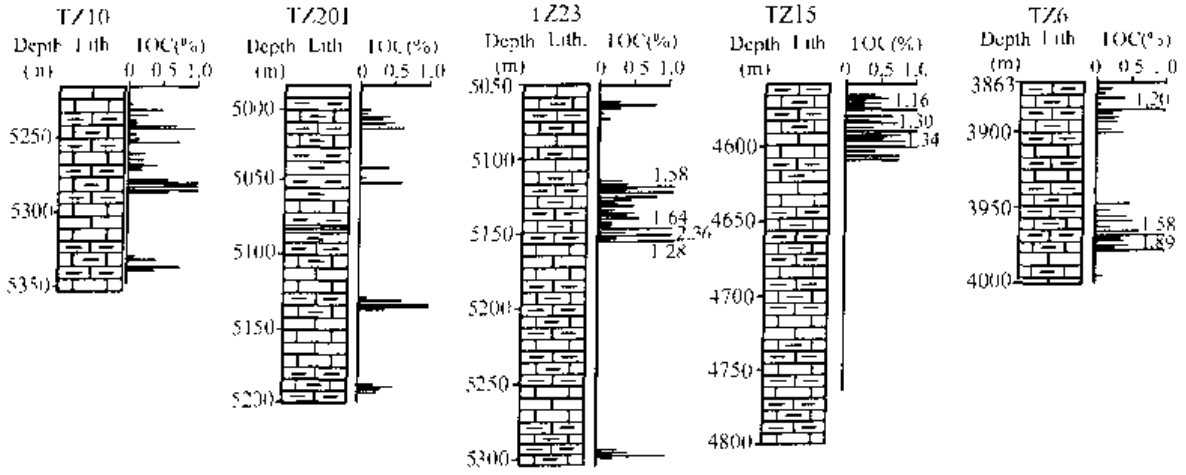


Fig. 2 Geochemistrical section of the Liangligetage formation (Upper Ordovician) of the northern slope of the Tazhong uplif in Tarim Basin.

extracts of the Middle–Upper Ordovician (as shown in Fig.3). It means that there is kin relation between them.

Fig 4 is a crossplot of triaromatic dinosteroids/(triaromatic dinosteroids + 3–methyl aromatic steroids) and 24–norcholestanes/(24– + 27–norcholestanes) in the rock extracts and oils, two data clusters are shown in the figure. The analyzed oils no matter wether it is from the Lunnan or from Donghetang oilfields located on Tabei uplift and Tazhong-4 oilfield fall all in the region of the Middle–Upper Ordovician extracts except those oils from Tazhong-45, Tazhong-12 and Caohu-2 wells. There is no evident relation between the analyzed oils and the Cambrian (Fig.4).

The distribution of C_{28} steranes gives a kind of similar evidence. The variation of the C_{28} steranes as the age can be reflected by the profile in Tacan-1 well. As shown in Fig.5. Lower Cambrian rock extracts in the Tacan 1 well have the highest abundance of C_{28} steranes, reaching 38% of the C_{27}~C_{29} steranes. the Upper Cambrian up to 32%, Lower Ordovician from 24%–32% and that of the Middle–Upper Ordovician is about 11% (Fig.5). That is to say, the C_{28} sterane content is gradually decreasing as the age from Cambrian to Ordovician. To the samples of all the penetrated Cambrian in the basin, the distribution of the C_{27}–C_{28}–C_{29} sterane shows an "oblique line" profile ($C_{27}<C_{28}<C_{29}$) or an "anti-L" profile ($C_{27}<C_{28}\leqslant C_{29}$) (Fig.6a). However, the overwhelming majority of the Middle–Upper Ordovician source rock samples reveals the asymmetrical "V" profile distribution, which is $C_{27}>C_{28}<C_{29}$ and the C_{29} content is the highest (Fig.6b).

The distributions of C_{27}–C_{28}–C_{29} sterane of the crude oils are similar to these of the rock extracts. Oil samples with "oblique line" or an "anti-L" profile distributions, however, are extremely few except those crude oils from Tazhong-45 well, Tazhong-16 well and Tazhong-24 well drilled along the Tazhong No.1 fracture belt. Moreover, the sterane distributions of asphalt in the reservoir are all shown as an "oblique line" or an "anti-L" profile (Fig.6c). It is illustrated that the source rocks of Cambrian indeed have generated hydrocarbon in the geological history and presently

contributed to the oil storage of some local regions. However, what is interesting is that the analyzed results of oil samples taken from the commercial oil pools and fields, including the Tazhong 4 and Lunnan and Donghetang, appears to be the asymmetrical "V" sterane distribution profile.

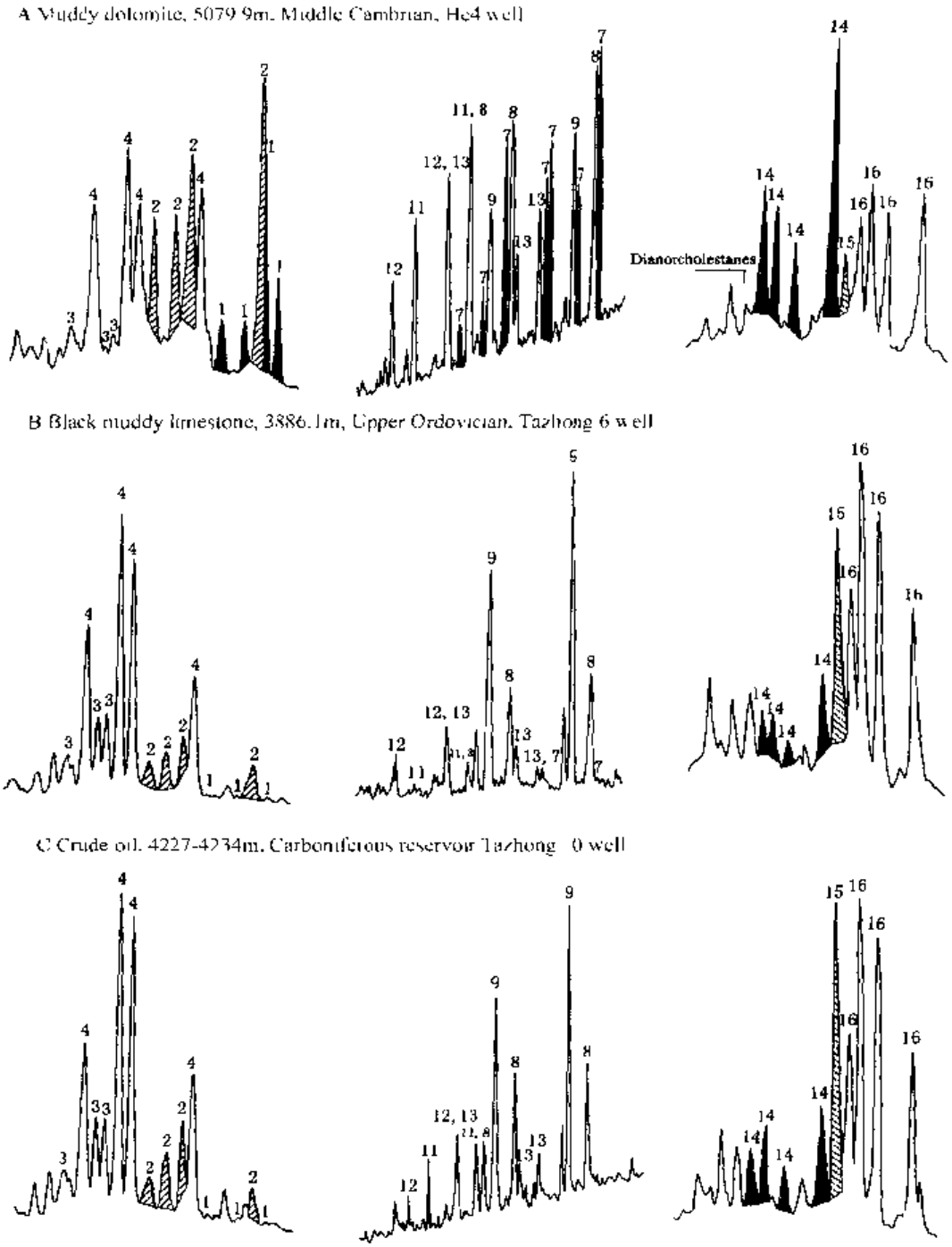


Fig.3 The distribution methylsterane (m/z 231→414, the left), triaromatic methylsteroid (m/z 245, the middle) and norcholestane (m/z 217→358, the right) within the crude oils and the extracts of Cambrian and Ordovician rocks, the experiment method as in references[5]. 1 = 4α, 23, 24-trimethyl cholestane (dinostrane); 2 = 4 α -methyl-24-ethyl cholestane; 3 = 3 α -methyl-24-ethyl cholestane, 4 = 2 α -methyl 24-ethyl cholestane; 7 = 4, 23, 24-trimethyl triaromatic cholesteroid (triaromatic dinosterane); 8 = 4-methyl-24-ethyl triaromatic cholesteroid; 9 = 3-methyl-24-ethyl triaromatic cholesteroid; 10 =

2–methyl–24–ethyl triaromatic cholesteroid; 11 – 4–methyl triaromatic cholesteroid(C_{27}); 12 = 3–methyl triaromatic cholesteroid(C_{27}); 13 = 4,24–dimethyl triaromatic cholesteroid(C_{28}); 14 = 24–norcholestane(C_{26}); 15 = 21–norcholestane(C_{26}); 16 – 27 norcholestane(C_{26}).

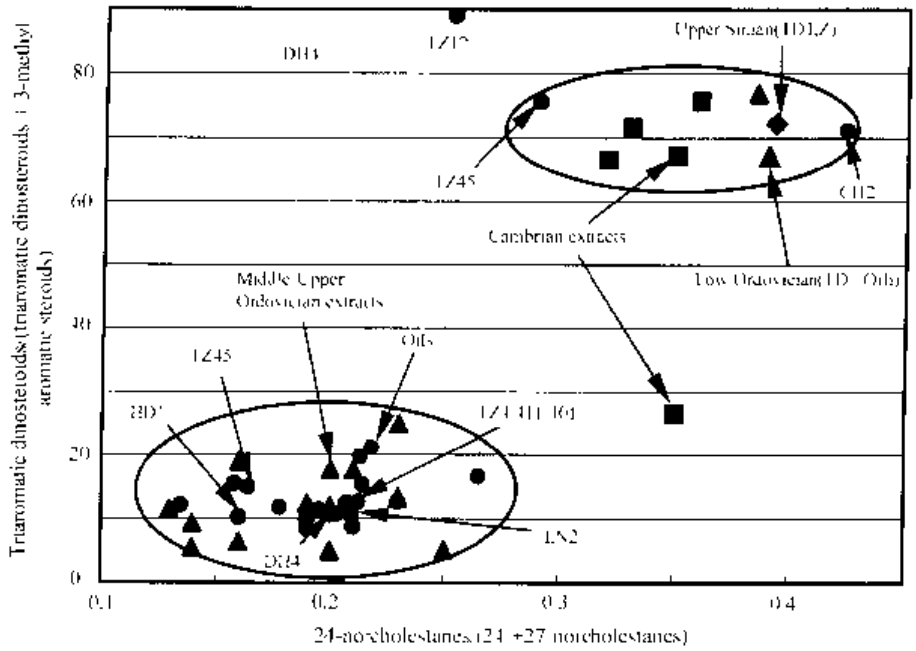


Fig.4 Plot of triaromatic dinosteroids/(triaromatic dinosteroids + 3–methyl aromatic steroids) and 24–norcholestanes/(24– + 27–norcholestanes) in the rock extracts and oils in Tarim Basin. The relative lower contents of triaromatic dinostranes and 24–cholestanes in the marine oils and Middle–Upper Ordovician rock extracts from the basin, comparing with the Cambrian rock extracts, suggest that these oils are very likely generated from Middle–Upper Ordovician but the Cambrian.

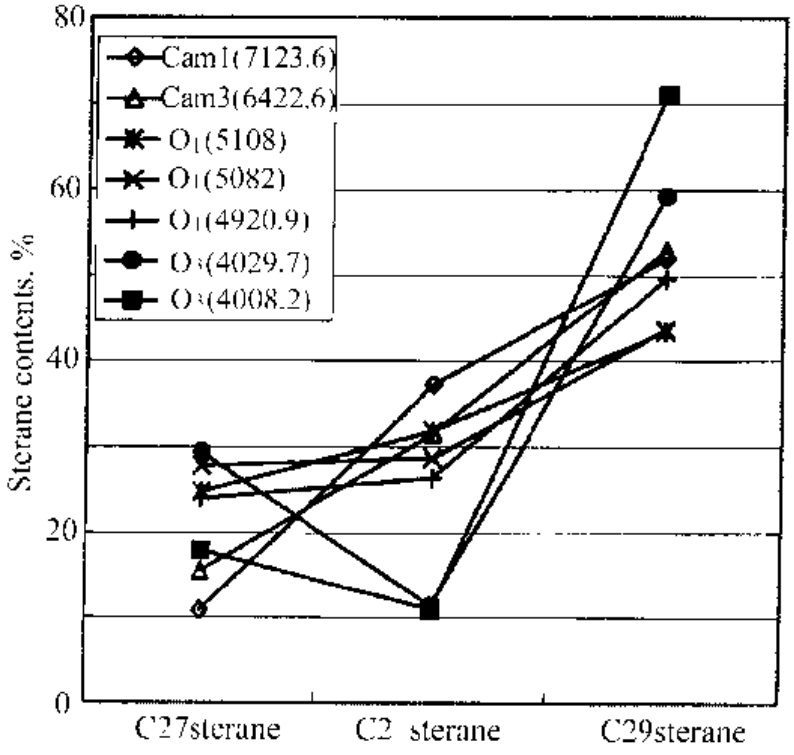


Fig.5 The distribution pattern of sterane in the Cambrian and Ordovician rock extracts, showing the sterane content decreasing with the geological age; the distribution changing from "oblique line" profile ($C_{27} < C_{28} < C_{29}$ = for Cambrian samples → an "anti-L" profile ($C_{27} \leqslant C_{28} < C_{29}$ = for Lower Ordovician samples→ asymmetric "V" profile ($C_{27} > C_{28} < C_{29}$ – for Middle–Upper Ordovician samples.

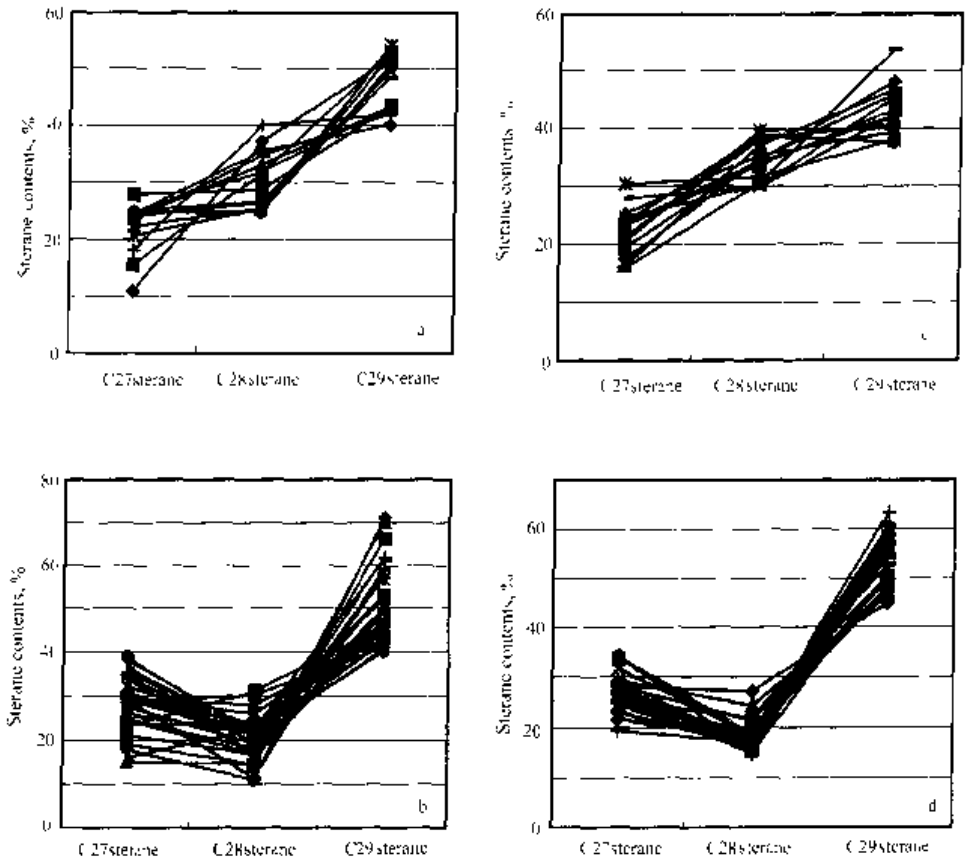


Fig. 6 The distribution pattern of sterane carbon number in the Cambrian and Middle–Upper Ordovician source rock extracts in Tarim Basin. The distribution of Cambrian shows higher C_{28} sterane, the carbon number distribution as an "oblique line" or an "anti-U" profile (a). The distributions of sterane in Middle–Upper Ordovician samples are asymmetric "V" profile (b). The distributions of sterane carbon number in most oil samples are as asymmetric "V" profile (d), which can be correlated with Ordovician rock extracts. A few sample of oil and asphalt in the reservoir taken from Tazhong 16 well (Ordovician), Tazhong 45 well (Ordovician) and Tazhong 24 well (Carboniferous) are similar in the sterane distributions to Cambrian extracts, suggesting that Cambrian rocks are very likely a supplier of these hydrocarbons(c).

It obviously suggests that they have some obviously relative property to the source rocks of the Middle–Upper Ordovician (illustrated in Fig. 6d).

It can be said that the Middle–Upper Ordovician rocks are really the significant source rock layers of the marine commercial crude oil of Tarim Basin according to the results as shown above.

2 The Maturity of the Oil and Hydrocarbon-generating History of the Middle–Upper Ordovician Source Rocks

The maturity of the crude oil ordinarily represents the mature degree of the source rock at which oil was generated in case of the fact that the evolution of oil after its migrating and accumulating into and in the reservoir is not respected. With analysis of hydrocarbon-generating history of the source rocks, the generating period of the crude oil can be understood. Generally speaking, in the geological age, the later the crude oil is formed,

the less opportunity it will have of being destroyed and easier to be preserved. The data of the maturity and the hydrocarbon generating history of the source rocks only in order to discuss further the probability and rationality of regarding the source rock of the Middle–Upper Ordovician as the hydrocarbon source rock from other points of view.

The identification of the degree of maturity of the crude oil is a problem which is not commendably resolved for many years. Among all of the biomarker parameters applied to determining it, the isomerization ratios of 20S/(20S−20R) and ββ/(ββ−αα) of C_{29} steranes are proverbially used[16]. However, isomers can be polluted and mixed each other[17] and affected by the lithofacies, bio-degradation and degree of maturity of source rocks[16]. So, these parameters have some limits when they are applied to evaluating the degree of maturity of oil generated in the Paleozoic basins. Here we use the C_7 temperature parameter that is recently prevalently adopted by the western oil companies to evaluating the degree of maturity of the marine oil in Tarim Basin. The C_7 parameter is based on the invariability of the value K1=(2–MH+2,3–DMP)/(3-MH+2, 4–DMP) and the systemic variation of the ratio of 2,4–DMP/2,3–DMP [18]. By regarding the ratio of 2, 4–DMP/2, 3–DMP (2–methyl-pentane) as the function of temperature, the C_7 parameter is not affected by time and the types of kerogen[19-20]. We can obtain the maximum temperature (℃) of the buried depth [=140−15(ln (2,4–DMP/2,3–DMP))] by calculating the value of 2,4–DMP/2,3–DMP of the crude oil. Then, we can converse it to the corresponding C_7 VRE value when the crude oil is generated according to the heat history of the basin. The crude oil generated temperatures of the principal oilfield of Tarim Basin and the C_7 VRE values have been listed in the Table 2. It is seen in the table that the generated temperatures of the oil range from 117 to 133℃ and the corresponding VRE values are between 0.78–0.92. It means that the maturity degree of the crude oil is only equal to a medium mature stage. The point is when and by which set of the source rocks did the crude oil with the medium maturity generate more possibly? Tacan-1 well that is the deepest well drilled on the Tazhong uplift in the basin could be an example for this discussion.

Table 2 C_7 temperature and VRE values of oils of Tarim Basin

oilfield/reservoir age	Temperature, ℃ (sample number)	C_7VRE, %(sample number)
Donghetang / Carboniferous	126 (2)	0.87
Yingmaili Ordovician	117—122 (2)	0.78
Lunnan / Ordovician	118	
Lunnan / Triassic, Jurassic	118—125 (3)	0.89
Sangtam / Ordov., Carb, Trassic	121—126 (8)	0.83—0.89 (3)
Jiefangqudong / Trassic	123 (2)	
Jilake / Carboniferous, Trassic	121—127 (2)	0.89
Tazhong Uplift Carboniferous	120—133 (11)	0.85—0.92 (5)
Tazhong N. slope/Carb., Sil., Ordov.	122—130 (11)	0.89

The thickness of strata and paleo-geotherm are two important factors affecting hydrocarbon generating history. The Lower Paleozoic and the Tertiary sections in Tarim Basin are thick and the Upper Paleozoic and Mesozoic layers are relatively thin. The Upper Cambrian–Lower Ordovician in Tacan-1 well has the thickness of 2510m on whose upper and lower parts purported Middle–Lower Cambrian and Middle–Upper Ordovician source layers were respectively developed. Because of such a kind of extremely thick sediments plus to the palaeo-geotherm gradient as high as 3.3℃/100m at Cambrian–Ordovician age resulted in the Middle–Lower Cambrian source rocks had reached its peak hydrocarbon generating in the Late Ordovician Period (Fig. 7). The maturity of organic matter was over 1.5%VRE at the Permian age and now it is about 2.25%VRE. The Middle–Upper Ordovician source rocks just entered the threshold of oil generating in the Late Permian. It is still in the low mature stage in the Mesozoic as a result of decreasing palaeo-geotherm gradient and it reached the peak of hydrocarbon generating as fast burial of the Tertiary since the Cretaceous (Fig. 7).

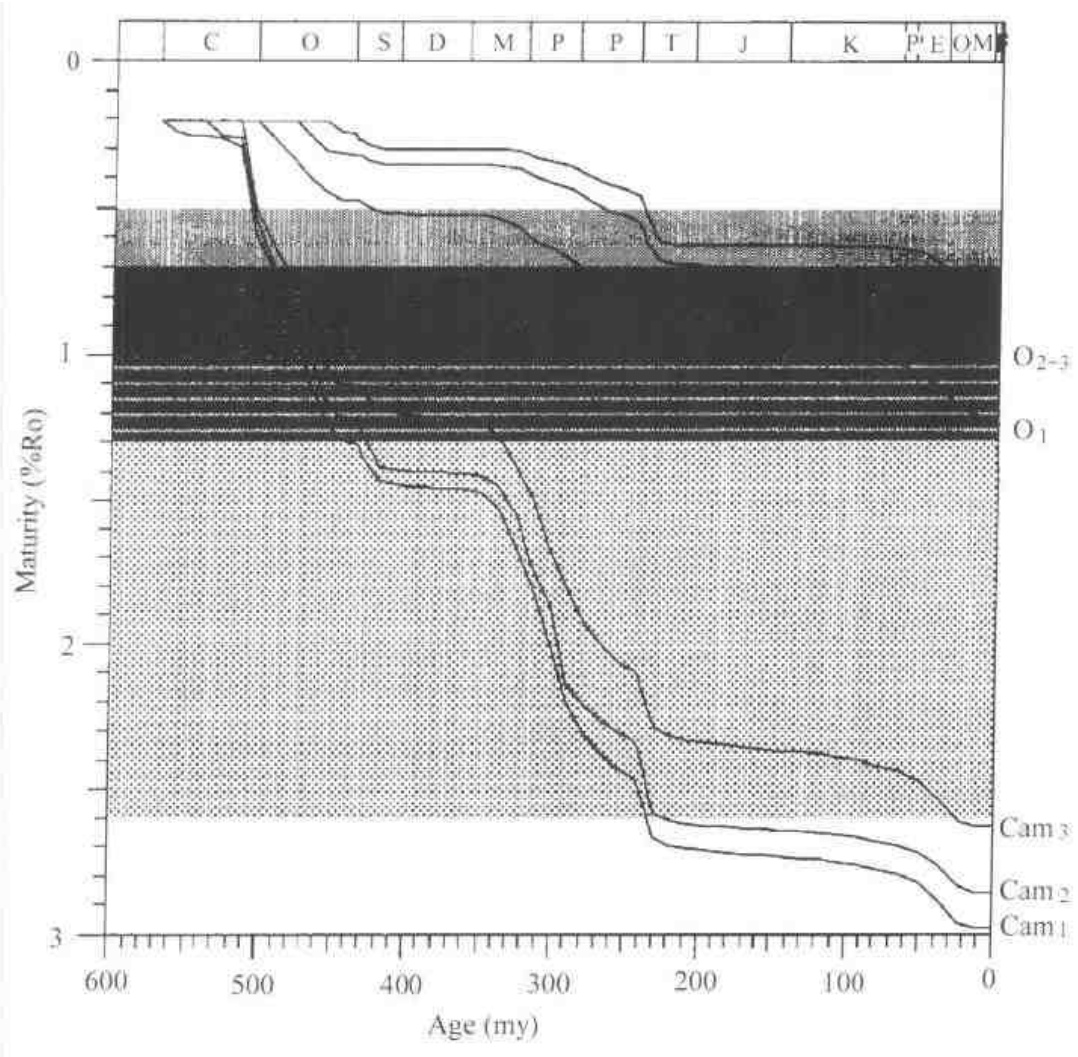


Fig. 7 The history of hydrocarbon-generating in the Tacan-1 well.

It is easily found that the history of hydrocarbon generating for two effective Middle–Lower Cambrian and Middle–Upper Ordovician source rocks are obviously asynchronous based on the observation of the evaluation histories as shown in Fig. 7. The hydrocarbon generating in the Middle–Lower Cambrian is early and the hydrocarbon-generated process is fast. It had gone through the oil-window in the late Caledonian. The asphalt extensively present in Silurian and other reservoirs are the chief products during this period. However, the hydrocarbon generating in the Middle–Upper Ordovician source rocks happened real late and the process is slower, which entered the generating peak in the Yanshan Episode and now it is still in the late maturity stage. This character is so in the uplift areas and is reflected even more in the depression regions in Tarim Basin. If the crude oil as mentioned above with the moderate maturity degree is generated from the Middle–Lower Cambrian, then the source rocks should have reached such matured degree in the late Caledonian or at least in the early Hercynian. It means that the massive marine crude oils in the basin have been generated at about 400–500Ma years ago. For such a long history, it is difficult for the crude oils to keep the normal characteristics because even the diffusion process can make it absolutely degenerative through the long geological history, and the several tectonic movements occurred subsequently should entirely destroy the oil storage. Even afterward there is still crude oil generated and preserved, it would be quite limited. Then, the only possibility is that the commercial oils currently found should be generated from the Middle–Upper Ordovician source rocks. The hydrocarbon-generating peak episode was during the Yanshan to the Himalayain. It means that the substantial crude oil was generated and preserved since around 200Ma. The reservoir structure analysis, fluid inclusion analysis and age dating of autogenous minerals have supported this conjecture.

3 Formation Model of Middle–Upper Ordovician Source Rocks

As shown in Fig. 8, over 5000m dark turbiditic flysch clastic sediments accumulate in the eastern region of the basin because of the violent subsidence during Middle–Late Ordovician age. The thick shale and sandstone sediments, however, are characterized by low TOC (commonly less than 0.2%) and can not be regarded as good source rocks. It suggests that the effective source rocks are only developed along the northern and southern slopes of the Manjaer depression, not in its center setting with the deepest sea water column, the richest mudstone and maximal thickness. Richness of organic matter in the platform edge slope lime-mud-mounds is related to high living beings productivity caused by the upwelling. The distribution pattern is similar to those of the modern western Africa continent shelf and the Peru continent shelf[21-23].

4 Conclusion

Identification of the major oil-source layers in Tarim Basin has been a controversial question for many years. Based on a comprehensive study, we discovered to develop the effective source rocks on the northern slope of Tazhong uplift and the southern slope of Tabei uplift, as well as on the open bay or gulf facies in the Keping area and the Awati de-

pression. Especially, by the oil-source correlation using age- or environment-specific biomarkers such as dinosterane, 24-norcholestane and C_{28} sterane etc., and analysis of the hydrocarbon-generating history, it has been verified that the currently found commercial oils should be mainly generated from this horizon. It is just this set of layer that makes Tarim Basin become an unique region in China in where there are both marine-genetic commercial gas pools and oil pools.

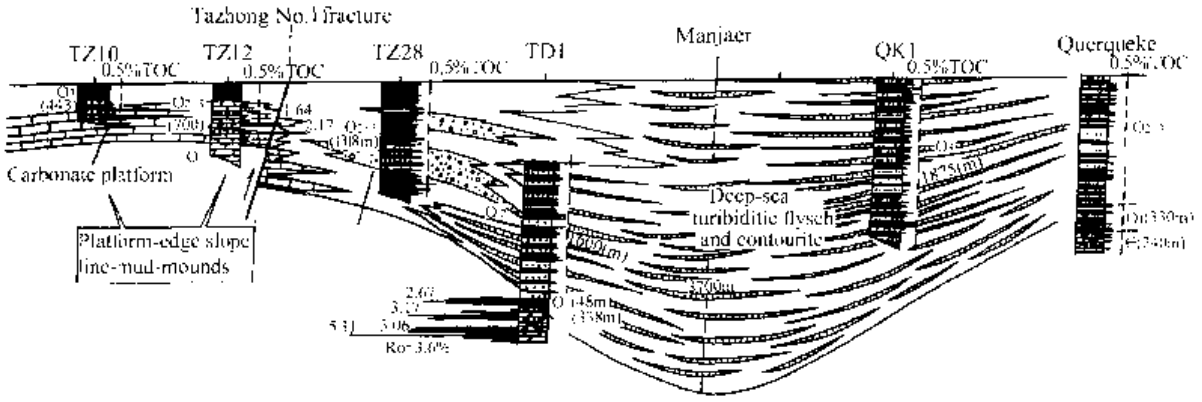


Fig. 8 A sedimentary section across N–S direction in the Manjaer depression of Tarim Basin, showing that the Middle–Upper Ordovician source rocks are distributed in the slope facies of the platform margin, not in the center of the Manjaer depression.

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History of Oil and Gas Accumulation in Central-Tarim Uplift

Li Guodu, Jin Zhijun, Zhang Shuichang*, Yang Haijun**

(Petrolium University of China (Beijing), 102249, Shuikulu st.1, Beijing, Changping, China

** Beijing Research Institute of Oil Exploration and Exploitation, 10083, Xueyuan st.20, Beijing, China*

*** Tarim Research Institute of Oil Exploration and Exploitation, 841000, st Tazhidonglu, Xinjiang, Korla, China)*

Li Guodu, male, born in 1963, graduated from Shandong College of Oceanography in 1984, and received his Ph.D. degree in Russian Academy of sciences in 1998. Now he is an assistant professor of University of Petroleum (Beijing). His major interest is reseach of theory and methods of exploration of oil and gas fields, structural geology and geochemistry of oil and gas.

Abstraction. During the period from Sinian to Ordovician the observed territory was under intensive subsidence .n the end of Ordovician - was under the platform folding, and paleouplift had been formed. During the period from Silurian to Cenozoic era under the conditions of intensive tectonic movement the territory experienced subsidence with oscillations, the amplitude of paleouplift becomes higher. Source rocks with high contents of aquagenic organic matter are fixed in section of Cambrian. Mid–Later Ordovician. In section of carbonaceous–permian strata are also found layers w th high contents of mixed organic matter. Repeated uplift and sequential erosion of underlying strata during forming of the cover strata sophisticated the scheme of hydrocarbons generation and the history of accumulation oil and gas on the territory. The history of oil and gas accumulation in Central-Tarim uplift can be divided into three stages. The first stage of oil accumulation in Tarim basin is related generation of liquid hydrocarbons by Cambrian source rocks in Ordovician. The second stage tied up with generation by Cambrian source rocks in Silurian, formed accumulations that partly broke down during late Hercynian dislocation. The third stage of forming of reserviors linked with oil and gas, which were generated by Ordovician source rocks in Carbonaceous period The most of the reservoirs formed in this period, most likely conserved till today. Resumption of oil and most likely gas generation by source rocks of Cambrian and Ordovician eras took place in the period since Cretaceous to Cenozoic inclusively, which was the fourth stage of forming accumulations.

Key words. Tarim basin, Central-Tarim uplift, tectononic evolution, source bed stratas, history, generation, forming oil and gas accumulation.

Introduction

The history of forming oil and gas accumulation on the considered territory has remained unclear. Some scientists assume that accumulations were formed in early Hercynian periods, while the others think in Himalayan period. As a result of recently geologocal exploration, new geological, geophisical and

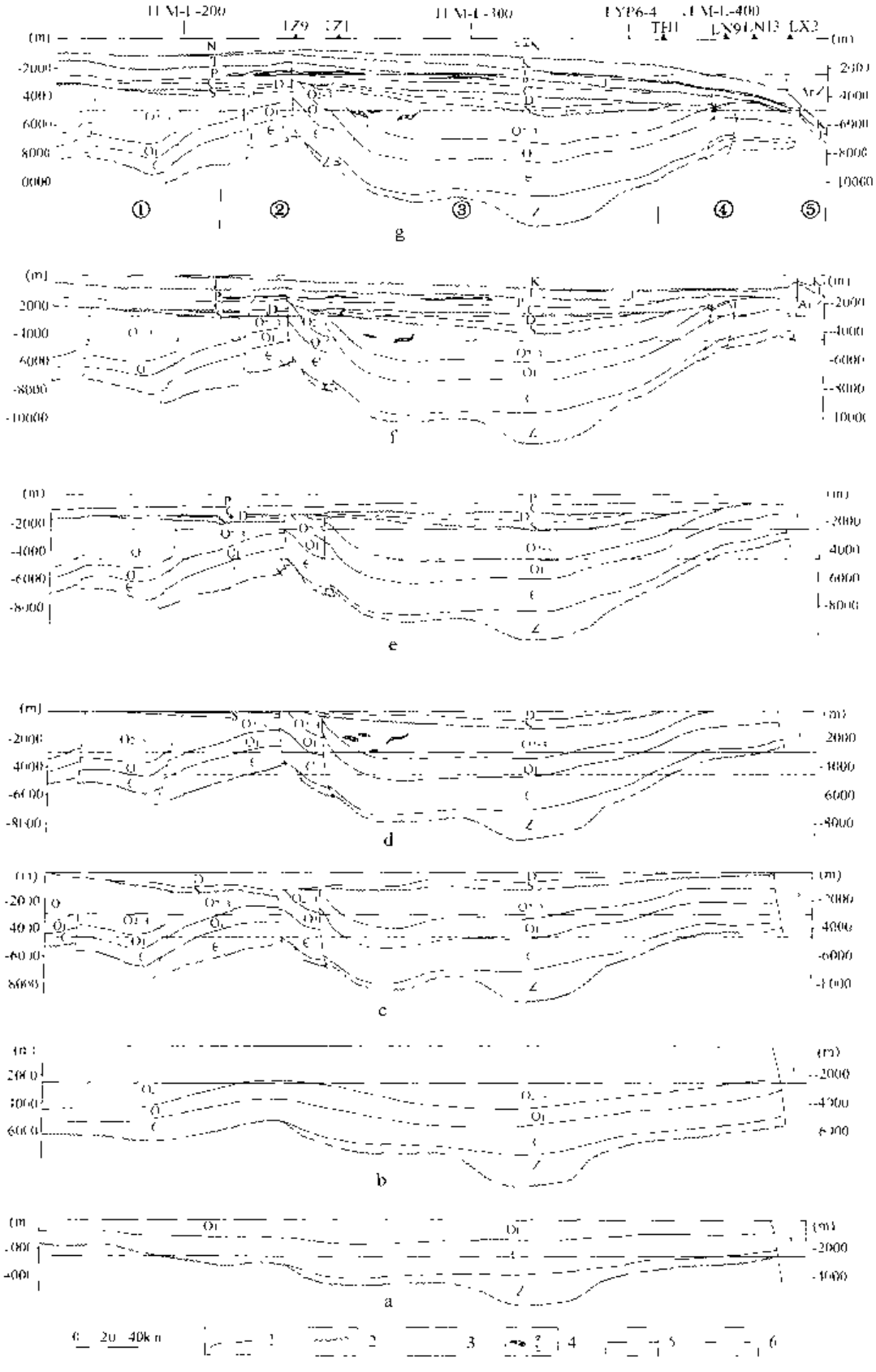


Fig. 1 Tectonic evolution of central Tarim Uplift.

history of Tarim platform development. This feature was caused by periodical addition of the terrains to Tarim craton, terrains had different sizes and migration speeds[5]. During collisions in the section of adjacent parts of craton were formed unconformities. According to magnetic field, it is supposed and proved by boring data that in the Middle and Upper Paleozoic widely occurred magmatism of mostly basalt and less granite type. Provided radiometric dating [1,4,6] pointed on Permian–Triassic age of this magmatism, as Sinian–Ordovician, Permian–Triassic magmatic rocks are characterized with high content of alkali.

In this period (after late Hercynian movements) the territory was under subsiding with some intervals, including post-Permian, post-Triassic–Jurassic and post-Cretaceous. Especialy during post-Triassic–Jurassic time the territory took a long time to rise. Central-Tarim uplift conserved as a big structural elements of the first rank.

We should underline that in this period on given territory carboniferous and later strata accumulated on the paleouplift, and on these strata were formed drape-like structures. It is approved by geological exploration that the carboniferous oil- and gas-bearing complex has a widespreading character. Moreover, in the centre part of uplift the carboniferous argillaceous strata overlain on the Ordovician carbonic strata through unconformity, as a result, reservoirs were formed.

During the period from Sinian to Ordovician in tectonic conditions of stretching on the territory of Tarim craton were accumulated huge marine carbonic strata. In the end of Ordovician in tectonic conditions of compression the given territory was under platfom folding, as a result paleouplift was formed. Form Silurian to Cenozoic, Tarim craton located as a connector between Paleoasian ocean and Paleotetis ocean, several terrains joined to Tarim craton. As a result, in intensive tectonic conditions the territory was under subsiding with oscillatory movement.

2 Concept about the Multi-staged Formation of Oil and Gas Reservoirs

According to modern concept about oil and gas generating it is accepted that during the process of catagenetic transformation of organic matters monotonically immersing sedimentary layer goes through proto- and early mezo-catagenetic (top) phase of intensive gas formation, main phase of gas formation and latemezo- and apo-catagenetic (deep) phase of intensive gas formation[7-9]. According to this even in monotonically immersing layer with trap in protocatagenes the forming of accumulations is multi-staged. Hydrocarbons, accumulated in earlier phases of oil formation, diffused, new its portions came into traps.

It is important to underline that the compound of liquid and gas hydrocarbons at different stages of catagenesis is not constant. That is why the compound of hydrocarbonic fluids in reservoirs depends greatly on compound and conditions of migration and accumulation into traps of hydrocarbons, which are generared by organic matter, and it also depends on the intensity of dispersion of hydrocarbons, accumulated during earlier stages, and on the trasformation of oil in reservoirs[10,11].

More complicated is the process of oil generation in layer, immersion of which has discontinuous character, especially when it takes a long time to rise. Oil and gas genera-

tion, and accumulation are long lasting processes, with multiple stages, discontinuous, so the scheme of monotonuous immersion of strata layer quite approximate.

Generalising data of wide sphere including data of paleostructural reconstruction and data of insoluble organic matters and bitumology. Kontorovich A.E. (1980) established a scale according to the depth of different stages of oil and gas generation by Riphean, Vendian and Lower–Middle Paleozoic source rocks in Siberian platform: 500m–1500m – upper zone of intensive gas generation, 1500–2500m – zone of starting and progressive development of oil generation processes, 2500–4500m – main zone of oil generation, 4500–5400 – zone of gas generation process decay.

It is mentioned above that in geological history Tarim craton, located between Paleotetis and Paleoasian oceans, went through very intensive tectonic situation. That is why during the process of forming Tarim basin were formed several unconformities, among them comparatively long and widely distributed are post Ordovician, prelate-Devonian, post-Permian, post-Triassic, post-Cretaceous and post-Kuche (N_2k). The greatest influence of formation and development of Central-Tarim uplift were made by post-Ordovician and pre-late-Devonian tectonic movements, which were accompanied with intensive uplift and following erosion. Research of changing of strata thickness according to seismic data, logging data and boring material, using results of wave analysis, show that during post-Ordovician and pre-late-Devonian periods the erosion amount was over 1000m [12]. Morcover, according to investigation it is considered that during the forming of Tarim basin thermal rates on the territory had been changing greatly with gradually cooling, besides two intervals (Sinian–Cambrian and Permian periods), in connection with mamtism, thermic rates temporally raised.

All the mentioned factors, without any doubts, proved that on the given territory gas and oil accumulation had multi-staged character. Moreover, rising and following arosion of underlying strata during the formation of the sedimentory cover made the scheme of generation organic matters and, of course, the history of oil and gas accumulations on the territory more sophysticated.

3 Space Distribution of Major Source Rocks

Problems of source rocks were studied in many works[13-16]. During the Eighth and Ninth "Five-Year" Plan (1990–2000) the specialists of Beijing petrolium exploration and development under the guide of Liang Digang and Zhang Shuichang studied the source rocks of Tarim basin. During the Ninth "Five-Year" Plan they redefined the lower line of surce rocks, which had industrial importance for hydrocarbons accumulation, and they considered that only those source rocks with organic carbon contents on rocks more than 0.4%, independently of rock type, could generate enough hydrocarbons, which could accumulate and form hydrocarbons reservoirs, having industrial importance [15]. By this criteria they redefined the distribution of source rocks.

In Cambrian sections source rocks with aquagenetic organic matters were accumulated in nonbalancing depressions and saline logunes. Their thickness are 100–300 m in Awati and Tangguzibasi depressions and on the territory in the south of boundery of

Lunnan-1 – Manxi-1 rift – Tazhong-28.

In the south–east part of basin on the East from Kunan-1 – Manxi-1 – Tazhong-32 in Upper Cambrian and Lower Ordovician were found source rocks with high content of organic matters, accumulated in unbalanced basins. Their thickness change greatly in 0–50 m.

Source rocks with high content of organic matters were also set in Middle and Upper Ordovician section, in the east part of basin and Awati depression. In roof part of Mid-Ordovician and lower part of Upper Ordovician were fixed source rocks with content of organic matters more than 0.5%. Their thickness change from 20m to 80m and reach 200m in Manjiaer depression. Source rocks were set in the middle part of Ordovician. Their thickness in Awati depression reach 30–90m, in Tanguzibasi

came under the study by many scientists. The results of their studies were published in articles and monographs [17,18]. But several key questions are still not clear, most likely, it is because this situation is connected with complexity of basin development, as was mentioned, with widely distributed unconformities in the section, with rising and following erosion of large scale, with magmatic processes in Permian period. We deal with this problem with regard to scale of rising and erosional amount with help of wave analysis [18]. The results of our researches completely coincided with mentioned results, gained according to criteria Kontorovich A. E. (1980) for source rocks of Riphean, Vendian and Lower–Middle Paleozoic of Sibirian platform. The results of our researches are given below.

In Late Ordovician period, Cambrian source

showed that although, during Triassic strata were formed, their thickness neutralized the thickness of erosional Permian strata. Moreover, the analysis of paleotemperatures over occlusions illustrates the process of cooling at the beginning of Tarim basin since Triassic. That is why the generation of hydrocarbons in Triassic period in any amount is not expected.

During Jurassic period for given territory is typical mainly rising. Only during the period since Cretaceous till Cenozoic the territory was under the intensive immersing. Doubtedly, it evoked renewing the generation processes of hydrocarbons of source rocks in different parts of the section. Among them, source rocks generated great liquid hydrocarbons and filled up the existing accumulations of carboniferous reservoirs.

As the information mentionec above, on the territory in Paleozoic section were found two complexities of source rocks – Cambrian and Mid–Upper-Ordovician. Generation of liquid hydrocarbons by source rocks for the first time happend in Late Ordovician time, which was the first stage of oil and gas accumulation in Tarim basin.

During post-Ordovician rising and following erosion a part of accumulations was reformed or destroyed. In Silurian period the generation of hydrocarbons by Cambrian source rocks renewed and generated hydrocarbons were migrated into traps of Ordovician and Silurian reservoirs. This is the second stage of accumulation of hydrocarbons in Tarim basin. Formed reservoirs of hydrocarbons were destroyed during Late-Hercynian dislocation. In Carboniferous–Permian time Ordovician source rocks began tc generate hydrocarbons. This is the third stage of hydrocarbons accumulation in the basir.. Already formed accumulations in this period mostly conserved till today. Renewing the generation of hydrocarbons by Cambrian and Ordovician source rocks happended from Cretaceous period up to now. which was the fourth stage of reservoir forming.

The discovered oil and gas reservoirs mostly had the complicated history of its formation and development. As an example we take Tazhong-4 reservoir, which is one of the greatest revealed reservoirs on this territory.

Tazhong-4 reservoir is located in the east of Central Fult Zone. According to the cover of bed C_{III}. which is the main oil- and gas-bearing komplex, picked out the brachyanticline with north–east stretching. On the territory there are three carboniferous horizons – from top to bottom C_I, C_{II} и C_{III}. C_I and C_{III} horizons showed as terragenic, C_{II} – organogenic limestones. Reservoirs are structural. oil with gas cap. massive and floating in water.

Analyses of paleostructures show that for the first time the structure was formed in Permian period with amplitude according to cover C_{III} in 80m. in pre-Triassic time amplitude of structure raised to 170m, at the end of Mezozoic the structure was already formed. During Cenozoic it changed less. That is why we can suppose that the first portion of oil in Tazhong-4 reservoir came into traps in Permian time on the second stage of hydrocarbon acumulations in Tarim basin. Petroleum were most likely generated by Ordovician, perhaps Cambrian source rocks and migrated to carboniferous traps over unconformities surfaces and faut zones. From Triassic to Jurassic, little of oil and gas came into traps, only in Cenozoic, in Himalayan cycle of tecnonic movements. when the territory was involved into immersing, oil from Ordovician strata migrated into carboniferous traps and

filled up the traps. This idea is proved by data of geochemical researches of Tazhong-4 reservoir and source rocks of Ordovician and Cambrian periods [13,15]

5 Conclusion

In the period from Sinian to Ordovician in condition of stretching on the given territory of Tarim craton were formed carbonic strata with great thickness. In the end of Ordovician in tectonic conditions of compression, the given territory was under platfom folding. As a result, paleouplift was formed.

From Silurian to Cenozoic, Tarim craton was between Paleoasian ocean and Paleotetis ocean, several terrains joined to Tarim craton. As a result, in intensive tectonic conditions, the territory was under subsiding with oscillatory movement.

On the territory, the process of oil and gas accumulation has multi-staged character. Rising and the subsequent erosion of underlying layers in forming the basin cover made it complicate the scheme of hydrocarbons generation and history of gas and oil accumulation on the territory.

Source rocks with high content of aquagenic organic matters are fixed in Cambrian and Mid–Upper Ordovician strata. They have enough big thickness and are widely spreading in basin.

In Carboniferous–Permian section also were fixed rocks with high content of mixed organic matter.

Generation of liquid hydrocarbons by Cambrian source rocks for the first time happened in Late-Ordovician time, which was the first stage of oil and gas accumulation formations on the territory of Tarim basin.

The second stage of hydrocarbon accumulation linked with generation of hydrocarbons by Cambrian source rocks in Silurian. The formed hydrocarbons partly destroyed during Late-Hercynian dislocation. The third stage of hydrocarbons accumulationsis is connected with generation of hydrocarbons by Ordovician source rocks in Carboniferous period. Formed accumulations in this period mostly conserved till today. Renewing of hydrocarbon generation by source rocks of Cambrian and Ordovician periods happened in the period from Cretaceous to Cenozoic, which was the fourth stage of accumulation of oil and gas.

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Genetic Groups of Natural Gas and Conditions for Gas Reservoir Formation in Tarim Basin, China

Zhao Mengjun Zhang Shuichang

(Research Institute of Petroleum E & D, CNPC, Beijing, China 100083)



Zhao Mengjun, born in 1965, graduated in the coal field and petroleum geology from the Research Institute of Petroleum Exploration and Development and received his Doctor's degree in 1994. Now he is senior engineer and is engaged in the research on the oil & gas geology and geochemistry

Abstract: In recent years, a great progress has been made in gas exploration in Tarim Basin. In fact, there are several gas genetic groups, which are related to different gas source rocks There are three sets of important hydrocarbon source rocks occurred in the basin. They are the Cambrian source rock which mainly generated gas in late period because of its high- and post-maturity, the Middle and Upper Ordovician source rock which generated not only oil but a so gas because of its special organic matters, and the Jurassic source rock which mainly generated gas because of its humic type kerogen Through gas source correlation, it is shown that the natural gas found in Tarim Basin at present is mainly derived from the three sets of significant hydrocarbon source rocks mentioned above The necessary conditions for forming the giant or supergiant gas reservoir are the five regional caps and several reservoir strata widely distributed over the basin. According to generation, accumulation and preservation, Tarim Basin has the conditions to form giant gas reservoir, and is rich in natural gas.

Key words: Gas groups, Gas source rock, Reservoir rock, Cap rock, Tarim Basin.

Introduction

Recently in China, Tarim Basin is the sole basin, where not only marine gas field but also nomarine gas field was found, with gas resources being $8.4\times10^{12}m^3$. The natural gas found at present was mainly distributed over Kuche foreland depression and Tabei and Tazhong uplifts. So far, commercial gas flow has been discovered in 9 of the 13 formational seqiences from Sinian to Quaternary, except Silurian, Devonian and Permian[1]. The gas reserves are mainly distributed in Tertiary-Cretaceous, Jurassic and Carboniferous, and the Ordovician reservoir is more and more important in the gas exploration in craton area.

1 Multi-groups of Natural Gas

Not only nomarine gas but also marine gas, not only condensate gas but also dry gas were found in Tarim Basin, and nitrogen-rich gas with nitrogen content 10%-27% was found also. According to

component and its carbon isotope of the natural gas, the natural gas in Tarim Basin could be classified into 2 genetic families: Nomarine gas and marine gas.

1.1 Nonmarine Gas

$\delta^{13}C_2$<−28‰ for nonmarine gas, and the differential for $\delta^{13}C_2$ to $\delta^{13}C_1$ of the gas is generally more than 8 (Fig.1).

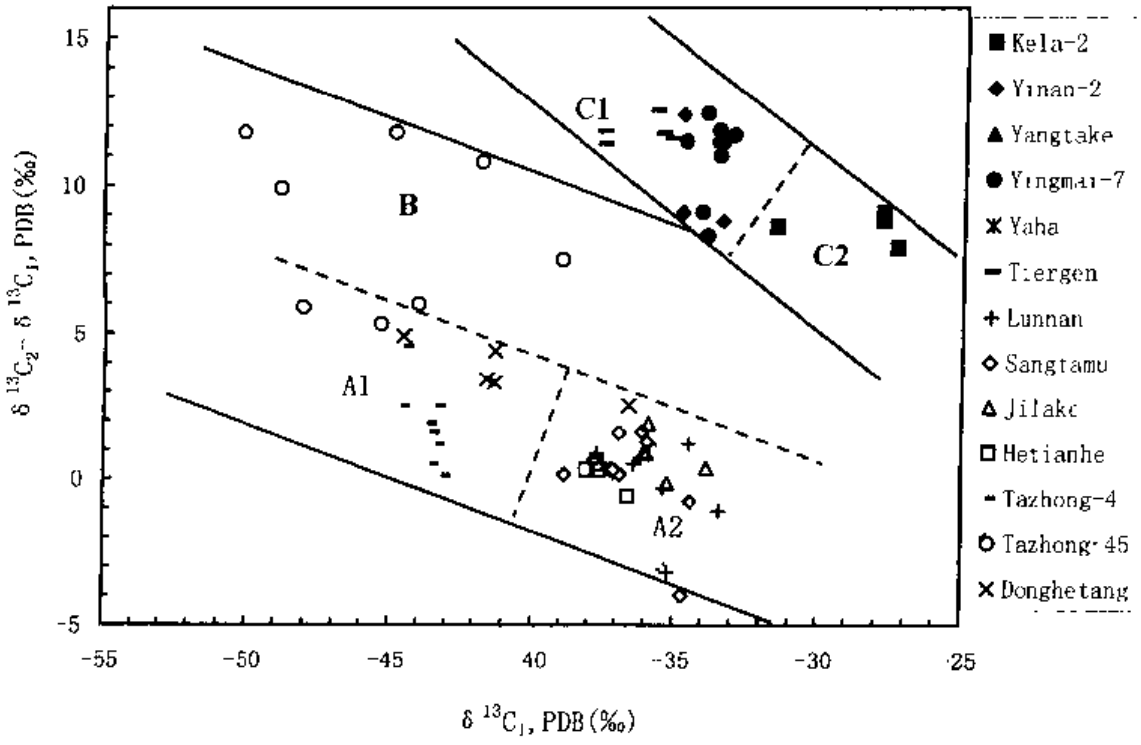


Fig.1 The genetic groups of natural gas in Tarim Basin.

A1–marine natura gas; A2–marine high–over mature gas; B–marine mature gas of bias humic type; C1–nonmarine wet gas; C2–nonmarine dry gas.

1.1.1 Nonmarine Wet Gas

In Yinan-2 gas reservoir, the content of C_1 is from 82.78%–94.41%, averaging 89.03%, and the content of C_2 is from 2.15%–10.02%, averaging 6.26%. In the condensate gas reservoirs of Yudong-2, Yangtake, Yingmai-7, Yaha and Tiergen in the north part of Tabei uplift, the content of C_1 is from 66%–92.38%, averaging 71.8%–88.31%, and content of C_{2-} is from 1.33%–26.18%, averaging 6.78%–17.25%. The condensate content of the condensate gas is 31.8%–185.6g/m^3 in the condensate gas reservoirs of Yangtake and Yingmai-7, and is 547.6%–760.3g·m^3 in the condensate gas reservoirs of Yaha and Tiergen. The values of $\delta^{13}C_2$, $\delta^{13}C_3$ and $\delta^{13}C_4$ are on the heavy side, for example, the values of $\delta^{13}C_2$ are generally −23‰ or so, which indicates typical coal measure-derived gas.

1.1.2 Nonmarine Dry Gas

The gas is found only in Kela-2 gas reservoir, the content of C_1 ranging from 90.41%–98.31%, averaging 96.58%, and the content of C_{2-} ranging from 0–1.56%, averaging only 0.57%. The values of $\delta^{13}C_1$ and $\delta^{13}C_2$ of the Kela-2 gas are obviously on the heavy side. $\delta^{13}C_1$ generally

being from −28‰− −31.5‰ and $\delta^{13}C_2$ from −18‰− −20‰.

1.2 Marine Gas

$\delta^{13}C_2$>−28‰ for marine gas, and the differential for $\delta^{13}C_2$ to $\delta^{13}C_1$ of the gas is generally less than 5 (Fig.1).

1.2.1 Marine Mature Gas

The group includes gas-cap gas in Tazhong-4 oil field and solution gas in Donghetang oil field. The average content of C is 64.6% and the average content of C_{2-} is 11.82% for the gas-cap gas in Tazhong-4 oil field, which belongs to condensate gas with very high condensate content being 885.7g/m^3. The nitrogen content of the gas is higher, ranging from 7.06%−27.63%, averaging 21.98%. The values of $\delta^{13}C_1$ and $\delta^{13}C_2$ are obviously on the light side, generally less than−40‰.

1 2.2Marine High- and Post- mature Gas

The content of C_1 of the gas in Ordovician and Carboniferous reservoirs in Lunnan area is from 89.62%−97.09%, averaging 93.83%, and the content of C_2 is from 0.57%−8.47%, averaging 1.94% The condensate content of the gas is relative y lower, mostly between 200 g/m^3 to 50g/m^3 The nitrogen content of the gas is much lower, generally less than 5%. The values of $\delta^{13}C_1$ are on the heavy side, generally being 33%− −37 ‰, and the values of $\delta^{13}C_2$ are lighter, generally consistent with the values of $\delta^{13}C$.

It is remarkable that the gas of Het.anhe gas field is dry gas with drying coefficient from 0.95 to 0.99. The average content of C_1 is 80.'% and the average content of C_{2-} is 2.1%. Moreover, there is minim H_2S in minim H_2S in the gas, being H_2S -bearing gas reservoir. Compared with the gas in Lunnan area by carbon isotope of component, the values of The content of $\delta^{13}C_1$ are on the light side, generally from 37%− −40‰, showing the carbon isotopic characteristic of the gas cracking from oil.

1.2.3 Marine Mature Bias Humic Gas

This group of the gas is mainly distributed in the northern slope of the Tazhong uplift, for example, the gas in Tazhong-45 volatility oil and gas field. The content of C_1 of the gas is lower with averaging 74.61% and the content of C_2 is 12.9% in average. The nitrogen content in Tazhong-45 is from 1.15%−9.05%, averaging 5.54%. The values of $\delta^{13}C_1$ is much lighter, generally from −42‰ to −50‰, and the values of $\delta^{13}C_1$ is relatively heavier, generally from −33‰ to −37‰[12].

2 Three Sets of Important Gas Source Rocks

The precondition of forming a giant gas reservoir is the gas source rock above all. The essential reason that Tarim Basin is rich in gas resources just lies in three sets of source rocks well developed in Tarim Basin.

2.1 Richer Cambrian Source Rock at High- and Post- maturity

The distribution of Cambrian source rock is controlled by sedimentary facies, which the starved basin facies and evaporitic lagoonal facies were most advantageous for source rock developing.

The lithology of the source rock of starved basin facies is black gray or grayish black micrite and thin layered

mudstone with horizontal laminated bed, with TOC averaging 1.75%, a maximum of 5.52%. The source rock with TOC more than 1% is from 120m to 415m in thickness. And the source rock is mainly distributed over the eastern area of Manjiaer Depression, i.e. the area to the east of the line from Luntai to Qiemo, and the southwest area of Tarim Basin, with well Tadong-1 and well Kunan-1 drilled the source rock. The organic matter of the source rock is the type I, with organic precursor mainly being planktonic algae.

The lithology of the source rock of evaporitic lagoonal facies is deep gray or grayish black, salty and gypseous micritic marl, with TOC averaging 0.86%, a maximum of 2.14%. The source rock with TOC more than 0.2% is from 288m to 324m in thickness, and the source rock with TOC more than 1% is 108m thick in well He-4. Tracing of seismic data indicated that the source rock is widely distributed in Bachu Uplift and Awati Sag, and the source rock was drilled in wells He-4 and Fang-1. The organic precursor in the source rock is mainly composed of haloplanktonic algae under saline water environment, constituting type I organic matter.

The both of the source rock mainly generated crude oil at lower-middle stage with Ro less than 1.5%. However, they mainly generated gas and became important gas source rocks because of higher maturity in late geological period. For examples, the Cambrian source rock in the eastern Tarim Basin and the southwestern Tarim Basin is at the stage of post- maturation with Ro values from 1.8% to 3.6%, generating dry gas. And the Cambrian source rock of evaporitic lagoonal facies in Bachu Uplift is at the stage of high maturation with Ro values from 1.65% to 2.10%, generating condensate and wet gas.

2.2 The Bias Humic Marly Source Rock in Middle and Upper Ordovician

The Middle and Upper Ordovician source was developed in marlaceous facies on the margin slope of carbonate platform, which could be divided into several sub sedimentary units such as marlaceous hills, pothole between hills, laminar marl hills and laminar biosparry micrite hills, with TOC averaging 0.75%, a maximum of 5.54%. The source rock with TOC greater than 0.2% is more than 400m, and the source rock with TOC greater than 0.5% could reach 80m. The source rock was mainly distributed on the northern slope of Tazhong Uplift and the southern slope of Tabei Uplift, and was drilled in 12 wells such as well TZ-12 and well TZ-10 etc in Tazhong area and in 4 wells such as well LN-46 etc in Tabei area. The source rock is composed of mainly macro alga, secondary planecktonic alga and concealed spores and is evaluated as type I–II. The source rock belongs to C facies of the Jones' facies (Jones et al, 1982) and could generate not only oil but also gas. The measured Ro values of the source rock are from 0.9%–1.3%, and the light crude oil and natural gas were generated.

2.3 The Jurassic Source Rock Mainly Generating Gas

The Jurassic source rock is mainly developed in paludal facies and semi-deep la-

custrine facies, with its lithology mainly being dark gray mudstone, carbargillite and coal. According to outcrop sections, the source rock is more than 600m thick, with very high TOC values, a maximum of 37.76% for mudstone. The source rock is mainly distributed on the 2 of foreland basins: Kuche Depression and Southwestern Depression of Tarim Basin, and was drilled in well Yang-1 and well Yinan-2. The source rock is type III and belongs to D facies of the Jones' facies (Jones et al, 1982) and could generate mainly gas, whether at the stage of maturation or at the stage of high maturation. The measured Ro values of the source rock are from 0.7%–1.5%, and the condensate and natural gas were generated mainly.

According to all discussed above, it is known that the Cambrian source rock could mainly generate gas in late period because of its high- and post- maturity, the Middle and Upper Ordovician source rock could generate not only oil but also gas because of its bias humic type organic matter, and the Jurassic source rock could mainly generate gas because of its humic type kerogen. So the reason that Tarim Basin is rich in gas resource is that there are the 3 sets of important gas source rocks in the basin.

3 The Natural Gas Found at Present Mainly from Source Rocks of Cambrian, Middle and Upper Ordovician and Jurassic

A new y perfect synthesized method of gas-source correlation has been presented, combining indirect correlation with direct correlation in gas-source correlation and considering petroleum geological conditions. The indirect correlation of gas-source is to achieve the goal through determining maturity and organic precursor of the source rock by inversion based on determining maturity and genetic type of the gas. The direct correlation of gas-source is to seek the relationship for the gas and the source using direct geochemical parameters of the gas and the source such as carbon isotopes of lighter hydrocarbons by advanced experimental measure and analytical technique. The synthesized correlation is to correlate the gas and the source by matching the indirect method anc the direct method based on the consideration of petroleum geological conditions. The synthesized discrimination of the gas sources in main gas reservoirs of the basin is achieved (Table 1), which indicates that the natural gas found in Tarim Basin at present is mainly derived from the three sets of significant hydrocarbon source rocks: Cambrian, Middle and Upper Ordovician and Jurassic.

4 Multi-sets of Reservoirs

Multi-sets of reservoir beds are developed in Tarim Basin. The storage capacity of carbonate reservoir beds is raised greatly because of later alteration, although the matrix porosity is very low. The gas reservoirs found in clastic reservoirs mostly are above type II, and the connectivity and thickness of the sandstone bed has influence on the scale of the gas reservoir. Here only some important gas reservoir strata such as Ordovician, Carboniferous, Jurassic and Creta-

ceous–Tertiary are discussed as follows.

Table 1 The assessment of the gas origin in main reservoirs of Tarim Basin

Structural zone or area	Gas fields	Representative wells	Gas source
Yiqikelike	Yinan-2 gas field	YN2	Nonmarine gases mainly derived from source rocks of Jurassic and Triassic in Kuche Depression
Kelasu	Kela-2 gas field	KL2	
	Kela-3 gas field	KL3	
Luntai Fault Uplift	Tai-2 condensate gas field	TAI2	
	Ti-3 condensate gas field	TI3	
	Yaha condensate gas field	YH1, YH2, YH4	
	Yaha buried hill oil-gas field	YH7X1	
	Yangtake condensate gas field	YT2,YT5	
Hongqi	Hongqi condensate gas field	YM6, DH23	
Nanka–Yingmaili	Yingmai-7 condensate gas field	YM7, YM9	
	Yudong-2 condensate gas field	YD2	
Lunnan	Lunnan oil-gas field Sangtamu oil-gas field Lunjiefangqu condensate gas field Jilake condensate gas field Lunnan buried hill oil-gas field	LN1, LN2 LN14, H128 FJ132 LN57 LG1, LG2	Marine gases mainly from high- and post-mature source rock of Cambrian
S slope of Tabei	Jinan-4 condensate gas field	JN4	
No.1 fault belt and N slope of Tazhong	Tazhong-24 oil-gas field Tazhong-10 oil-gas field Tazhong-45 oil-gas field	TZ24, TZ161 TZ10 TZ45	Marine gases mainly from O2+3 marl source rock
Main fault block of Tazhong	Tazhong-1 condensate gas field	TZ1	Marine gases mainly from Cambrian and secondarily from C2+3
	Tazhong-6 condensate gas field	TZ6	
	Tazhong-44 condensate gas field	TZ44	
Mazatage	Hetianhe gas field	M4, M2, M8 M3, M5	Marine gases mainly from high- and post-mature Cambrian
Bird mountains	Shan-1 gas reservoir	S1	
	Kekeya condensate gas field	KT2, KT8	Nonmarine gas from J

4.1 Ordovician

The both reservoir types of weathering crust reservoir and inside reservoir are mainly developed in Ordovician carbonates. The interstitial space of the former is formed under weathering karsting action and structural karsting action, the reservoir chiefly belonging to fracture-cavity type and fracture-solution cavern type with porosity less than 2%. For example, the oolitic beach limestone in the interval of 2026.25—2041.2m of well Ma-4 in Hetianhe gas field is much developed of high-angle fractures and solution pores and cavities, belonging to cavity-fracture type. After midway testing in the interval of 2031.34—2140m using 7mm flow nipple, the gas daily

output is $12.9\times 10^4 m^3$.

4.2 Carboniferous

The reservoir lithology of Carboniferous is not only carbonate rock but also clastic rock. The best clastic reservoir bed is Donghe sandstone, with reservoir space mainly being original intergranular pores. For example, the reservoir belongs to type I in the interval of 3597—3648m of the well TZ-402, with the porosity being from 15%—20% and the permeability being from $10\times10^{-3}\ \mu m^2$—$100\times10^{-3}\ \mu m^2$. The reservoir lithology of Carboniferous carbonate rock mainly is bioclast limestone, with reservoir space mainly being pore, solution cavern and fracture. For example, the averaging porosity is 3.55% and the averaging permeability is $2.23\times10^{-3}\ \mu m^2$ for 88 samples of Carboniferous bioclast limestone in Hetianhe gas field.

4.3 Jurassic

The gas reservoir rock of the delta—fluvial facies is developed in Jurassic and belongs to type II, with reservoir space mainly being intergranular pores and intergranular solution pores, averaging porosity 14.75% and averaging permeability $210.19\times10^{-3}\ \mu m^2$. The reservoir rock of Jurassic in Kuche Depression is very special, with much lower porosity and permeability, and yet is high quality due to developed fractures. The reservoir space is fracture-pore type, with averaging porosity 7.47% and averaging permeability $5.42\times10^{-3}\ \mu m^2$ in the intervals gained commercial gas flow of the well Yinan-2.

4.4 Cretaceous–Tertiary

The multilayers of gas reservoir rock of delta front—fan delta plain facies is developed in Cretaceous in Kelasu structural belt, the storage space being mainly the original intergranular pores, with averaging porosity 9.5% and permeability mainly between $1\times10^{-3}\ \mu m^2$—$10\times10^{-3}\ \mu m^2$. Finally, the reservoir of Suweiyi Formation in Eogene belongs to alluvial fan—flood plain facies and the reservoir of Jidike Formation belongs to alluvial facies, both of the storage spaces dominantly being intergranular pores, and the reservoir capacity basically being medium porosity and medium permeability, with averaging porosity 14.6% and permeability mainly between $109.88\times10^{-3}\ \mu m^2$—$893.89\times10^{-3}\ \mu m^2$.

5 Multi-sets of Regional Cap Rocks Being Necessary Condition Forming Giant– medium Sized Gas Reservoirs

The drilled wells opened out that 5 sets of regional cap rocks were generally developed in Tarim Basin from top to bottom, which presented good preservation condition being necessary in shaping multi-sets of reservoir- cap assemblages to form gas reservoirs. Especially, the regional cap rocks in huge thickness are indispensability in forming giant—medium sized gas reservoirs.

5.1 The Salty and Gypseous Bed in Eogene

The predicted thickness of the bed is more than 3600m in Kuche Depression and generally is from 100—534m in the northern part of Tabei Uplift, under which the bottom sandstone in Eogene and good reservoir in Cretaceous were developed. Some big—medium sized

oil-gas fields, such as Kela-2, Yaha, Yingmai-7 and Yangtake and a series of hydrocarbon-bearing structural belts, have been found in the reservoir-cap assemblage. The area of the cap rock could attend $13.3\times10^{4}km^{2}$ in the northern part of Tarim Basin and the Southwest Depression.

5.2 The Coal Measure Strata of Middle and Lower Jurassic

It is 300—800m thick in Kuche Depression and is 250—400m thick in Lunnan area and the eastern area of Manjiaer Depression. The area of the strata is more than 10×10^{4} km^{2} in the northeastern part of Tarim Basin. Under the coal measure strata, good sandstone reservoirs were developed in Middle and Lower Jurassic especially in the bottom of Jurassic and in underlying Triassic. A series of oil-gas fields and hydrocarbon-bearing structural belts such as Lunnan, Sangtamu, E.Jiefangqu, Jilake, Jinan-4, Yiqikelike and Yinan-2 have been found at present in the reservoir-cap assemblage.

5.3 The Salty and Gypseous Mudstone in Carboniferous

It is 207m thick drilled in well Tahe-1 in the northern slope of Manjiaer Depression, is 30—50m thick drilled in wells Mnxi-1 and He-2 in the central part of the basin, and is maximum of 340m in Kalashayi outcrop section in the western part of Bachu Uplift. The distributing area of the cap rock is $9.8\times10^{4}km^{2}$, the salty and gypseous mudstone changed into the Lower- and the Upper- mudstone members of Carboniferous in sedimentary facies toward Tazhong with 200—300m thick, which is composed of good cap rocks of Donghe sandstone reservoirs such as Tazhong-4 and several commercial hydrocarbon-bearing structural belts and weathering crust type reservoirs such as Bird mountain structural belt and Mazatage structural belt found at present.

5.4 The Mudstone of Middle and Upper Ordovician

It is 5000—7000m thick in central Manjiaer Depression and changes into much thinner toward uplift generally being 220—600m thick. The distributing area of the cap rock is more than $30\times10^{4}km^{2}$ with the Ordovician carbonate reservoir under the cap rock. The inner commercial oil-gas reservoirs such as Yingmai-2 in Tabei Uplift and TZ-45 and TZ-162 in Tazhong Uplift, have been found in the reservoir- cap assemblage.

5.5 The Salty and Gypseous Bed in Middle and Lower Cambrian

It is 404m thick drilled in wells He-4 and Fang-1. Tracing of seismic data indicates that it is 1400m thick in Yingmaili area and is 400m in the deep place under TZ-4 oil-gas field. The salty and gypseous bed mainly distributes over the western part of Tarim Basin and is $19.3\times10^{4}km^{2}$ on area. Up to now, there is no commercial oil-gas reservoirs found under the cap except rich source rock and gas show in dolomite under the gypseous interval of well Tacan-1.

6 Conclusion

1. There are multi-groups of natural gas in origin in Tarim Basin, which mainly being nonmarine wet gas, nonmarine dry gas, marine mature gas,

marine high- and post-mature gas and marine mature bias humic type gas.

2. The basic reason that the basin is multi gas groups in origin is that there are 3 sets of important gas source rocks, i.e. the Cambrian source rock which mainly generated cracking gas in late period because of its high- and post- maturity, the Middle and Upper Ordovician source rock which generated not only oil but also gas because of its bias humic organic matter, and the Jurassic source rock in the foreland basin which mainly generated gas because of its humic type kerogen.

3. It is aslo confirmed that the natural gas found at present is mainly related to the source rocks of Cambrian, Middle and Upper Ordovician and Jurassic.

4. The multi-sets of cap rocks are developed in Tarim Basin, i.e. the salty and gypseous strata of Cambrian, the mudstone of Middle and Upper Ordovician, the salty mudstone of Carboniferous, the coal measure strata of Jurassic and the salty and gypseous strata of Eogene, which could shape many sets of reservoir-cap assemblages.

5. Tarim Basin is provided with the necessary geological conditions forming giant and super giant sized gas reservoirs, which decides that the basin is rich in natural gas and has widest foreground in gas exploration.

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Peculiarities of Tectonic Development of the Tarim Platform in the Neogene

A.K. Basharin*, S.Yu Belyaev*, A.E. Kontorovich*, Li Guodu, G.S. Fradkin***

(**Institute of Petroleum Geology SB RAS, **Beijing Petroleum University*)



Basharin, A.K. – born in 1929. Leading researcher in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1959 – graduated from Moscow State University in geological survey and search for mineral deposits. 1965 – held a PnD, 1990 – D.Sc. in geology. His current interests include regional geology and tectonics of petroleum basins in Russia and neighboring territories.

In view of discovery of the petroleum potential of the Xinjiang Uygur autonomous area, the interest for the geology of this region has been sharply aroused. Various geological, geochemical, and geophysical materials published in the papers, large monographs and generalized in the numerous maps [1-18] are available for this area, including the Tarim Platform which is a major element of Xinjiang. Stated below is based on analysis of data on the above-listed materials.

When studying the geology and petroleum potential of the Tarim Platform, we paid attention to the combination of two interrelated facts:

(1) a great thickness of the Mesozoic-Cenozoic, mainly continental deposits forming such basins as Qaidam, Junggar and Tarim. The latter accumulated up to 7–10 km of sediments only in the Cenozoic, which is equal to the total thickness of the entire Sinian and Paleozoic.

(2) a considerable number of orogenic phases which manifested themselves in tectonic deformations (folding, thrust-nappe manifestations, formation of other structural forms). Only during the Meso–Cenozoic the two Indo–Sinian, three Yanshan and two Himalayan orogenic phases have occurred.

Below we shall dwell on analysis of these facts and the role of the last phase of the Himalayan orogeny in the formation of the present-day structure of the Tarim basin.

When analyzing tectonic movements, two methods of investigations are used: analysis of unconformities and analysis of time of manifestation of deformations and their types.

Analysis of unconformities provides the opportunity to establish that at the definite time this area experienced deformations removing it from the levels of sedimentation, but their quantitative and kinematic characteristics remain uncertain.

To analyze the time and forms of manifestation of deformations, data on unconformities, facies and their thickness are used. If deformations occur in the process of sedimentation (synsedimentary), sediments mark the time of their manifestation, succession, and dynamics. Postsedimentary deformations

are recorded as an instant action and are expressed by an angular or azimuthal structural unconformity.

We should note that deformations both in plan and in sections (in three-dimensional models) can manifest themselves locally or regionally. Though this subdivision is conventional, it is of great significance for spatial analysis. However, it is very difficult to determine the particular areas of manifestation of deformations and their intensities with very sparse network of observations. Drilling data, which most frequently lack the reliable elements of occurrence basic for analysis of any deformational forms, are also difficult to use. Interpolation and extrapolation of data on adjacent areas provide rather approximate models of areal and stage-by-stage deformation. They are responsible for many errors in determination of distribution, intensity, amplitudes, and other parameters of deformations, and, consequently, for a general estimate of one or another diastrophism.

Seismic data are of great help for determination of the distribution boundaries of deformation field, however, they are not always available, particularly at the first stages of investigations.

The degree of knowledge of Northwestern China is not uniform. The most of available data refer to the Tarim Platform. It is thought to be studied much better than the bordering folded structures and Jungar basin, therefore, the investigations are based on data on this area.

Xinjiang is located at the place of convergence of the areas of Hercynian, Pacific and Himalayan orogenies [19]. It is known that that the final phased of the Hercynian orogeny is attributed to the end of the Paleozoic and can be assumed to be the Paleozoic/Mesozoic boundary. The Pacific (or Verkhoyansk) orogeny manifested itself in the folded rimming of the Pacific ocean in the Middle Jurassic. The Himalayan orogeny was most active in the Neogene, though there is evidence that this orogeny is still "alive".

The geological and tectonic maps[14, 12] suggest that in the Northern Tien Shan Mt., Junggar Ridge region and further northwards the Mesozoic–Cenozoic deposits occur sharply unconformably on the basement represented by the dislocated Precambrian–Phanerozoic strata with intrusions to form the basal horizons of the epi-Hercynian Platform cover. Local deformations, which represent the response to collision processes continuing south and east of Xinjiang, manifest themselves in the Mesozoic–Cenozoic cover as folded structures and faults.

In the fold belts rimming the Tarim Platform, the major phase of the Himalayan orogeny is confined to the end of the Neogene, in places to the Early Quaternary. This is evidenced by fold and fault dislocations in the marginal protrusions of the platform (Fig.1, Fig.2). Structurally conformable occurrence of the layered sequences, starting from the Sinian, is observed in the folded structures of these protrusions. Disturbances are observed if these regional deformations superimpose the local deformations of earlier phases. If we take into account that these protrusions are shifted into the Tarim Platform from the folded systems and that these folded structures are characteristic of the adjacent zones of these folded areas, a very high importance of this final phase of the Himalayan orogeny would become quite understandable. It is this phase which is worthy of referring to as the Himalayan super-regional diastrophism.

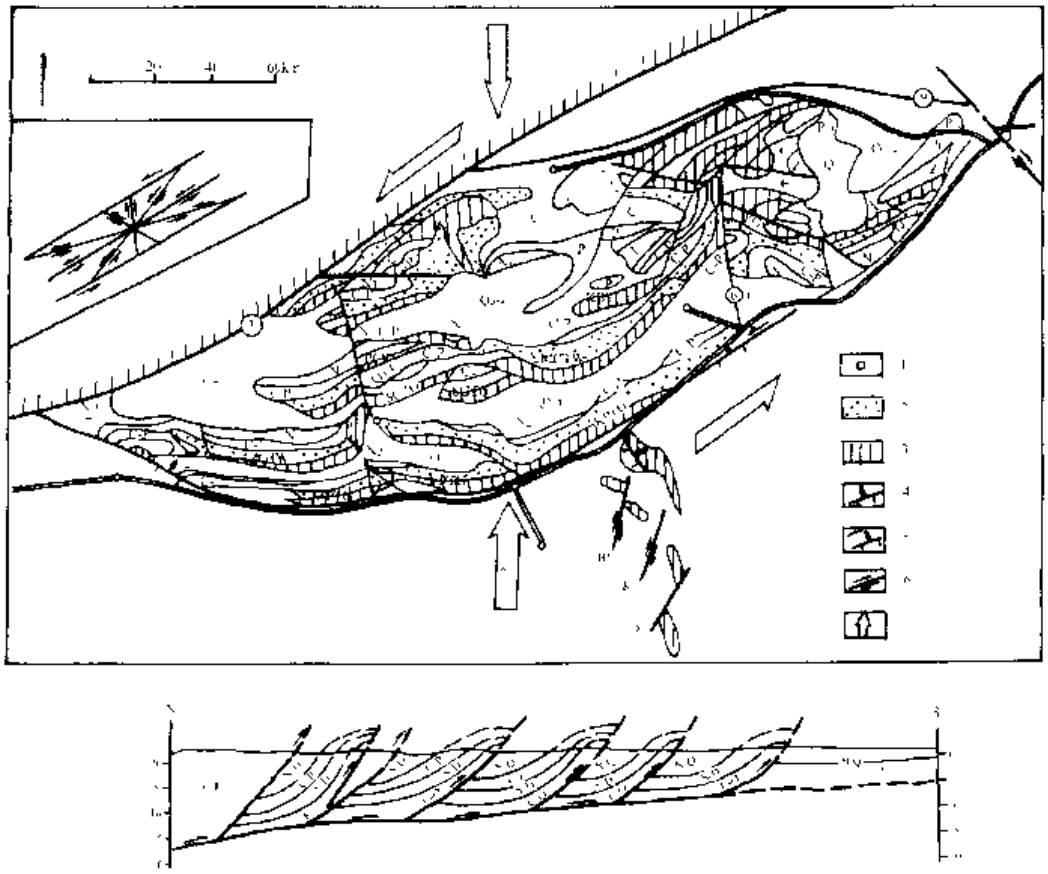


Fig.1 Sketch geological maps and structural profiles of Kelpin protrusion. 1.indices of stratigraphic subdivisions. 2.Silurian and Devonian deposits, 3.Cambrian and Ordovician deposits. 4–6.different types of faults (displacement directions are indicated by arrows). 7.directions of compression and shift. Arabian figures in circles - names of faults. Proper Latin letters - names of structures.

Analysis of facies maps compiled for the Sinian–Phanerozoic cover of the Tarim Platform has revealed that from the Early Sinian to the end of the Paleozoic [4, 9, 10, 11] the strike of facies zones was from the north to south and was sharply changed into east–west.

This regularity can be easily explained: it is at this time when the formation of the Wegener's Pangea ends and the Indo–Himalayan plate collides with the North Asian plate, the southern part of which had been cratonized by that time. The Sinian–Paleozoic north–south zonation can be related to a turn of the Tarim lithospheric plate during its migration. But in this case the possibility of incorporating the Tarim block into the larger Turkmen–Sinian–Korean (Caucasus–Turkmen–Chinese) [20] or the North China lithospheric plates becomes questionable [21]. This problem still needs solution. It is important to note two circumstances.

Firstly, one should pay attention to that the northern and southern extensions of the Sinian–Paleozoic facies zone are cut by large faults bordering the Tarim Platform in the south and north. Herewith, zonation is also

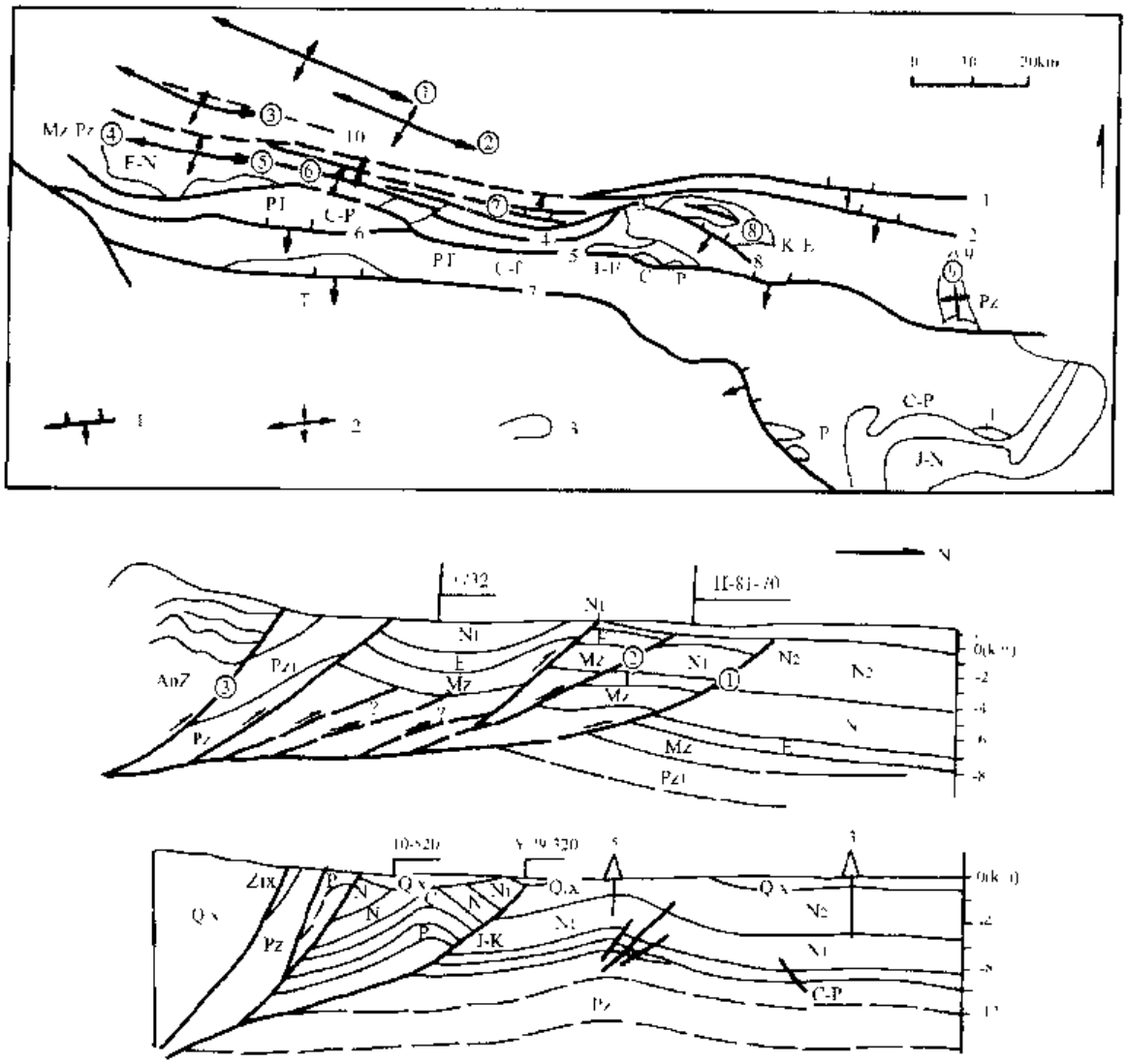


Fig.2 Sketch geological maps and structural profiles of Tikeliktag protrusion (as modified from [8, 9. and others]).1.overthrusts and nappes (arrows along the direction of displacer), 2.axes of anticlinal folds. 3.boundaries of stratigraphic subdivisions. Arabian figures - names of faults and overthrusts. Arabian figures in circles - names of anticlinal structures.

preserved in the marginal uplifts displaced across the regional thrust faults. To explain these facts, it should be assumed that in the Hercynian times the dimensions of the Tarim craton were much larger than those of the present-day Tarim Platform and the platform facies extended from north to south into the areas presently occupied by folded systems.

Secondly, judging from drilling and geophysical data, fold deformations which manifested themselves in the Tarim Platform cover during the Sinian–Paleozoic times, are expressed locally and have no relation to faciec zonation (Fig.3,4). Fold dislocations are represented by large primary (confirmed by structural maps)troughs,depressions swells

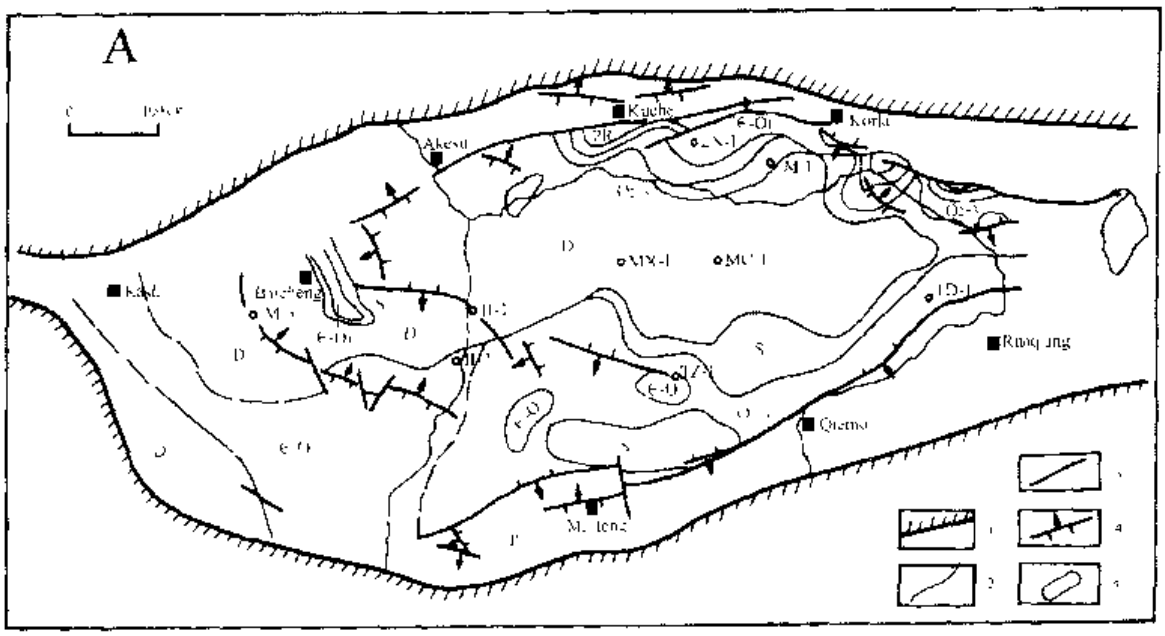


Fig.3 Geological maps with outstripped post-Devonian deposits (as modified from [3, 8, 9, 11, and others]). 1.boundaries of the Tarim Platform, 2.boundaries of stratigraphic subdivisions.; 3.faults with uncertain kinematic characteristics; 4.thrust faults; 5 intrusions.

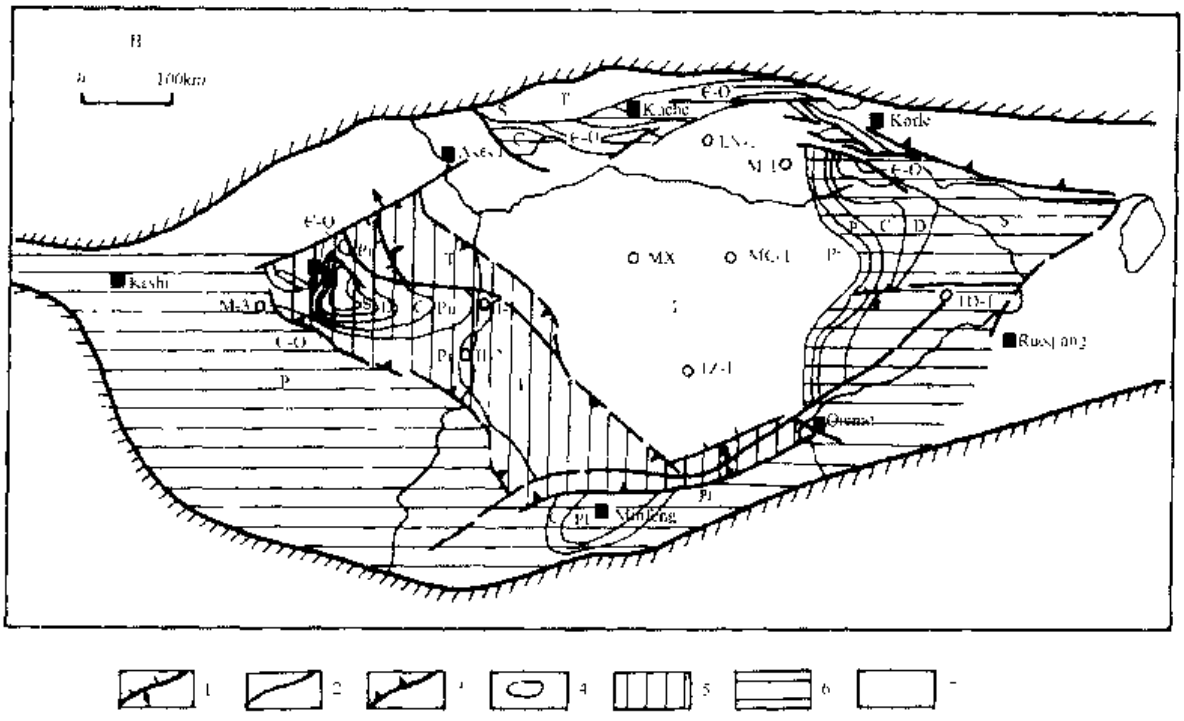


Fig.4 Geological maps with outstripped post-Triassic deposits (as modified from [3, 8, 9, 11, and others]). 1, thrust faults; 2.boundaries of stratigraphic subdivisions; 3.boudary of pinch-out of the Jurassic deposits; 4.intrusions; 5–7.areas of distribution of Jurassic deposits on the underlying deposits; 5.with angular unconformity; 6.with stratigraphic break; 7, conformably.

and uplifts complicated by synsedimentary faults. These structures complicate post-sedimentary superimposed folds and faults. Secondary local, individual structures and those manifesting themselves in different times can be considered as platform. However, their intensity clearly exceeding usual platform dislocations should be marked. Numerous manifestations of these forms make the duced by local, but intense dislocations. Generally, stratigraphic hiatuses are more characteristic of ancient platform covers than significant angular and azimuthal unconformities.

(2) over deformations cannot be considered as typically folded, they are rather of "resonance" character and reflect long-distant orogenic processes.

(3) No foreland structures had formed in the peripheral parts of the Tarim Platform. However, the Sinian rift settings in its Tien Shang margin [23] were responsible for the initial stages of isolation of the Tarim craton from the Late Proterozoic Pangea.

(4) In the Paleozoic and Mesozoic deposits no molasse sequences are present, which could testify to orogen existence in the craton margins during the formation of deformations in the cover. Only Tertiary deposits forming thick complexes along the northern and southern flanks of the platform can be considered as molasses.

Tarim Platform cover not quite "standard": it is composed of platform facies but is dislocated as a folded region. These structures are referred to by some authors as folded platform complexes [22].

Thus, the structural features of the Tarim Platform cover are as follows.

(1) In the Tarim Platform cover section numerous unconformities occur which are in

The above-stated evidences of that during the Paleozoic and Mesozoic the mountain-folded (orogenic) structures did not form near the Tarim Platform. Taking into account a high density of stratigraphic hiatuses and local angular and azimuthal unconformities in the section of the Upper Paleozoic and Mesozoic–Cenozoic sequences of the cover, it would be reasonable to make a conclusion that they formed as a response during the Hercynian, Pacific, and Himalayan (early) orogenies. Location of the Tarim block at the junction of corresponding orogenies favoured the manifestation of these deformations. Only in the Neogene the Xinjiang region has transformed into an orogenic district during strong collisional compressions resulting from the collision of the Indo–Himalayan and North Asian lithospheric plates, but in the inner parts of its constituent microcontinents (terranes), foreland structures with molasse infilling have formed.

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Regional Estimation of the Tarim Platform Petroleum Potential from the Results of Analysis of the Formation History of its Sedimentary Cover

S.Yu. Belyaev., A.E .Kontorovich, Li Guodu*, A.K.Basharin, L.M.Burshtein, G.S.Fradkin, O.G.Ariskina

*(Institute of Petroleum Geology SB RAS, *Beijing Petroleum Institute)*



Belyaev, S Yu. – born in 1951. Head of laboratory in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences 1976 - graduated from Novosibirsk State University in geological survey and search for mineral deposits. 1984 – held his PhD in geology. His current research interests include regional geology and tectonics of petroleum basins in Siberia and neighboring territories.

The Tarim petroleum basin coincides areally with the Tarim Platform, the area of which is about 560 thousand square, km [1]. The Sinian and Phanerozoic formations have been distinguished in the sedimentary stratum of the basin overlapping the erosional surface of the pre-Sinian basement.

Analysis of thickness of the sediments preserved in the present-day structure of the cover [2-8] performed for 13 stratigraphic levels, allowed the construction of a series of maps illustrating the increase in the cover thickness in time and typical location of the areas of maximum sediment accumulation.

The total thickness of the cover is greatest in the Southwest trough where it exceeds, from calculation results, 2000 m and in the Manjaer depression of the Northern trough (more than 15 000 m). Such great thickness of sedimentary formations are questionable and can be related to a repeated recurrence of some fragments of the section in the marginal parts of the platform (for example, in the Kashgar depression) where a thrust-nappe structure of the mantle is highly probable.

Analysis of the geologic–geophysical data (lithologic, seismic, petroleum geology, structural, and others) allowed the establishment of three oil source rock complexes (Cambrian–Ordovician, Carboniferous and Triassic–Jurassic) in the cover section of the Tarim Platform. It has been established that the boundaries between the sedimentary stages, formational and structural-formational complexes and structural stages are related to the periods of tectonic activation induced by the processes in the mobile areas surrounding the Tarim rigid block (Paleoasian ocean in the north and Paleotethys in the south) [9].

However, a series of maps illustrating the increase in the sedimentary cover thickness of the Tarim basin does not allow analysis of the burial history of each of the three oil source rock complexes distinguished (the Cambrian–Ordovician, Carboniferous and Triassic–Jurassic), the estimation of the degree of their thermal maturity, and indication of their location in the platform.

The methods developed at the Institute of Petroleum Geology SB RAS made it possible

to obtain electronic versions of the original sketch maps in isopachs showing the increase in time in thickness of the deposits overlapping oil source rocks for the entire Tarim Platform. The maps of residual thickness of deposits of different age, taken from the published papers [1, 3-8, 10-12], were used as initial material. As a result, three series of sketch maps have been constructed, which show the increase in thickness of the overlapping deposits in geologic history for the Cambrian–Ordovician, Carboniferous and Triassic–Jurassic complexes. The total thickness of the sediments, overlapping each of the three oil source rock complexes in the modern structure, is shown in Fig. 1. The dynamics of sediment accumulation resulting from analysis of these maps is thought to allow a more precise and objective estimation of regional prospects of the petroleum potential for each of the oil source rock complexes.

Temperature regime is known to be a defining factor for hydrocarbon generation. The authors assumed the temperature gradient to be 3°C per 100 m, which is an average for platform areas, even though Van Shejiao, Kan Uichzhu and other investigators [3, 4] provide data that it is lower for the Tarim Platform than for the West Siberian Plate. Assuming the temperature interval of the main phase of oil generation (oil window) to be from 60 to 150°C, we obtain the interval of depths for the oil window to be about 2000–5000 m. It should be noted that the Chinese investigators have drawn the plots of burial and thermal maturity of oil source rocks for some structures from seismic survey and drilling data [12], but no areal analysis was made. Analysis, the results of which are given in more details below, provided the opportunity to determine the time and areas of entering the oil window and passing out of it for each of the oil source rock complexes, what is shown in Fig.2, and to estimate the regional prospects of their petroleum potential.

The Cambrian–Ordovician Complex.

By the end of the Silurian this complex had entered the oil window in the eastern part of the Northern trough (Manjaer depression), where the thickness of overlying strata exceeded 2000 m and had reached 3000 m by the end of the Devonian. By the end of the Carboniferous, the thickness of the overlying complex had reached 4000 m in this area, and in the west of the Central Tarim uplift the oil source rock complex entered the oil window in some limited areas. The thickness of the overlying complex in the Mantszyar depression exceeded 4500 m. By the end of the Triassic, the oil source rocks of this age had entered the oil window throughout the entire Southwest trough, Central Tarim uplift, except the Bachu uplift and Northern trough. At the end of the Jurassic, the thickness of the overlying complex exceeded 5000 m in the central part of the Manjaer depression and in the extreme southwestern parts of the Yarkenda and Kashgar depressions, and the Cambrian–Ordovician deposits passed out of the oil window here. By the beginning of the Cenozoic, the areas, where the thickness of the overlying complex exceeded the maximum possible, had extended, but in the Bachu uplift the thickness had not yet reached 2000 m. At the present time the the Cambrian–Ordovician oil source rocks are in the oil window in the Konquehe monocline, Central Tarim (except Bachu uplift) and



Fig. 1 Thickness of the sediments overlapping the oil source rock complexes in the present-day structure.

A--Cambrian--Ordovician. B- –Carboniferous; C-- Triassic -Jurassic. **A B C**

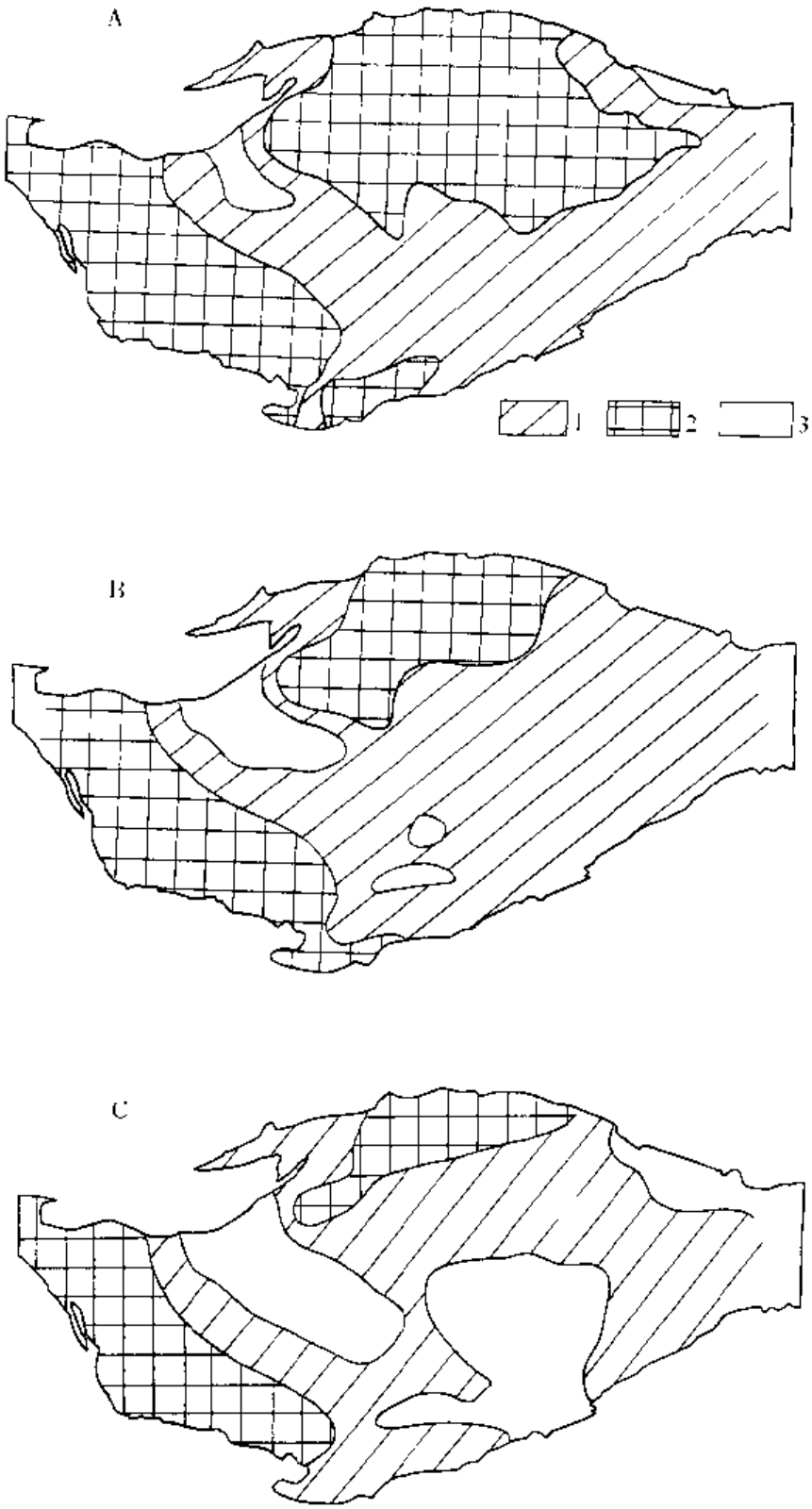


Fig. 2 Areas which presently are in the main zone of oil generation. A B C

A-- Cambrian- Ordovician; B- - Carboniferous; C-- Triassic–Jurassic oil source rock complexes.

Areas: 1-- in oil window; 2-- which passed out of oil window; 3-- which did not enter oil window.

Southern Tarim uplifts.

The Carboniferous complex.

The Carboniferous oil source rocks entered the oil window at the end of the Triassic when the thickness of the overlying complex had reached 2000 m in the Awat depression and the central part of the Central Tarim uplift. By the end of the Jurassic, the Carboniferous deposits had entered the oil window in the central part of the Manjaer depression and in the Yarkenda and Kashgar depressions. By the beginning of the Cenozoic, the areas entering the oil window in these structures had extended, covering the Khetyan depression. In the extreme southwestern parts of the Yarkenda and Kashgar depressions, in which the thickness of the overlying complex exceeded 5000 m, the Carboniferous deposits passed out of the oil window. At the present time the Carboniferous deposits are in the oil window over the most part of the Tarim Platform, except its southwestern, deeply buried part and Bachu and Northern Tarim uplift where they had not yet entered the oil window.

The Triassic–Jurassic complex.

By the end of the Cretaceous, the rocks of this oil source rock complex had already entered the oil window in the most buried parts of the Kashgar and Yarkenda depressions, and presently had already passed out of the oil window as a result of rapid Cenozoic sedimentation in the Northern Tarim uplift and Awat depression of the Northern trough. They had not yet entered the oil window in the Bachu, Central Low and Southern Tarim uplifts and are in the oil window in the remainder of the platform.

The revealed regularities in the geologic history of the sedimentary cover and burial history of the oil source rock complexes of the Tarim platform are necessary to be taken into account in regional predictions of petroleum potential. The authors understand that the presented results are sketchy. As has been already pointed out above, the temperature gradient for the Tarim Platform may appear to be essentially lower than that accepted in this work. Besides, the temperature gradient is, probably, dissimilar in the different areas of the platform and for the different periods of geologic history. Moreover, the temperature interval of the oil window is different for humic and sapropelic organic matter. For this reason, the authors consider this work as a preliminary and offering a further cooperation. Taking into account specified data listed above and using the proposed technique, one can construct detailed maps and schemes which are more conformable to the reality.

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Evolution of Structure and Petroleum Potential of the Yenisey-Baykit Region of the Siberian Platform and Tarim Basin

A. K. Basharin, S. Yu. Belyaev, Li Guodu*, G. S. Fradkin

*(Institute of Petroleum Geology SB RAS, * Beijing Petroleum Institute)*



Basharin, A.K. – born in 1929. Leading researcher in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1959 – graduated from Moscow State University in geological survey and search for mineral deposits. 1965 – held a PhD, 1990 – D.Sc. in geology. His current interests include regional geology and tectonics of petroleum basins in Russia and neighboring territories.

The Yenisey-Baykit block (an area about 160 thousand km^2) of the Siberian Platform is bounded by the Yenisey River valley in the west, approximately at the 102-nd meridian in the east, the longitudinal segments of the Podkamennaya Tunguska and Chunya Rivers in the north, and by the Angara River in the south. The Tarim Platform (an area about 560 thousand km^2) is located in the northwest of China and is bounded by the mountaneous-folded Tien Shan Ridges in the north and by the Kunlung and Tsienlin Ridges in the south.

In the Riphean the Tarim Platform and Yenisey–Baykit block were the inner parts of the consolidated craton — the Early Proterozoic Pangea, on the surface of which rifts, aulacogens, grabens, regmatic zones and other troughs began to form. Later a part of these structures transformed into zones of continental spreading and then they opened as oceans and marginal seas. The main structural features defining the individual characteristics are newly formed [1]. An interval of the geologic history of the compared objects, which is of interest for us, starts from the moment of the initiation of the Neogean structural configuration.

In the Yenisey–Baykit block, the Archean–Proterozoic basement is overlapped by a thick cover of mainly marine Riphean and Paleozoic deposits [2-8]. Their sections are outcropped in the Yenisey Ridge and in the Irkineyeva salient and have been penetrated by boreholes throughout the entire Baykit anteclise. Several deep boreholes have penetrated the pre-Riphean basement.

Five stages, characterized by a specific geodynamic regime, have been distinguished in the Riphean–Phanerozoic history of the Yenisey–Baykit region (Fig.1).

1. In the Riphean, a shallow-water epicratonic, east–west trending trough was initiated, which occupied the central zones of the present-day Yenisey Ridge and extending into the Yurubchen–Tokhomo zone; in the west, it is traced under the present-day West Siberian Plate. The products of the weathering crust and mature terrigenous sediments were drifted into this flat trough from the bordering peneplanized uplifts, and in places ferrous

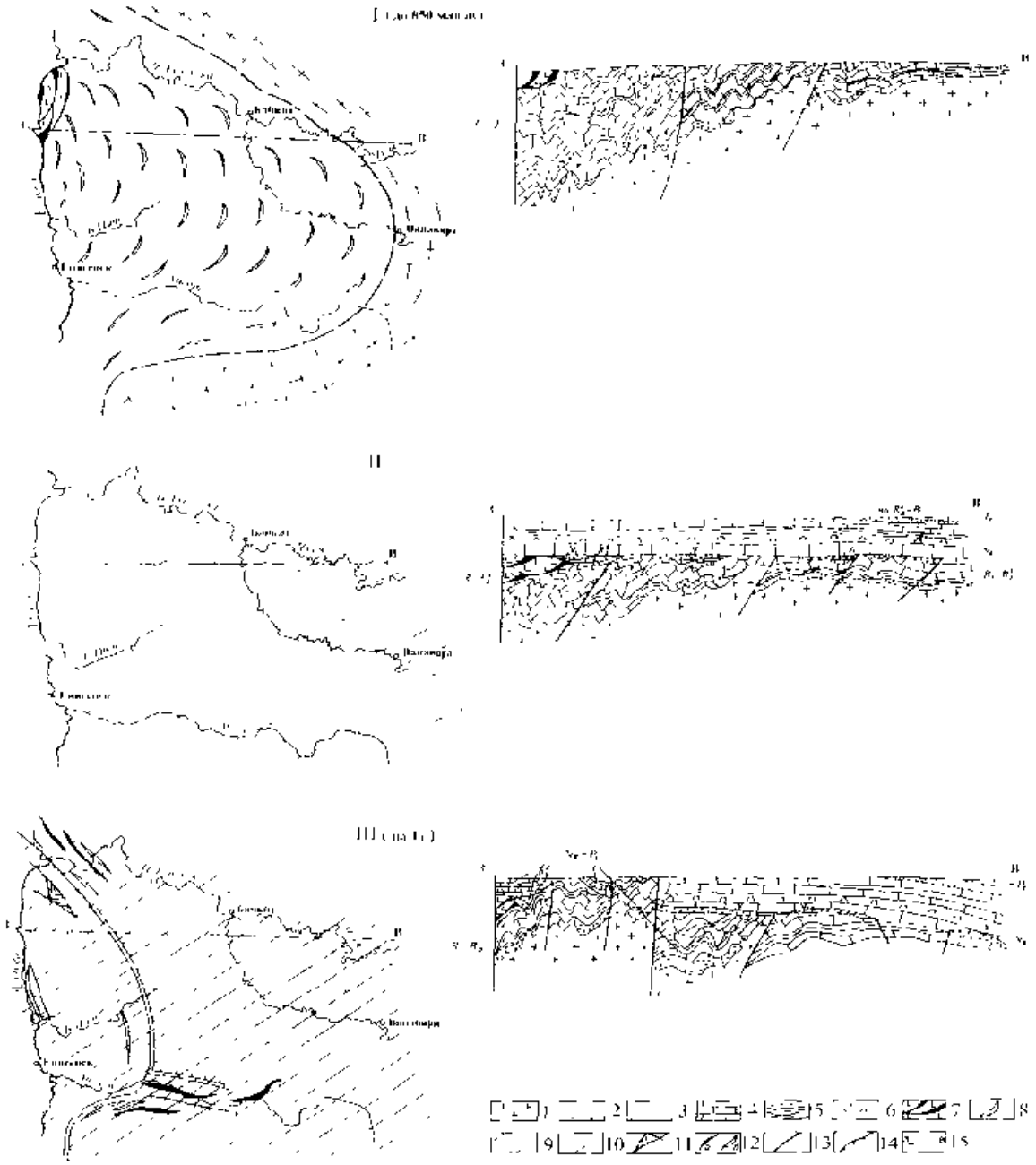


Fig. 1 The model of evolution of the Yenisey–Baykit block structure .

I– the middle of the Late Riphean, II– the end of the Paleozoic, III – the beginning of the Mesozoic.

1–pre-Riphean crystalline basement, 2–6 - sedimentary formations (2–terrigenous polymictic, differently rounded, mainly coarse-grained), 3–terrigenous polymictic, mainly fine-grained, 4 -carbonate chemogenic and organogenic, 5–of different types, including black shales, 6–evaporitic: 7–ophiolites; 8–region of distribution of the Riphean folded formations; 9–region of distribution of the Vendian–Permian formations; 10–region of outcrops onto the surface of the Riphean dislocated formations; 11–Vendian–Phanerozoic formations, bounded by faults, within the Yenisey Ridge; 12–anticlines (a) and synclines (b) in the formations of the platform cover; 13 -dome-shaped structures; 14–faults; 15–steep faults with monoclinally onlapping layered strata (striation in the direction of slope); 16–lines of profiles. *Yenisey Angara B. Pit P. Tunguska Chunya* Yeniseysk Vanavara Baykit.

and evaporitic deposits accumulated. Since the Sukhopit time, the re-orientation of the basin in the north–south direction has occurred: carbonate–shale and partly terrigenous, organic-rich deposits accumulated in the narrow and deeply downthrown blocks of the faults. At the same time, magmatic processes activated in the rifts and within the island arcs [2, 6].

Such regime of development is related to opening of the Kas–Yenisey marginal sea. At that time the Sukhopit–Tungusik basin not only extends in the north–south direction, but partly having inherited a primary east–west orientation, intrudes into the North Asian craton as a wide bay, predetermining the future structure of the reentrant [6].

2. During the first half of the Late Riphean (up to 850 Ma), the accumulated volcanogenic-sedimentary layered strata have undergone strong fold-nappe deformations, which were most clearly expressed in the west of the present-day Yenisey Ridge. The intensity of magmatism, deformations, and metamorphism becomes weaker towards the east, in the direction of the Baykit zone, and attenuates completely in the vicinity of Vanavara.

3. After the break and active short-term denudation, sedimentation repeatedly recommenced in the study area. It locally occurred in the Chingasan basin, which preserved the features of intermontaneous trough; the Precambrian deposits of the southeastern West Siberian Plate also formed in the basins of Chingasan type [6, 8]. During the Vendian, transgression becomes more widespread and stable. Polyfacies terrigenous–sulfate–carbonate and evaporite sediments accumulated in the extensive shallow-water basin.

In this period, the structural and geodynamic conditions were less favourable for accumulation and preservation of organic matter. The Riphean deposits entered the zones of generation and formation of hydrocarbon pools. The Cambrian regional seal composed of salt strata favoured their preservation.

4. At the end of the Paleozoic and beginning of the Mesozoic, the Yenisey–Baykit region underwent arch-block deformations. Compression and relative movement of individual plates between the Angara and Tunguska blocks have been confirmed by poorer deformation of the Riphean–Vendian–Paleozoic layered strata from the Yenisey Ridge to the Baykit region. West of the Velmo fault, both fold and fault deformation are not observed [4, 6]. This is also evidenced by folding features in the northern and southern parts of the Yenisey Ridge, where the folded sequences of the basement are commonly outcropped in the cores of narrow anticlines and the young (Permian–Triassic) deposits are preserved in the troughs of synclinal folds [6, 8]. The steep flanks of the pre-Riphean basement seem to outcrop in these zones, within which the marginal parts of the pre-Baikalian folded complex, bounding the Riphean Yenisey–Baykit reentrant, wedge out.

5. During the Mesozoic and Cenozoic, the study area underwent upwarping. Since the Early Triassic, the western margin of the Siberian Platform, together with the Kas microcontinent, has been overlapped by sediments of the West Siberian Plate from the period of accumulation of rift volcanogenic and volcanogenic–terrigenous deposits. With regard to the plate, the Yenisey–Baykit block serves as a shield.

In the Tarim Platform, the beginning of the Late Precambrian is defined by the boundary

of 1.85 Ga. The Late Precambrian includes the Middle–Upper Proterozoic (1.85–0.85 Ga) and the Sinian (850-570 Ma), i.e., the Neogean stage of development here starts earlier than in the Siberian Platform.

Six stages have been distinguished in the Neogean history of the Tarim Platform. The age boundaries between them are frequently uncertain [9-15].

1. The Middle-Upper Proterozoic volcanogenic-sedimentary formations occur in the marginal salients of the platform and in the central parts of its bordering folded structures. These deposits are supposed to form in wide troughs only in the periphery of the platform. Correlation with the sections of the Siberian platform and other platforms has been considered repeatedly [9-14]. The distribution of carbon-containing deposits and seals in the sequences of the same age is rather similar. By analogy with the Yenisey-Baykit region, high oil and gas potential can be also suggested for the Riphean deposits in the Tarim Platform, though the quantitative estimation of resources is still difficult due to lack of actual data.

2. At the boundary of 850 Ma, the Middle-Upper Proterozoic deposits have been dislocated, that completed the formation of the Tarim Platform basement [9-11].

3. The Sinian-Early Paleozoic stage is characterized by a slow subsidence of the area and accumulation of mainly carbonate deposits. The north-south orientation of facies zones becomes evident during the Cambrian. Herewith, they extended north and south of the present-day platform, which is caused by large sizes of the craton during the Early Paleozoic. Shallow-water shale-carbonate sediments, in places containing gypsum, anhydrites, and salts, accumulated in the western part of the Tarim craton. To the west, this facies zone was replaced by biohermal limestones and flyschoid strata. This zonation is particularly evident in the Ordovician deposits. Magmatic activity is widely expressed. The Sinian basaltic and rhyolitic tuffs are the oldest in the cover [5]. The Aibihus movements, which manifested themselves at the end of the stage, were responsible for the formation of a series of large anticlines and synclines. Oil source rocks in the Cambrian and Ordovician deposits have been detected in the northern trough, as well as in the North- and Central Tarim uplifts.

4. The Silurian Permian stage is characterized by a gradual change of marine regime of sedimentation into continental one. This is expressed in migration of sedimentation regions, differentiation of vertical movements, repeated change of marine sediments into continental ones in the section, activation of faulting, and a wide manifestation of magmatism. A series of unconformities and breaks has been distinguished. Thrust faults, nappes and wrench faults are of importance in the marginal zones of the craton [12-15]. At that time no classic folded ensembles and accompanying orogenic structures have formed; marginal troughs or similar elements have not formed in the margins of the Tarim Platform.

Organic-rich oil source rock horizons and overlying seals have been identified in the Middle–Upper Paleozoic polyfacies and different-type formations. In particular, the oil source rocks in the Carboniferous deposits are considered to be one of the main hydrocarbon sources in the Tarim Platform [11, 12, 15]. Oil- and gas-bearing complexes have been distinguished in the Silurian and Carboniferous marine sandstones; oil and gas pools have been found in them in the North- and Central

Tarim uplifts.

5. During the Mesozoic–Cenozoic stage, lacustrine, lacustrine–marshy and fluvial terrigenous sediments with coal horizons accumulated in the intracratonic depressions and foreland troughs of the Tarim Platform [12, 15]. The Indo–Sinian (Triassic), Yanshan (Jurassic and Cretaceous) and Himalayan (Cenozoic) tectonic movements affected the accumulation of oil source rocks, the hydrocarbon migration and formation of their accumulations. Anticlinal, stratigraphic, and structural-tectonic traps formed and the surfaces of unconformities and faults could serve as migration passways.

Oil and gas pools have been discovered in the Jurassic deposits of the Kuchai trough, in the Neogene deposits of the southwestern trough, and in the Triassic, Jurassic, Cretaceous, Paleogene, and Neogene strata of the North Tarim uplift.

6. The Himalayan orogeny completed the formation of the structural configuration of the Tarim Platform and its bordering fold-nappe orogenic structures. At that time the platform developed in a ramp regime. Falling behind the bordering orogenies by upwarping, it played the role of a large intermontane depression, filling with terrigenous sediments. Compression of the platform from the north and south led to the deformation of pre-Meso–Cenozoic surface and formation of deep (to 7–9 km) foreland troughs. With increasing the distance from the bordering, the troughs become shallower and disappear at all in the central part of the platform.

Finally, we shall emphasize some similar and different features of the characterized regions in terms of their geologic history and estimation of geodynamic prerequisites of the petroleum potential.

In the Tarim platform and in the western part of the Siberian Platform, the Archean–Proterozoic crystalline basement is overlapped by moderately dislocated volcanogenic–sedimentary Upper Proterozoic–Phanerozoic cover. The Upper Proterozoic formations similar in depositional environments and matter composition are the oldest in the covers. In the western Siberian Platform, extensive centers of oil and gas generation and oil and gas accumulation zones are associated with the Riphean strata, large hydrocarbon pools have been discovered and their petroleum potential is estimated as very high. The petroleum potential of coeval deposits in the Tarim Platform has not yet determined reliably, but there are regional geodynamic prerequisites for this.

During the Sinian–Ordovician stage of development, the strata of marine sediments, comparable in thickness, accumulate in the compared regions. The most important difference is a wide distribution of thick halogene formations in the Siberian Platform and their sharply subordinate role in the Sinian and Cambrian sections in the Tarim platform. A reverse relationship is observed in the development of glacial deposits and manifestations of rift magmatism.

Unlike the pre-Silurian events, the geodynamic regime of development, paleogeographic conditions of sedimentation and matter composition of the Middle–Paleozoic, Mesozoic and Cenozoic deposits are characterized by principal differences.

In the Yenisey–Baykit region, the marine conditions of sedimentation which appeared in the Riphean, are traced until the end of the Paleozoic; the change of geodynamic regimes occurred at the Paleozoic/Mesozoic boundary. In the Tarim Platform, a sharp change of ma-

rine, submarine and continental sedimentation occurred as early as in the Silurian and high-amplitude tectonic differentiation is distinctly expressed, which ended with setting in the continental regime. Intermittent was conditions, favourable for the formation of oil source formations and accumulation of regionally continuous seals.

During the Mesozoic and Cenozoic the differences between the regions were still more contrasting. In the Siberian Platform the deposits of this age are almost absent, though in the adjacent area of West Siberia they are ubiquitous. In the Tarim Platform Mesozoic and Cenozoic deposits (to 8 km) are widespread and large oil and gas pools have been discovered in some horizons. At this time intense orogenic movements occur in the bordering mobile belts. They created fold-nappe structures and induced the cover deformations in the marginal zones of the platform.

The above features of similarity and differences in the structure and development of the platform regions of Eastern Siberia and North China should be taken into account in their further study and estimation of the petroleum potential of heterochronous complexes.

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Fold Tectonics of Jurassic Complex of the Mesozoic-Cenozoic Cover, Northern West Siberian Plate.

S.Yu.Belyayev, A.E.Kontorovich, G.F.Bukreyeva, E.V.Deyev, S.V.Zinovyev, V.O.Krasavchikov, S.S.Yershov, D.V.Kosyakov, P.S.Lapin, S.N.Novikova, G.G.Shemin

(Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia)



Belyaev, S.Yu. – born in 1951. Head of laboratory in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1976 - graduated from Novosibirsk State University in geological survey and search for mineral deposits. 1984 – held his PhD in geology. His current research interests include regional geology and tectonics of petroleum basins in Siberia and neighboring territories.

The purposeful investigation of the West Siberian Plate commenced in the 1950s with the discovery of large hydrocarbon reserves in its interior. Construction of various structural and tectonic models of the West Siberian Plate is of particular importance for understanding its tectonic structure and thus allows more reliable assessments of the regional petroleum potential. Currently available compilations such as tectonic maps and schemes of the West Siberian Plate (WSP) which were made in various years by N.N.Rostovtsev, F.G.Gurari, V.P.Kazarinov, V.S.Bochkarev, K.G.Boyarskich, A.E.Kontorovich, K.I.Mikulenko, I.I.Nesterov, M.Ya.Rudkevich, V.S.Staroseltsev, V.S.Surkov and other investigators, played a significant role in examination of the tectonics of the WSP's sedimentary cover. Each of the proposed models was based on the available geological and geophysical data. Information accumulated by this time as well as the newly-elaborated processing techniques enable us to construct regional models describing a structure of the WSP's cover at a new quality level. The present study debates one model characterizing the fault tectonics of Jurassic deposits, which constitute the lower horizons of the northern WSP (Fig.1).

Concepts of fault deformations of the platform covers are generally based on the analysis of structural maps, which provide information on a relief of lithological, age or geographical boundaries. Choosing the boundaries for the construction of structural maps depends on their geological significance and persistence in area. Application of geophysical data in structural reconstructions has been predetermined by a paucity and irregular distribution of deep wells penetrated the lower horizons of the cover in the northern WSP. The CDP data played the governing role. A network of regional CDP seismic lines uniformly covering the northern parts of the Plate, outlines the structure of Jurassic deposits by reflectors B and T, whereas the lower distribution limit of these deposits coincides roughly with the reflector Ia [1]. The reflector

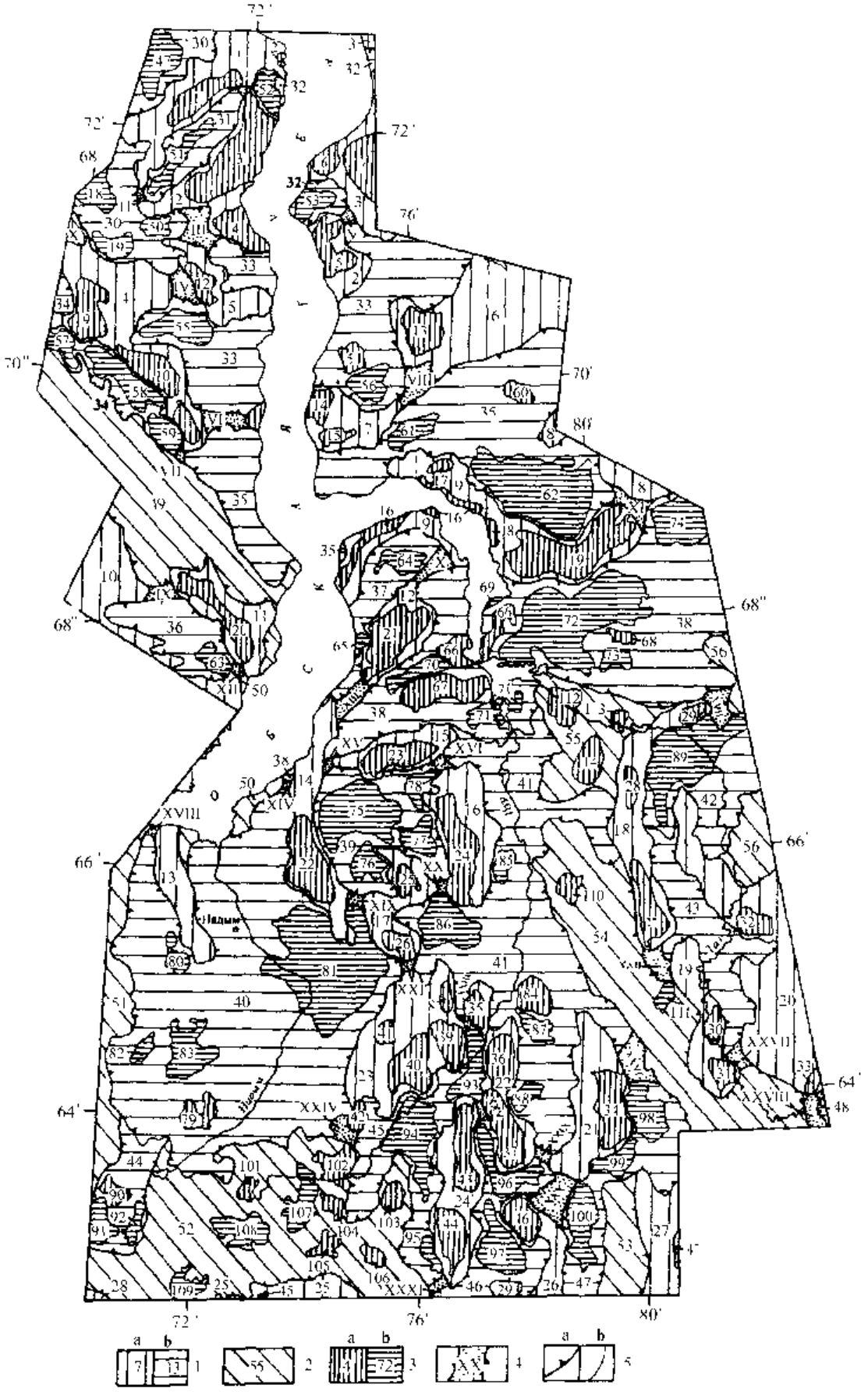


Fig.1 Fault tectonics map of Jurassic complex of the sedimentary cover in the northern West

Siberian Plate (compiled by A.E.Kontorovich, S.Yu.Belyayev, E.V.Deyev, S.V Zinovyev).

1 2–first-order structures: 1a positive, 1b negative, 2–intermediate (monoclines); 3 –second-order structures (a–positive, b negative); 4 –connection structures (saddles); 5 –structure boundaries (a–first-order, b–second-order). First-order positive structures (1–29): 1–North Yamal megaswell (1 –Malygin swell, 2–Drovyanoy swell), 2–Middle Yamal arch (3- North Tambey swell, 4–South Tambey domal uplift, 5–Pekseda d.u.), 3–North Gydan arch (6 West Zeleniy Mys d.u., 7 E.Zeleniy Mys d.u.), 4–Nurmin megaswell (8–Kharasavey swell, 9–Bovanenkovo d.u., 10 N.Arctic swell, 11–S.Arctic swell), 5–E.Bovanenkovo megaswell (12–E.Bovanenkovo d.u.), 6 Gydan arch (13–Gydan d.u.), 7–Napalkovo megaswell (14–Geofizicheskoye d.u., 15–Trechbugornıy swell), 8–Tanama–Ust'–Port arch, 9–Messoyakha megaswell (16–Lower Messoyakha swell, 17 Lower Totoyakha d.u., 18–unnamed d.u , 19- Middle Messoyakha swell), 10–Shchuchiy salient, 11– S.Yamal megaswell (20–Noviy port swell), 12- Yamburg megaswell (21 Yamburg d.u.), 13 Yarudey megaswell, 14–Medvezhiy megaswell (22–Medvezhiy swell), 15- Pestsoviy megaswell (23–Pestsoviy swell), 16–Lower Pur megaswell (24–Central Urengoy swell), 17–Tanlov megaswell (25–Yubileynoye d.u., 26–Yamsovey swell), 18- Chasel'ka megaswell (27–S.Russkiy swell, 28–Russkiy swell, 29–Russko - Rechenskoye d.u.), 19–Tol'ka megaswell (30–N.Tol'ka swell, 31– Tol'ka d.u.), 20–Krasnosel'kup salient (32–Krasnosel'kup d.u., 33–Shirtovo swell), 21–Kharampur megaswell (34–Kharampur swell), 22 Etypur megaswell (35–W.Tarkosale swell, 36–Inguzem d.u., 37–Etypur swell), 23–Northern arch (38 N.Gubkino swell, 39 Purpe swe,. 40–Pyakupur d.u., 41 Upper Tanlova swell, 42–Muravlenko d.u.), 24–Vyngapur megaswell (43 Vengayakha swell, 44 Vyngapur d.u.), 25–Surgut arch (45–Tror Yegan trough), 26–Tagrin megaswell (46–Yarayner d.u.), 27–Upper Tol'ka megaswell, 28 Lyamino arch, 29- Var Yegan megaswell. The numbers and the names of second -order structures are given in brackets. First-order negative structures (30–48): 30 Seyakha mega-trough (47–unnamed trough, 48–Pyasyadayakha trough, 49–Tivteyakha trough, 50 Pyyakoyakha trough), 31–Upper Tambey mega-trough (51–Upper Tambey trough), 32–Khabiyakha megatrough (52–Drovyanaya trough, 53–Mongteyakha trough), 33–Tadebyayakha mega-trough (54–Tadebyayakha d.u., 55- UpperYasaveyakha trough, 56–unnamed trough), 34 E.Baydaratskiy mega-trough (57–unnamed trough, 58–Murtyyakha trough, 59 Upper Yayakha trough), 35–Anti-Payuta mega-trough (60–Yartoyakha d.u., 61 Syda trough, 62–E.Anti-Payuta trough), 36–Baydaratskiy mega-trough (63- W.Noviy Port trough), 37–Parus mega-trough (64–Aderpayuta trough, 65–unnamed trough), 38–Bol'shaya Kheta mega-depression (66– Yurkharov swell, 67 Olikumin swell, 68–Khal'mer–Payuta d.u., 69–unnamed depression, 70- unnamed trough, 71–Khadurtey trough, 72–N.Taz depression, 73–unnamed depression, 74–S.Messoyakha depression), 39–Neruta mega-depression (75 Upper Nyda depression, 76–unnamed depression, 77–W.Urengoy depression, 78 unnamed trough), 40–Nadym mega-depression (79–Kheta d.u. 80 unaamed trough, 81–Upper Tanlova depression, 82–Upper Kheygiyakha trough, 83–Left Kheta depression), 41 Middle Pur mega-trough (84–E.Tarkosale d.u., 85–W.korotchayevo depression, 86–Yagenetta depression, 87–N.Kharampur depression, 88 -S.Kharampur depression), 42- Lower Taz mega-depression (89 Lower Taz depression), 43–Middle Taz mega-trough, 44–Lyamino–Tanlovo mega-trough (90–W.Vatlor d.u., 91- Vynglor depression, 92–E.Vynglor trough), 45 Pyakupur–Amputa mega-trough (93–E.Purpe trough, 94 Pyakupur trough, 95–Amputa trough), 46–Yarayner– Etypur mega-trough (96- Etypur trough, 97–Yarayner depression), 47–Upper Agan mega-trough (98 E.Kharampur depression, 99 unnamed trough, 100–Upper Agar trough), 48–Kas mega-trouga. The numbers and the names of second-order structures are given in brackets.

Monoclines (49-57): 49–Yuribey, 50–Noviy Port, 51–Upper Poluy, 52–N.Surgut (101–Upper nadym d.u., 102–Kollektivnoye d.u., 103–Noyabr'sk d.u., 104–Itur d.u., 105–Kholmogory d.u., 106–Pogranichnoye d.u., 107–Soimfor trough, 108–Soim depression, 109–unnamed depression), 53–Upper Tol'ka, 54–Khadyr–Yakha (110–Urengoy d.u., 111–unnamed depression), 55–Taz (112–Taz d.u., 113–Ust'-yurideyakha d.u., 114–Zapolyarnoye d.u.), 56–Sidorov–Suzun. The numbers and the names of second-order structures are given in brackets.

Connection structures (I–XXXI): I–W.Drovyanaya, II–Middle Pyyakoyakha, III–S.Tambey, IV–E.Bovanenkovo, V–N.Pekseda, VI–Yaptik Sale, VII–Lanz, VIII–Ventoy, IX–S.Yuribey, X–N.Yamburg, XI–Kharvutayakha, XII–Noviy Port, XIII–S.Yamburg, XIV–Nyda, XV–Upper Khadutta, XVI–Middle Tab'yakha, XVII–Tukolanda, XVIII–Shuga, XIX–Pangoda, XX–S.Sedayakha, XXI–Yamsovey, XXII–Chasel'ka, XXIII–W.Tarkosale, XXIV–S.Muravlenkovo, XXV–E.Vengayakha, XXVI–E.Kharampur, XXVII–N.Tol'ka, XXVIII–Shirtovo, XXIX–Middle Etypur, XXX–Yarayner, XXXI–S.Vyngapur.

B is the best expressed and clearly traceable throughout the most territory of the Plate. Its wide areal extent together with the drilling and log data allowed this reflector to be confidently ascribed to dark bituminous argillites of the Bazhenov Formation. The only exception is the interfluve of the Nadym and Taz rivers, where the tracing of the reflector B on seismic lines has been somewhat hampered by alteration of the composition of sediments. Bituminous argillites which crown the Upper Jurassic section are substituted by the Maryanov Formation deposits. The latter is composed of argillites with siltstone and sandstone interbeds. The Maryanov deposits are considered to be transitional from the western type of Upper Jurassic sections (mainly argillaceous Bazhenov and Georgiev Formations) to the eastern one characterized by sandy-argillaceous composition and anomalously large thickness (Upper Sig subformation and Yanovstan Formation). A change in lithology of Upper Jurassic rocks (increasing sand content of the sequence and loss of bituminosity) undoubtedly affects the reflection images. That is why the clinoform reflections B_{Ya} depicting the Yanovstan deposits [2], and subhorizontal reflections B_{20} and B_{40} correlating with the tops of the Sigov and Vasyugan Formations, respectively (Galunskiy V.A., 1993), appear in reflection-time sections instead of the wave B. A generalized map has been constructed based on the reflector B_{20} because it delineates a top of the Jurassic subhorizontally stratified sediments.

A regional structure contour map through horizons B–B_{20} (Fig.2) was constructed using a computer mapping technique [3] that enabled us to make reliable correlation between maps with the contours of different scales (from 1:50 000 to 1:200 000) and quality. Construction of the maps has been always controlled by deep drilling data bases. The most comprehensive structural map of the Jurassic complex was used as a basis for creating a map of fold tectonics of Jurassic deposits of the study area.

The map showed in Fig.1 indicates different-order fold dislocations. Their morphology (size, a degree of closeness and isometrisity) and a character of coordination were used as the underlying criteria for their delineation and classification. A more detailed structural map used as a basis for map construction allowed a picture of fault dislocations to be more accurately delineated and be ever changed in principle in a number of cases.

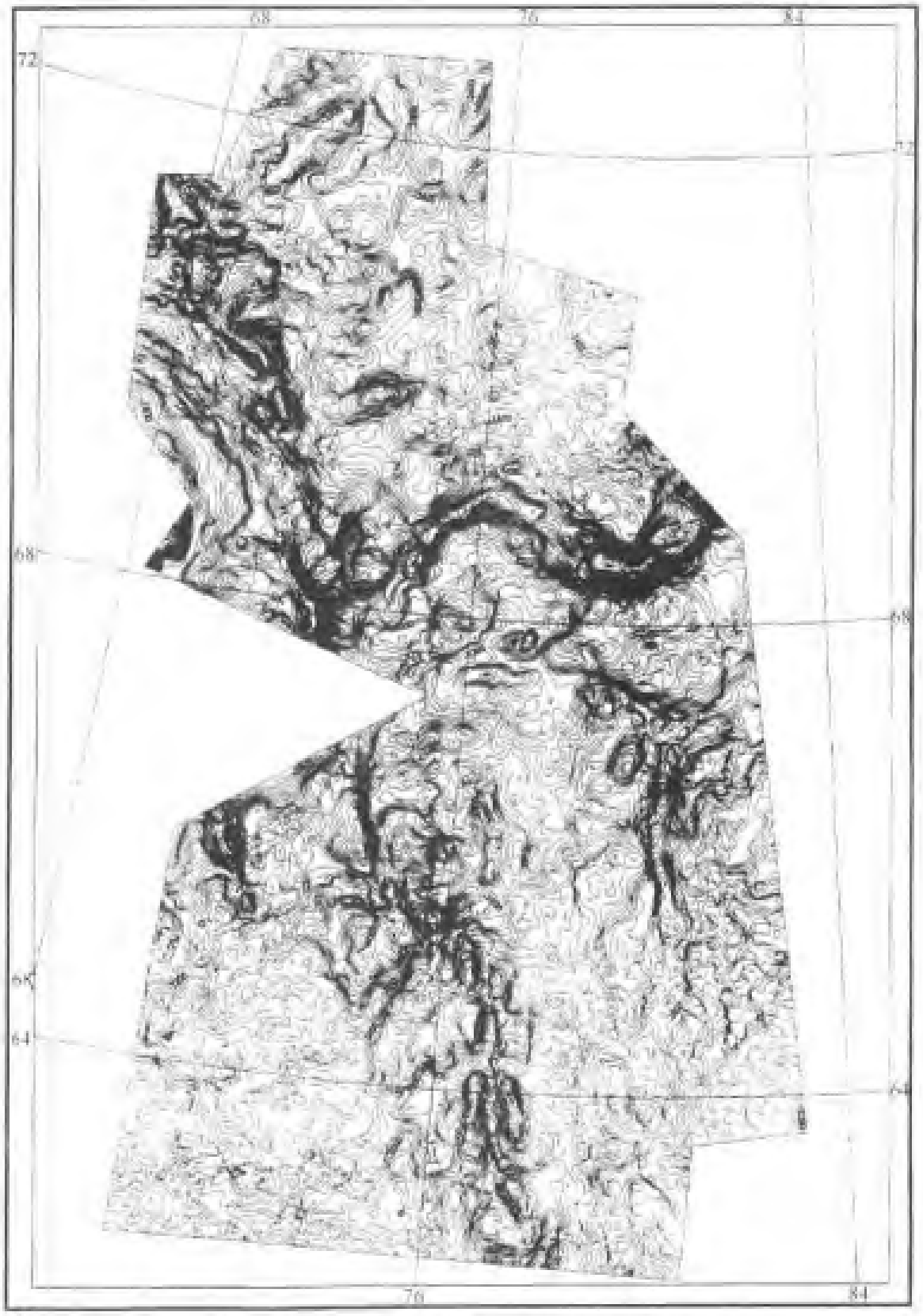


Fig. 2 Map showing a relief of the Jurassic complex top in the northern West Siberian Plate
(compiled by A.E.Kontorovich, V.O.Krasavchikov, S.Yu.Belyayev, G.F.Bukreyeva, P.S.Lapin, S.N.Novikova, E.V.Deyev, S.S.Ershov, S.V.Zinovyev).

The two systems of swells and troughs separating them are the most contrasting. The first system (Pur Nadoyakha) is characterized by a combination of positive and negative structures of submeridional and north–west orientation. The procedure of morpho-tectonic analysis of a relief of structural surfaces [4] enabled a more detailed and accurate mapping of the inner structure of a system. A number of regions has been recognized within the Nadym Taz interfluve. These are the Tarko–Sale, Pur, Russko–Chasel'ka, and Tel'ka regions, which differ by a structure, orientation of morphostructures, a type and Degree of dissection, amplitude-gradient characteristics of the structural surface relief. These regions reveal the block non-uniformity of the Jurassic deposits[5]. The most contrasting manifestation of fault structures are observed in the Tarko–Sale and Russko–Chasel'ka regions.

The Tarko–Sale region is located in the interfluve of the Nadym and Pur rivers. The structures recognized here are being traced further northwestward and complicate a structure of the Jurassic complex within the inner part of the Plate (central Yamal peninsula) and its western slope (Shchuchiy salient, Yuribey and Noviy Port monoclines). The structure of the region appears as a belt, en-eche.on system of contrast swells and troughs. Most of them are characterized by asymmetrical profile and step-like structure. The tops of positive structures and the bottoms of negative one are separated by slope zones with highly-variable amplitudes ranging from 400–500 to 1200 m.

The conjugate Chasel'ka mega-swell, Middle Taz trough and Lower Taz mega-depression are recognized in the central Russko Chasel'ka region. The amplitude variations exceed there 600 m.

The Messoyakha–Gydan system of fault dislocations of sublatitudinal and northeastern orientation is located discordantly to the Pur–Nadoyakha system. The most intensive dislocations are typical of the Bol'shaya Kheta region [5]. It is characterized by sharp variations in amplitudes of a top of the Jurassic complex within one slope. For example, they reach 2000 m on the Messoyakha mega-swell. The deepest mark of the Jurassic complex top (over 4700 m) is observed in the Bol'shaya Kheta region.

High amplitude-gradient characteristics of slopes of most of faults identifiable in the Pur–Nadoyakha and Messoyakha- Gydan systems are likely to indicate disjunctive limitations.

The Nadym region [5] isometric in a plan-view is distinguished in the southwestern part of the study area in addition to the two above-mentioned belt systems. Its southern part is recognized as the North Surgut monocline, which passes to the north into the Nadym mega-depression.

Plotting the base of the Jurassic complex [6], deep seismic profiles may help examination of the behavior of fault structures identified in a vertical section. A combination of structural maps, fault tectonic maps and seismic profiles can serve as the morphological frame of a model for the present-day tectonics of Jurassic deposits in the lower part of a sedimentary cover of the northern West Siberian Plate [7].

A fault tectonics model for the Jurassic complex is essential for evaluation of its regional petroleum potential that is confirmed by analysis of the oil, oil/gas and gas pool location within Jurassic section. It has been

revealed that 65% of the Jurassic pools located in the Nadym-Taz interfluve were ascribed to first-order positive structures (mega-swells, arches and salients), 13% to first-order negative structures (mega-troughs and mega-depressions), and 19% to intermediate structures (saddles and monoclines). Additional 19%, among the pools situated within first-order negative and intermediate structures, are controlled by second-order positive structures. The remaining pools are associated either with local positive structure or lithological traps.

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Influence of Traps on the Petroleum Potential Sedimentary Basins with Intense Trap Magmatism

(As Exemplified by the Tunguska Sedimentaty Basin of the Siberian Platform)

A.E. Kontorovich [1], F.V. Khomenko [1], L.M. Burshtein [1], A.L. Pavlov [2]

([1] *Institute of Petroleum Geology SB RAS, Novosibirsk;* [2] *Institute of Geology SB RAS, Novosibirsk, Russia*)



Kontorovich, A.E. – born in 1934. Academician. Director of Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1956- graduated from Tomsk State University in physics. 1964- held a PhD in geology. 1969 – D.Sc. in geology. His current research interests include petroleum geology, organic geochemistry, analysis of hydrocarbon resources and economic evaluation of the development of Russia's fuel and energy complex

Sedimentary basins (SB) with intense trap magmatism, which manifested itself during one or another stage of their geologic history, are distributed over almost all ancient platforms of the world. Numerous intrusions of high-temperature and mobile basic magma into the platform cover essentially affected all parameters of sedimentary rocks controlling both the hydrocarbon (HC) generation and preservation and the quality of oil and gas accumulations in host strata. This circumstance is responsible for equivocal prediction of oil and gas potential in these regions. To assess reliably their prospects, it is necessary that the trap influence on petroleum potential of the regions with a wide distribution of basite intrusions should be taken into account.

Investigations, carried out in IPG SB RAS and SNIIGG&MS, provided the opportunity to reveal the main criteria of trap influence on the petroleum potential of host deposits [1-6] and to develop the principles for predicting the petroleum potential of sedimentary basins and regions with intense manifestation of trap magmatism [7]. They were performed in several stages.

During the first stage, based on geologic and geophysical data, a model of a basin is reconstructed by the moment of onset of intense manifestation of magmatism, and oil and gas resources of the basin at that period are estimated using a routine technique. Methods for estimating HC resources in poorly explored petroleum basins and for predicting their distribution in three-dimensional geological space, have been developed by one of the authors earlier [8, 9].

The second stage of such estimation is the construction of models of sills, magma-feeding conduits and dikes in the sedimentary cover for both the whole region and its individual areas promising for oil and gas. This is made on the basis of studying natural outcrops and analysis of geological survey, deep drilling, seismic survey, gravity and magnetic prospecting, and drilling data. Firstly, the

sections of individual boreholes are constructed which show the areas of localization of source rocks, reservoirs and intrusions. Then, the geologic sections characterizing the position of intrusions relative to individual reservoirs and oil source formations are constructed from borehole and geologic survey data, taking into account geophysical investigations (in the first place, seismic exploration). The constructed sections serve as a base for isopach maps of sills which are contained in particular stratigraphic subdivisions of the sedimentary cover. These maps also show magma-feeding conduits and zones of mass transition of sills from one hypsometric level to another. The range of stratigraphic subdivisions, for which such constructions are made, is defined by the number and total thickness of sills contained in them. These constructions are obligatory for the intrusions located near oil source rocks and regionally continuous reservoirs. Based on such geological materials, small-scale constructions are made for the sedimentary cover of the whole SB that allows the identification of general regularities of distribution of trappean intrusions across an area and section. This reconstruction of the framework of magmatic bodies in the sedimentary cover and correlation of major petroleum-generative and productive subdivisions with the sedimentary cover enables us to ascertain the following.

· The character of relationship of structural configurations in different stratigraphic subdivisions of the sedimentary cover that, in turn, would essentially specify the hypsometric position of the productive horizons, projected sections of deep stratigraphic and wildcat boreholes to be drilled, as well as seismic geologic models, on which geologic interpretation of seismic observations is based.

· To outline the zones of high-fractured rocks that would allow the localization of the secondary high-porous fractured reservoirs, formed due to decrease in volume of magma during its hardening and located in both endo- and exocontacts of trappean bodies, as well as the newly-formed migration paths of fluids controlled by intrusions.

· Besides, the models constructed would provide the basis for fulfilling the third stage -- the reconstruction of maximum temperatures of sedimentary rock heating and creation of 3D-model of maximum geotemperature field which existed in the basin immediately after magmatic activity had ceased. The techniques of determining the maximum temperatures of sedimentary rock heating have been developed in the United Institute of Geology, Geophysics and Mineralogy SB RAS [10, 11], the main statements of which are reduced to the following.

· Emplacement of magmatic bodies is assumed to occur successively and the preceding intrusion had time to cool up to background temperatures by the moment of formation of the following intrusion [10].

· Based on previously constructed sections, thermal-physical modeling of heating of sedimentary rocks by trappean intrusions was made according to particular geological conditions of the study area, provided the sequential emplacement.

· Calculations performed are confirmed by bimineral thermometers used in the particular geologic situation. In particular, it is reasonable to use a calcite-dolomite geologic thermometer for the sections, which are dominated by carbonate rocks [11]. In other cases, a thermometer, most suitable among those considered in [10], is used.

Based on the obtained data and geological materials, models of maximum heating of sedimentary rocks are constructed in the form of geological profiles that allows the assessment of the size of zones with defferent degrees of heating -- from the zones of maximum temperatures located in exocontact parts of the section to zones of normal catagenesis temperatures.

· Maps of heating of productive horizons are drawn, based on which zonation of the area was then made by degree of heating in the different parts of the sedimentary cover by magmatic heat.

Use of these materials provides the opportunity to reconstruct the temperature regime of the sedimentary basin interior during a maximum development of trap magmatism. In turn, this makes it possible to ascertain the size of zones with different heating degrees -- from high-temperature zones, where organic matter (OM) and naphthides have been completely metamorphosed to form insoluble stages, to zones, where OM is capable to generate hydrocarbons of variable phase composition. Besides, it becomes possible to ascertain the parts of the section and rock volumes which after trap emplacement were involved in the zone whose conditions corresponded to the main zone of oil generation. In the first place, this is the upper part of the sedimentary section, which, prior to trap emplacement has not reached depths where HC generation becomes possible during a normal evolution of the basin.

Determination of maximum temperatures of heating of sedimentary rocks and identification of magmatogene temperature zonation made it possible to specify the processes of interaction of HC fluids with formation waters and host rocks induced by magmatic heat.

To ascertain the degree and scales of transformation of HC components and their host environment, chemical-kinetic modeling of such processes was made based on the principles of equilibrium thermodynamics. It was performed within the range from temperatures of normal catagenesis to temperatures of maximum heating of host formations in near-contact zones of trap intrusions (25–700° C). Lithology of sedimentary formations filling in the sedimentary basins is variable. There are basins with mainly sulfate/carbonate (Tunguska), terrigenous alumosilicate (Parana) and mixed type (Karroo) of sediments. Correspondingly, the models were created for both sulfate/carbonate [12] and terrigenous aluminosilicate matrices. The main results of the work performed is as follows.

· At temperatures above 500° C (i.e., in narrow near-contact zones) almost pure carbon is remained in the system if hydrocarbons are present; complex hydrocarbons are intensely destructed within the range of temperatures of 300–500° C and hydrocarbon gases are sharply dominated by methane.

· sulfur-organic components (mercaptans), the composition of which is simplified with increasing temperature, are newly formed in the system where the matrix is represented by sulfate/carbonate rocks in liquid phase. Besides, the chemical composition of hydrocarbon compounds is simplified. In gaseous phase, carbon dioxide and hydrogen sulphide content increases with increasing temperatures, in HC gases the amount of sweet components sharply decreases and methane content increases. In solid phase, calcite is newly formed, dolomite and anhydrite are destructed, inducing the appearance of secondary porosity in oil-containing rocks. If anhydride is in excess in the system, hydrocarbon gases

(at temperatures above 300° C) are almost absent, and carbonic acid gas and hydrogen sulphide are major components; native sulfur appears in the composition of sedimentary rocks, the amount of which monotonically increases with temperature.

· In the system where the matrix is represented by sedimentary aluminosilicate rocks, decomposition of complex compounds and removal from liquid phase of sulfur, mainly transforming into a sulphide form and partly hydrogen sulphide, occur in HC fluid. Gaseous phase is enriched in methane, carbon dioxide, hydrogen and nitrogen-containing compounds. Host deposits are transformed into quartz–chlorite–illite–talc rocks with epidote and graphite. The amount of the latter directly depending on the content of HC components in the system. At temperatures above 300° C amphibole appears in appreciable quantities.

Modeling results are confirmed by the actual data acquired when studying oil and gas deposits of the Tunguska petroleum basin [12, 13, 14, 15].

The above criteria of trap influence on petroleum potential of sedimentary basins allow essential corrections to be introduced into quantitative estimation of hydrocarbon resources already at this stage of investigations in the areas with intense manifestation of trap magmatism.

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The Paleozoic and Triassic Petroleum Potential of the Central Regions of West Siberia
(new data and petroleum potential)

N.P. Kirda, N.V. Sennikov, E.A. Yolkin, M.A. Levchuk

(Institute of Petroleum Geology, SB RAS)



Kirda, N.P. – born in 1938. Leading researcher in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1964 – graduated from Moscow Institute of petrochemical and gas industry in geology and prospecting for oil and gas fields. 1985 – held his PhD in geology. His current scientific interests include the problems of petroleum geology of the West Siberian petroleum basin.

The main reserves and estimated resources of oil and gas in West Siberia are nowadays associated with Valanginian-Hauterivian (Neocomian), Berriasian-Lower Valanginian (Lower Cretaceous), Upper Jurassic, and to a less extent with Lower-Middle Jurassic deposits. The West Siberian petroleum basin's potential are not however restricted by the revealed potential of aforementioned stratigraphic intervals. The results of investigation and exploration obtained during the last decade by the Institute of Petroleum Geology SB RAS and by exploration and production enterprises, accordingly, enable a scientific forecast of raw material resources occurred in deeper buried complexes of the Lower Jurassic, Triassic and Paleozoic.

The West Siberian petroleum complexes are characterized by different levels of their knowledge. Lower Cretaceous and Upper Jurassic deposits are the best explored by geophysical survey and drilling. The poorer explored are Lower Jurassic deposits which have been penetrated by sparse wells. As regards the Pre-Jurassic sedimentary and volcano-sedimentary complexes, they have been penetrated only by few wells and thus remain the least explored target of West Siberia.

Shatskiy (1932) has made the first forecast of the Paleozoic petroleum potential. A.A. Trofimuk (1964, 1991) set forth the most keen problem concerning the Paleozoic potential of West Siberia, insisting on the importance of systematic exploration within new promising complexes associated with Triassic, Paleozoic and Upper Proterozoic deposits to increase and keep up production of hydrocarbon raw material.

The natural occurrence of hydrocarbon reservoirs in erosional-tectonic escarpments of the Pre-Jurassic complexes overlapped by Mesozoic deposits was known since 1935, when the first 850 cu m/d inflow of nitrogen-methanic gas and a gas-water blowout were yielded from a well drilled nearby the Makushino railway station and the town of Petukhovo in the southern West Siberia, respectively. The first oil show interpreted as being of the Paleozoic genesis was obtained in the Kolpashevskaya key borehole in 1954 (Gurari, 1959). The first blowout of oil from the upper Pre-Jurassic complex was yielded at

the Medvedevskoye field, Tomsk district, in 1963, that of gas was obtained at the Karabashskoye field in the south of the Tyumen district in 1964. Later on, a number of discoveries was made in the Tomsk and Novosibirsk districts, as well as in the central West Siberia.

The analysis of cores sampled from wells which penetrated the Pre-Jurassic deposits in the central West Siberia (Krasnoleninsk, Salym, Ust'-Balyk, Var Yegan and Nikol'sk regions) provided the faunal evidences for the dating of deposits from the following stratigraphic intervals:

- Lower Ordovician (lower Poludennaya Fm.: limestones with argillite interbeds containing conodonts and trilobites),
- Upper Ordovician (upper Poludennaya Fm.: limestones and calcareous argillites containing brachiopods),
- Lower Silurian (Larino Fm. containing tabulates),
- Lower Devonian (Var Yegan stratum: basalts, argillites, siltstones, limestones with conodonts and tentaculites),
- Middle Devonian (Yubileynaya stratum: argillites, limestones with foraminifera),
- Upper Devonian (Luginets Fm.: limestones with conodonts and fishes),
- Lower Carboniferous (Kekhoreg Fm.: argillites, limestones with foraminifera),
- Middle-Upper Carboniferous (limestones with conodonts),
- Permian (Yagun and Priozyornaya strata: argillites, sandstones, gravelstones with fishes) (Decisions, 1999).

All Triassic stages were recognized on the Krasnoleninsk arch. A fragmentary study of them and their composition are given in Fig. 1.

To date, a wide stratigraphic range of petroleum potential of the Pre-Jurassic complexes has been confirmed in numerous well columns of West Siberia. Besides individual shows many wells yielded oil and gas inflows. Oil production rates from Pre-Jurassic deposits on erosional-tectonic escarpments vary from insignificant amounts (1-5 cu m/d) to 400 cu m/d.

Silurian deposits penetrated in the southeast of the region are the oldest ones in which oil shows have been revealed at large depths. It was recognized that oil and condensate pools are next to one other in the Lower Carboniferous and Upper Devonian sections (North Var Yegan field) in the central parts of the region, on erosional-tectonic escarpments, within fractured and karsted terrigenous-carbonate deposits (Trofimuk, Kirda, 1990). In the central regions of West Siberia, commercial oil inflows were obtained from eroded deposits unconformably underlying the Triassic effusive-sedimentary rocks on the Krasnoleninsk arch at the Ur'yevskoye field (Kirda et al., 1995, 1997 and other).

Several independent objectives are recognized within the Pre-Jurassic complex: (a) a zone of contact between Pre-Jurassic complex and Jurassic rocks (Kontorovich et al., 1975); (b) erosional-tectonic escarpments of Pre-Jurassic rocks overlapped by Jurassic platform and Triassic volcano-sedimentary deposits (Kirda et al., 1976, 1995, 1997 and other); (c) deep horizons of the Pre-Jurassic complex whose Paleozoic stratigraphic intervals contain dolomites, sedimentary breccias and other types of the rocks with good poroperm properties, which are overlapped by good seals (Trofimuk, 1964; Kontorovich et al., 1975; Kirda et al., 1976, 1995, 1997 and other).

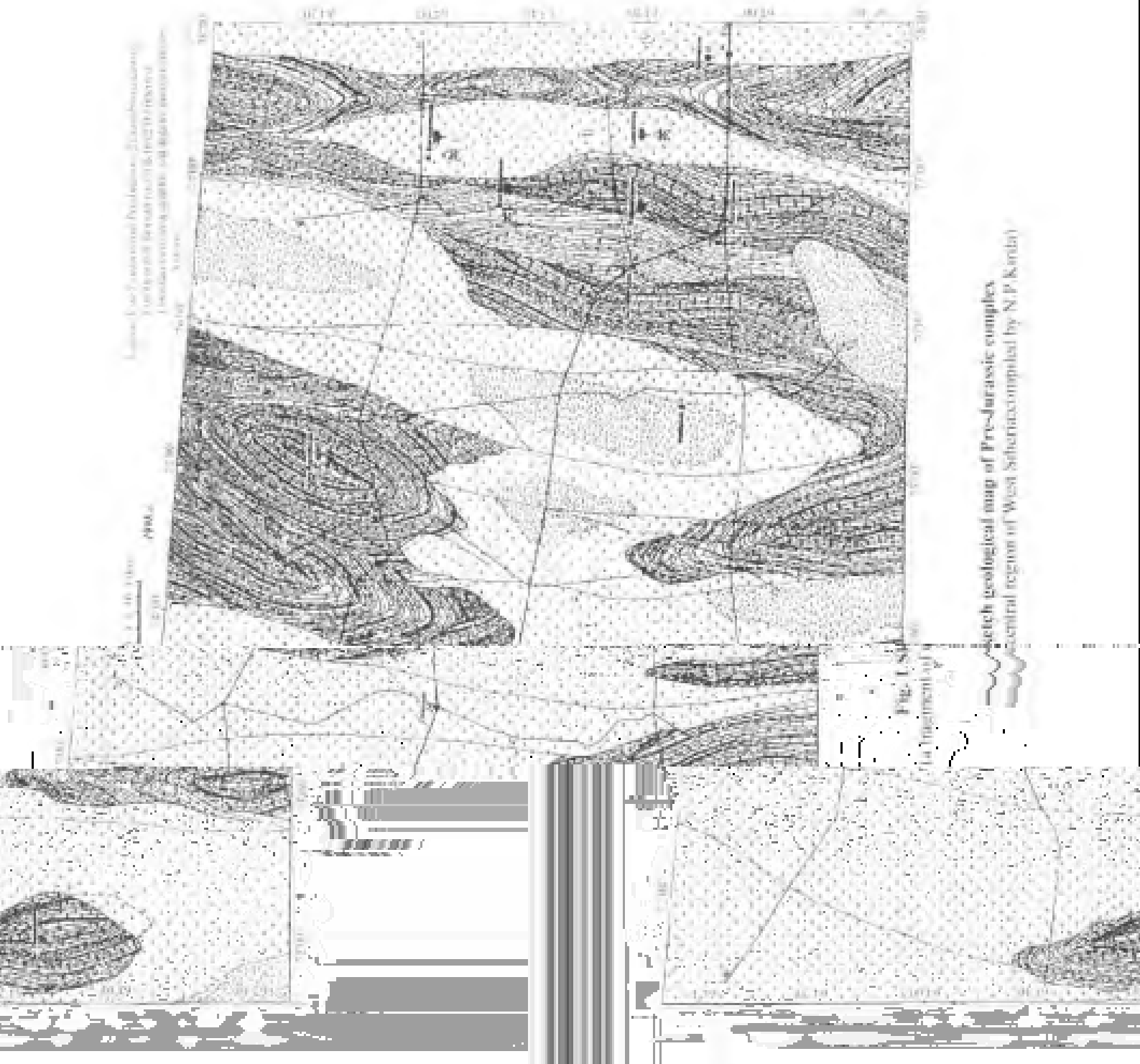
Estimating the maturity level of organic matter from the Paleozoic strata it is notewor-

thy that dispersed organic matter is rather catagenetically mature ($MC_3^2 - AC_2$) (Kontorovich et al., 1975; Ennakov, Skorobogatov, 1988; Vyshemirskiy , 1971; Fomin, 1994, 1995). Density of argillaceous, argillaceous-carbonate, carbonate and effusive rocks of the Jurassic varies from 2.18 to 2.85 g/cu cm, thus being within the same range as that of the rocks from petroleum complexes recognized on the East European platform, PreUral trough and other petroleum provinces.

The Pre-Jurassic complexes' sections are widely variable in their composition, structural-formational parameters and a mode of occurrence (Fig. 1). Their various depositional histories caused the different formation histories of reservoir rocks and seals. Heterogeneity is produced by structural forms and their morphological elements, faults, fractures, zones of stress concentration, hypsometry and geometry, mutual orientation of structural-tectonic forms, lithological composition etc. (Fig. 2). All Pre-Jurassic complexes are composed of argillites, siltstones, sandstones, conglomerates, breccias, laminated, argillaceous, clastic and reefal limestones, lavas and tuffs of various composition (Fig. 1, 2). These rocks demonstrate wide facies changes and regular replacements in transition from one structural-facies zone to other.

Revealed on the geologic longitudinal sections of West Siberia are the zones of arched uplifts and shear zones on their flanks, as well as zones of synclinal troughs. Their structures are complicated by fractures some of which are the deep faults. Such large faults must have been neck channels through which the effusive acid and basic rocks erupted in the late Hercynian and during the Kimmerian tectogenesis. The largest structural forms are thought to have developed during the main folding stages. A structural-material characteristics of large tectonic units (anteclises, arches, syneclises, depressions, anticlinal and synclinal zones) depends also on a stratigraphic succession of the complexes. Three stages can be recognized in a structural history of the Pre-Jurassic sedimentary complex of the area under consideration. Each of these stages has been signified by the development of structural-formational complexes which differed in their quality: (a) a base complex of the Pre-Ordovician age (probably Precambrian), (b) a deformed paleoplate complex aged from Ordovician to Permian inclusive, and (c) Triassic early-platformal complex.

In the studied West Siberian sections penetrated by wells beneath Jurassic deposits the rocks on erosion-tectonic escarpments have the factor of open porosity ranging from 20 to 30 %, that of effective porosity 18-25%. Permeability is 12×10^{-9} μm. However, the rocks having the reservoir properties of porous type are not abundant within the Pre-Jurassic complexes. This is accounted for the fact that the reservoir properties of these rocks strongly depend on intensity of fracturing, processes of leaching, recrystallization, dolomitization, and silicification, geochemical and other secondary factors. The fractures of different genetic types have been distinguished. These are the diagenetic fractures, stylolites, release fractures, congruent fractures and fractures feathering the faults. The aforementioned fractures developed in various stages of geologic history, hence, have had an ambiguous impact on the formation of reservoir properties of the country rocks. This should be taken into account in estimation of



Sketch geological map of Pre-Jurassic complex
Central region of West Siberia (compiled by N.P.Kirda)

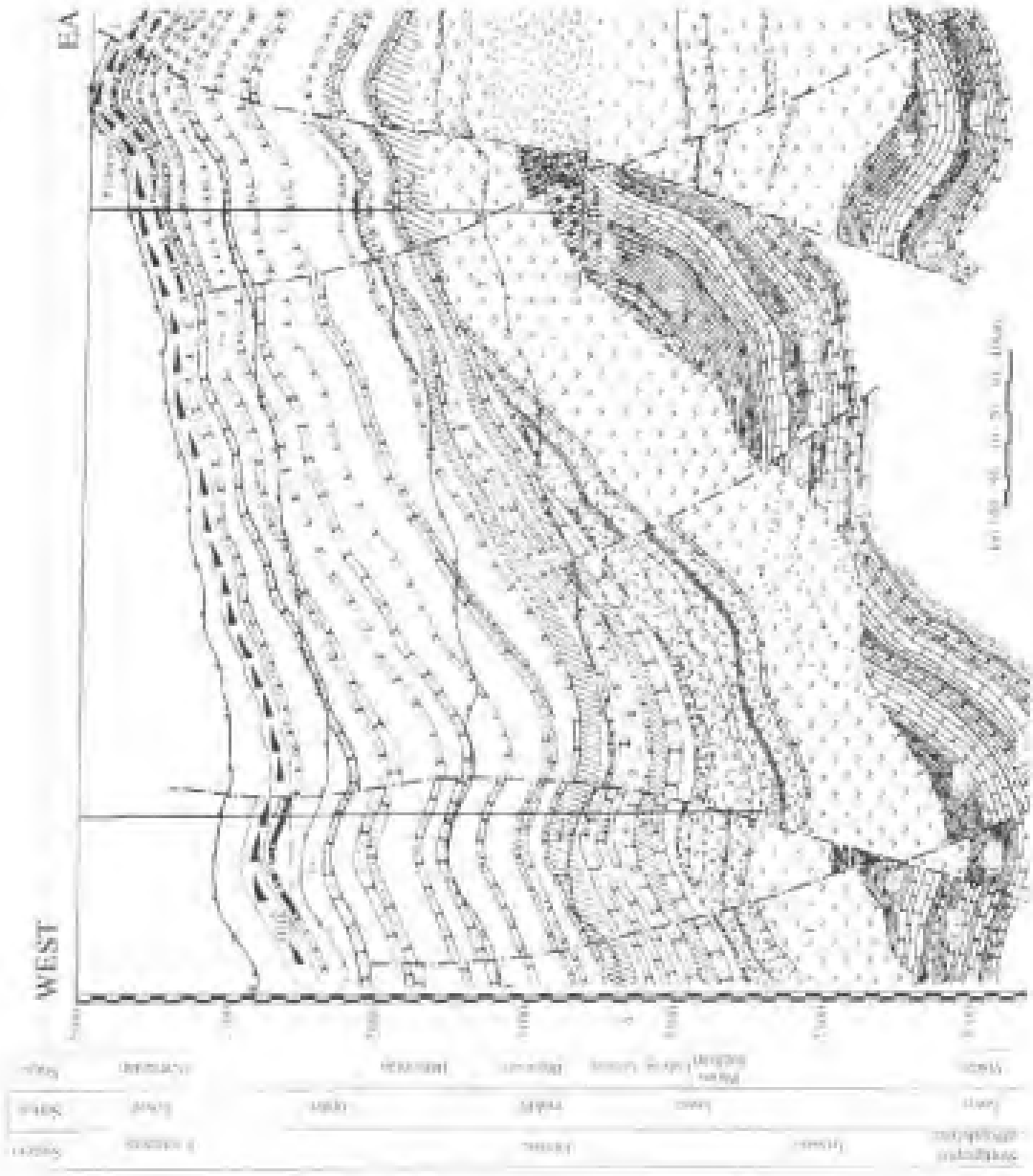


Fig. 2 Geological cross section of Jurassic deposits and Pre-Jurassic complexes
(Uf'yeskoe oil field; compiled by N.P.Kirda)

the poroperm properties of rocks and seismic data interpretation. Leaching played a critical and final role in development of epigenetic reservoirs and appears to have been the most active witain the zones of stratigraphic and angular unconformities (erosion-tectonic escarpments, short-term breaks in sedimentation in the terrigenous-carbonate sections).

The revealed regularities of a geological structure of Pre-Jurassic complexes (Paleozoic, Triassic) of the West Siberian plate enabled the petroleum potential to be predicted in two main directions (Trofimuk, 1964; Kontorovich et al., 1975; Kirda et al., 1976, 1995; Taik et al., 1997). The first is the potential prediction for deep-seated (4-7 km) stratigraphic complexes of Pre-Jurassic age. The second is the potential prediction in conditions of erosion-tectonic escarpments and elevated surfaces of Pre-Jurassic complexes overlapped by the Lower Jurassic seals.

The main problems connected with the first direction were caused by a great number of rocks diverse in their genesis and, hence, lithologo-formational composition which constitute structural-tectonic sedimentation zones different by stratigraphic filling, thicknesses and distribution areas.

While predicting in the second direction, it should be taken into account that the erosion-tectonic escarpments were developing during active rock disintegration and high territory elevation prior to the cover formation. In the vicinity of the Pre-Jurassic base surface, especially within erosion-tectonic escarpments, the rocks of Pre-Jurassic complexes are nearly everywhere disintegrated, karsted and appear as a massive, capacious reservoir overlapped mainly by argillaceous deposits of the Jurassic.

The Triassic volcano-sedimentary complex is revealed by drilling and seismic survey to overlays unconformably the deformed and washed out Paleozoic deposits. Crusts of weathering formed during the Pre-Triassic were confined to this zone of contact. Paleozoic deposits preserved after wash out are composed of weathered, disintegrated or karsted rocks which appeared as a massive reservoir overlapped by the Triassic effusive-sedimentary rocks.

The main reservoirs predictable in all stratigraphic intervals of Pre-Jurassic complexes are of fractured-vuggy and fractured types. In addition, some pools appear to have been associated with a massive reservoir occurred in reef buildups that is supported by ubiquitous calcarenites.

Based on the available data several oil and gas discoveries, perhaps fairly large and productive ones, can be predicted in Pre-Jurassic complexes within several stratigraphic intervals:

(1) Reservoired in erosion-tectonic escarpments of Pre-Jurassic complexes in structures prepared by seismic prospecting along a reflector A which corresponds to the upper boundary of Paleozoic deposits where they contact with Jurassic rocks.

(2) Beneath a cover of the Triassic effusive-sedimentary rocks which overlay unconformably the eroded Paleozoic deposits. This near-contact weathered layer exhibited favourable conditions for the formation of terrigenous-clastic horizons, as well as of the rocks containing epigenetic reservoirs. Oil inflows obtained from under the Triassic effusive-sedimentary sheet can serve as convincing evidence for the petroleum potential.

(3) Under conditions of short-term (hidden) stratigraphic hiatuses, whose boundary inter-

vals are predicted to be of the Devonian-lower Lower Carboniferous and are penetrated in individual wells.

(4) In terrigenous-carbonate and dolomitic deposits of the Devonian, Silurian, and Ordovician which were intersected by individual wells and are overlapped by argillites and argillaceous limestones.

(5) Within large faulted zones which bear-fracture structural forms are confined to, as well as in the dynamic stress zones in Paleozoic deposits and in the Triassic volcano-sedimentary stratum. Such conditions could result in the formation of columnar pools.

(6) Under conditions of linear-focus distribution of fracturing, karsting and dolomitization which would result in the presence of non-traditional traps and oil and gas pools in the Lower Ordovician basal horizons and, perhaps, given these horizons in deeper stratigraphic horizons of the Vendian-Cambrian age.

The available data give evidence of significant hydrocarbon potential that can be found in deep-seated (5-7 km and more) Pre-Jurassic complexes of West Siberia.

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Maps of Distribution of Physicochemical Properties of Oils in West Siberia

A.E. Kontorovich, L.S. Borisova, D.V. Kosyakov, V.O. Krasavchikov, P.S. Lapin, S.N. Novikova, E.P. Strekhletova

(Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences)



Kontorovich A.E. – born in 1934. Academician. Director of Institute of Petroleum Geology. Siberian Branch, Russian Academy of Sciences. 1956- graduated from Tomsk State University in physics. 1964- held a PhD in geology, 1969 – D.Sc. in geology. His current research interests include petroleum geology, organic geochemistry, analysis of hydrocarbon resources and economic evaluation of the development of Russia's fuel and energy complex.

In the complex of investigations of the petroleum potential of large regions and in planning oil and gas exploration activities, the composition of hydrocarbon fluids studied in detail at the up-to-date level, can serve as a basis for differentiation of predicted oil resources by quality and also contains information which allows planning regional and exploration–appraisal activities in the definite stratigraphic complexes.

Regional regularities of changes in composition of the West Siberian oils drew attention of investigators even at the early stages of the basin study. The first schemes of variations in density and sulfur content of oils were published as early as 1965–1967 (F. G. Gurari, N. P. Zapivalov, A. E. Kontorovich, I. I. Nesterov, A. V. Ryl'kov, O. F. Stasova, B. P. Stavitskii, and others). Later, such schemes were repeatedly constructed mainly in SNIIGG&MS, ZapSibNIGNI and IG&RGI. The general drawback of these sketch maps was, firstly, almost a complete lack of information on the northern regions of the mega-basin and insignificant volume of sampling for the remainder of West Siberia and, secondly, the sketch maps were hand-drawn, without using computers.

In the 1980's, the regular study of the petroleum potential of the Mesozoic deposits of the West Siberian northern regions started, and for the first time it has become possible to construct the maps of prediction of oil properties defining the conditions of development of fields and oil transportation and refining.

The Institute of Petroleum Geology SB RAS collected information on physicochemical properties of oils and condensates for more than 1500 samples which allowed characterization of most oil fields and pools of West Siberia.

The goal of investigation is to reveal the regularities of variations in composition of the West Siberian oils for the entire petroleum basin and to construct a set of maps showing physicochemical properties of oils for four oil-producing horizons of West Siberia, such as the Upper Jurassic, Lower–Middle Jurassic, Berriasian–Hauterivian, and Hauterivian–Aptian. Oils from the Achimov stratum are considered separately.

The principle of systematization of physicochemi-

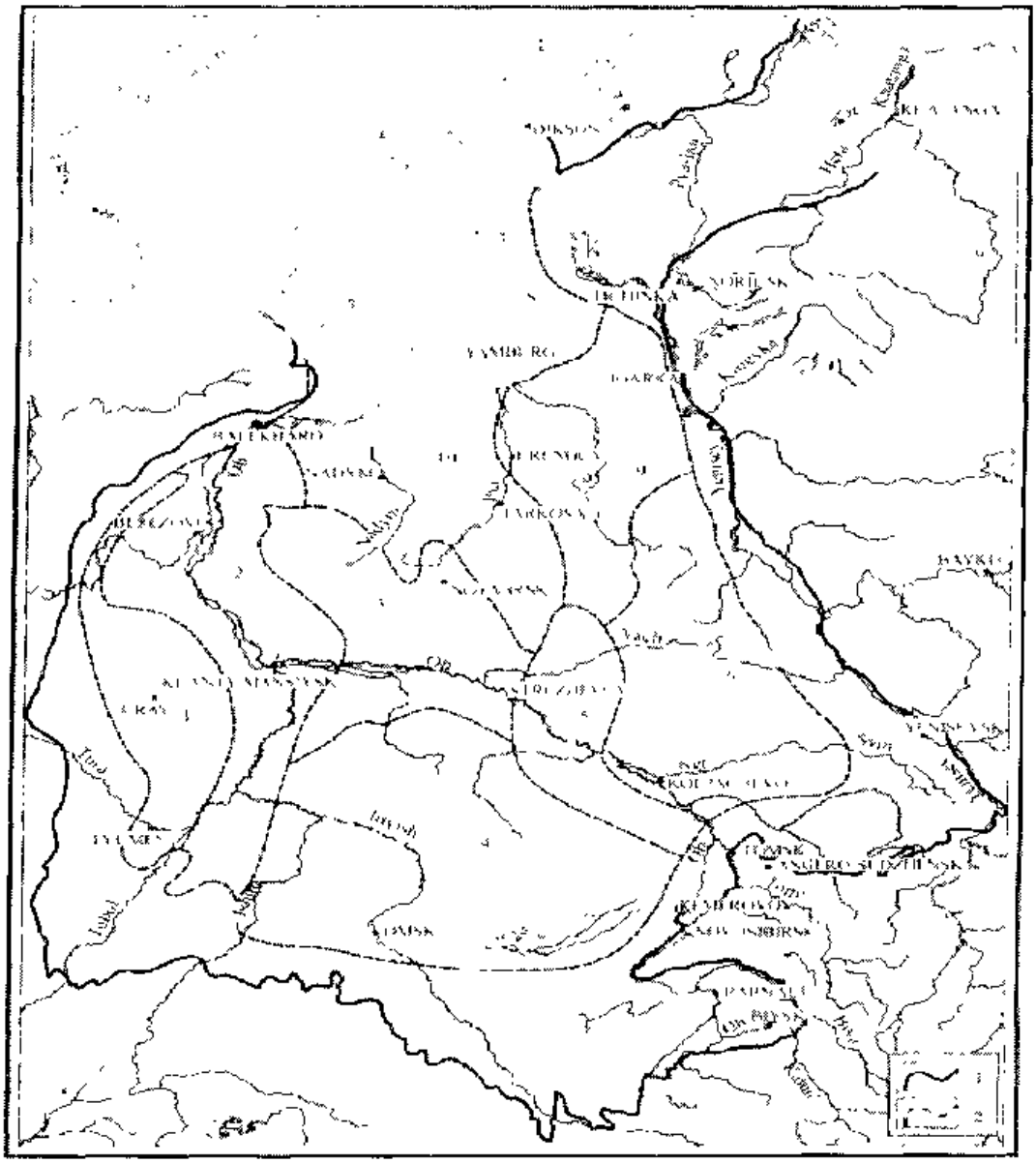


Fig. 1 Map showing the petroleum regions of the West Siberian basin.

Boundaries: 1- the West Siberian sedimentary basin ; 2-Petroleum regions: 1-Pre-Ural, 2-Frolov, 3-Middle Ob; 4-Kaymysov, 5-Vasyugan, 6-Paydugin, 7-Yamal, 8-Gydan, 9-Pur-Taz, 10-Nadym-Pur.

cal properties of oils by "stratigraphic belonging" was widely used in papers by O.A. Radchenko, T.A. Botneva, A.N. Guseva, A.E. Kontorovich, O.F. Stasova, and others. This approach makes it possible to reveal oils of variable physicochemical properties in each stratigraphic horizon of West Siberia.

The set of maps for each reservoir includes the

300°C, content of resins and asphaltenes, and Pr/Ph ratios. Now the atlas of maps of physicochemical properties of the West Siberian oils is prepared for publication. This paper considers the distribution of some physicochemical properties of oils from the Upper Jurassic deposits of West Siberia.

Solution of investigation problems is based on

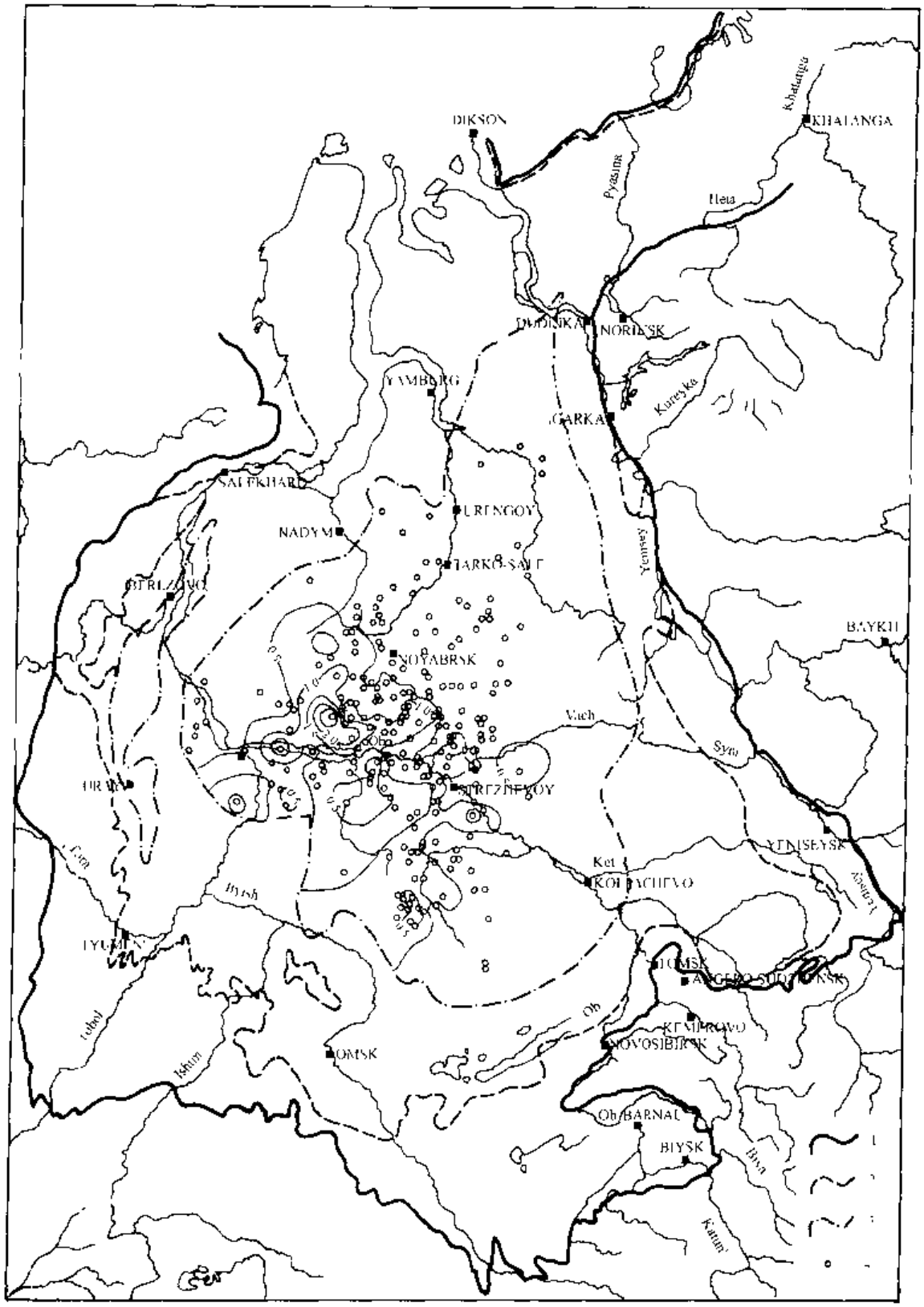


Fig. 3 Map showing the sulfur contents in oil from the Upper Jurassic depositsof the West Siberian Province(%). Boundaries: 1–the West Siberian sedimentary basin; 2–the Upper Jurassic deposits;3–the areas prospective oil and gas discoveries in complex; 4–points of oil sampling in the fields.

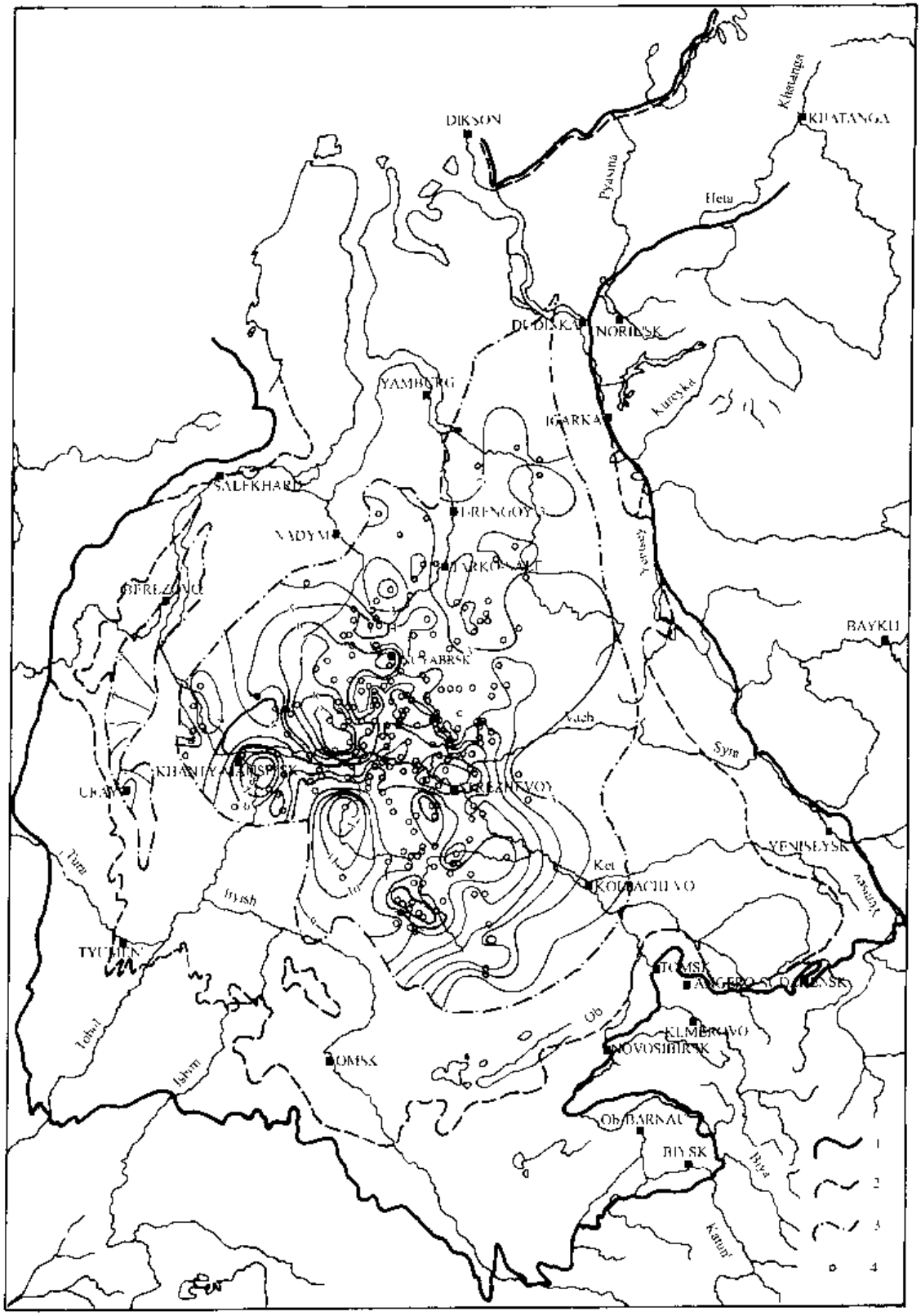


Fig. 4 Map showing the resin contents in oils from the Upper Jurassic deposits of the West Siberian Province(%). Boundaries; 1–the West Siberian sedimentary basin; 2–the Upper Jurassic depos ts; 3 -the areas prospective oil and gas discoveries in complex; 4–points of oil sampling in the fields

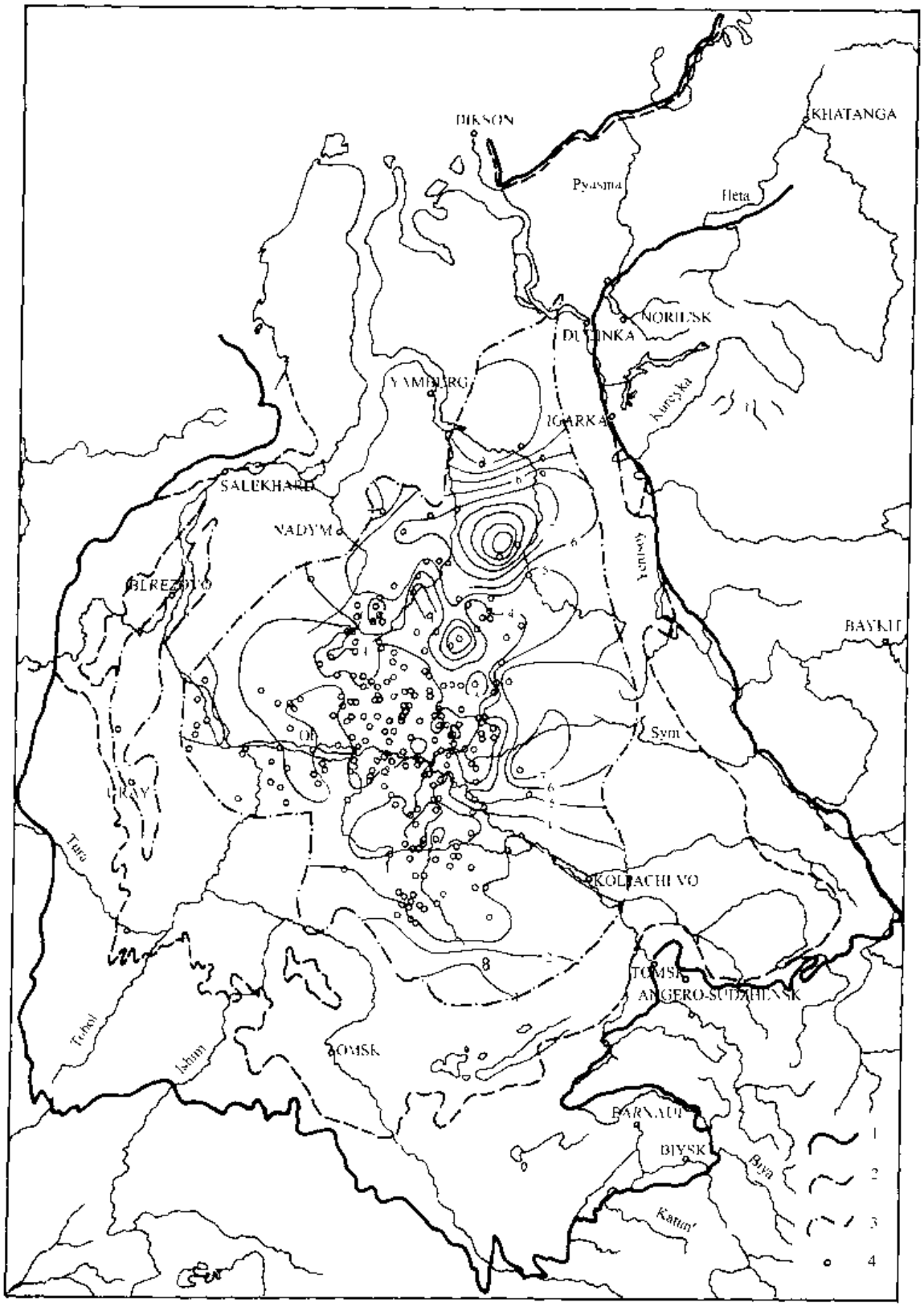


Fig. 5 Map showing the paraffin contents in oil from the Upper Jurassic deposits of the West Siberian Province (%). Boundaries: 1–the West Siberian sedimentary basin; 2–the Upper Jurassic deposits; 3–the areas prospective oil and gas discoveries in complex; 4–points of oil sampling in the fields.

Jurassic deposits of the Middle Ob' and Kainysov petroleum regions. In the northern regions of West Siberia, where stronger thermobaric conditions of sedimentation existed, mainly light, low-resinous, low-sulfur and high-paraffinaceous oils (type A) accumulated. We also think that the general interrelation and common character of variation in oil parameters of beds J_1 and J_0 are mainly caused by peculiarities of depositional environments and fossilization of the initial OM.

Thus, the established relationships between the composition of hydrocarbon fluids and geological conditions of occurrence and constructed maps of the distribution of uniform-type fluids throughout the basin make it possible to predict, from geochemical point of view, the quality of oils, to identify major productive complexes in poorly explored areas, to specify the type of a pool, and etc.

Prediction of Petroleum Accumulation Zones in the Vendian and Lower Cambrian Subsalt Carbonate Deposits of the Central Parts of the Siberian Platform.

G.G. Shemin

(Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences, Novosibirsk)



Shemin G.G. – born in 194. Head of laboratory in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1969 – graduated from the Novosibirsk State University in geological survey and search for mineral deposits. 1974 – received his PhD, 1994 – D.Sc. in geology. He is currently studying petroleum geology and conducting the evaluation of hydrocarbon resources of Siberia.

Introduction

The central regions of the Siberian Platform include the Nepa–Botuoba and Baykit anteclises, Katanga and Vilyuchan saddles, and Predpatom regional trough. The main amount of drilling and geophysical exploration for oil and gas has been carried out in the study area; in total 30 oil and gas/condensate fields, containing over 50 pools, among which are large-sized ones, have been there discovered. The regions under consideration are the main zone of petroleum potential in the Siberian Platform generally assigned to the Vendian and Lower Cambrian subsalt terrigenous and carbonate deposits.

The Vendian–Lower Cambrian carbonate deposits which are the subject of this paper, are noticeable for their composite structure, prolonged depositional history and specific conditions of oil and gas pool formation. A procedure described in the following was specially developed for predicting petroleum potential of these deposits.

1 Procedure of Prediction

The procedure applied for prediction of the petroleum potential of carbonate deposits is based on a combination of the detailed stratigraphic, tectonic, paleogeologic, lithologic, facies, geophysical, geochemical, and hydrogeological studies. The procedure allows for an importance assessment of each of criterion of the petroleum potential prediction and enables us to distinguish between areas of different potential, petroleum accumulation zones, and priority exploration targets.

The results of detailed correlation between the members of cyclic composition (cyclites) have been taken as a stratigraphic basis for the petroleum potential prediction. It has been carried out by correlating the sections closest in stratigraphic volumes and composition, following the rules of a member succession through the section, the order of variations in member thicknesses, as well as a variation trend of the lithological composition.

The applied procedure enabled us to subdivide and correlate the examined carbonate deposits into the following regocyclites which are distinctly expressed in the section: Lower Danilovo, Middle Danilovo, Upper Danilovo, and Usol'ye, each of which contains several (3 to 13) members. The results of detailed correlation were laid as a basis for a cyclostratigraphic chart of Vendian and Lower Cambrian deposits that depicts the time distribution of regocyclites and cyclic members, local stratigraphic divisions (formations and subformations), productive horizons and reservoirs.

The results of the correlation performed as well as exploration, geophysical and analytical information allowed the three regional reservoirs to be distinguished in the Vendian–Lower Cambrian carbonate deposits: Lower Danilovo, Upper Danilovo, and Usol'ye, each of which comprised both permeable and sealing horizons.

The tectonic criteria of predicting the petroleum potential of the revealed reservoirs were the present-day and paleostructure plans, presence of faults, including thrust dislocations, and trappean magmatism as well. As regards a technique of tectonic investigations, the main attention was paid to the enhancement of reliability of paleotectonic reconstructions because within the Siberian platform applicability of a thickness method is restricted by hiatuses, zones of uncompensated downwarping, dislocated sections which are the result of both fault and salt tectonics, also by trappean magmatism, as well as salt washing out by infiltration water.

The conducted paleotectonic studies gave new results. In particular, as regards the time of formation, the present-day structural plans of the revealed oil and gas fields are attributable to a post-sedimentary type. During the Vendian and Early–Middle Paleozoic periods, a petroleum accumulation zone involved the arched portion of the Katanga paleoanteclise which embraced the northeastern part of the Baykit anteclise and the northwestern part of the Nepa–Botuoba one as well as the northern areas of the platform.

The estimate of the reservoir petroleum potential of both present-day and paleostructural plans has been performed in a routine manner. Faults, thrust dislocations and trappean magmatism have inevitably affected the poroperm properties of reservoir rocks, being hence taken into consideration in estimating the quality of permeable horizons.

The lithologic-facies criteria of evaluating the reservoir petroleum potential included the qualitative characteristics of the reservoir constituents (permeable and sealing horizons) and reservoirs themselves. The qualitative estimate of the impermeable beds has been carried out relative to their thicknesses, lithological and mineralogical compositions.

The qualitative estimate of permeable horizons was based on a wider range of parameters, namely a specific capacity of reservoir rocks, including their thickness and porosity, permeability and heterogeneity.

An overall estimate of the reservoir quality was performed by summarizing the qualitative estimates of the reservoir constituents (sealing and permeable horizons).

The geochemical criteria of predicting the reservoir petroleum potential were the data on - the organic matter distribution by complexes, - a degree of its catagenetic transformation, - rock generative potential, - trend and time of HC migration out of zones of petroleum generation to zones of petroleum accumulation. In addition, while estimating the reservoir

potential, a special attention was paid to the amounts of HC expelled from the underlying terrigenous deposits.

The hydrogeological criteria of predicting the reservoir potential included the data on reservoir hydrodynamic and hydrochemical zonation.

Carbonate complexes on the Siberian platform have composite hydrodynamic conditions. On its margins, formation pressures approximate to hydrostatic values, being abnormally high within the platform interior. Salinity and concentration of chemical components in formation waters from carbonate deposits vary widely. Strongly concentrated and saturated brines contain high bromine. Saline composition is usually dominated by calcium and magnesium chlorides. Water exchange is hampered and even close to stagnancy. On the whole, the carbonate reservoirs are characterized by favourable hydrogeological criteria for the petroleum potential prediction.

As yet no adequate technique for estimating the reservoir petroleum potential based on the total of criteria has been elaborated. The most disputable issue is that concerning the estimation of information content of each of criteria. The author demonstrates that as applied to the Siberian platform, the criteria of predicting the petroleum potential can be ranked as follows: lithologic-facies ones are the most, geochemical ones are less, tectonic and hydrogeological are least informative.

Based on the rank and reliability of the above criteria the distribution areas of the revealed reservoirs can be thus recognized as areas of various perspectives: highly perspective, perspective, medium-perspective, less perspective, and least perspective areas.

The petroleum accumulation zones are interpreted as parts of the reservoirs characterized by a similar structure, similar conditions of formation and preservation of oil and gas pools. Within the carbonate reservoirs only the lithological zones of petroleum accumulation could be recognized. They are divided by different qualifications, such as a type of forecast traps and predominant fluids, levels of petroleum potential, a size of forecast oil and gas pools.

The priority exploration targets are assumed to be the most perspective and best explored portions of petroleum accumulation zones recognized by a combination of geological and geophysical data. The probability of new discoveries and/or extension of the outlines of already-discovered pools within these targets seems to be very high.

2 Characterization of Petroleum Accumulation Zones

Two maps (Figs. 1, 2) provide the main results of the petroleum potential prediction for the best explored and most promising Lower Danilovo and Usol'ye reservoirs of Vendian–Lower Cambrian carbonate deposits in the central Siberian platform. Shown on these maps are the categories of perspective areas, petroleum accumulation zones, priority exploration targets, forecast trap and fluid types, and pool sizes.

The Vendian Lower Danilovo gas-oil reservoir is characterized by occurrence of less, least and partly medium perspective areas. Highly perspective and perspective areas are predicted to occur only in the central and northwestern parts of the Nepa–Botuoba anteclise where the giant Yeryoma–Chona and perspective Peleduy petroleum accumulation zones have been recognized.

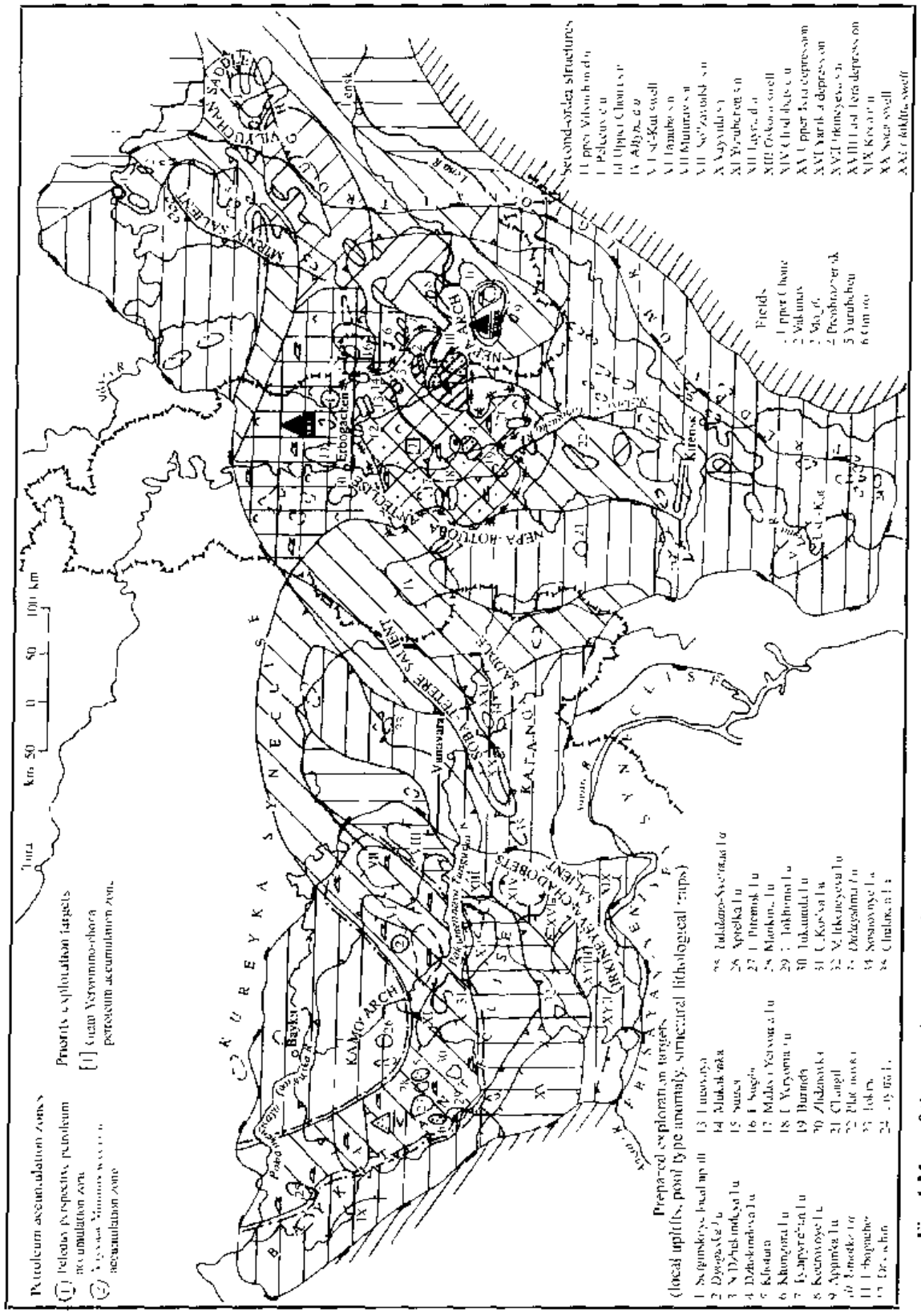


Fig. 1 Map of the petroleum potential prediction for the Lower Danilovo regional reservoir of the central Siberian Platform.

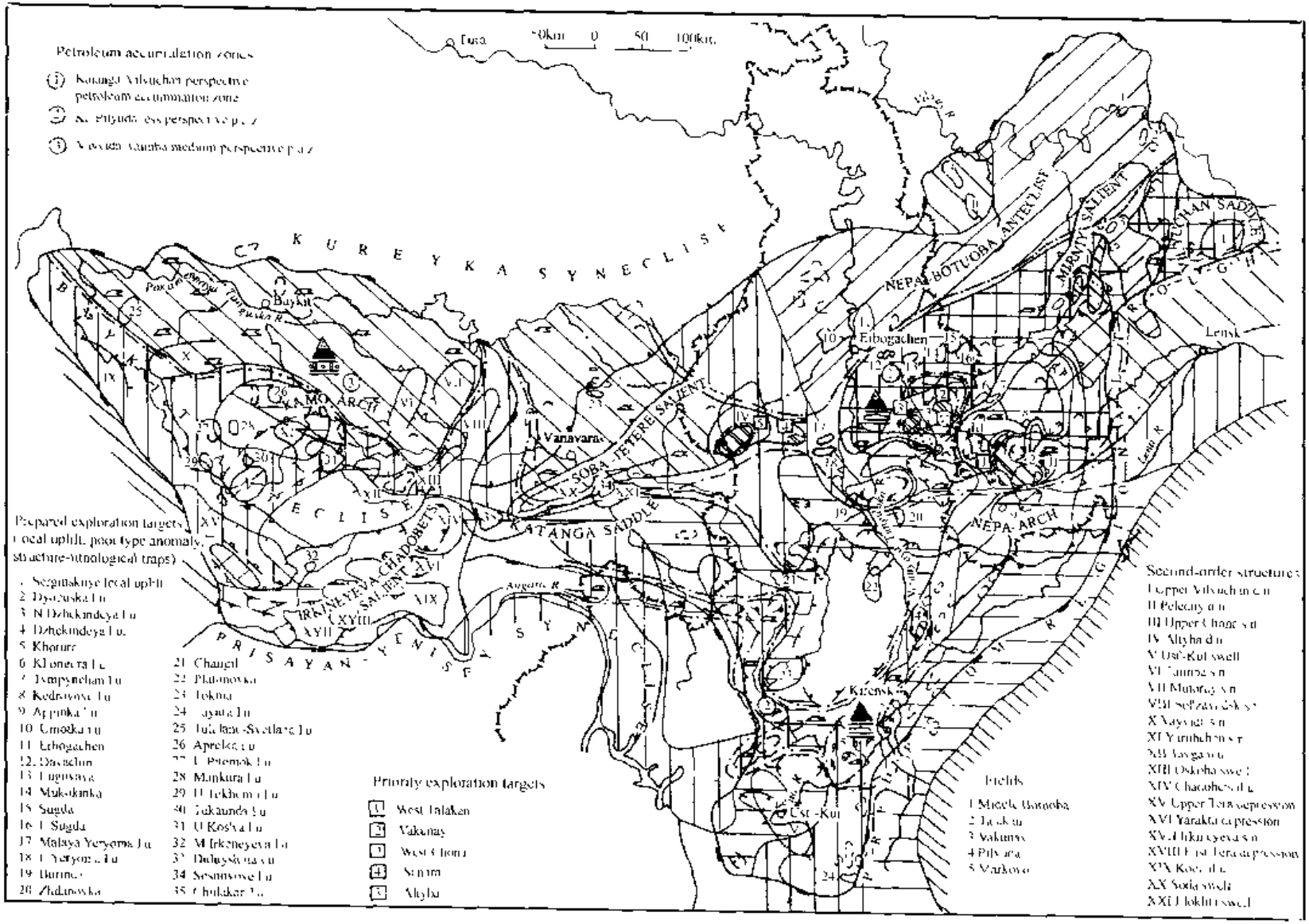


Fig. 2 Map of the petroleum potential prediction for the Usol'ye regional reservoir of the central Siberian Platform.

Legend for Fig. 1 and Fig.2

1–4 – contours of fault structures of: 1 – super-order (anteclise, syneclise), 2 – saddles, 3 – first-order (arch, salient), 4 – second-order (domal uplift, swell, structural nose, trough, depression); 5 – overthrust zone; 6–8 – limits of: 6 – permeable horizons of the reservoirs, 7 – the reservoir rocks, 8 – reef-like and organogenic buildups occurrence; 9 – reef-like and organogenic buildups; 10–17 – perspective areas of: 10 – I category (highly perspective), 11 – III category, 12 – IV category (perspective), 13 – V category, 14 – VI category (medium perspective), 15 – VII category, 16 – VIII category (less perspective), IX category (least perspective); 18 – boundaries of areas with a different potential; 19 – boundaries of the petroleum accumulation zones: a – confident, b – less confident; 20–22 – types of petroleum accumulation zones genetically related to: 20 – pinching out of deposits, 21 – reef-like and organogenic buildups, 22 – carbonate strata of organogenic genesis; 23–25 – types of petroleum accumulation zones recognized by the predominant fluid: 23 – oil-bearing, 24 – oil- and gas-bearing, 25 – gas-bearing, 26–27 – petroleum accumulation zones where: 26 – predominating traps are associated with lenticular sections with the rocks of enhanced poroperm properties surrounded by lithologically homogeneous deposits, 27 – see 26 – anticlinal traps; 28 – boundaries of the priority exploration targets; 29–31 – areas with the proved (a) and predicted (b) reservoir rock saturation: 29 – gas, 30 – gas/oil, 31 – oil; 32–33 – prepared exploration targets, 32 – structures, 33 – pool-type anomalies (PTA); 34–36 – recognized exploration targets: 34 – structures, 35 – PTA, 36 – structural-lithological traps; 37 – administrative boundaries.

Recoverable resources of the Yeryoma–Chona PAZ amount to 1.5 billion tons of oil. The reservoir rocks are identified as the Preobrazhenskiy horizon, which has been formed under similar facies condition and has undergone similar post-sedimentary processes resulted in a porous reservoir type. The object was confined to a large lithological trap genetically related to an organogenic massive. Oil saturation of the reservoir rocks is a result of two important events. During the late Precambrian and Phanerozoic, the territory of this PAZ corresponded to the most uplifted part of the Nepa–Botuoba anteclise to which in different periods hydrocarbons expelled from the adjacent PAZ. It has been identified the absence of a regional seal underlying the Preobrazhenskiy horizon within the Yeryoma–Chona PAZ that promoted supply of hydrocarbons into a reservoir from underlying terrigenous reservoirs.

The Lower Cambrian Usol'ye gas-oil reservoir is characterized by widespread occurrence of perspective and medium perspective areas in the northern and central parts of the Nepa–Botuoba, Baykit anteclises and Katanga saddle. Three PAZ have been recognized within highly perspective areas as follows: the most promising Katanga–Viluychan PAZ, less promising Vayvida–Taimba PAZ and least promising Kato–Pilyuda PAZ. Six priority exploration targets have been delineated within the first PAZ: West Talakan, Vakunay, West Chona, Sanara, Altyba, and Middle Botuoba–Chayanda. Genetically, all these petroleum accumulation zones are of lithological type, of which two (Katanga–Vilyuchan and Kato–Pilyuda) being associated with reef-like and organogenic buildups. In the Katanga–Vilyuchan PAZ, large- and medium-sized hydrocarbon pools are predicted in anticlinal and lithological traps; medium and small-sized oil and gas pools occurred mainly in lithological traps are forecasted within other PAZs.

Geochemistry of Gasoline from the West Siberian Oils

L.S. Borisova, D.V. Kosyakov, V.R.Livshits, E.A.Fursenko

(Institute of Petroleum Geology, SB RAS, Novosibirsk, Russia)



Borisova, L.S. – born in 1948. Senior researcher in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1971- graduated from Novosibirsk institute of geodesy, aerial photography and mapping in optics and spectroscopy. 1988 – held her PhD in geology. She is currently studying organic geochemistry of oils from the West Siberian basin.

An important achievement of organic geochemistry for the past decades is the possibility to diagnose genetically oils and differentiate them by the source rock accumulation conditions and secondary processes' trends. For the separation of oils into genotypes rather effective use is made of the information on a low-molecular hydrocarbon composition (C_5–C_8)[1].

The individual hydrocarbon composition of each light fraction (125°C), arenes in the 125–150°C fraction, normal C_{30}–C_{40} and isoprenoid C_{13}–C_{20} alkanes has been analyzed using the traditional method of gas-liquid chromatography of unfractionated oils and condensates. Analyses were performed on capillary columns equipped with 25–30 plates (carrier gas: H_2) in isothermal temperature regime using a back purge system on the chromatograph evaporator.

During the past years, the Institute of Petroleum Geology, SB RAS, has accumulated a data bank on the geochemistry of Jurassic and Cretaceous oils and condensates. Comprehensive material on the composition of C_5–C_8 hydrocarbons of West Siberian oils and condensates was classified and analyzed using the newest computer technologies and original data processing and reduction algorithm elaborated by the authors. All information obtained was compiled into 40 volumes of 300 pages each. While classifying the data into books and volumes, the authors adopted that petroleum zonation which has been accepted for West Siberia.

A data bank involves the information on geological sampling conditions, the analyses performed, physical and chemical characteristics of oil and condensates, on a composition of free and oil gases as well as the comprehensive information on individual hydrocarbon composition of a gasoline fraction of oils and condensates, and normal and isoprenoid alkane distributions in oils. Each petroleum area was illustrated by a general oil and gas field location map and generalized lithological columns showing the main productive horizons.

The work is based on a single system of the data processing and representation. It is note-

worthy that extensive and unique information on the individual hydrocarbon composition of oil and condensate gasolines accumulated for many decades has not yet been thoroughly generalized due to a large data set (ca. 70 parameters) which was incapable of interpretation when processing this information manually. From huge amount of information investigators chose and used at best several parameters which allowed, according to them, to solve some particular task [2, 3, 4, 6-8].

Another important direction of the work is genetic typification of oils and condensates based on the statistical processing of gasoline composition data. Analyses of the collection consisting of 200 to 1000 samples of the Mesozoic West Siberian oils revealed evidence that the low-molecular oil hydrocarbons contain detailed information about the oil nature. A cluster analysis was chosen as a mathematical tool for examining a "genetic code" encoded in the oil composition. Automatic classification was preceded by a correlation analysis, which allowed 22 of the most representative parameters to be chosen from a set of 200 analytical parameters for the oil gasoline fraction composition. The cluster analysis of the data has resulted in the differentiation of all Mesozoic oils of West Siberia into several genetic families, determination of their spatial localization. Each of the distinguished oil family has been correlated with a corresponding geochemical facies.

The goal of the present paper is to show the possibility of applying low-molecular hydrocarbon parameters as a tool for a genetic classification of oils on the basis of 250 samples using the newest computer technology and original, elaborated by the authors data processing algorithm. Oils and condensates from Upper Jurassic deposits (160 fields) of West Siberia were chosen as the object of investigation. The correlation analysis is aiming to:

Determine genetically related parameters for low-molecular components of the oils and establish the nature of this relationship;

Ascertain to what extent can the information used in a cluster analysis be excessive;

Reduce dimensions of the initial attribute space through a selection of the most informative attributes from total source ones.

Strong correlation between individual parameters of the low-boiling oil fractions display that they look like an ensemble in which the ratio between different components is stochastically but rather strongly controlled by the whole history of each particular oil. Given a large number of meaningful relations, no strongest correlation coefficients between parameters (>0.90), allowing the relation close to a functional were revealed, so that the parameter set chosen for clustering is thought to be non-excessive.

In carrying out a cluster analysis use was made of the Word algorithm as a clustering algorithm. Euclidean distance was chosen

The goal of automatic sample classification (cluster analysis) is to divide the whole population of the objects under examination into relatively small number of uniform groups or clusters which are hierarchically organized. The results of cluster analysis are represented as a tree diagram. Four families (I–IV) were distinguished using a cluster analysis for variations in the hydrocarbon composition of gasoline fractions from Upper Jurassic oils (Fig. 1).

A wide range of C_5–C_8 hydrocarbons, including alkanes of a normal and iso-structure, cyclopentanes and cyclohexanes, arenes were identified in the composition of gasolines from each oil family.

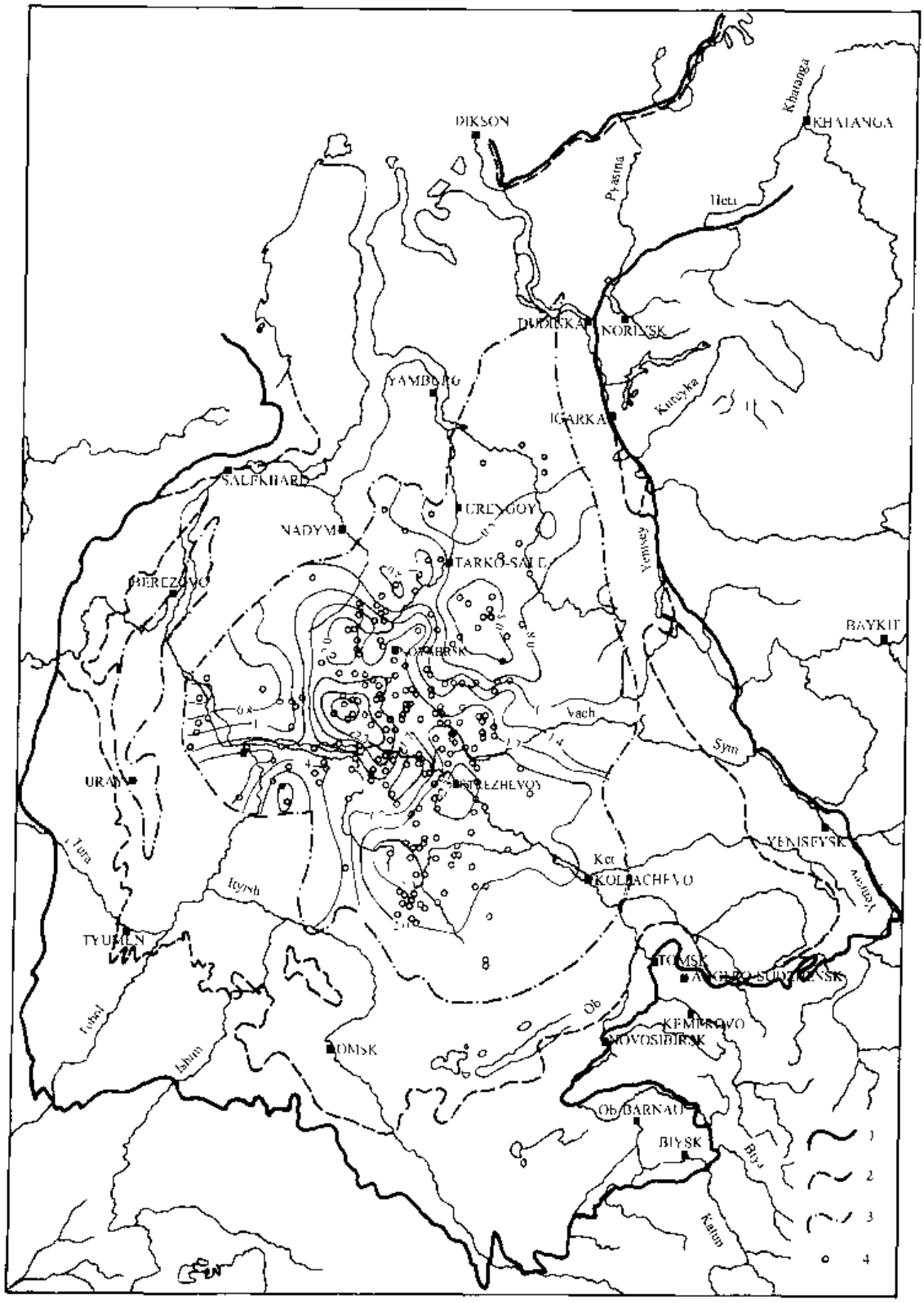


Fig. 1 Map showing distribution of sum of cyclopentanes/sum of cyclohexanes ratio in oils from the Upper Jurassic deposits of the West Siberian Province.

Boundaries. 1—the West Siberian sedimentary basin. 2—petroleum regions 1—Pre-Ural. 2—Frolov. 3—Middle Ob. 4—Kaymysov. 5—Vasyugan. 6—Paydugin. 7—Yamal. 8—Gydan. 9—Pur—Taz. 10—Nadym—Pur

The most abundant family consists of the oils from the Middle Ob petroleum area(103 samples). Gasoline fractions from this oil family are characterized by a high alkane and cyclopentane content. Based on their physical and chemical composition, these are heavy, sulphurous and resinous oils; pristane to phytane ratio does not exceed 1.00 that suggests a typically marine genesis of the oils from this family.

Condensates from the northern West Siberia were singled out as a separate family represented by a small sample consisting of 25 condensates. These condensates showed a high yield of light fractions (32%); they are low-sulphurous and low-resinous, practically asphaltene-free. A gasoline fraction of the condensates shows a distinct preponderance of naphthenic hydrocarbons over alkanic ones with cyclohexanes being twice as much as cyclopentanes. The Pr/Ph ratio considerably exceeds 2.00, thus allowing to propose their continental origin.

The gasoline composition of oils from the northern West Siberia resembled that of the condensate family. The only difference is the type of fluid: these oils are light with relatively low cyclohexane and branched alkane content. The distribution area of the second in sample size oil family semicircularly embraces that of the first family which contains the oils from the Middle Ob region. Based on their physical and chemical properties, Pr/Ph ratio (1.00–2.00) and the gasoline composition parameters these oils seem to have been derived from a mixed in various proportions organic matter which was buried in coastal and shallow marine sediments.

Typically marine oils were derived from mainly aqueous, planktonic and bacteriogenic organic matter of the Bazhenov Formation which was buried in a sea at various distances from the land and in various sediment diagenesis regimes that naturally accounts for the specific features of their composition. The sources of typically continental oils were fresh lakes, perhaps, at time brackish due to short-term ingressions, as well as lacustrine-marshy or lacustrine-alluvial deposits of Lower–Middle Jurassic.

Thus, the new approach to oil and condensate typification using a routine method of mathematical statistics and data on the individual composition of low-boiling hydrocarbons enabled us to subdivide Upper Jurassic oils and condensates into the families of different genesis and to localize graphically the distinguished oil families of West Siberia.

Because many investigators reported a pivotal role of the organic matter type in the formation of a gasoline hydrocarbon composition [2,3,6-8], it was of interest to trace how the most informative parameters allowing a distinct classification of oils by the types of source organic matter (Table 1) vary throughout the territory of West Siberia. Sketch maps were performed using a Surfer package for field coordinates.

Table 1 Basic genetic parameters for an oil gasoline composition.

Parameters	Marine OM	Continental OM
Σ cyclopentanes/Σ cyclohexanes (K_1)	> 0.7	< 0.6
Ethyl benzene/Σ xylenes (K_2)	> 0.2	< 0.2
n-heptane/methylcyclohexane (K_3)	> 1.0	0.1–0.6
n-xylene/o-xylene (K_4)	< 2.0	> 2.0

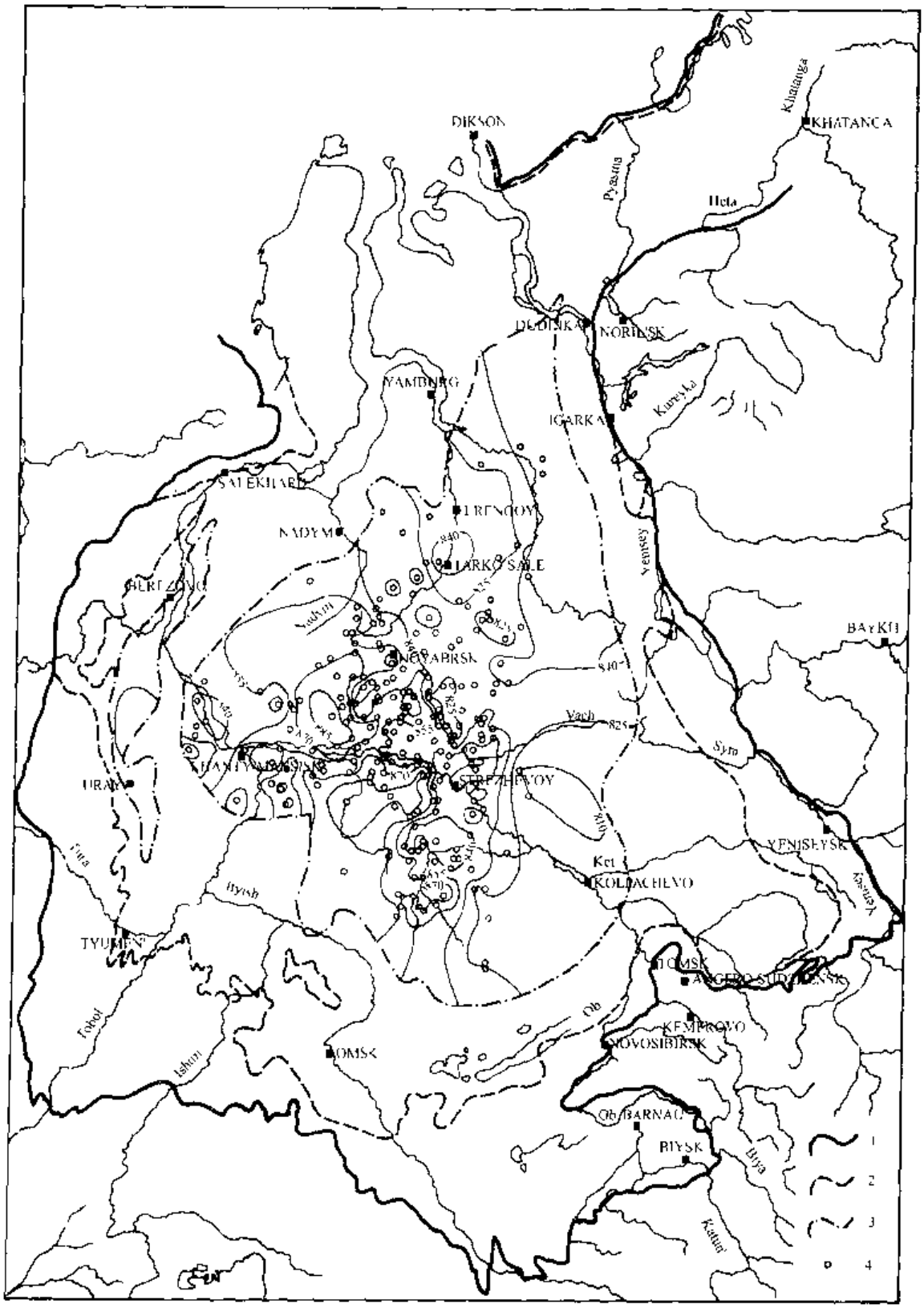


Fig. 2 Map showing distribution of ethylbenzene/sum of xylene ratio in oils from the Upper Jurassic deposits of the West Siberian Province. Boundaries: 1-the West Siberian sedimentary basin; 2- the Upper Jurassic deposits;3- the areas prospective for oil and gas discoveries in complex; 4-points of oil sampling in the fields.

The Σ cyclopentane/Σ cyclohexane ratio (K_1) is assumed as a criterion for recognition of a role played by organic matter in the formation of a gasoline fraction composition: a preponderance of the five- over the six-membered naphthenes indicates the dominating impact of sapropelic organic matter [2, 3, 6-8]. As seen from the K_1 distribution map (Fig. 2), oils from the most examined fields were derived from marine organic matter: K_1>0.7. These oils are as a rule from the Vasyugan and Bazhenov Formations of the Middle Ob petroleum area. Oils from the same deposits but from the northern Nadym–Pur and Pur–Taz petroleum areas have K_1<0.7, hence can be attributed to a mixed genesis.

The distribution of the ethylbenzene to the sum of xylenes ratio (K_2) for the examined Upper Jurassic oils and condensates is close to K_1 values. Many sources reported [3, 4] that given the K_2 values ranging from 0.2 to 0.5, these oils might have an origin from marine organic matter. Based on the available information these are Upper Jurassic oils from the Middle Ob petroleum area matching the confined requirement, whereas for the oils from the northern Nadym–Pur and Pur–Taz petroleum areas this value does not exceed 0.2 (Fig. 2). The K_3 and K_4 values have the same distribution.

The investigations performed reported a decreasing role of marine facies northeastward from the southern Middle Ob region. This finding is supported by our data on the Pr/Ph ratio distribution over West Siberia territory. For the Middle Ob oils this parameter approximates one and varies from 2 to 8 in oils from the northern and arctic territories. These results are consistent with the data reported in early works by A.E.Kontorovich and O.F.Stasova [5], which asserted that continental oils (type A) were replaced by dominantly marine ones (type C) in passing from gas-bearing regions in the north to oil-bearing ones in the Middle Ob area at the boundary between the Nadym–Pur, Middle Ob, and Vasyugan petroleum areas.

Thus, proposed in the paper sketch maps showing the variations of the most informative parameters of a gasoline composition of Upper Jurassic oils from West Siberia enabled us to observe a gradual replacing of the continental oils by marine ones from the north to the south.

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The Present-Day Features of Russia's Petroleum Complex Functioning

A.G.Korzhubayev, D.A.Gofman, S.V.Ermachkov, A.V.Novikova, P.A.Polosukhin, A.S.Ulanova

(Institute of Petroleum Geology, SB RAS Novosibirsk, Russia)



Korzhubaev A.G. – born in 1970. Senior researcher in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences 1992 - graduated from Novosibirsk State University in economical cybernetics. 1999 – held his PhD in economics. He is currently engaged in a geological and economic assessment of oil and gas resources.

Energy is the leading element in a functional structure of present-day world's economy Production and consumption of energy resources grew as the productive forces developed. The structure of energy mix was continuously changing both in Russia and all over the world. During the first three quarters of the XX century, coal was gradually substituted by oil; whereas the last decades showed a stable tendency towards increasingly greater role of gas, nuclear energy and renewable sources [1, 2]. Currently, the share of gas and oil in the world's fuel and energy mix accounts for over 63%. Under conditions of increasingly stricter environmental regulations and given significant explored and estimated reserves, prospective and forecast resources of gas, its role in world's energy and non-energy sectors is projected to grow inevitably in the first decades of the XXI century. Improvement of comprehensive transportation and utilization network is another factor in increased gas role. The last decades are notable by the intensive development of pipeline transport, formation of a LNG infrastructure, building of highly efficient gas turbine thermal power plants, marked increase in a gas share in motor fuel, and also by the advancement of new technologies into gas chemical industry.

Currently, the leading energy sources are coal, oil and gas, with the latter two being dominant that is accounted mainly for economic, production and power advantages of hydrocarbons which correspond to a present-day level of productive forces development, including power generation and power consumption. GDP and the standard of living in the country highly correlate with the level and structure of energy consumption that, in turn, largely depends upon the degree to which the energy complex can function stably and effectively.

Russia's energy complex involves those industrial branches that carry out production of energy resources (oil, gas, coal, shale, peat, gas condensate), their processing, transportation of hydrocarbon gases (natural, petroleum, wide light HC fraction), oil and refined products through special transmission networks,

maintenance of hydrocarbon storage infrastructure, as well as electric and thermal power generation, distribution and conversion.

The production facilities of Russia's energy complex include 134 thousand of oil producing wells, 6.4 thousand of gas wells, oil refineries with 261 million tons of total crude capacity. In 1992, the capacity of Russia's refineries totaled 320 million tons of crude. In 1991–1999, structural reorganizations have resulted in a partial cut down of unprofitable, out-moded and physically worn out production facilities for the primary oil refining with the increasing share of secondary processes. The defined capacity of electric power plants amounts to 205 million kW, a length of the power supply line is 2554 thousand km. As of 1.01. 1999 151 coal mines and 75 open pits with total output of 336.5 million tons have been in operation in the country. The production facilities of the complex belong to shareholding companies and are mainly privatized (except for crude and refined product transportation).

Russia has about 46.8 thousand km of oil, 152 thousand km of gas and 20 thousand km of refined product long-distance trunk pipelines to supply consumers with fuel and energy sources. About 85% of Russia's crude and gas condensate move by pipelines. Oil transmission through trunk lines is carried out by Transeft, the 100% state-owned pipeline open stock company. Gazprom O/S owns all country's gas trunk lines.

Involved in Russia's energy complex are also machine-building plants, construction, trade and marketing enterprises, scientific-research and planning and designing institutes, analytical and service centers. The number of organizations, enterprises and institutes of various specialization and ownership that constitute Russia's energy complex exceeds 10,000.

During the late XX- early XX century, the country accounted for about 10% of the world's primary energy production and over 7% of the world's primary energy consumption. In 1999, the production of primary energy and energy sources in the country amounted to 1386 million tons of conventional fuel. In 1999, coal production in Russia accounted for 250 million tons (or 5.3% of the world's total) that was fifth in the world, after China, the U.S., India, and Australia. The major deliveries of produced coal are to meet the inland needs, but some portion is intended for export. Russia accounts for 9% of the world's crude and about 26% of the world's natural gas production. In 1999, the country's electrical and thermal power generation amounted to 845 billion kW·hr and 1129 million Gcal, respectively. Russia's share in global energy resource markets accounts for 11%.

The volume of energy resources and the efficiency of their use in the country's economy largely reflect a degree of technological advancement of a national economy, its industrial structure, as well as climatic and resource conditions. Hydrocarbons are currently accounting for 85% of Russia's energy balance. Russia's petroleum complex is the most important structural subdivision of the energy complex and is pivotal to the country's economy on the whole. Its huge mineral resource and technological base is an important factor for effective and stable functioning of both energy sector and economy.

In 1999, Russia was number 3 in crude production (304.7 million tons), after Saudi Arabia and the U.S. Annual export from the country exceeds 130 million tons of crude and 60 million tons of refined products. Gas

production amounted to 591 billion cu m in 1999. Russia plays a noticeable role in world's gas markets, having 33% of global explored reserves and providing about 45% of the world's natural gas export. In 1997–1999, Russia's gas exports chiefly to markets of Western Europe and CIS countries accounted for 200–202 billion cu m.

Since 1992, Russia's oil and gas industry has experienced drastic changes in financial conditions, its managerial, legal and ownership structure. Restructuring of the oil industry on the basis of the Ministry of oil and refining industry has resulted in consolidating several oil and gas vertically integrated companies (VICs) as open stock companies, which embraced oil and gas producing, refining and marketing enterprises. Subsequently, most of VICs have been privatized via selling the government's shares in VICs in auctions and investment bidding. Rosneft O/S is currently the only company with 100% government's stake. Russia's VIC Gazprom has been established as an Russian joint stock company on the basis of the Ministry of gas industry and then was privatized in part by Russian and foreign investors and transformed into open stock company. To date, the government has a 38% stake in Gazprom, the world's largest gas concern. Meanwhile, the gas industry has retained a single technological, managerial, and financial vertical.

During the past two years, mergers and acquisition (M&A) activity has flourished in the Russian oil and gas sector, though not so intensively as in 1992–1997, in time of mass privatization and consolidation of VICs. Current-day activity in the corporate stock market is being stimulated mainly by oil majors' wish to expand their producing and refining facilities and to make their operations more territorially and technologically balanced. The main instrument of asset re-distribution was buying up the holding's (or its subsidiary's) controlling interests in bidding or auctions, or from a head holding or portfolio investor, as well as attaining majority control of VICs' enterprises through the bankruptcy either of a holding or its subsidiary. The most impressive megamerger was at yearend 1998, when Yukos O S acquired a controlling interest in Eastern Oil Co. (VNK) that resulted in the ownership of most VNK's subsidiaries (two production associations Tomsneft and Tomskneftegazgeologiya, the 6.5 million tons crude capacity Achinsk refinery, and marketing affiliates Tomsnefteproduct, Khakasnefteproduct and Novosibirsknefteproduct) by Yukos. In addition, the holding gained control of all VNK's license areas in Western and Eastern Siberia. In 1999, the best capitalized Russia's VIC Lukoil merged the KomiTEK company, which having annual production of 3.6 million tons of oil, has had the E&P licenses for fields in the Timan–Pechyora petroleum province with total reserves of about 700 million tons. In 2000, a number of companies showed interest in acquiring big stakes in RUSIA petroleum O S company (a subsidiary of Sidanko O/S) which holds a development license for the giant Kovykta gas-condensate field located in the Irkutsk District.

Currently, 11 largest VICs account for 89% of Russia's oil production and have over 96% of the explored reserve base in natural resource allocation. The highest levels of production were demonstrated by Lukoil, Yukos and Surgutneftegaz (57, 44.7, and 37.6 million tons, respectively) which totaled for about 46% of Russia's oil and gas-condensate production. Several companies, such as Lukoil,

Yukos, Rosneft, Zapubezhneft etc., have licenses and carry out the exploration and development works abroad in fields of Kazakhstan, Azerbaijan, Vietnam, Iraq, Iran, Angola and some other countries.

Over 30% of the crude produced by these companies is exported mainly to Europe through terminals at Ventspils, Kaliningrad on the Baltic Sea to the North European market and terminals at Novorossiisk, Tuapse, Odessa on the Black Sea to the Mediterranean market (mainly to Italy), and also by Druzhba pipeline to Germany, Poland, Chech Republic, Lithuania, Slovakia, Hungary, Yugoslavia and other countries. Export volumes to Asian countries are as yet insignificant because of the lack of developed transport infrastructure – a pipeline network from Western Siberia to the east terminates in the town of Angarsk (Irkutsk District), throughput capacity of border posts at China boundary (Zabaykalsk–Manchuria, Grodekovo–Suifenghe) is insufficient, while that of an oil storage terminal in the port Vostochniy (town of Nakhodka, Primorskiy Kray) amounts to 5.8 million tons a year.

About 70% of crude produced by Russian oil companies is destined for their own refineries as well as for other VICs' refineries under processing deals. In 1999, 80% of total crude refined in Russia was destined to the refineries owned by 11 largest VICs. With several refineries in Samara, Novokuybyshevsk, Syzran, and Achinsk, Yukos refines the largest amounts of crude (over 20% of gross value). Some of Russia's oil companies have their refining facilities abroad. For example, Lukoil has acquired controlling interests in Rumanian and Ukrainian refineries; and Slavneft petroleum company comprises Belarussian refineries. A number of Russia's VICs (Lukoil, Yukos, Rosneft, Sidanko, Tyumen Oil company etc.) besides their refining subsidiaries comprises petrochemical plants.

In addition to oil, companies produce associated petroleum gas. In 1999, production of this gas amounted to about 30 billion cu m. The largest producers of associated gas among VICs are Surgutneftegaz, with annual production of over 11 billion cu m, and Rosneft (its subsidiaries Purneftegaz and Sakhalinmorneftegaz), with 5 billion cu m/year. Large state regional power plants in European portion of Russia and Western Siberia are fueled by associated gas and condensate. In particular, such big power stations as the Surgut-1 (3380 MW) and Surgut-2 (6400 MW) situated in the Khanty Mansi Autonomous Okrug, Tyumen District, the largest country's region-oil producer, use associated petroleum gas to generate electricity.

The major producing and transporting subdivision of the gas industry is Gazprom concern. It produces over 94% of Russia's total free and associated gas, not to mention oil. In 1999, Gazprom produced over 556.5 billion m^3 of natural gas and about 10 million tons of oil. In addition to its production and transportation facilities, the company owns an effective system of underground gas storage facilities comprising 21 storage units with an active capacity exceeding 70 billion cu m. During a heating period of 1999–2000, the maximum daily withdrawal could reach 450 million cu m of gas. Most of Gazprom's current production of natural gas and condensate comes from Cenomanian and partly Neocomian pools in the north of the West Siberian petroleum province. Along with the production activity associated with exploration, production and transportation of gas within the

country, Gazprom has launched large projects focusing on the expansion of an export pipeline network (construction of the trunk gas pipelines Yamal–Europe with throughput of over 70 billion cu m, a subsea "Blue flow" crossing the Black Sea, with throughput of 16 billion cu m, etc.) and on the development of fields abroad (in Iran, Quatar, India etc.). The company's high operational and financial performance was achieved mainly at the expense of the efficient, technologically balanced, centralized structure which has been formed as early as 1970–1980, and as a result of rational investment policy pursued by the company.

Owing to immense audited reserve base of Russian petroleum companies, many foreign financial and industrial firms show interest in buying their shares, because together with the economic growth, improvement of the investment climate and increase of the Russia's credit rating against a deepening world's energy crisis, the shares of Russian petroleum and energy companies should inevitably advance. Moreover, a foreign stake in Russia's VICs allows access to energy resources of corresponding license areas. Thus, Ruhrgaz, a German gas concern, recently acquired a stake in Gazprom; BP Amoco acquired a 10% stake in Sidanko, and about 30% of Lukoil's shares are distributed among minor foreign investors through a mechanism of American Depository Receipts (ADRs).

The economic growth that started in Russia promotes the increase of investments into oil and gas projects. The immense resource and technological potential of the petroleum complex together with the further expansion of investment activity will enable not only to meet growing inland energy demand but also to increase export supplies both to the west and east [3,4,5]. According to estimates made in IPG SB RAS, given the adequate capital investments, the development of Siberian and Far East oil and gas resources after meeting Russia's domestic demand for oil and gas, will allow large export deliveries to Asia–Pacific countries, first of all to China, during the first decades of the XXI century. Crude exports from the Eastern Russia to Asia–Pacific countries could be expected at 34–45 million tons/y, gas exports could reach 120–135 billion m^3/yr. Russia's petroleum companies have all pre-requisites to increase their operational performance, to ensure both territorial and technological diversification of their activity, as well as to expand contacts and strengthen their position in the world's markets.

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Kovykta and Upper Chona Fields in the Vendian Terrigenous Deposits of the Siberian Platform

V. A. Topeshko

(The United Institute of Geology, Geophysics and Mineralogy SB RAS, 630090, Academician Koptyug Ave. 3, Novosibirsk, Russia)



Topeshko, V.A. – born in 1945. Senior researcher in the Institute of Petroleum Geology, Siberian Branch. Russian Academy of Sciences. 1972 – graduated from Novosibirsk State University in geological survey and search for mineral deposits 1991 –received her PhD in geology. Her current scientific interests include the problems of petroleum geology of Siberia.

Abstract: The paper describes the geological structure of the largest fields in the Siberian Platform, the Kovykta gas condensate field and the Upper Chona gas condensate-oil field. Lithological and reservoir characteristics of the productive deposits is given, and the prospects of HC pool extension in the terrigenous complex are substantiated.

Key words: oil, gas, condensate, field, pool, reservoir, sandstone, terrigenous.

The Upper Chona gas condensate-oil field and the Kovykta gas condensate field are among the largest in the Siberian Platform. The Kovykta field is located in the northeastern part of the Angara–Lena petroleum region (PR), 350 km northeast of the city of Irkutsk, and the Upper Chona field is in the central part of the Nepa–Botuoba PR, 270 km north of the town of Kirensk.

The Angara–Lena PR is located in the southern Siberian Platform. In the Angara–Lena PR, coinciding in area with the superorder structure, Angara–Lena step, drilling in small amounts was performed as early as the 1930'. In the 1940's, drilling of key boreholes started. The first small oil and gas inflows were produced in the Bol'shaya Razvodnaya and Osa prospects. Later exploration activities increased sharply. The petroleum potential of the Vendian terrigenous rocks and Lower and Middle Cambrian rocks has been proved.

In 1975, the Bratsk gas condensate field was discovered in the northern Angara–Lena PR. A middle-sized gas-gas concensate pool has been found in sandstones of the Parfyonovo productive horizon of the Chora Formation (Vendian). The pool is bedded, arched and is bounded in the east by a fault plane. In the northwest the pool contour is controlled by lithology and from the other sides-by gas water contact (GWC).

In 1977, the Atovo gas condensate field was discovered in the southern part of the Angara–Lena PR. A small-sized pool has been found in the sandstones of the Parfyonovo productive horizon of the Chora Formation (Vendian). The pool is bedded, arched,

lithologically sealed. Commercial oil and gas inflows were produced from the Osa productive horizon of the Usol'ye Formation (Lower Cambrian)

Oil and gas condensate inflows, including commercial ones, were obtained in the Parfyonovo, Southern Raduy, Bil'chir, Krivaya Luka, Birkino, Kazarkino areas and others. Exploratory success ratio was rather high. Hydrocarbon inflows have been obtained almost in every third area which was braught into drilling.

The Kovykta gas condensate field (Petroleum basins, 1995) is located 350 km northeast of Irkutsk, in the northeastern part of the Angara–Lena PR. Deep drilling activities started here owing to the detection by seismic survey of the Kovykta uplift--a large dome-shaped structure of northeastern trending. The Kovykta field (Fig.1) was discovered in 1987 by the deep stratigraphic borehole-281. A gas condensate pool has been found in the Parfyonovo productive horizon of the Chora Formation (Vendian). In 1988, exploration activities were activated. Based on exploratory drilling, the structural configuration of the top of the productive deposits is presented as a monoclinal slope upwarping southeastwards with a gradient of 1.3–3.5m km. The presence of dome-shaped structure was not confirmed by drilling. There is some evidence that the field is broken by faults into three blocks, among which the southwestern block is the most high-amplitude and extensive. The amplitude of displacement for the blocks is 38–45m in the buried northwestern part and 5–9m in the uplifted southeastern part (Geology and program, 1998).

The Parfyonovo horizon shows a regional areal distribution and is overlapped and underlain by the members of siltstone–argillite rocks of 8–17 m and 100–110 m in thickness, respectively. Within the drilled part of the field, the horizon thickness increases from 40 m to 75 m from the southwest to the northeast. Based on lithologic-petrographic studies, the Parfyonovo horizon has been subdivided into the upper bed (P_1) and lower bed (P_2). Bed P_2 includes the main portion of gas condensate reserves of the Kovykta field. In the southwestern part of the field, supplementary objectives for addition to gas and gas condensate reserves are bed P_1 as well as the stratigraphically underlying Bohan horizon of the Lower Pechora Subformation (Vendian) and the Upper Riphean basal horizon.

Beds P_1 and P_2 are essentially different in lithologic composition, depositional environments and reservoir parameters. Bed P_1 is composed of grey, light-grey, fine-grained to silty, sandstones. Clastic rocks account for 80% on average and are represented by quartz, feldspars, fragments of various rocks and less commonly, micas. Rock cement is mixed carbonate–clayey, with anhydrite being present sporadically. Cementation is of porous, contact type. Due to intense regeneration of clastic material, clastic rocks are characterized by dense compaction and low porosity (5%–7%). Permeability is $(0.01–0.4)\times10^{-15}m^2$, i.e. almost zero. The deposits of bed P_1 were formed in coastal-marine environments. Their thickness varies from 20m to 40 m, reaching maximum values in the central part of the field. In bed P_1, reservoir rocks have been identified only in well-30 and well-31 in the southeast of the field. They have produced gas influxes to 80 thousand m^3 day during joint testing with bed P_2.

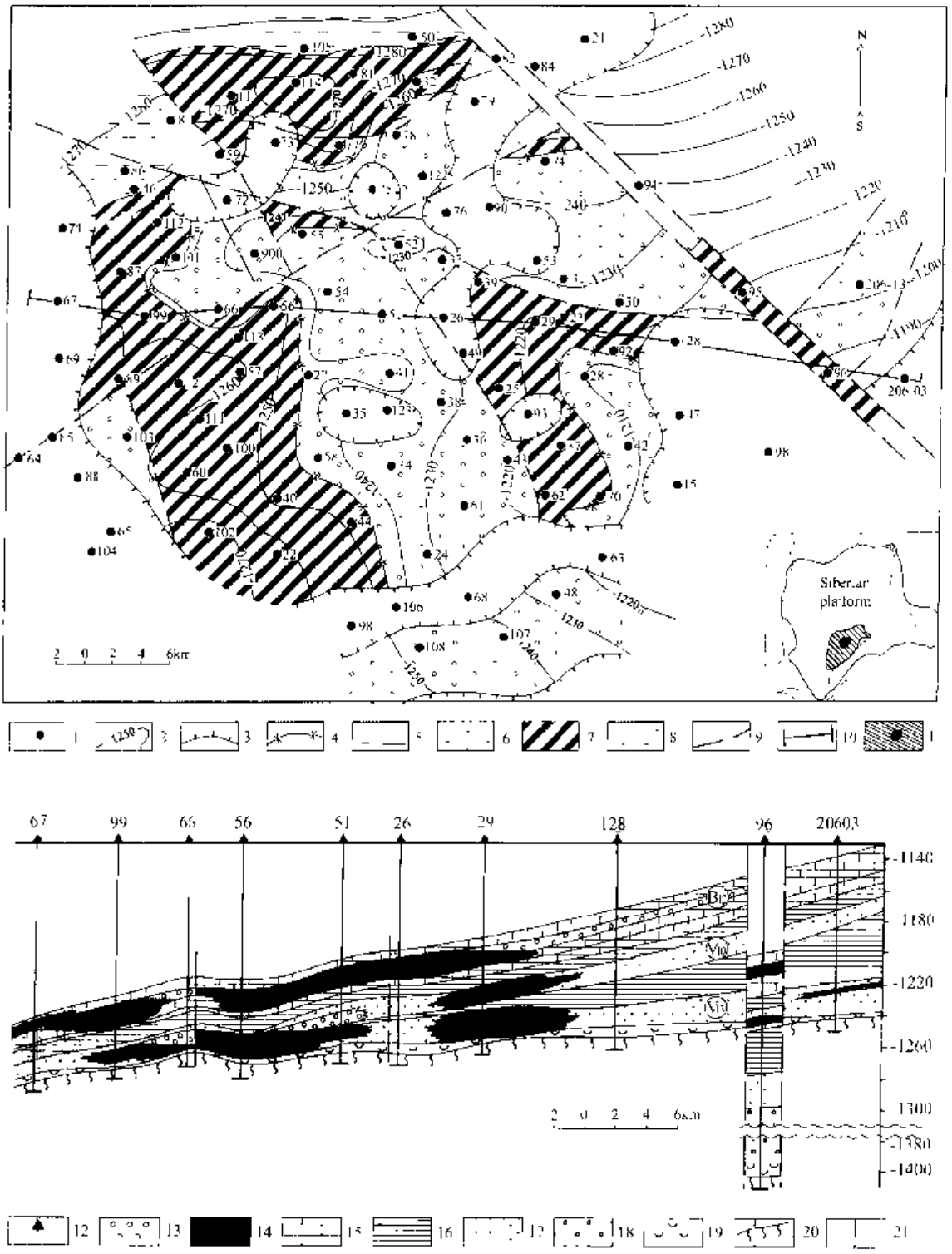


Fig.1 Kovykta field. 1—structure contours for the top of bed P_2; 2—inferred external limit of gas content. 3—saturation of reservoirs with gas; 4—boundary of reservoir distribution; 5—faults (a—proved, 6—inferred); 6—wells (a—drilled, b—projected), %; 7—line of profile; areas for exploratory and deep stratigraphic drilling: Ch—Chikan, G—Gruznovka. In the inset: 8—location of the Angara—Lena petroleum region and Kovykta field.

Bed P_2 is composed of greenish-grey inequigranular sandstones with admixture of coarse-grained and gravel fractions. Grading of the terrigenous material relative to bed P_1 is worse. Sandstones are polymictic, the clastic portion is represented, as in the upper bed, and sulfate by composition. Reservoir type is porous. The deposits of bed P_2 accumulated under conditions of deltaic facies with braided network of river arms and valleys (Geology and program, 1998).

Based on logging data, bed$_2$ rock porosity reaches 19% (weighted average 15%) and 22% (weighted average 13%) from core data. Gas permeability reaches $990x10^{-15}m^2$ (weighted average $19x10^{-15}$ m^2). The total thickness of bed P_2 increases from 20 m in the south and southwest to 40 m in the north and northeast. Effective pay increases from 4 to 30 m in the same direction. The tests of bed P_2 produced the inflows of gas-condensate mixture from 34 to $300000m^3$/day and separated gas from 35 to 265000 cu m/day.

Production rates of the wells increased northwards and northeastwards according to increasing the values of effective pays and filtrational-porosity properties of reservoirs.

Use of the modern technological methods of drilling in productive deposits and enhanced oil recovery, particularly, capillary impregnation with methanol as well as horizontal drilling of boreholes, represent a significant chance to increase the production rates of wells.

Separated gas from the pool of the Parfyonovo horizon on average contains 91.7% methane, 6.1% methane homologues, 1.7% nitrogen, and 0.25% helium (geology and program, 1998). Average formation pressure is assumed to be 25.7 MPa, formation temperature is 53° C.

by quartz, feldspars, micas, and fragments of various rocks. However, quartz content is lower in comparison to bed P_1; at the same time feldspar content increases. Cement of rocks is film-porous, and clayey-carbonate

Presently exploration activities continue in the field. Facies replacement of reservoir rocks of the Parfyonovo horizon by impermeable rocks has been detected only in the southwest of the field during drilling of wells 1 and 174 in the Chikan prospect (Fig.1). A clear tendency of worsening of reservor properties of the sandstones does not occur in other directions. In the northwest of the field, based on drilling data of wells 1 and 134 in the Gruznovka prospect, the limit of oil and gas content has been drawn at an absolute depth of 2287 m. Geological structure of the pool in the Parfyonovo horizon evidences of its confinement to a giant lithological trap.

Detection of reservoirs in all wells drilled in the field, constant values of their reservoir parameters testify to a high probability of further extension of a productive contour and addition to gas and gas/condensate reserves. Comparison of the proved gas and gas/condensate reserves to the expected estimation of their resources allows us to suggest that nowadays only their third part has been discovered.

The Nepa–Botuoba PR is located in the southeastern Siberian Platform. It includes the superorder structure, Nepa–Botuoba anticlise, and the adjacent first-order structure, Vilyuchan saddle (Nepa–Botuoba, 1986). Active exploration work started in this area in the 1960's after the Markovo oil-gas/condensate field had been discovered in 1962. In 1960's–1970', following the discovery of the Markovo field, the Yarakta,

Ayan, Middle Botuoba, Vilyuy–Dzherba, Danilovo, Tas–Yuryakh and Khotogo–Murbay oil and gas fields have been discovered. In these fields hydrocarbon pools have been discovered in the Vendian terrigenous and carbonate deposits and Lower Cambrian carbonate deposits (Petroleum basins, 1994).

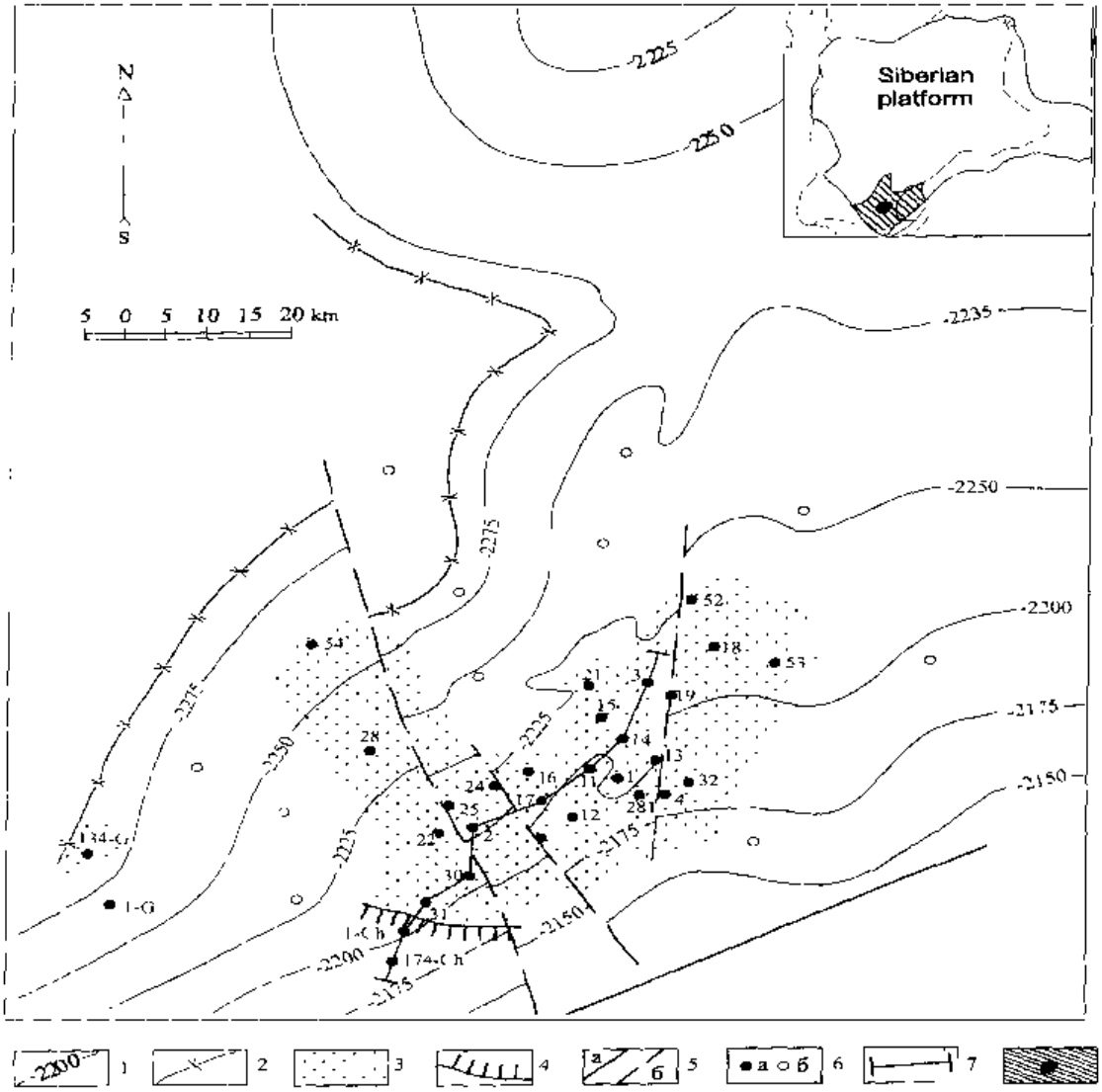
In 1976, drilling of six deep stratigraphic Upper Chona boreholes started which resulted in the discovery of the Upper Chona gas-gas/condensate field in 1978. In the 1980's, extensive exploration activities were conducted here. As a result, large hydrocarbon pools have been found in the lower part of the sedimentary cover and reservoirs have been detected in its upper part (The Yarakta–Chona, 1999).

The Upper Chona field is located in the center of the Nepa arch--the most uplifted part of the Nepa–Botuoba anteclise. In 1976, the Upper Chona uplift was explored by seismic survey and the areas for deep drilling were delineated. Deep drilling has not confirmed the southeastern closure of the fold. The field is confined to a structural salient. The salient was broken into blocks by faults controlling oil and gas accumulation (Fig.2). In the northeastern part of the field the Upper Chona–Talakan graben has been mapped. Vertical displacement along the surface of the crystalline basement reaches 100 m.

The Upper Chona field is multipool. Commercial oil and gas accumulations have been found in carbonate beds B_1 (Osa bed) of the Usol'ye Formation (Lower Cambrian), B_3, B_4, and B_5 (Ust'–Kut bed) of the Tetere Formation (undivided Vend–Cambrian), B_{12} (Preobrazhenska bed) of the Katanga Formation (Vendian) and in terrigenous beds B_{10} and B_{13} of the Nepa Formation (Vendian). Insignificant HC inflows have been produced from the carbonates of the Khristoforovo bed of the Bel'skaya Formation (Lower Cambrian).

Most of oil and gas reserves of the field are confined to the basal part of the sedimentary cover--the Nepa Formation. Its deposits are built up of two transgressive cycles, each of which is represented by sandstones and overlying argillites. At the base of the formation, the B_{13} bed sandstones occur on the surface of the crystalline basement or on the crust of weathering developed on the basement. In the graben zone they are underlain by the pre-Nepa (precise age is not determined) "rubbish-like" sandstones and gravelstones. Bed B_{13} is composed of alternating layers of grey and brownish–grey and feldspar–quartz sandstones, argillites, and siltstones. Its typical feature is an enhanced (to 15 mcr) natural radioactivity of sandstones due to their enrichment in potassium feldspars, fragments of the basement weathering crust. Interlayers of gravelstones and coarse-grained "rubbish" sandstones occur in the lower part. Improvement of grading and upward-fining of grains up the section are common. Porosity of the Bed B_{13} sandstones varies from 8 to 20%, maximum permeability is $800 \times 10^{-15} m^2$ (Petroleum basins, 1994). Effective pay varies in different zones from 0.7m to 8.5 m, the type of reservoir rocks is porous. The maximum rate of production is 150 m^3/day of oil and 90000 cu m/day of gas.

The total thickness of bed B_{13} decreases regularly northwestwards due to onlapping onto the upwarping surface of crystalline basement and erosion from 20m up to wedge-out. It is overlain by the argillite-siltstone member which serves as a seal for bed$_{13}$ and bed B_{10} in the southeast of the field. This member, like bed B_{13}, also wedges out northwestwards due to erosion preceding the



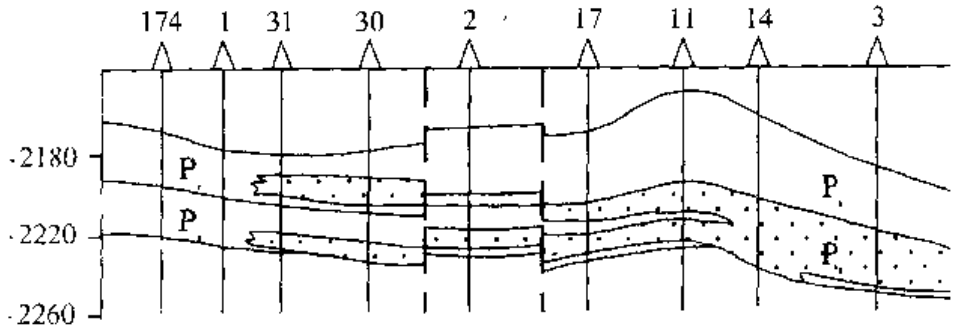


Fig. 2 Upper Chona field in the map.

1–wells, 2–structure contours of bed V_{10} reservoirs, 3–lines of wedging out of reservoirs; external contours, 4–gas content, 5–oil content; saturation of bed with, 6–gas, 7–oil, 8–water; 9–tectonic faults, 10–line of section. In the inset: 11–location of the Nepa–Botuoba PR and Upper Chona field. In the section: 12–well; saturation of bed with: 13–gas, 14–oil; 15–dolomites; 16–argillites, 17–impermeable sandstones, 18–pre-Nepa sandstones and gravelstones, 19–crust of weathering; 20–crystalline basement, 21–faults.

accumulation of bed B_{10}. The line of its wedge-out is subparallel to that of bed B_{13} and transects the field from southwest to northeast. Thus, bed B_{13} is directly overlain by bed B_{10} over the most part of the field that creates conditions for their hydrodynamic connection in some areas.

Bed B_{10} is represented by grey, light-grey, mainly quartz fine-, and middle-grained sandstones. Porosity of sandstones reaches 20%, mean values 12%–14%, permeability is $(200–300)x10^{-15}m^2$. The total thickness of the bed decreases northwestwards from 18 to 5 m, with minimum values being marked in the zone where bed $_{13}$ is absent and bed B_{10} rests on the crystalline basement. Effective pay of the bed reaches 9 m. The type of reservoir rock is porous. The maximum rate of gas production from bed $_{10}$ is 100000 cu m/day.

Formation pressure and temperatures due to hydrodynamic relation are the same for beds B_{10} and B_{13} and equal 15.3–15.9 MPa and plus 18–19° C. Abnormally low pressure of 13.3–14 MPa is recorded only in the extreme northeastern block of the pool and in the graben separating it from the major field.

Lithological factors affecting the migration, accumulation and preservation of HC pools in the southern Siberian Platform and, in particular, in the Upper Chona field have been differentiated into primary (synsedimentary) and secondary (postsedimentary) ones. The primary factors are responsible for sand content in the section, inhomogeneity, dissection, discontinuity, grading of psammitic material, amount and material composition of cement, extention of productive beds. Secondary processes made the processes more complex. These are recrystallization and fracturing which increase pore volume and permeability, as well as leaching of carbonate cement under the influence of aggressive formation waters and chemical and physical weathering. Secondary cementation, sulfatization, silicification, halitization, and regeneration of detrital grains make a negative effect on filtrational-porosity properties of rocks.

Combination of the primary and secondary processes, being both positive and negative, as well as irregular compaction of sediments, made the structure of productive beds more inhomogeneous. The diversity of depositional environments and complex combination of initial factors and superimposed effects were responsible for a complex geological structure of reservoirs in the Upper Chona field and adjacent areas (Lithology, 1988).

In the terrigenous complex of the Upper Chona field, the pool contour has formed at the expense of halitization almost throughout its entire extension, except the north and northwest, where the contour is controlled by water-oil contact, and the northeast, where a fault bounding the graben serves as a seal (Fig. 2). The pool is complicated by the zones of lithologic replacement of reservoirs by impermeable rocks which were penetrated within the productive field. Thus, the pool in the terrigenous complex is non-anticlinal, bedded, blocky, lithological, and tectonically sealed.

In the Upper Chona field exploration activities finished early in the 1990'. However, analysis of the geological structure and petroleum potential of this area evidences of the possibility of a significant extension of the productive field.

The Upper Chona field is located in the central part of the Nepa–Botuoba anteclise favourable for the accumulation and preservation of HC pools. As a result, it is surrounded by "satellite" pools. A pool, separated from

the main productive field with a strip of dense halitized sandstones, has been oustripped south of the Upper Chona field (Fig.2). In the adjacent area commercial HC accumulations have been found in the terrigenous complex of the Vakunayka and Tympuchikan fields, in the Preobrazhenka and Western Ignyalin pprospects drilled by exploratory and deep stratigraphic wells (The Chona, 1996).

An extensive areal distribution of reservoirs in the terrigenous complex and a significant stratigraphic interval of petroleum content which provide a high density of HC reserves and resources are responsible for high prospects of the Nepa–Botuoba and Angara–Lena petroleum regions, particularly, in the areas adjacent to the Kovykta and Upper Chona fields.

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Carbonate Sedimentation in the Ripean Basins of Eastern Siberia

Ye. M. Khabarov

(Institute of Petroleum Geology SB RAS, Novosibirsk, Russia)



Khabarov E.M. – born in 1952. Head of laboratory in the Institute of Petroleum Geology, Siberian Branch, Russian Academy of Sciences. 1976 - graduated from Novosibirsk State University in geological survey and search for mineral deposits. 1984 – held his PhD in geology. He is currently studying the sedimentology of Siberia.

Formation of reservoir properties of carbonate rocks is known to be a long-term process proceeding during the entire stages of their geologic history and is defined, to a large extent, by depositional environments. Some investigators do not attach much significance to identification of primary depositional inhomogeneity of the Precambrian rocks, assuming that they are structurally and genetically uniform and, in addition, are essentially changed by secondary processes. In particular, the ability of microbial communities to create reef and reef-like buildups with corresponding structural-morphological elements has been questioned. However, types of carbonate rocks and their depositional environments in the Precambrian, as has been shown by recent investigations during 10-15 years, were diverse and are much similar to the Phanerozoic. Major groups of carbonate deposits and depositional models of their formation are considered below. The objective of investigation is the Riphean carbonate formations of Eastern Siberia where they account for significant parts of the sections. They formed in geodynamically different sedimentary basins and cover mainly the entire spectrum of type models of the Late Precambrian carbonate accumulation (Fig.1).

It has been ascertained that primary generation of carbonate particles in the Late Precambrian basins, as in the Phanerozoic, occurred with direct and indirect involvement of bios. However, absence of lime-producing organisms of different types in the Precambrian was responsible for a relative uniformity of carbonate grains and also not always distinctive structural-morphological differentiation of sedimentary systems which are, as a whole, homologous to the Phanerozoic ones. The most prominent among them are carbonate platforms with a rim close to the shelf edge or slightly distant, classic (homoclinal) and supergentle carbonate ramps differring in the dominance of autochthonous biogenic or storm processes, and deep-water slope and basinal deposits, in the formation of which gravity processes were of major importance. The principal models of carbonate sedimentation in the Riphean basins of Eastern Siberia are shown in Fig.2 (Khabarov, 1999).

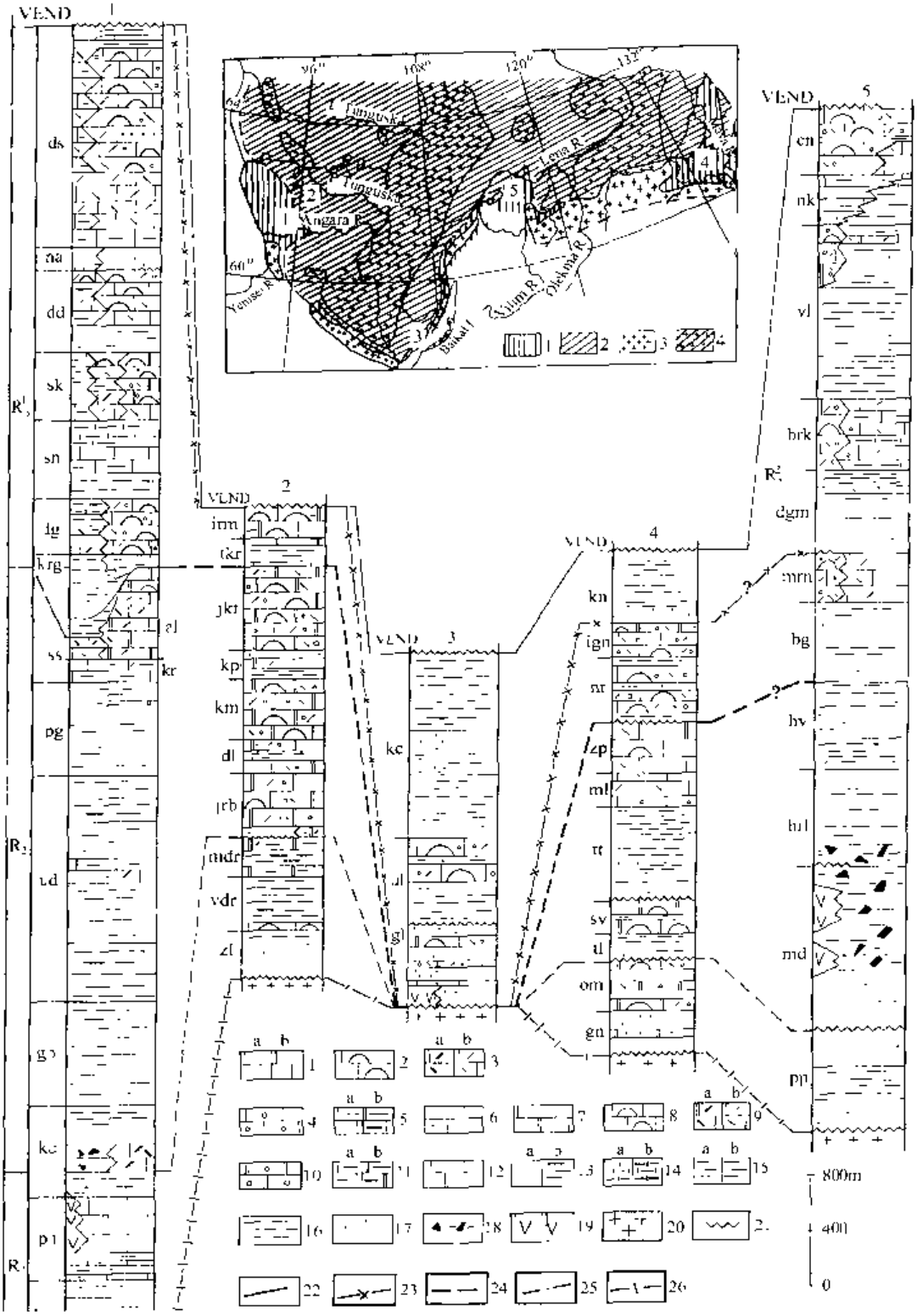


Fig. 1 Distribution and correlation of the Riphean deposits of southern Eastern Siberia.

Rocks. 1 6-limestones: 1–siltite-micritic, partially recrystallized, 2 stromatolitic, 3–coarse (a) and fine-intraclastic (b), 4–oolitic-peloid-pisolitic, 5-clayey (a) and clayey-carbonaceous (b), 6-arenaceous; 7 12–dolomites: 7–siltite-micritic, partially recrystallized, 8–stromatolitic, 9 coarse (a) and fine-intraclastic (b), 10 oolitic-peloid-pisolitic, 11–clayey, 12 arenaceous; 13–15 argillites: 13–low-carbon (a) and carbonaceous (b),

14 calcareous (a) and calcareous-carbonaceous (b), 15–silty (a) and silty-carbonaceous (b), 16–siltstones; 17–sandstones; 18 coarse-clastic rocks with sandy-argillaceous matrix; 19–volcanogenic-sedimentary deposits, 20 Archean-Early Proterozoic basement; 21–unconformable boundaries; 22–26–lower boundaries of: 22– Vendian, 23–upper portion of the Upper Riphean (Baikalian), 24–Upper Riphean, 25–Middle Riphean, 26–Lower Riphean.

Formations: krp–Karpinskiy Khrebet, pn–Penchenga, kd–Korda, gh–Gorbilok, ud–Uderey, pg–Pogoryuy, ss Sosnoviy, kr–Kartochki, al–Alad'yina, krg–Krasnaya Gora, dg–Dzhur, sn–Shuntara, sk–Seryi Kluts, dd–Dadykta, na–Nizhneangarsk, ds–Dashka, zl–Zelindukon, vdr–Vehdrehshe, mdr–Madra, jrb–Yurubchen, dl–Dolgokta, km–Kuyumba, kp–Kopcheta, jkt–Yukta, tkr–Tokur, irm Irehmehkehn, gl–Goloustenskaya, ul–Uluntuy, kc–Kachergat, gn–Gonam, om–Omakhta, tl–Talyn, sv–Svetlinskaya, tt–Tottinskaya, ml–Malga, zp–Tsipandinskaya, nr–Neryuenskaya, ign Ignikan, kn–Kandyk, pp–Purpul, md Medvezhevskaya, hrl–Khorlukhtakh, hv–Khaiverginskaya, bg–Bugarikhta, mrn–Mariinskaya, dgm Dzhemkukan, brk–Barakun, vl–Valyukhta, nk–Nikol'skaya, cn–Chenchinskaya. Legend for the scheme of distribution of the Riphean deposits in the modern structure of southern Eastern Siberia: 1–2–areas of dominant distribution of the Riphean deposits: 1–exposed, 2–overlain by younger formations; 3–4–areas of dominant distribution of the pre-Riphean complexes: 3–exposed, 4 overlain by the Vendian–Phanerozoic deposits. Figures indicate location of the sections. The lower part of the section (up to the Tottinskaya Formation) of the Uchur-Maya region was constructed from data [Semikhatov, Serebryakov, 1983].

Carbonate sedimentation is known to be controlled by the rate and style of tectonic subsidence of the basement, the climate, relative and eustatic variations of sea level, the production intensity of carbonate material, the volume and periodicity of siliciclastics input into a basin and the preceding topography.

It is essential that most of these factors are interrelated, and their total impact on the carbonate accumulation processes strongly depends on the type of a sedimentary basin. For this reason, in order to understand the general regularities of carbonate accumulation, it is important to reveal the relationship between different carbonate sedimentary systems and types of basins which developed in the Late Precambrian, particularly, in Eastern Siberia.

Carbonate platforms occur in the basins of passive margins, on near-platform slopes of back-arc basins, less commonly in foreland basins, and sometimes in rift basins, including intracratonic ones. Paltforms are characterized by: (1) a relatively distinct distribution of sedimentary zones; (2) a well-expressed rim with stromatolitic barrier reefs and grainstone shoals; (3) rhythmic structure of deposits of the inner part of the platform associated with the formation of peritidal and subtidal progradational and aggradational cycles of shallowing. There have been distinguished aggradational, progradational, retrograde and complex platforms, the development of which strongly depends on sea-level variations. In particular, during a lowstand of sea level, carbonate deposits can be exposed and underwent the processes of meteoric diagenesis. Transit of siliciclastic material through the platform with its input into a deep-water foreplatform depression is possible during the same phase.

Ramps which transform into shelf slopes (distally steepened ramp, from Read, 1985) can form in the same basins. These ramps are also characterized by reef-like structures and oolitic-intraclastic shoals.

A wide development of barrier reefs and

reef-like buildups and oolitic-intraclastic shoals, as well as shallow cycles in the carbonate platforms. suggests a mass and predicted distribution of carbonate rocks with potentially good primary porosity and filtrational properties.

Homoclinal and supergentle carbonate ramps are characteristic of intracratonic extensive basins with a delayed rate of the basement subsidence. They are characterized by: 1) indistinctive lithofacies belts: 2) rhythmic structure which is associated with the formation of aggradational and progradational cycles of shallowing; 3) absence of well-structured reefs, even though patch reefs and grainstone shoals are widespread: 4) a wide development of storm deposits. In the carbonate ramps the sedimentation processes depend much on different-scale variations of sea level. because at small angles of bottom slope a very rapid migration of sedimentary zones occurs. With a sharp rise of sea level, the area of intense carbonate formation decreased and deepening of the basin occurred. With sea level highstand, grainstone shoals and stromatolitic buildups prograded seawards. Formation of thick stromatolitic buildups was limited by subsequent fall of sea level and their rapid progradation into deep-water part of the basin. In such basins the carbonate rocks with potentially good reservoir properties are sharply localized in the form of narrow linear belts. Usually they occupy the upper parts of progradational and aggradational shallowing-upward cycles and may occur almost throughout the entire basin. Along with this, extensive zones with prevalence of stromatolitic buildups or oolitic-intraclastic grainstones are marked in them (Khabarov, 1999).

Large carbonate banks formed mainly in back-arc and foreland basins in the periods of activation of synsedimentary tectonic movements. The latter created the systems of uplifts and depressions that predetermined a spatial localization of carbonate banks. In case banks reached a fair weather wave base, sedimentary complexes with good primary filtrational-porosity properties could form on them.

Within the oil-bearing Baikit anteclise, the Riphean deposits are composed mainly of early diagenetic dolomites. among which stromatolitic, micritic, and oolite-peloid–pisolite-intraclastic grainstones and packstones are distinguished. Grainstones and stromatolitic rocks dominate (Fig.1).

These types of rocks are involved in the structure of lithologic complexes which aredifferent in composition, structure. and depositional environments. Thirty lithocomplexes have been distinguished in the Riphean deposits. Their thickness varies from the first tens of meters to 250 m, but usually is about 100 m. The complexes formed mainly in the peritidal and subtidal environments of carbonate, sometimes moderately limited shelf. Westwards, within the Yenisey Ridge, slope and basinal plain environments occurred (Kontorovich et al., 1996; Khabarov, 1999). Sedimentation was largely controlled by different-scale variations of sea level which was reflected in the lateral migration of depositional environments to form lithologic complexes with different primary reservoir properties. During sea level lowstand, carbonate accumulation became poor or ceased, with transit of siliciclastic material. The most significant falls of sea level are marked by decrease in $\delta^{13}C$ values and increase in $^{87}Sr/^{86}Sr$. Shoal deposits, as well as those of poorly expressed interbar depressions with

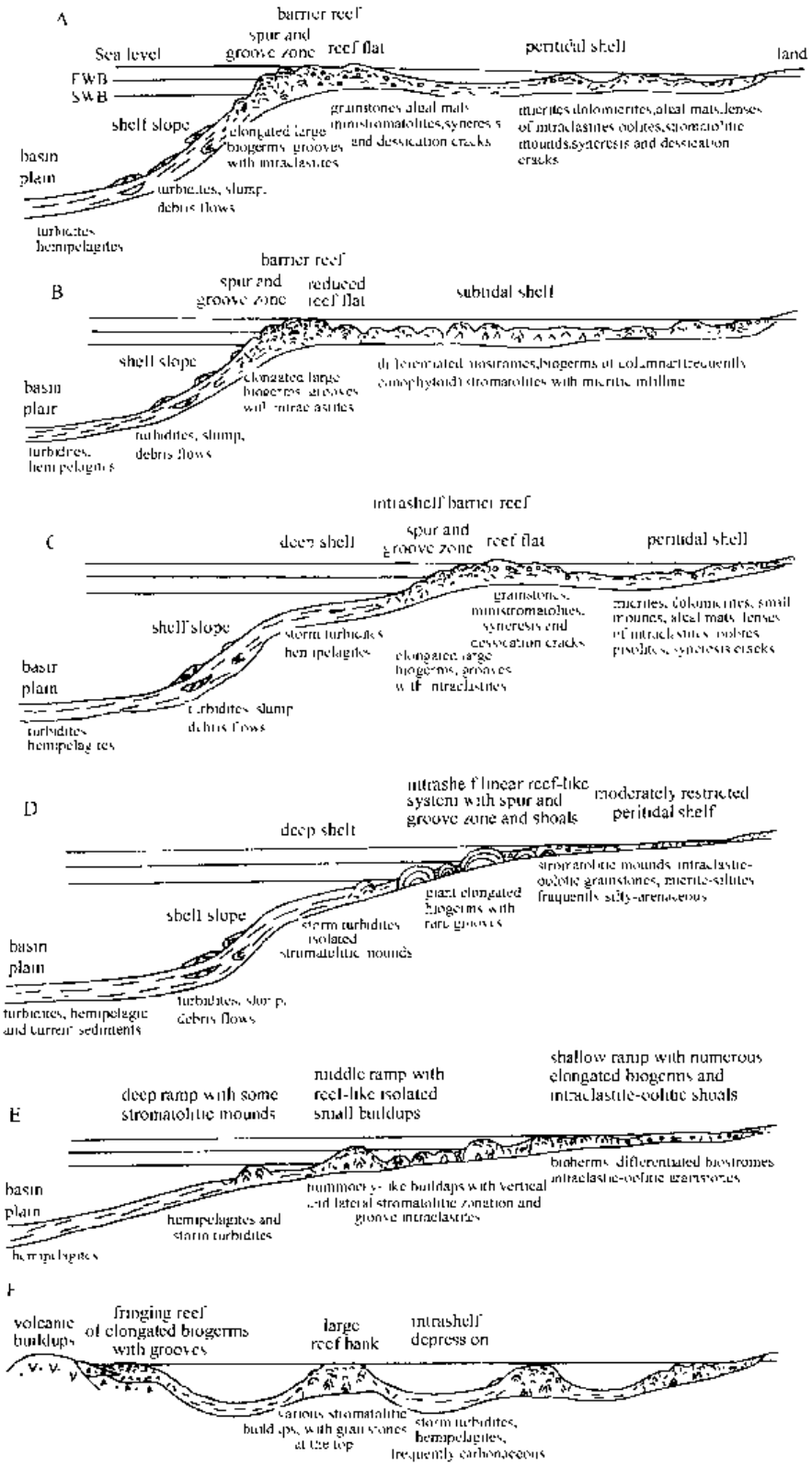


Fig. 2 Principal schemes of formation of the carbonate deposits in the Riphean basins of Eastern Siberia.

A barrier reef system of the margin of the carbonate platform with a wide peritidal inner shelf (rim of the carbonate platform coincides with the edge of the shelf), B–barrier reef system of the margin of the carbonate plat-

form with a wide subtidal inner shelf (rim of the carbonate platform coincides with the edge of the shelf), C–intrashelf barrier reef system of the margin of the carbonate platform, the rim of which is distant from the shelf edge. D–linear intrashelf reef-like system of open carbonate shelf - ramp (distally steepened ramp, from Read, 1985), E–system of patch, biostromes and bioherms, poorly structured linear reef-like buildups of homoclinal carbonate ramp with a gradual transition into a moderately deep-water basin, F–system of large reef-like banks (isolated carbonate platforms) and fringing reefs in a moderately deep-water basin. FWB–fair weather wave base, SWB–storm wave base.

active accumulation of laminites and grainstones–packstones, possess good primary reservoir characteristics. Such environments appeared periodically, but were most developed in the Yurubchen, Kuyumba, and, less commonly, Yukta times.

The carbonate rocks of the Baikit anteclise show extensive postsedimentary alterations of rocks: recrystallization, cavern formation, stylolitization, silicification, and fracturing. We note, in the first place, an important role of early diagenetic processes, essentially affecting the formation of filtrational-porosity properties of carbonate rocks. Fenestrae or their relicts, which in most cases affected greatly the processes of later recrystallization and formation of secondary caverns, occur in the deposits of the Yurubchen, Kuyumba and, less commonly, Yukta Formations. Silicification was widespread, which occurred during the earliest diagenesis as evidenced by well-preserved sedimentary microstructures. However, siliceous material was recrystallized and redistributed during later stages of diagenesis. Fracturing is multistaged. Fracturing was most intense during Early Baikalian tectonic events (~850Ma). Cavern formation is mainly associated with fracturing of this stage. Formation of karsts occurred in the pre-Vendian time.

Correlation between sedimentary structure of rocks and the degree of postsedimentary alterations is observed. The carbonate complexes with good primary reservoir properties usually display more intense postsedimentary rock transformations which favoured the formation of reservoirs of fractured and cavernous-fractured types.

Finally, we should note that carbonate sedimentation in the Late Precambrian basins as well as the Panerozoic ones, is associated with life activity of bios which was directly or indirectly involved in producing calcium carbonate. Both shallow-water and deep-water carbonate sedimentary systems are much homologous to the Phanerozoic ones. Diversity of sedimentary basins was responsible for the formation of a wide spectrum of carbonate deposits which possessed potentially good reservoir properties. Secondary processes have largely changed the primary filtrational-porosity characteristics of the Riphean carbonate deposits, however, their relation to sedimentary struetures has still preserved. Therefore, when estimating the reservoir properties of the Late Precambrian carbonate rocks, much emphasis should be placed on paleogeographic reconstructions with predicting and studying the zones of reefs, grainstone shoals and other types of deposits -- potentially good reservoirs. Of major importance also is the analysis of relative variations of sea level, because lowstand phases are favourable for subaerial exposure of carbonate deposits which is accompanied by meteoric diagenesis.

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INTRODUCTION OF RESEARCH INSTITUTE OF PETROLEUM EXPLORATION AND DEVELOPMENT

Jia Chengzao and Gu Jiayu

Research Institute of Petroleum Exploration and Development of CNPC (RIPED), a famous academy of petroleum science, directly under the CHINA NATIONAL PETROLEUM CORPORATION (CNPC), is only comprehensive organization for scientific research and technological development on all aspects of the upstream of petroleum industry ,such as oil gas exploration and development, drilling and production engineering, equipment and instrumentation, oilfield chemistry and computer application.

There are about 1400 staffs and workers and 27Departments in RIPED, in which Senior engineers of 28%,engineers of 26%,assistant engineers of 20%and others of 26%.There are 74doctors and 180 masters.

Research organization on oil and gas geological exploration and development & production in RIPED are Petroleum Geology Dept.. Petroleum Geophysics Dept., Remote-sensing Geology Dept., Nature Gas Dept., Geological Laboratory Center, Oil & Gas Field Development Dept., Production Engineering Dept., Thermal Recovery Dept., Enhanced Oil Recovery Dept., Fracturing & Acidizing Techniques Service Center, Porous Flow & Fluid Mechanics Dept. Software Research Center and Computer Application Technology Dept.

With nearly 50 years development of China petroleum industry, RIPED has been growing up a mature and versatile academic institute, Not only does she posses high sophisticated instruments and devices, but the more important she bring up a large group of competent experts with extensive knowledge and rich field experiences covering all aspects of petroleum science.

RIPED has wide international ties closely linked to the institutes and companies of several tens countries around the world in the academic exchange and research cooperation. RIPED has strong interests to cooperation with more and more countries. It is confident that such bilateral scientific and technological cooperation will benefit both sides and promote petroleum technologies in oil industry.

INTRODUCTION OF INSTITUTE OF PETROLEUM GEOLOGY, SIBERIAN BRANCH OF THE RUSSIAN ACADEMY OF SCIENCES

A.E. Kontorovich and N.V. Sennikov

The average-listed number of the workers of the Institute, as of January 1, 2000, is 242, of them 132 scientific workers, including one full member of the Russian Academy of Sciences, two corresponding members of the RAS, 34 doctors of science, 52 candidates of science, 76 workers having higher education without scientific degree, 47 young specialists aged under 35, 29 workers take post-graduate courses, of them 18 persons take full-time post-graduate courses.

The Russian Foundation for Basic Research officially supports two scientific schools:

The School of A. E. Kontorovich - Naphthide genesis and its evolution in the Earth's history.

The School of the corresponding member of RAS A. V. Kanygin - The world and regional regularities of evolution of the Late Precambrian and Phanerozoic ecosystems of Siberia, parallel zonal scales and paleobiogeographic reconstructions.

Major Scientific Goals

• Oil and gas problems: a) naphthidogenesis and its evolution in the Earth's history, worldwide and regional regularities of oil and gas field distribution; b) organic geochemistry.

•Sedimentary basins: biota composition, evolution and chorology of the Precambrian and Phanerozoic paleobasins as the basis for distinguishing the regularities of biosphere evolution, development of stratigraphic charts with different scales and methods of deep stratigraphy of petroleum basins; b) regional tectonics of platform areas; c) sedimentology.

• Formation conditions of giant oil and gas fields. Mineral-raw material problems of geoeconomy and geopolicy: a) assessment of oil and gas resources onshore and offshore of the Russian Federation, prediction of development of the Siberian oil and gas complex, its role in fuel-energy complex of Russia with regard for the worldwide tendencies; b) theoretical principles of methods and new technologies for prediction, prospecting and exploration for oil and gas fields.

•Resources, dynamics and conservation of underground waters: geological development of the system water-rock-organic matter as the basis for solution of hydrogeological and environmental problems in the Siberian basins.

Trends in Scientific Activities and Types of Work

Complex investigation of sedimentary petroleum basins, paleontology, stratigraphy, organic geochemistry, assessment of oil and gas resources onshore and offshore of RF, prediction of development of the oil and gas complex of Siberia and its influence on the fuel-energy complex of Russia, theoretical foundation of methods and new technologies of prediction, prospecting, and exploration for oil and gas fields, hydrogeology, and geoecology.

The Institute was granted three licenses by the RF Ministry of Natural Resources for performing all types of geochemical works and for constructing geological composite and areal maps of different-scales.

The Institute carries out investigations at high scientific level according to the approved plans of research works and fundamental investigations according to the orders made by the Ministry of Natural Resources, Ministry of Fuel and Energy of Russian Federation, Administration and Regional Committees on natural resources of the Tomsk and Novosibirsk regions, Yamal-Nenets and Evenk autonomous areas, Krasnoyarsk kray, Khakass Republic, oil and gas companies such as JSC "Gazprom", SC "Lukoil", "Yukos", "Sibneft", "Slavneft", and others.

The work concerning the scientific substantiation of the Precambrian petroleum potential of the Siberian Platform was awarded by the 1994 State Prize of the Russian Federation in the field of science and engineering. Academicians A. A. Trofimuk and A. E. Kontorovich won the Prize.

Professor Yu. N. Karogodin (within the collective body of authors) won the 1998 State Prize of the Russian Federation in the field of science and engineering for a series of works "Creation and realization of scientific-methodical foundations for prediction, prospecting, exploration, and exploitation of hydrocarbon fields of Northernmost Siberia".

The Institute of Petroleum Geology SB RAS carries out the entire cycle of geologic and economic studies of the oil and gas complex of Russia, concerning: a)short-, medium-, and long-term predictions of development of this complex both at macro-, and microlevel with regard for the worldwide and national regularities of energy consumption, dynamics of its structure and efficiency, as well as natural properties of the development of producing fields of economy; b) the whole cycle of vertical integration in oil and gas industry is investigated from the exploration for hydrocarbon fields to their development, conservation, and marketing of production with differentiation by countries, economic regions, and managing subjects; c) from individual petroleum provinces and regions to some petroleum-producing enterprises and companies; d) geologic-economic developments are performed, starting from assessing the petroleum potential of the Federation subjects up to studying the sections of some prospects and wells; compiled are the programs of prospecting, exploration, and evaluation works in petroleum provinces and regions, with prediction of works in local areas and location of well spudding; e) compiled are the programs of reproduction of the mineral-raw base in

allocated and non-allocated underground resources, programs of underground resource licensing at the bids granting the right for their use.

Publications

The Institute publishes monographs and papers on petroleum potential, stratigraphy, paleontology, lithology, and sedimentology, hydrogeology and geoecology, structure and geologic history of petroleum basins and adjacent areas; tectonics of the platform regions; geochemistry of oils, geochemistry of biomarker hydrocarbons and oil source rocks; atlases and sets of various petroleum geology maps to a scale from 1:200 000 to 1:1 000 000 (of geologic knowledge, structural, tectonic, geologic, licensed prospects promising for oil and gas, organic matter catagenesis, oil-, and gas-generating potential of deposits); data basis on geochemistry of kerogen, oils, and condensates; thematic reports on the results of investigations ordered by the Ministries, departments, administrations of the Federation subjects and companies of the oil and gas complex.

Ten large works have been performed acoording to the order made by the Ministry of Natural Resources, Ministry of Fuel and Energy of Russia, Administrations and Regional Committees on natural resources. The works have been compiled as voluminous composite reports with graphic enclosures containing maps, atlases, and sets of various petroleum geology maps to a scale from 1:200 000 to 1:1 000 000 (of geologic knowledge, structural, tectonic, geologic, licensed prospects promising for oil and gas, organic matter catagenesis, oil-, and gas-generating potential of deposits); data basis on geochemistry of kerogen, oils, and condensates. The reports contain comprehensive data on the investigated problem, definite conclusions and recommendations. The copies of these reports are kept at the geologic funds of the Institute. The results of the investigations are widely used by the Ministries, Administrations of the Federation subjects, companies, etc. A series of documents were passed to the Government of RF and have been highly appreciated. The leaders of the Government were charged to use them in the definite forecasts and projects.

State Programs

Programs of the Ministry of Natural Resources, Ministry of Fuel and Energy of Russia and the program "Poisk" of the Siberian Branch of the Russian Academy of Sciences.

The Federal specific program of economic and social development of Siberia (FSP "Siberia"); Project "Energy strategy of Siberia".

State scientific-technical program "Global changes of environment and climate".

International Projects

Company "Petroconsultants S.A." (Switzerland), coordinator academician A. E. Kontorovich

Company "GeoMark Research, Inc." (USA), coordinator academician A. E. Kontorovich

"Engineering Advancement Association of Japan (ENAA)", coordinator academician A. E. Kontorovich

Orders Made by the Companies of Oil and Gas Complex

Eastern oil company

Oil State Company "Slavneft"

"Nadymgazprom" JSC "Gazprom"

JSC "Noyabr'skneftegaz"

"Nizhnevartovskneftegaz"

Orders Made by the State Regional Committees on Natural Resources

The Committee on Natural Resources of Krasnoyarsk Kray

The Committee on Natural Resources of Khakass Republic

The Committee on Natural Resources of Tomsk region

The Committee on Natural Resources of Yamal-Nenets autonomous area, JSC "SibNATS"

The Committee on Natural Resources of Evenk autonomous area

Works in Cooperation with the Research Institutes Subordinate to the Ministries

Siberian Research Institute of Geology, Geophysics and Mineral Resources (SRIGGMR) of the Ministry of Natural Resources

Krasnoyarsk Research Institute of Geology, Geophysics and Mineral Resources (KRIGGMR) of the Ministry of Natural Resources