УДК 553.98.041(477) *DOI: https://doi.org/10.32822/naftogazscience.2017.01.015*

PETROLEUM POTENTIAL OF THE WEATHERED, FRACTURED, AND HYDROTHERMALLY ALTERED BASEMENT RESERVOIRS: CASE STUDY FOR UKRAINE

O.A. Kitchka[1], O.P. Petrovskyy[2], T.O. Fedchenko[3], K.Ye. Shniukova[4], G.O. Kuzmanenko[5], A.R. Solomyanyi[6], T.P. Koghut[7]

[1] *Centre for Petroleum Geology and Seismic Studies, SE «Naukanaftogaz», Vyshneve, Kyiv Oblast, Ukraine,* E-mail: kitchka@naukanaftogaz.kiev.ua
Deputy Head of the Department

[2] *STC 'DEPROIL' Ltd., Ivano-Frankivsk, Ukraine,* E-mail: oleksandr.petrovskyy@deproil.com
Prof., DrSc in Physics & Maths, Director

[3] *STC 'DEPROIL' Ltd., Ivano-Frankivsk, Ukraine,* E-mail: tetyana.fedchenko@deproil.com
PhD in Physics & Maths, Deputy Director

[4] *M.P. Semenenko Inst. for Geochemistry, Mineralogy & Ores Formation, NAS Ukraine, Kyiv, Ukraine,* E-mail: shniukova@i.ua
DrSc in Geology, Leading Researcher

[5] *Inst. of Geological Sciences, NAS Ukraine, Kyiv, Ukraine,* E-mail: geology7@ukr.net
PhD in Geology, Senior Researcher

[6] *SE 'SouthUkrGeologia', Dnipro, Ukraine,* E-mail: solomianyi@ukr.net
Chief Geologist

[7] *Centre for Petroleum Geology and Seismic Studies, SE «Naukanaftogaz», Vyshneve, Kyiv Oblast, Ukraine,* E-mail: tkogut@naukanaftogaz.kiev.ua
Head of Department

The weathered crystalline crust (WCC) is a transitional geobody occurring between the intact basement and sedimentary cover and representing the result of complex geological and geochemical processes called weathering that impacted the topmost part of the crystalline bedrock. WCC studies are important for useful ore minerals and hydrocarbon exploration. Until present, around 450 of the discovered petroleum fields in the world are solely or partly attributed to the weathered, fractured and altered basement rocks of different consolidation age and known for all continents excluding Antarctica. Much more petroleum production comes from weathered and altered volcanics, and metasedimentary Precambrian, Paleozoic, and Mesozoic rocks, usually considered incorrectly as barren ones. Giant oil and gas fields produce crudes from crystalline basement and granite wash in the USA, Venezuela, Brazil, Libya, Kazakhstan, Russia, China, Yemen, Vietnam, etc. The commercial discoveries of oil and gas took place during the last decades in the weathered basement along the buried Northern flank of the Late Devonian Dnieper-Donets paleorift as well in Ukraine. Some basement reservoirs are

characterized by unique geochemical features and may contain commercial reserves of noble gases like helium. A sophisticated new technique applying a joint inversion of seismic and gravity data and adjusted by other geological and production data allows building of a geodensity model of a WCC reservoir and confident delineation of prospective basement reservoirs.
Key words: Crystalline basement reservoirs, deep weathering front, hydrocarbon fields, hydrothermal alterations, fracturing and leaching, seismic interpretation, Ukrainian Crystalline Shield, Dnieper-Donets basin

НАФТОГАЗОВИЙ ПОТЕНЦІАЛ ВИВІТРИЛИХ, ТРІЩИНУВАТИХ ТА ГІДРОТЕРМАЛЬНО ЗМІНЕНИХ КОЛЕКТОРІВ КРИСТАЛІЧНОГО ФУНДАМЕНТУ ЧЕРЕЗ ПРИЗМУ УКРАЇНСЬКОГО ДОСВІДУ

О.А. Кичка [1], О.П. Петровський [2], Т.О. Федченко [3], К.Є. Шнюкова [4], Г.О. Кузьманенко [5], А.Р. Солом'яний [6], Т.П. Когут [7]

[1] *Центр нафтогазогеологічних та сейсмічних досліджень ДП «Науканафтогаз», Вишневе, Київська область, Україна,* E-mail: kitchka@naukanaftogaz.kiev.ua
Заступник завідувача відділу

[2] *ТОВ НТК «ДЕПРОІЛ», Івано-Франківськ, Україна,*
E-mail: oleksandr.petrovskyy@deproil.com
Професор, доктор фіз.-мат. наук, директор

[3] *ТОВ НТК «ДЕПРОІЛ», Івано-Франківськ, Україна,* E-mail: tetyana.fedchenko@deproil.com
Кандидат фіз.-мат. наук, заступник директора

[4] *Інститут геохімії, мінералогії і рудоутворення ім. М.П. Семененка НАН України, Київ, Україна,* E-mail: shniukova@i.ua
Доктор геол. наук, провідний науковий співробітник

[5] *Інститут геологічних наук НАН України, Київ, Україна, E-mail:* geology7@ukr.net
Кандидат геол. наук, старший науковий співробітник

[6] *ДКП «Південукргеологія», Дніпро, Україна, E-mail:* solomianyi@ukr.net
Головний геолог

[7] *Центр нафтогазогеологічних та сейсмічних досліджень ДП «Науканафтогаз», Вишневе, Київська область, Україна, E-mail:* tkogut@naukanaftogaz.kiev.ua
Завідувач відділу

Кора вивітрювання кристалічного фундаменту (КВФ) являє собою перехідне геологічне тіло між незміненими кристалічними породами та осадовим чохлом і є результатом комплексу геологічних та геохімічних процесів, які змінюють горішню частину кристалічного цоколю. Дослідження КВФ важливі с точки зору пошуків і розвідки корисних копалин, нафти і газу зокрема. На теперішній час в світі відкрито близько 450 родовищ нафти і газ, які пов'язані повністю чи частково з вивітрилими, тріщинуватими, або гідротермально зміненими породами кристалічного фундаменту різного віку консолідації на всіх континентах, окрім Антарктики. Ще більше відомо промислових

вуглеводневих акумуляцій у вивітрилих та змінених вулканітах та метаосадових докембрійських, палеозойських та мезозойських гірських породах, які зазвичай вважаються безперспективними. Гігантські за запасами нафтові і газові родовища відкриті в кристалічному фундаменті та перевідкладених корах його вивітрювання в США, Венесуелі, Бразилії, Лівії, Казахстані, Росії, Китаї, Ємені, В'єтнамі і т.д. Останніми десятиліттями в Україні родовища нафти і газу були відкриті в кристалічному фундаменті Північного борту пізньодевонського Дніпровсько-Донецького палеорифту. Деякі колектори фундаменту мають унікальні геолого-геохімічні характеристики і можуть містити промислові запаси благородних газів, таких як гелій. Новітня технологія, що використовує спільну інверсію сейсмічних і гравіметричних даних скоригованих з врахуванням наявної геолого-геофізичної та промислової інформації, дозволяє побудувати просторову геогустинну модель резервуару в КВФ та впевнено оконтурити перспективні зони в ньому, що насичені вуглеводнями.
Ключові слова: колектори кристалічного фундаменту, фронт вивітрювання, нафтогазові родовища, гідротермальні зміни, тріщинуватість та вилуговування, сейсмічна інтерпретація, Український кристалічний щит, Дніпровсько-Донецька западина

НЕФТЕГАЗОВЫЙ ПОТЕНЦИАЛ ВЫВЕТРЕЛЫХ, ТРЕЩИНОВАТЫХ И ГИДРОТЕРМАЛЬНО ИЗМЕНЕННЫХ КОЛЛЕКТОРОВ КРИСТАЛЛИЧЕСКОГО ФУНДАМЕНТА ЧЕРЕЗ ПРИЗМУ УКРАИСКОГО ОПЫТА

А.А. Кичка[1], А.П. Петровский[2], Т.А. Федченко[3], К.Е. Шнюкова[4], Г.А. Кузьманенко[5], А.Р. Соломенный[6], Т.П. Когут[7]

[1] *Центр нефтегазогеологических и сейсмических исследований ДП «Науканефтегаз», Вишневое, Киевская область, Украина,* E-mail: kitchka@naukanaftogaz.kiev.ua
Заместитель заведующего отделом

[2] *ООО НТК «ДЕПРОЙЛ», Ивано-Франковск, Украина,*
E-mail: oleksandr.petrovskyy@deproil.com
Профессор, доктор физ.-мат. наук, директор.

[3] *ООО НТК «ДЕПРОЙЛ», Ивано-Франковск, Украина,*
E-mail: tetyana.fedchenko@deproil.com
Кандидат физ.-мат. наук, заместитель директора

[4] *Институт геохимии, минералогии и рудообразования им. Н.П. Семененко НАН Украины, Киев, Украина,* E-mail: shniukova@i.ua
Доктор геол. наук, ведущий научный сотрудник

[5] *Институт геологічних наук НАН України, Киев, Украина,* E-mail: geology7@ukr.net
Кандидат геол. наук, старший научный сотрудник.

[6] *ДКП «Южукргеология», Днипро, Украина,* E-mail: solomianyi@ukr.net
Главный геолог

[7] *Центр нефтегазогеологических и сейсмических исследований ДП «Науканефтегаз», Вишневое, Киевская область, Украина,* E-mail: tkogut@naukanaftogaz.kiev.ua
Заведующая отделом

Кора выветривания кристаллического фундамента (КВФ) переставляет собой переходное геологическое тело между неизмененными кристаллическими породами и осадочным чехлом и есть результатом комплекса геологических и геохимических процессов которые изменяют самую верхнюю часть кристаллического цоколя. Исследования КВФ важны с точки зрения поисков и разведки полезных ископаемых, нефти и газа в частности. На данный момент в мире открыто около 450 месторождений нефти и газа, которые полностью или частично связаны с выветрелыми, трещиноватыми или гидротермально измененными породами кристаллического фундамента разного возраста консолидации и на всех континентах, за исключением Антарктики. Еще большее число промышленных угле водородных аккумуляций открыто в выветрелых и измененных вулканитах и мета осадочных докембрийских, палеозойских и мезозойских горных породах, которые обычно считаются бесперспективными. Гигантские по запасам нефтяные и газовые месторождения открыты в кристаллическом фундаменте и его пере отложенных корах выветривания в США, Венесуэле, Бразилии, Ливии, Казахстане, России, Китаэ, Йемене, Вьетнаме и т.д. За последние десятилетия в Украине местрождения нефти и газа были открыты в кристаллическом фундаменте Северного борта позднедевонского Днепровско-Донецкого палеорифта. Некоторым коллекторам фундамента присущи уникальные геолого-геохимические характеристики и они могут содержать промышленные запасы огородных газов, таких как гелий. Новейшая технология, которая использует совместную инверсию сейсмических и гравиметрических данных, скорректированных с учетом всей имеющейся геолого-геофизической и промысловой информации, позволяет построить пространственную геоплотностую модель резервуара в КВФ и уверенно оконтуривать перспективные зоны в нем, которые насыщены углеводородами.
Ключевые слова: коллекторы кристаллического фундамента, фронт выветривания, нефтегазовые месторождения, гидротермальные изменения, трещиноватость и выщелачивание, сейсмическая интерпретация, Украинский кристаллический щит, Днепровско-Донецкая впадина.

Introduction

This study originates from a fieldtrip organized by *SE SouthUkrGeologia* for the Geological Survey of Norway (*NGU*) research team to visit outcrops of the weathered crystalline crust (WCC) in the central-eastern Ukraine and the wellbored cores repository in Dnipro city to examine weathering profiles for the different bedrock of the Ukrainian Crystalline Shield (UCS) in 2013. Later the researchers from Ukraine have joined *NGU* in the frame of the “Crustal Onshore-Offshore Project" to feature in nutshell all aspects of the UCS WCC geological evolution, spatial development, structural features, compositional and geochemical varieties, thermal field features of the craton, as well as useful minerals hosted by

WCCs, including hydrocarbon accumulations in basement reservoirs. The study has embraced the problems of areal and linear WCC development as well as key drivers to produce weathering profiles typical for different crustal mega-blocks composing the UCS. Main attention was paid to the peculiarities of the Paleozoic and most powerful Mesozoic weathered crust formation. Total thickness of all four WCC zones of complete weathering profile vary greatly over the UCS mega-blocks depending on their tectonic evolution, basement paleorelief, and course of peneplanation processes. The last zone of laterites is rarely preserved in the form of sporadically spread bauxite duricrust over the WCC developed in ultrabasic parent rocks. The WCC profiles typical for acid, basic, ultrabasic igneous bedrock as wells as metamorphic ones like ferruginous quartzites of the UCS were described in brief and accompanied by chemical analyses for WCCs of different types. The description of important WCC outcrops in the UCS that are easily accessible for observation and study has been illustrated with images and cores, maps, and cross-sections. We have selected representative locations to characterize the deposits of primary and alkaline kaolins in the Volyn mega-blocks as well as typical ore deposits attributed to the UCS WCC in the Middle-Dnieper mega-block. A short review of hydrocarbon discoveries in the basement of the Northern Flank of Dnieper-Donets basin as well as the hydrocarbon potential of the basement reservoirs of the world have been also provided. An original and quite new technology of integrated joint seismic and gravity data inversion for recognizing and mapping of the basement weathered crust and hydrocarbon reservoirs is provided by *Deproil Ltd. Co*. from Ivano-Frankivsk and illustrated with practical case studies. A separate study featuring the UCS thermal field and variations of its heat flows and rock conductivity using borehole measurements and geothermal modeling was made as well. This paper is mainly focused on hydrocarbon accumulation hosted by WCC reservoirs.

The weathered crystalline crust (WCC) is a transitional geobody occurring between the monolithic crystalline basement and sedimentary cover and representing the result of complex geological processes called weathering that impacted the topmost part of the crystalline bedrock. From the other hand, formation of the weathered crust is a complex geological and geochemical phenomenon combining chemical alteration of the bedrock, in-situ bleaching and leaching of the primary mineral constituents, its fracturing, destruction and transformation into totally different matter of the weathered crust like laterite or kaolin. Re-worked and re-deposited material of WCC forms deposits of secondary or re-deposited weathered crust, important for useful ore minerals and hydrocarbon (granite wash) exploration. Long-term geological epochs of basement peneplanation by weathering agents: solar radiation, temperature, rock-water interaction, as well as biotic impact led to formation of thick multi-stadial WCCs, as areal and linear ones, like that one which can be observed in numerous basement outcrops in the Ukrainian crystalline shield stretching across the whole country from the west-northwest to the east-southeast.

Weathered crystalline crust features in central-eastern Ukraine

The Ukrainian Crystalline Shield (UCS), including its slopes is one of the best-outcropped Precambrian terrains with world-class weathered crystalline crust outcrops representing wide variety of the igneous and extrusive rock types, metasedimentary, metavolcanic, dynamometamorphic, metasomatic, pegmatite and migmatite bedrocks aged from Neoarchean to Vendian, as well as ore bodies and placers of different origin and type. This substantiates an existence of different types of the multistage weathered crust profiles of areal type over the vast areas of the craton and linear types along its lengthy deep fault zones. There are six geo-blocks traditionally distinguished in the structure of Ukrainian Crystalline Shield (Fig. 1).

Regularities of deep weathering development, mineralogy, geochemistry, ore content of WCC profiles upon the bedrocks of different petrology and consolidation age were studied in Ukraine since early 50's of the last century.

Numerous industrial reports, maps, many papers and monographs, and thousands of boreholes feature geological peculiarities of WCCs in the UCS. An application of that knowledge gained from analog outcrops studies benefits for exploration of basement WCC reservoirs developed in the late Devonian Dnieper-Donets paleorift shoulders composed by Precambrian crystalline rocks.

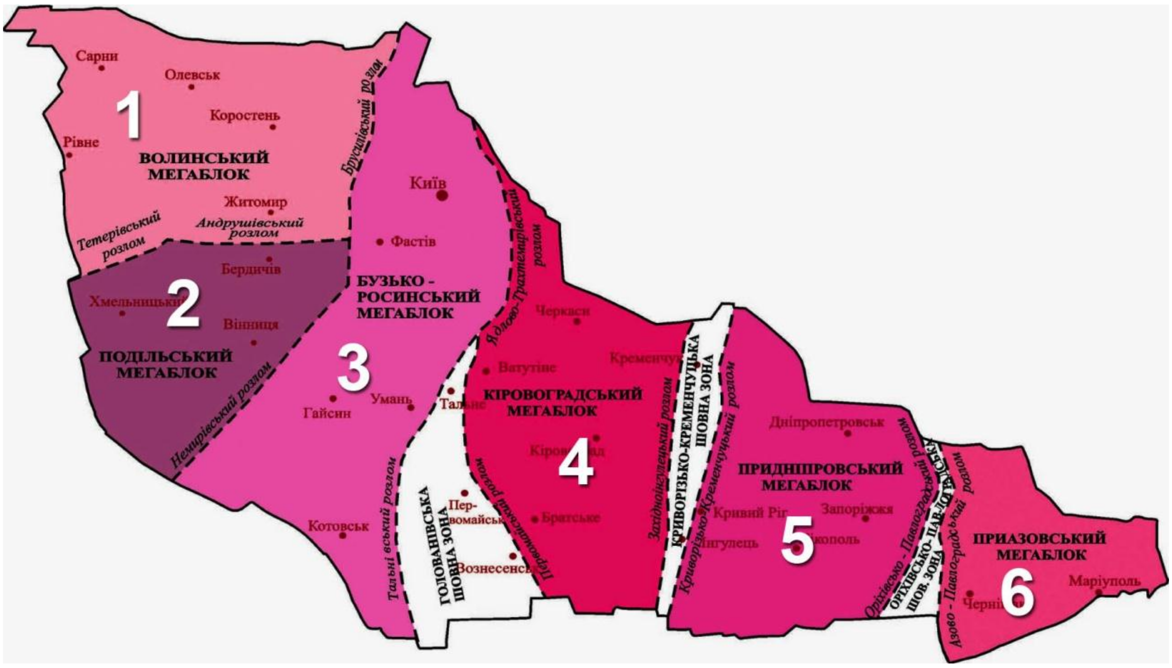


Fig. 1. Main tectonic geo-blocks of the UCS by Kostenko (2015): Volyn (1), Podolian (2), Ros-Bougian or Ros-Tikych (3), Ingoulets or Kirovogradian (4), Middle-Dnieper (5), and Peri-Azov (6).

The thickness of WCCs depends on composition of the primary rocks, degree of their permeability (being a function of their structural and textural features) and relief of the crystalline basement. Areal WCC has a thickness varying from 1 to 60 m with its maximum values characteristic of watersheds. The depth of linear WCC penetration exceeds 150 m. A zonal structure is typical as for areal as for linear WCC though the boundaries between the zones of the latter are not distinct so their recognition is a conditional to some extent.

WCC zonation is caused by different degree of original minerals transformations and their substitution with hypergene products. Upon this feature in a WCC profile it can be recognized four mineral-geochemical zones (going upward), corresponded to the mineral-geochemical zones of disintegration, leaching (initial decomposition), clay minerals (spotty hydromicaceous zone of dominating hydrolysis), oxides and hydroxides (final hydrolysis and oxidation) Fig. 2.

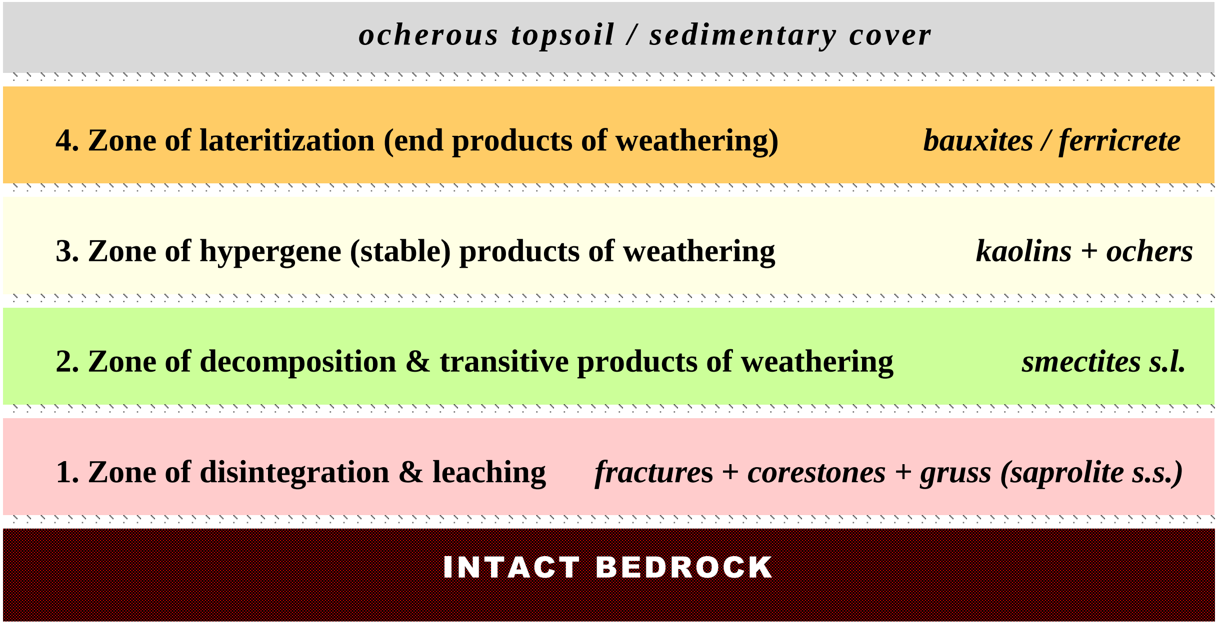


Fig. 2. Main mineral-geochemical zones of the weathered crust developed upon crystalline rocks.

One of the important WCC outcrops is located in ‘transition zone’ between the Folded Donbas and Peri-Azov crystalline massif.

The outcrops of the weathered crust developed upon granites are located 1.5 km east of Styla town, right bank of Mokraya Volnovakha river, Donetsk oblast (Fig. 3, upper left). Precambrian feldspar granites of the Styla horst are covered here with Devonian sandstones of Givetian stage. A clayey-micaceous horizon (Fig. 3, upper right) is observed below the contact with Mid-Devonian sandstones and the gruss of granites is gradually changed downward into a so-called ‘dismantled’ or sectional rock and blocky structure of the fractured saprolite granite massif with corestones, of 15-20 m thickness (Fig 3., bottom image). A similar outcrop of the weathered Stylian granites is located nearby on the other side of the Mokraya Volnovakha river. The granite was produced in the small abandoned quarry ‘Rose of Azov’.

Areal distribution of WCC is controlled by ancient topography of the basement and recent relief features.

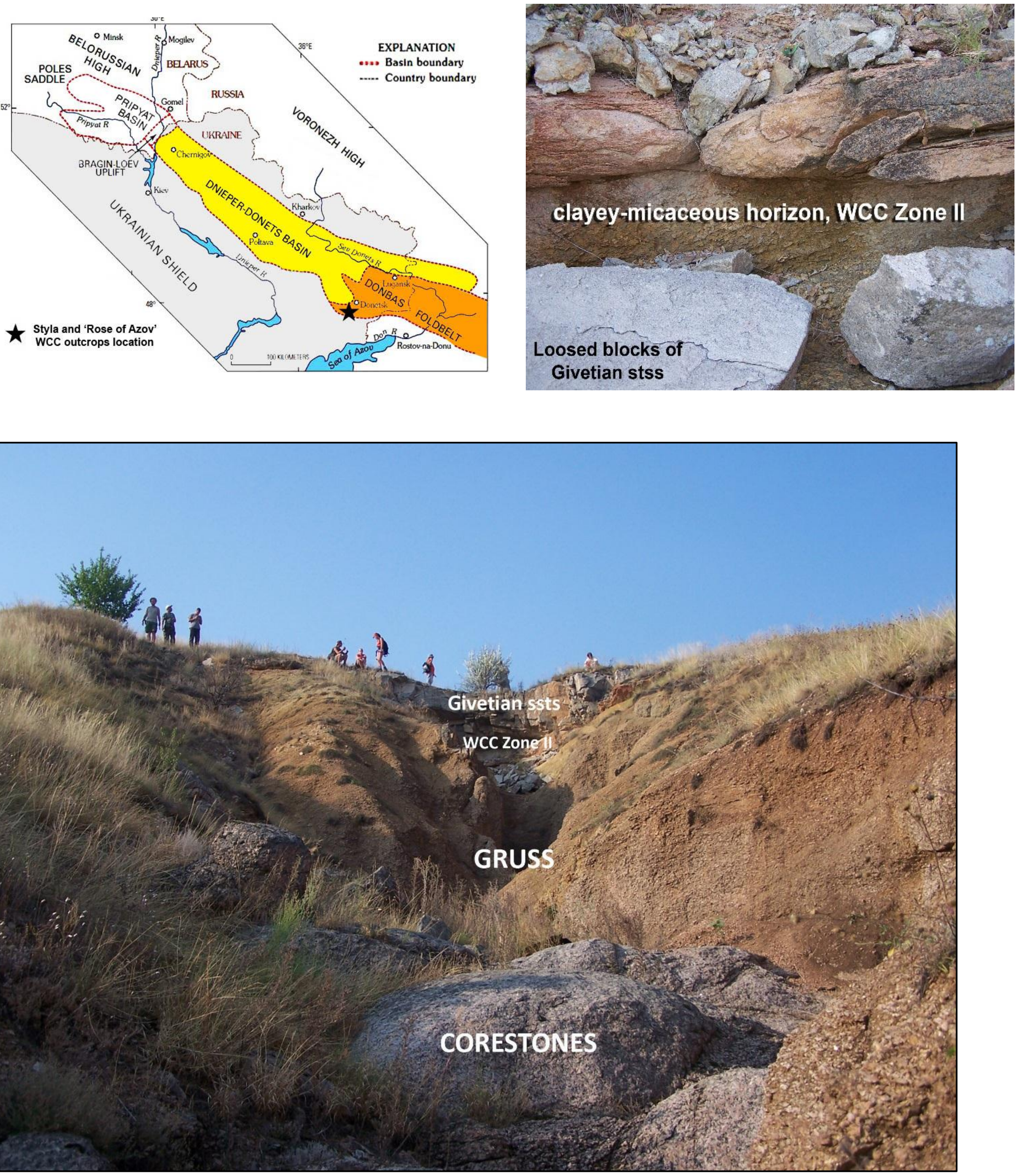


Fig. 3. Styla outcrop: transition from gruss to pillow-like sculptured surface (corestones) of the Peri-Azov block granites (bottom image). Outcrop location and the clayey-micaceous horizon of the WCC zone II in the Stylian Precambrian granites are shown on upper left and upper right images, respectively.

However, within ancient and some present-day river valleys the weathered crust is completely eroded. By the morphology and character the weathering profiles, and sometimes, due to their thickness, two types of WCC are recognized, the areal and linear (fault-related) one. The latter is developed very locally and attributed to (slightly widen) zones of some faults. In some cases it is possible to recognize the mixed type of WCC, a linear-areal one (cellular or blocky). The thickness of linear crust was increased to 150-200 m (except of much deeper hypergene zones preserved within the Kryvyi Rig-Kremenchuk structural belt, see Fig. 4). Linear weathering in the Kryvyi Rig fault zone can reach 1400-1600 m (Kheraskov, 1963) that speaks in favor of ultradeep paleo-circulation of groundwater carrying oxygen. This phenomenon also indicates a very rugged ancient topography.

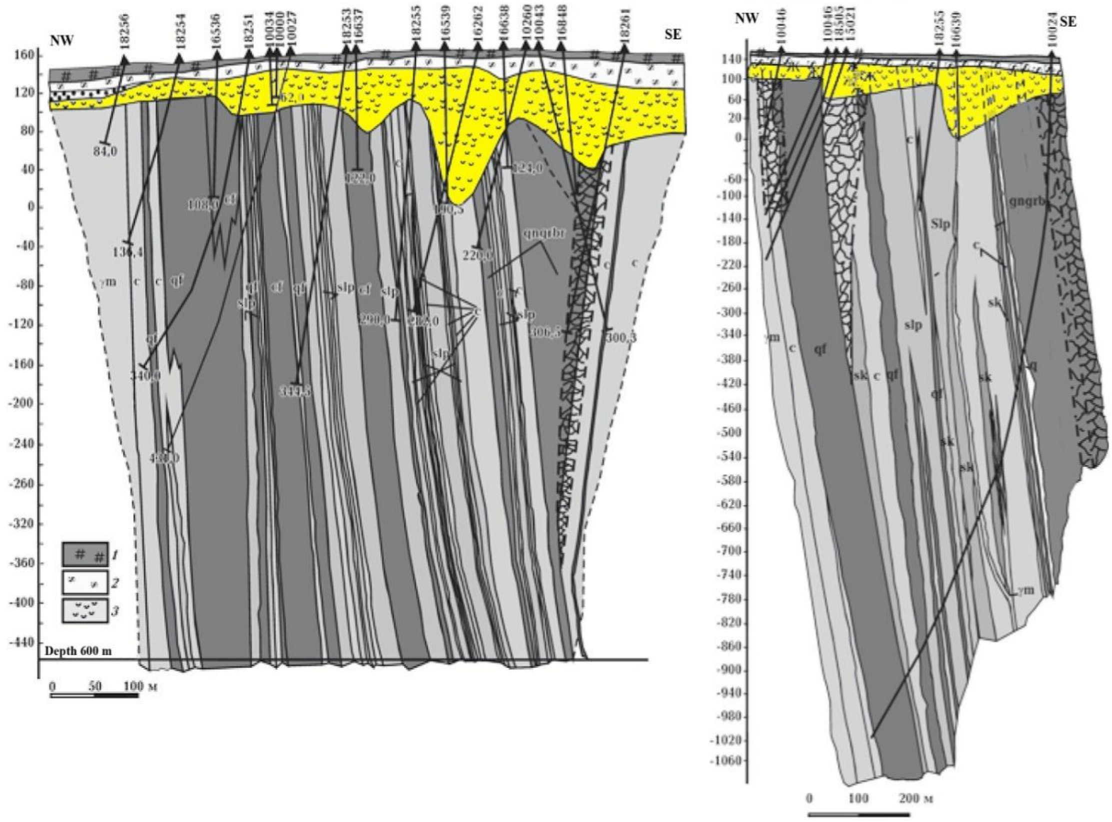


Fig. 4. Two cross-sections of the Moldovsky iron ore deposit illustrating development of the linear WCC (shown in yellow) along the faulted and vertical dipping Middle Proterozoic ferruginous quartzites. *1 – soils and loams, 2 – sand-clayey sediments, clays, 3 – kaolinite-hydromicaceous weathered crust* (Entin et al. 2015).

It should be noticed that the above mentioned thickness values do not reflect the thickness of the deepest part of the disintegration zone, i.e. the zone of deep fractures and fissures of faintly and locally altered crystalline bedrock that provides the percolation front of weathering down to the basal platform / aquitard for groundwater in the fractured crystalline massif (Fig. 5).

The thickness of this fractured "root" or "mantle" may be equal to the total thickness of the above WCC zones. It is worth to take into consideration another factor controlling rates of the weathering front propagation: the trickier the WCC becomes the slower the weathering front moves downward because thick kaolinite zone prevents meteoric water permeation into the disintegration zone (after diagenesis and initial lithification of those in-situ newborn rocks) thus buffering and retarding the weathering occur. It is possible to suppose that this process of WCC deepening stops when the weathering-induced fractures reaches the local equilibrium erosion base. As a consequence of this the permeable horizons in the WCC are formed due to removal of soluble minerals from the bedrock to the drainage basin and settling of them at the basal platform interface (Fig. 5).

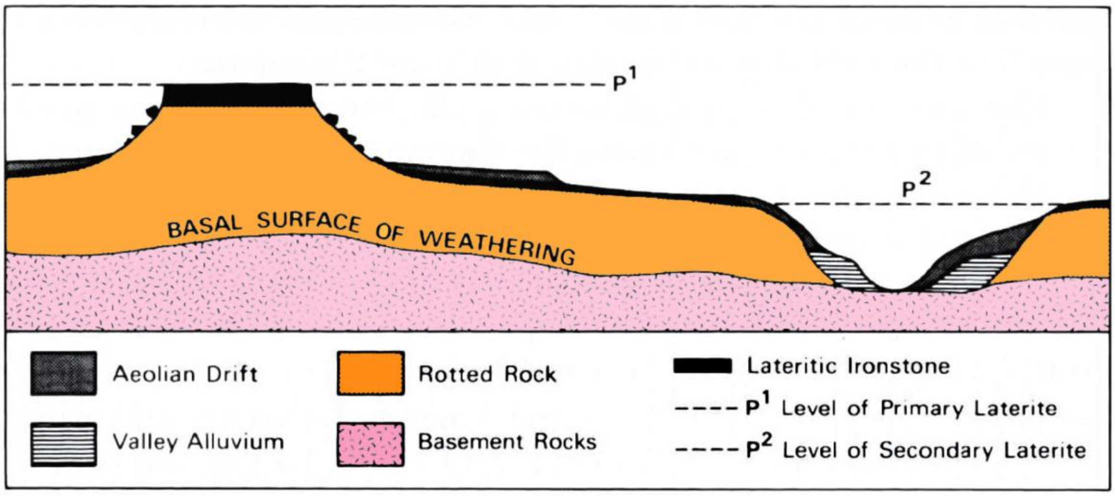


Fig. 5. Two-cycle laterite formation, landscape development and preservation of the weathered materials (Small, 1978).

This model is one of the possible explanations for the existence of the prominent reflection horizon - 'VIIth' - below the WCC developed in crystalline basement of the northern and southern flanks of the Dnieper-Donets basin. It is interesting to emphasize that CDP (common depth point technique) mapping of these flanks clearly demonstrate the deepening of that horizon basinward that also could support a paleo-drainage origin. A similar feature - the base of aquifers below the WCC / basal surface of weathering - is observed in the African craton (Fig. 6), India, and South America (Rabasso, 2010; Walter *et al.*, 2015).

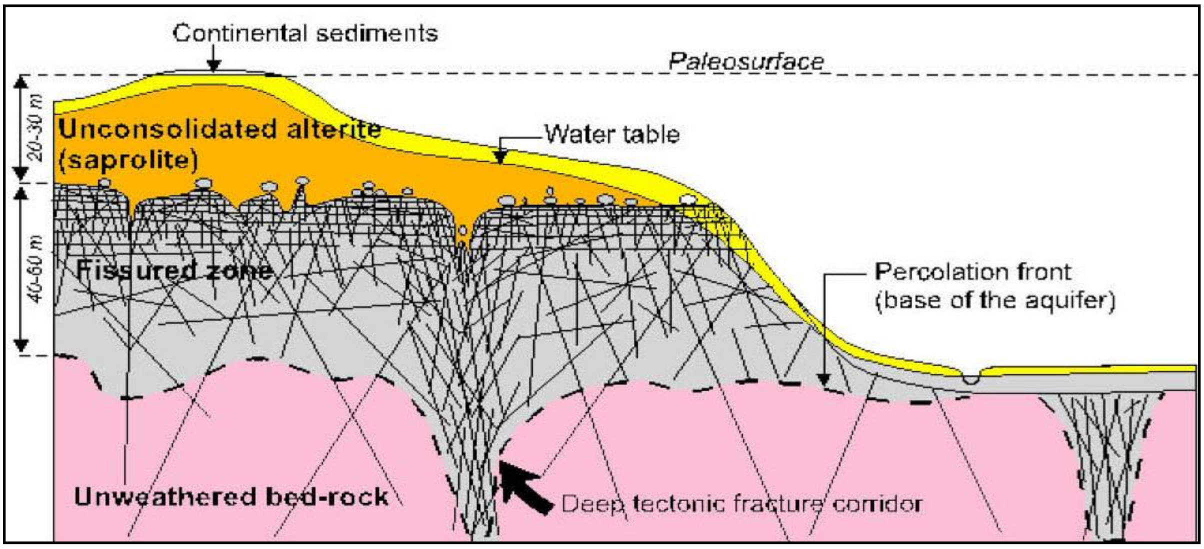


Fig. 6. Idealized single phase weathering paleoprofile in the crystalline basement, crosscut by the current topography, the original cartoon at the top (Wyns et al., 2004).

Global hydrocarbon potential of the weathered, fractured and hydrothermally altered basement reservoirs

Hydrocarbon exploration targeting basement reservoirs is a challenging task with regard to the fundamentals of petroleum geology and routine industrial practices. Until the 80's of the last century the discoveries of commercial oil and gas in the crystalline basement were made accidentally or during exploration mistakes and were often treated as curiosities. By now, commercial production of hydrocarbons from fractured crystalline basement is well documented, for the petroleum basins across the globe hosting weathered, fractured and/or altered basement fields.

Until present, around 1% of the discovered petroleum fields in the world are solely or partly attributed to the weathered, fractured and altered basement rocks of different consolidation age and known for all continents excluding Antarctica. Much more petroleum production comes from weathered and altered volcanics, and metasedimentary Precambrian rocks, usually considered incorrectly as barren ones.

It is well known, that Precambrian rocks can preserve some residual generation potential as well as crystalline rocks can bear original one in the form of fluid inclusions saturated with liquid and gaseous hydrocarbons. Giant oil and gas fields produce crudes from crystalline basement and granite wash in the USA, Venezuela, Brazil, Libya, Kazakhstan, Russia, China, Yemen, Vietnam, etc. Some basement reservoirs are characterized by unique geochemical features and may contain commercial reserves of noble gases like helium. The closest to Norway petroleum production from basement reservoirs is known west of the Shetland and in the Moray Firth sub-basin (not to mention abundant oil manifestations from the Lewisian Complex in Scotland).

To present time more than 450 oil and gas fields in 54 countries and more than 100 sedimentary basins (Gavrilov et al., 2010; Koning, 2014) with commercial productivity of the crystalline basement of different type are known worldwide over all continents except Antarctica. Figure 7 shows a quite comprehensive overview of the basement hydrocarbon discoveries compiled by Geoscience Ltd. (Gutmanis et al. 2015).

Among these ones there are several of well-known fields such as Panhandle-Hugoton (Mid-Continent), tandem La-Pas - Mara (Maracaibo basin, Fig. 8), Carmopolis (Sergipe-Alagoas), Augila-Nafoora (Sirte), Oymasha (Manghyshlak, Fig. 9), NE Beruk (Sumatra), White Tiger (Fig. 10), Black Lion and Ruby (offshore Vietnam), Clair (the Atlantic frontier), Rolvsnes in the North Sea basin (Fig.11), Novoporovskoye in the West Siberia and other unique HC accumulations.

The term ‘basement’ includes true crystalline basement as well as the so-called intermediate (or acoustic) basement represented by folded metamorphic (weathered and fractured) rocks prospective for hydrocarbons (e.g. the West Siberia mega-basin).

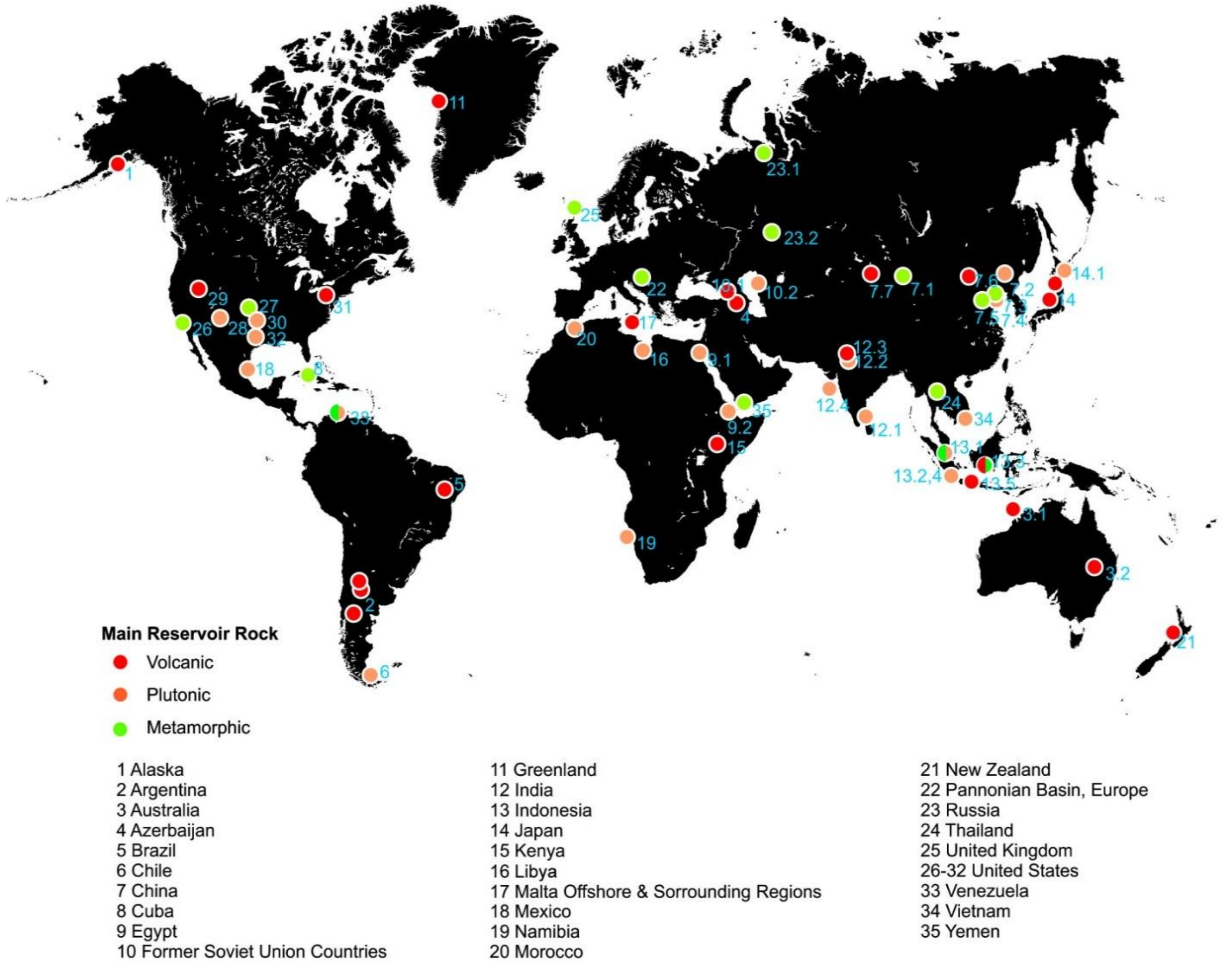


Fig. 7. Commercial occurrences of hydrocarbons in the basement reservoirs of different type and origin at global scale (Gutmanis et al., 2015).

Nowadays, basement reservoirs exploration hotspots are evolving offshore Vietnam (Cuu Long basin), Yemen (Say’un-Masila basin), Russian Federation (West & East Siberia mega-basins), PR China (‘buried hills’ Bohai Bay basin, etc.), offshore the UK and Norway in the North Sea (Zhuravliov & Oblekov, 2000; Trice, 2014; Lie et al., 2016) and so on.

Some highly elevated basement horsts affected by tectonic rejuvenation and hydrothermal alteration (Areshev et al., 1992; Cuong & Warren, 2009, Fig. 11) are characterized by extra high initial flow rates of oil, absence of oil-water contact (OWC) and consequently waterless production, and even dead oil saturation of the basement rocks below the horst toe (Gavrilov et al., 2010).

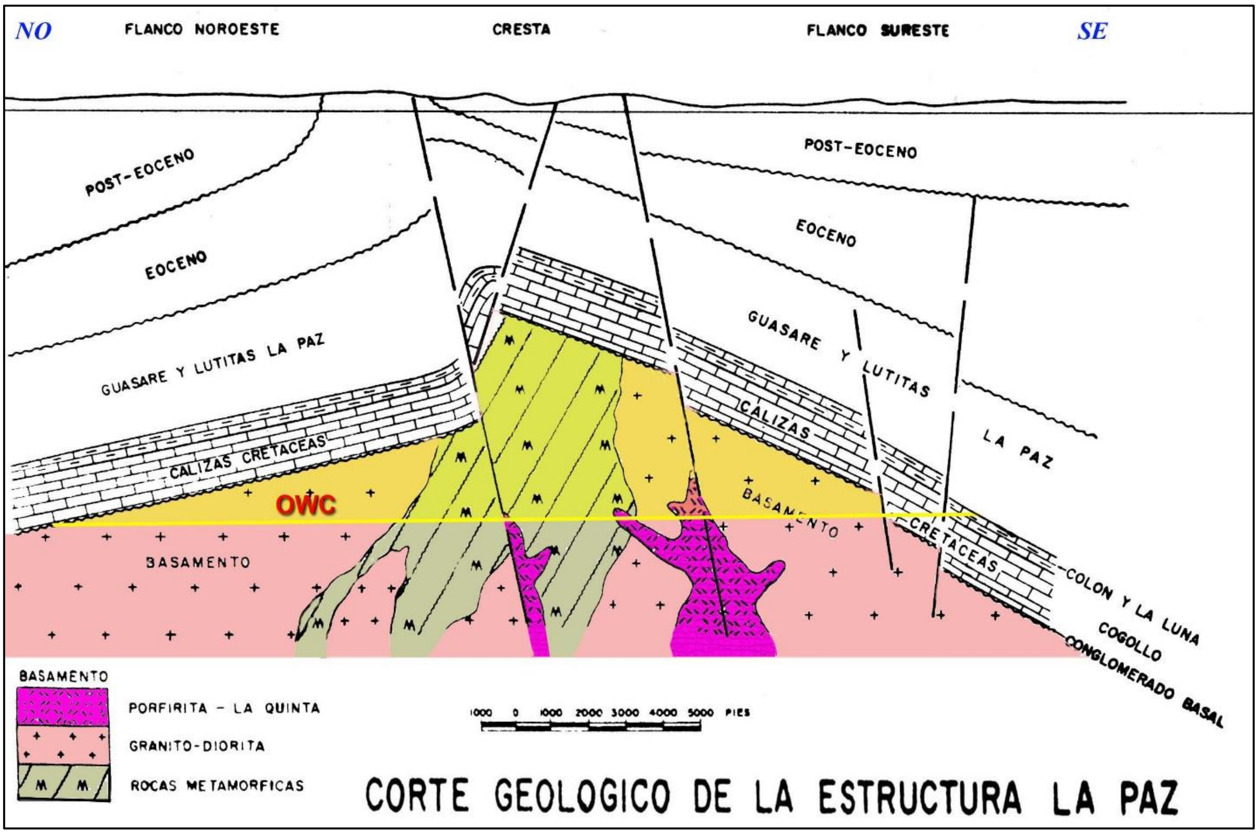
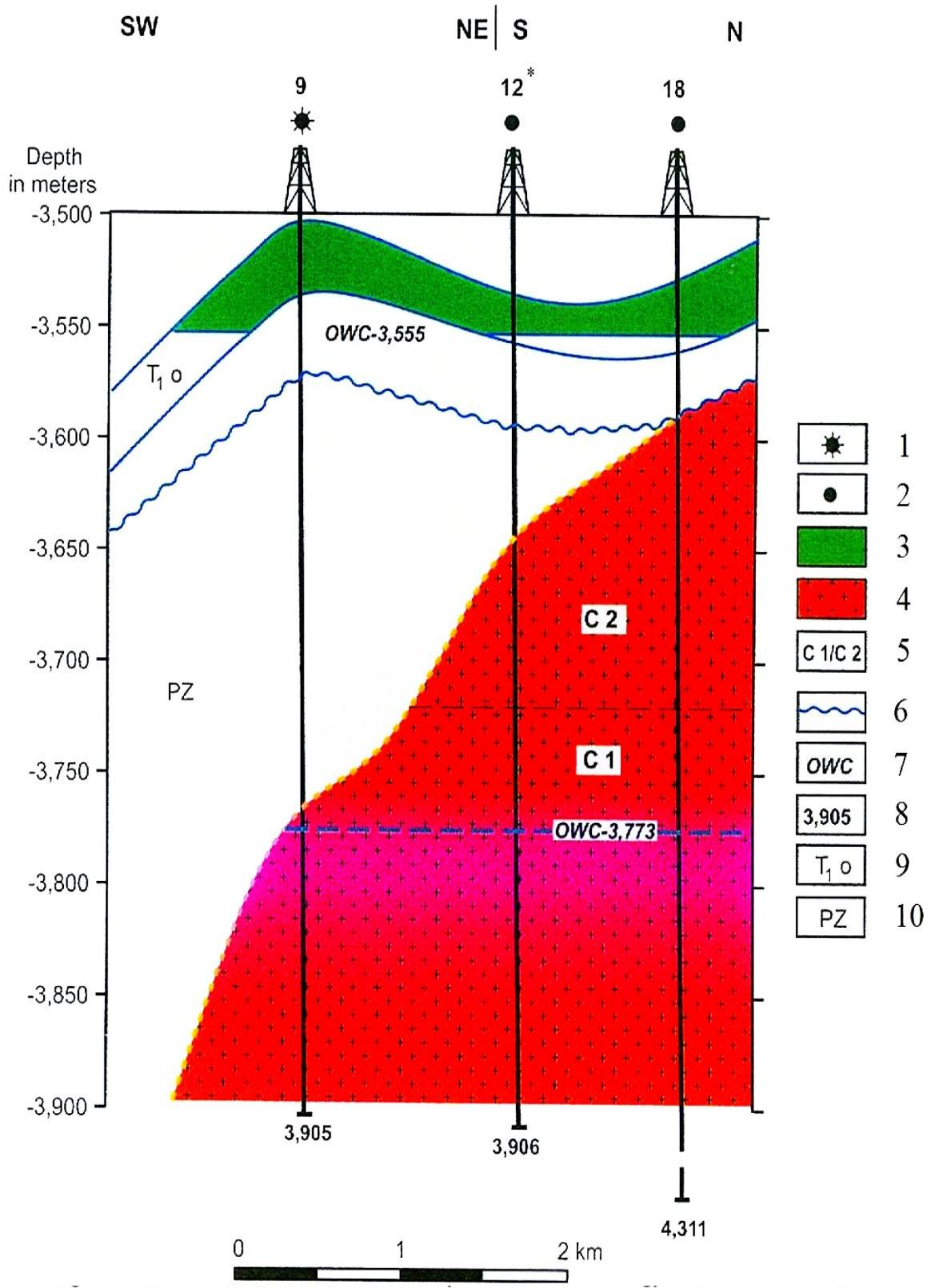


Fig. 8. La Pas – Mara oil field, La Perriha buried ridge, the Maracaibo basin, Venezuela. OWC – oil-water contact (Guariguata & Richardson 1959).

To understand the nature of hydrothermally impacted basement reservoirs can consider hydrothermal alteration as a kind of upward 'hypabyssal weathering' producing additional porous volume in the buried but elevated rock domain.

A quite interesting basement oil discovery was recently made within the buried Rona Ridge, West of Shetlands by Hurricane Energy plc. Weathered basement reservoirs can represent preferential exploration targets (Areshev et al., 1992), but while the process of subaerial exposure can result in enhanced porosity and permeability, it can also generate porosity and permeability inhibiting clays, which reduce the reservoir potential. Offset and analogue data indicate that at Lancaster such processes are expected to be concentrated within the longer and better-connected fault planes as well as along joint systems hydraulically connected to unconformity surfaces (Fig. 12).



1 – oil & gas well; 2 – oil well; 3– oil pool; 4 – granitoid; 5 – category reserve limit; 6 – unconformity; 7 – oil/water contact; 8 – TD in drilled meters; 9 – Lower Triassic (Olenek Fm); 10 – Paleozoic metamorphite.
**Well 12 tested about 1,380 BOPD from the fractured and/or weathered granite*

Fig. 9. Oymasha oil field cross-section, Mangyshlak, Turan plate, Kazakhstan (Morariu, 2012).

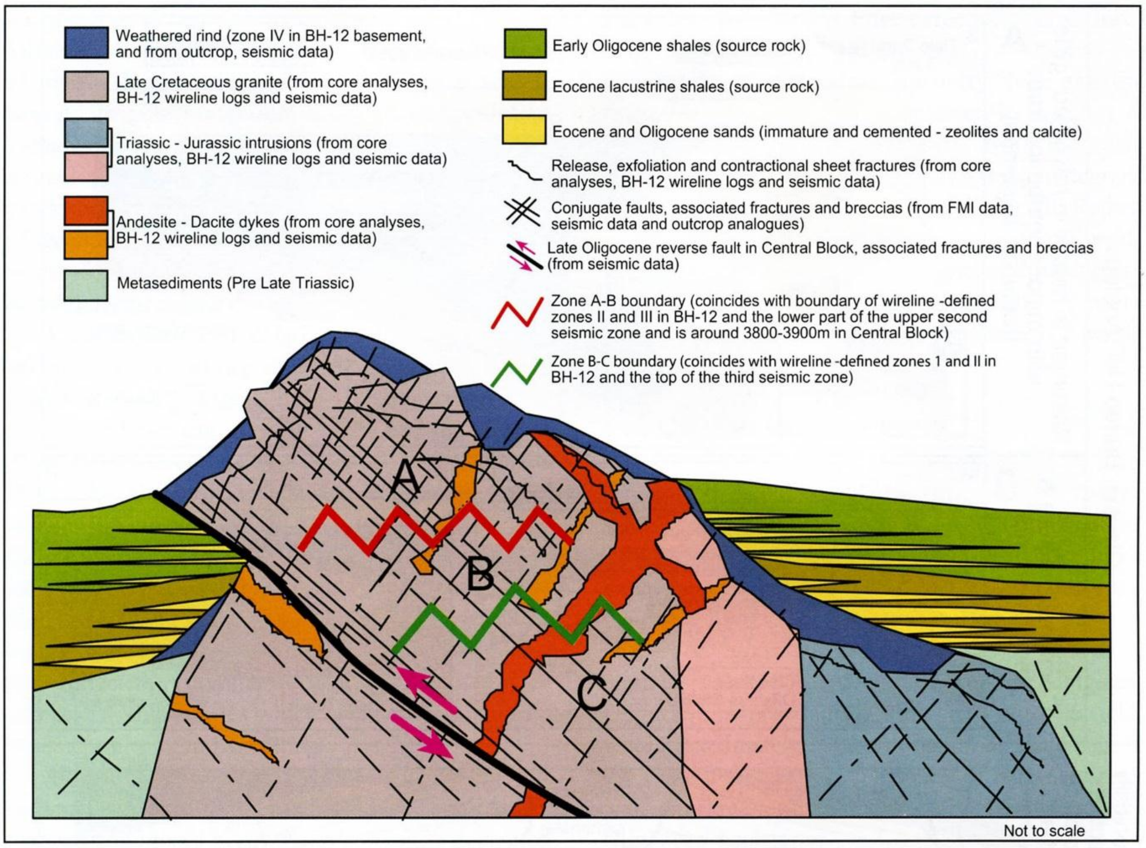


Fig. 10. Bach Ho inverted basement horst hosting White Tiger oil field offshore Vietnam, zones A+B, Cuu Long basin (Cuong & Warren, 2009).

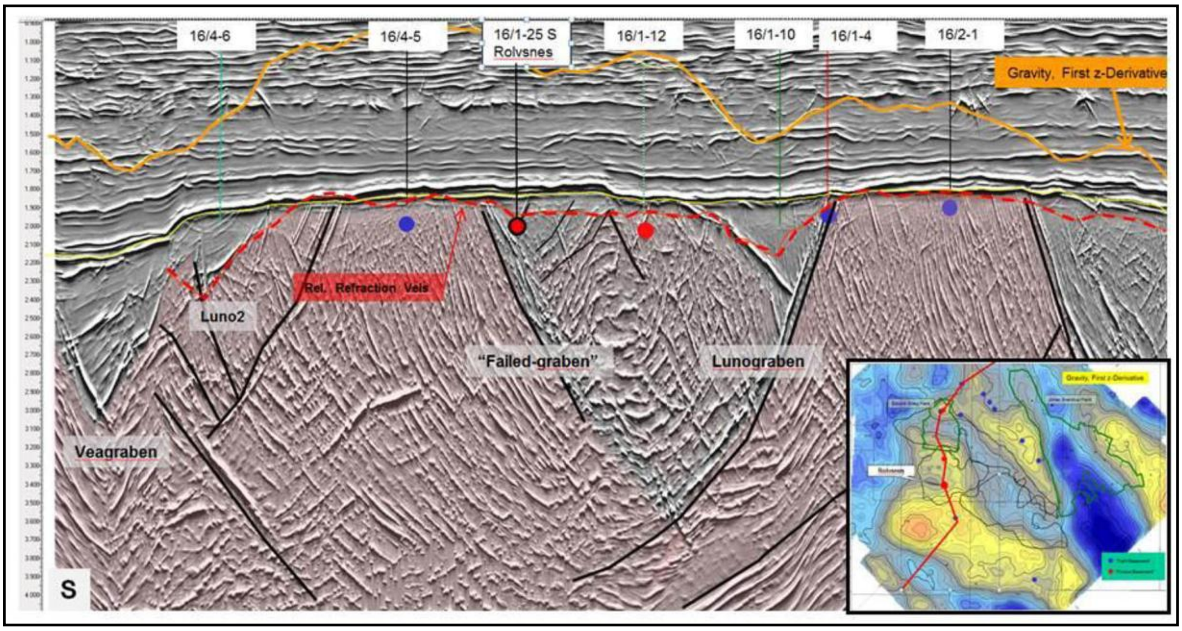


Fig. 11. Rolvsnes basement oil discovery (red circles) in the North Sea basin, offshore Norway (Lie et al. 2016). The basement reservoir is represented by WCC preserved from erosion at the Utsira paleo-high in a downthrown tectonic block.

Evidence of hydrothermal alteration of the Rona Ridge basement is explicitly noted in offset well 208/27-2 by the presence of minerals such as epidote, iron pyrite and chlorite. These minerals are commonly associated with vein fill within the Rona Ridge basement core. Hydrothermal products including epidote, opaque magnetite or goethite and sericite/talc are also recorded from sidewall cores recovered from the Lancaster Discovery. It is also worth noting that hydrocarbon stained calcite vein fill is ubiquitous in the Rona Ridge basement cores and is also described in basement cuttings and sidewall cores recovered from Lancaster. The field is developed by horizontal wells like in the neighboring Clair oil field where the production comes from the fractured basement and tight Devonian-Carboniferous sandstones.

The simplest model to fill basement reservoirs with hydrocarbons is based on assumption that hydrocarbons generated in the sedimentary source rocks have migrated/expelled into adjacent basement hills or horsts and entrapped by their secondary porosity and sealed by impermeable sediments or fault planes. This scenario usually works well for WCC basement reservoirs. For intra-basement fractured reservoirs in is necessary to apply eventual decompression episodes due to tectonic dilation or rapid uplift. For deep-seated basement hydrocarbon reservoirs, it is necessary to suppose an occurrence of internal intra-basement sources of hydrocarbons (for example metamorphic rocks with residual generation potential or crustal or even upper mantle sources for dry gas).

It is believed that the WCC basement level is the deepest and final frontier for oil and gas exploration. However, rather prolific pay zones have been encountered in the deep fractured subsoil of some fields in the West Siberia 1000 m below the top of the weathered Paleozoic basement (see general view of the petroleum-prone metasedimentary basement in Fig. 13). It is worth mentioning that prolific basement reservoirs are often spatially related to strike-slip zones where rock crushing and mylonitization expand to great depths (Kitchka, 1997).

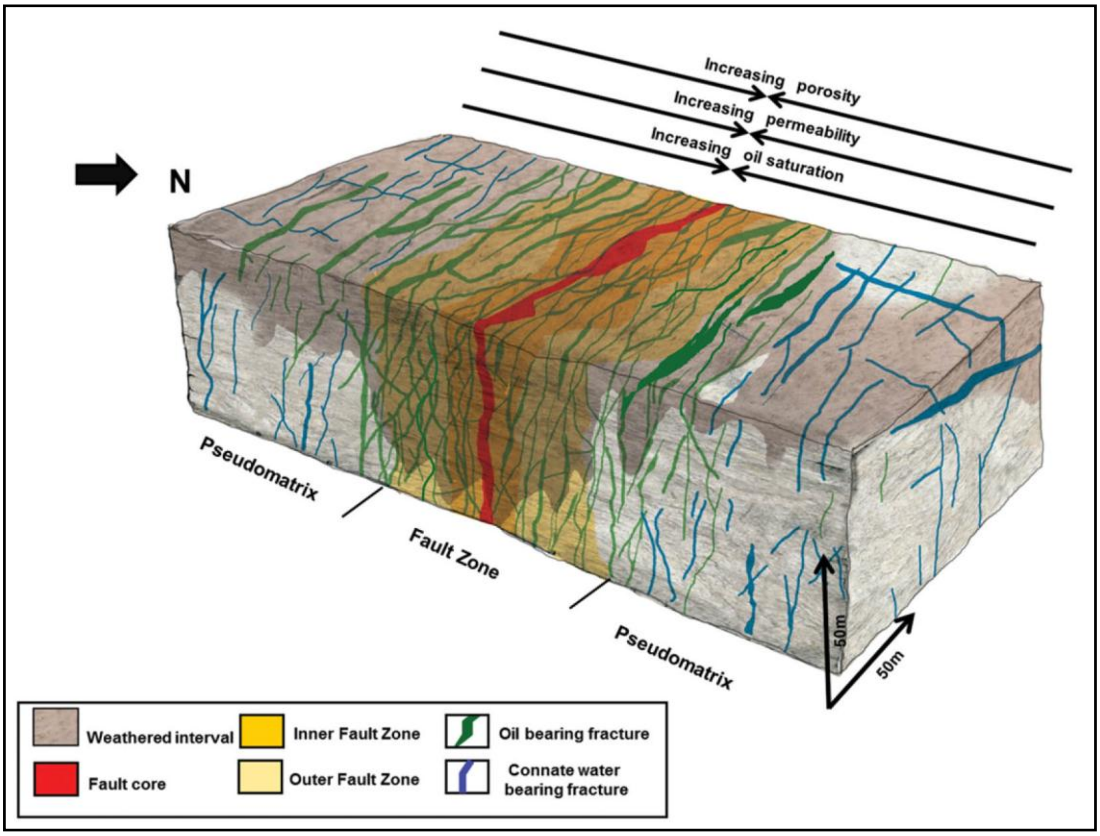


Fig. 12. Conceptual model of basement reservoir of the Lancaster field within its structural closure. The formation is divided into three facies: an Inner Fault Zone; an Outer Fault Zone (both of which combine to make up a Fault Zone) and Pseudomatrix zone. (Trice, 2014).

Briefly, three basic types of basement reservoirs are recognized in practice as following:

- weathered crystalline crust (WCC) resembling sedimentary reservoir rocks (disintegration & leaching zone of a full weathering profile) sealed by the non-reservoir rocks of kaolinization/hydromication zones
- fractured and hydrothermally altered reservoirs where secondary porosity is triggered by tectonic dilation and/or mineral transformations of the bedrock

vein-like (or fault-related) reservoirs

It is also worth to mention the existence of quite specific granite-wash reservoirs, though these are actually sedimentary tongues of granitoid debris attached to the eroded granitoid highs (e.g. Midcontinent basins in USA).

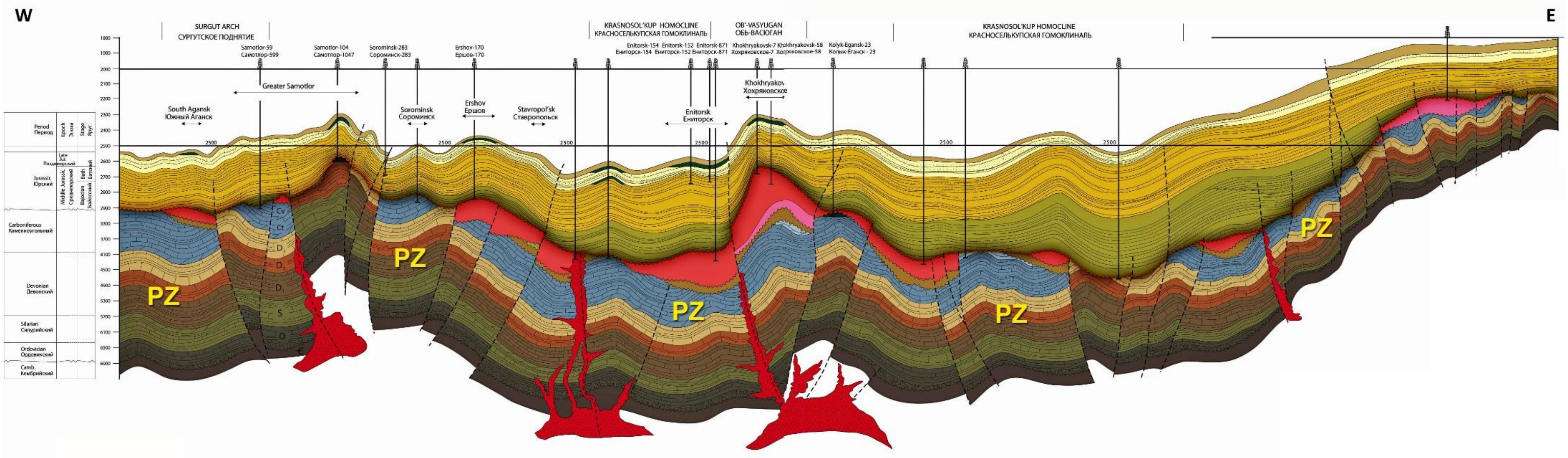


Fig. 13. An example of a transitive/acoustic/metasedimentary/volcanic basement, eastern part of the West Siberia mega-basin from the Greater Samotlor to Krasnoselkup homocline, with discoveries of oil and gas fields in the WCC (shading line), fractured and hydrothermally altered Paleozoic basement, after Kirda, (2005) and cited by Blackbourn (2014).

Hydrocarbon prospects of the crystalline basement reservoirs in Ukraine

General results

The commercial discoveries of oil and gas took place during the last decades in the weathered basement along buried flanks of the Late Devonian Dnieper-Donets paleorift which separates the Ukrainian Shield from the Voronezh Massif. These discoveries are of practical and fundamental importance to characterize the WCC and basement reservoirs. Since 1985 over dozen of oil and gas fields, such as Khukhra and Yuliivka, have been discovered along the Northern Flank of the Dnieper-Donets paleo-rift basin (DDB), NW Ukraine (Discoveries..., 2005), see Fig. 14. Most of them are related to the structural traps for quite continuous and 10-25 m thick reservoirs made up of the pre-Early Visean WCC disintegration zone developed in different Precambrian crystalline rocks of the faulted margin of the paleorift, though some pay zones occur much deeper (for example, 200 m below the top-basement of the fractured and mylonitized hornblendites in the Yuliivka field).

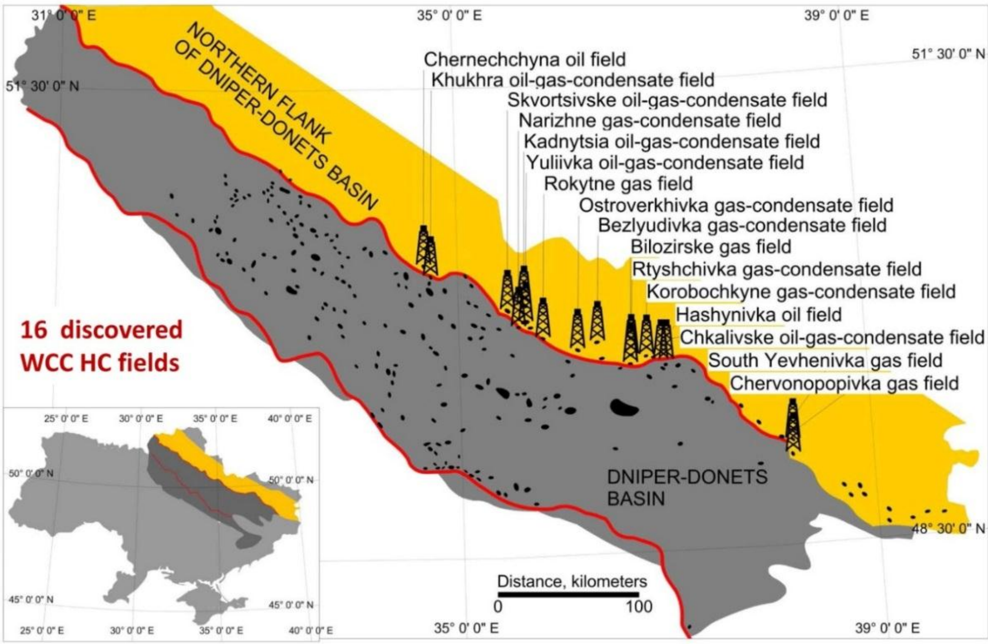


Fig. 14. Basement-reservoired HC fields discovered in the WCC of the Dnieper-Donets paleorift Northern Flank.

Dnieper-Donets paleorift zone

The Dnieper-Donets Rift or Pripyat-Dnieper-Donets Rift (also referred as a "paleorift" or "aulacogen") is an east-west running rift in the Sarmatian Craton that developed and was most active in the Paleozoic. The rift extends from the Caspian Basin in Russia through the Donbas region to northeastern Ukraine . The Dnieper-Donets basin (600 km long, 40 to 90 km wide and 2.5 to 12 and more km deep increasing along its strike) is almost entirely in Ukraine, and it is the principal producer of hydrocarbons in this country. The basin is bounded by the buried Voronezh Crystalline Massif of the Russian craton to the northeast and by the Ukrainian Crystalline Shield (UCS) to the southwest.The Dnieper-Donets paleorift was the site of Devonian magmatic activity that begun in the Late Frasnian and peaked during a Famennian mantle plume formation. Extensional tectonics was also most active during the Famennian with the last amagmatic extensional event occurring in the very beginning of Early Carboniferous. The basin is principally a Late Devonian rift that is overlain by a Carboniferous to Early Permian postrift sag. Southeastward, the Dnieper-Donets basin has a gradational boundary with the Donbas foldbelt, which is a structurally inverted and deformed part of the basin.

The sedimentary succession of the basin consists of four tectono-stratigraphic sequences. The prerift platform sequence includes Middle Devonian to lower Frasnian, mainly clastic rocks that were deposited in an extensive intracratonic basin. *The Upper Devonian synrift sequence* probably is as thick as 4–5 kilometers. It is composed of marine carbonate, clastic, and volcanic rocks and two salt formations, of Frasnian and Famennian age that are deformed into salt domes and plugs. *The postrift sag sequence consists* of Carboniferous and Lower Permian clastic marine and alluvial deltaic rocks that are as thick as 11 kilometers in the southeastern part of the basin. The Lower Permian interval includes a salt formation that is an important regional seal for oil and gas fields. The basin was affected by strong compression in Artinskian (Early Permian) time, when the southeastern areas were uplifted and deeply eroded and the Donbas foldbelt was formed. *The postrift platform sequence* includes Triassic through Tertiary rocks that were deposited in a shallow platform depression that extended far beyond the Dnieper-Donets basin boundaries.

A single total petroleum system encompassing the entire sedimentary succession is identified in the Dnieper-Donets basin. More than half of the reserves are in Lower Permian rocks below the salt seal. Most of the remaining reserves are in upper Visean-Serpukhovian (Lower Carboniferous) strata. Two identified source-rock intervals are the black anoxic shales and carbonates in the lower Visean and Devonian sections. However, additional source rocks are possibly present in the deep central area of the basin. The source rocks are in the gas-generation window over most of the basin area; consequently gas dominates over oil in the reserves (Ulmishek, 2001).

As it was afore-mentioned, the main stage of rifting occurred during the late Frasnian - Devonian end span (370 to 363 Ma). Over its entire extent the rift basement is faulted into blocks of various sizes with fault offsets in the range 100–2000 m, leading to a typical rift type depositional environment with high and laterally variable rates of subsidence, formation of grabens and half-grabens within the basin, and uplift and erosion of the rift shoulders (Stovba & Stephenson, 2003). Thus, two elevated areas - the northern and southern rift flanks (shoulders) were exposed to weathering and erosion. The former one seemed to be a higher because the DDB is a bit asymmetric with its depocenter shifted to the northern marginal fault of the basin, which is steeper than southern one.

The fundamental studies and exploration data testify that the Paleozoic WCCs of 100-200 m and more thickness controls occurrences of basement hydrocarbon accumulations at the Northern Flank of the DDB. One of the principal questions is to date the age of its WCCs more precisely. From one hand, the weathered Precambrian rocks within the Northern flank is covered with the Lower Carboniferous sedimentary rocks aged from Tournaisian to middle Early Visean depending on the distance of a basement block from the marginal fault and its elevation. So the simplest answer about the age of WCC there is pre-Carboniferous in general and early Carboniferous (cumulated during several interrupting epochs) in restricted sense because of a rather tectonically quiet regime and tropical climate on the East European Platform that time. However, on the other hand, there are data supposing at least twofold larger depth to the weathering paleo-front at the Northern Flank (i.e. WCC thickness) in some localities and areas. It looks like the effect of older Late Devonian and pre-Middle Devonian weathering is preserved from erosion and overprinting by early Carboniferous weathering epoch. In the UCS the effect of the Paleozoic and earlier weathering epochs is completely eliminated by a deep erosional cut and erased by the powerful Mesozoic weathering.

It is necessary to take into account that the main faults within the Northern flank is of Devonian age being formed during the rifting stage and later re-activated during the sag stage of thermal subsidence of the basin and its shoulders (Stovba & Maystrenko, 2001). The seismic data allow speculating about the relics of Late Devonian half-grabens preserved sporadically from erosional cut within the Northern Flank. There is consequently a possibility to consider a model of two-level WCC cumulating during the Early Carboniferous and older weathered crust. The peak of late Devonian elevation of rift shoulders has produced a weathered crust with a larger depth to the disintegration zone (basal platform, see Chapter 4) than during the later and weaker early Carboniferous weathering that produced a new basal platform because the new equilibrium erosional surface controlling basinward groundwater discharge moved upwards.

The enigmatic seismic horizon, named “VII” (there is a particular order of indexation for CDP reflection horizons in the DDB applying Roman numerals, for example “V” with sub-indices - like Vb_2 for the the Bashkirian carbonates - for the key reflectors in the Carboniferous sequence, “VI” for Devonian ones) has been recognized and mapped in the Precambrian basement of the Northern Flank and played an important role in hydrocarbon exploration in this frontier area (Fig. 15). The matter is that the last steady reflector, namely $V\text{в}_2$, which is attributed to the base of Upper Visean stage sediments, is located too far from the top of the true basement surface and cannot be properly used for exploration of the basement reservoirs. On the other hand, the VIIth horizon is located close to the Precambrian basement surface in only a few places and completely absent in some areas. This is a unique feature of the DDB flanks that mimics the true basement/sedimentary cover interface and nothing similar is reported from other petroleum provinces in the world as far as we know. Typically, it is traced 80-100 m and more below the sedimentary cover base; therefore it was used to explore the basement reservoirs in the area of the first discoveries, namely the Khukhra-Chernetchyna and Yuliivka hydrocarbon fields and in the central and eastern parts of the Northern Flank.

Based on the results of the mapping program it was found that steady reflections near the top of the Precambrian basement (VII horizon or VII group/package of horizons) is recognized at a depth of 80-200 m (down to 450 m in some places) beneath its top generally plunging to the basin depocenter. The origin of VII reflector is still debatable but most common explanation is to link this feature to the bottom of the weathered crystalline crust or so-called "decompaction" zone.

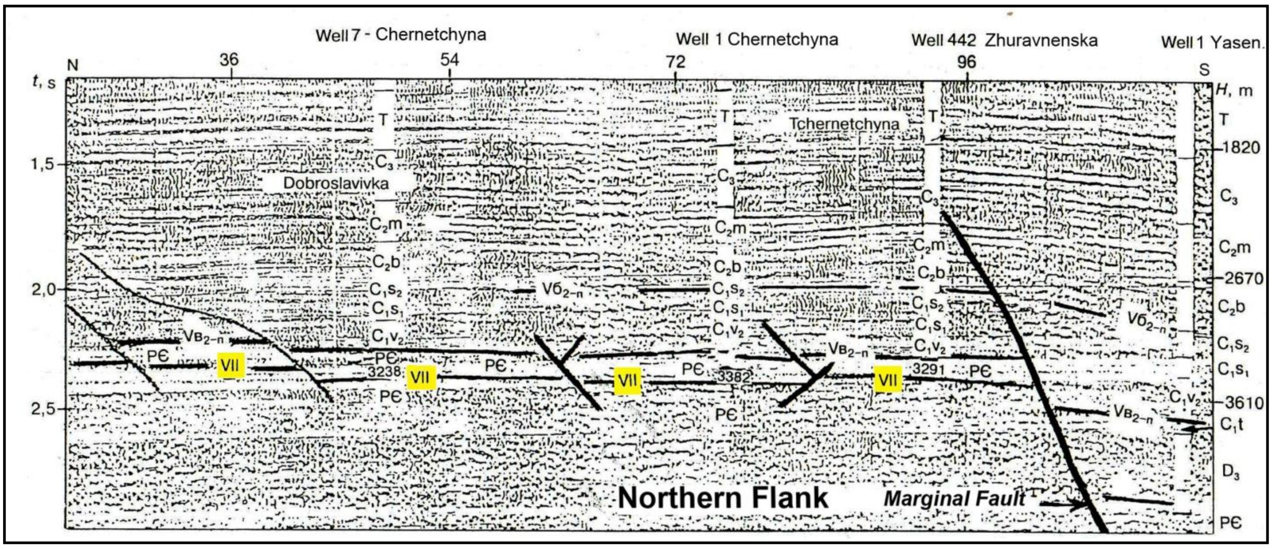


Fig. 15. Seismic line through the exploration wells Chertnetchyna-1 and Yasenove-1 in the Okhtyrka basement promontory at the Northern Flank to the DDB (Discoveries…, 2005). The VIIth seismic horizon is highlighted in yellow.

The reflector is not artificial and does not represent some kind of multiples because the original reflector between the weathered basement and the basal sedimentary sequence is absent due to a gradual density and velocity transition from sedimentary to crystalline rocks and irregular and rugged character of the buried saprock relief with seismically invisible corestones. It was found that this reflector crosses internal basement structures of different composition thus resembling in that way the bottom-simulating reflector characteristic of a gas hydrate base in offshore settings.

Hence, the seismic horizon mapped by reflection studies at the flanks of the Dnieper-Donets basin that mimics the true basement / sedimentary cover interface and gradually lowering basinward can be interpreted as the surface of deep weathering paleo-front or so-called basal platform (aquitard for paleo-groundwater flow) where precipitation of some soluble minerals of the WCC have occurred (compare with Fig. 6).

The axonometric view of the map built on the VII horizon in the area of Okhtyrka basement promontory that was formed by the steep and high-amplitude Northern Marginal fault and the transversal Verkhivtsevo-Lgov deep fault is shown in Fig. 16. The buried ridge of the weathered basement of Khukra-Chernetchyna oil prospects are shown in yellow, the surface of VII horizon is in white, the top of Frasnian salt controlling the structures in the graben is shown light green, and the basement fault planes are in red.

It is quite understandable that updip horizontal migration of hydrocarbons from Devonian and Carboniferous reservoirs towards the Northern Flank could use permeable rocks of the WCC (zone of rock disintegration and leaching) for further redistribution and filling the traps in fractured and weathered basement rocks and sedimentary reservoirs of Visean, Serpukhovian and Bashkirian age.

Some typical hydrocarbon discoveries and exploration results.

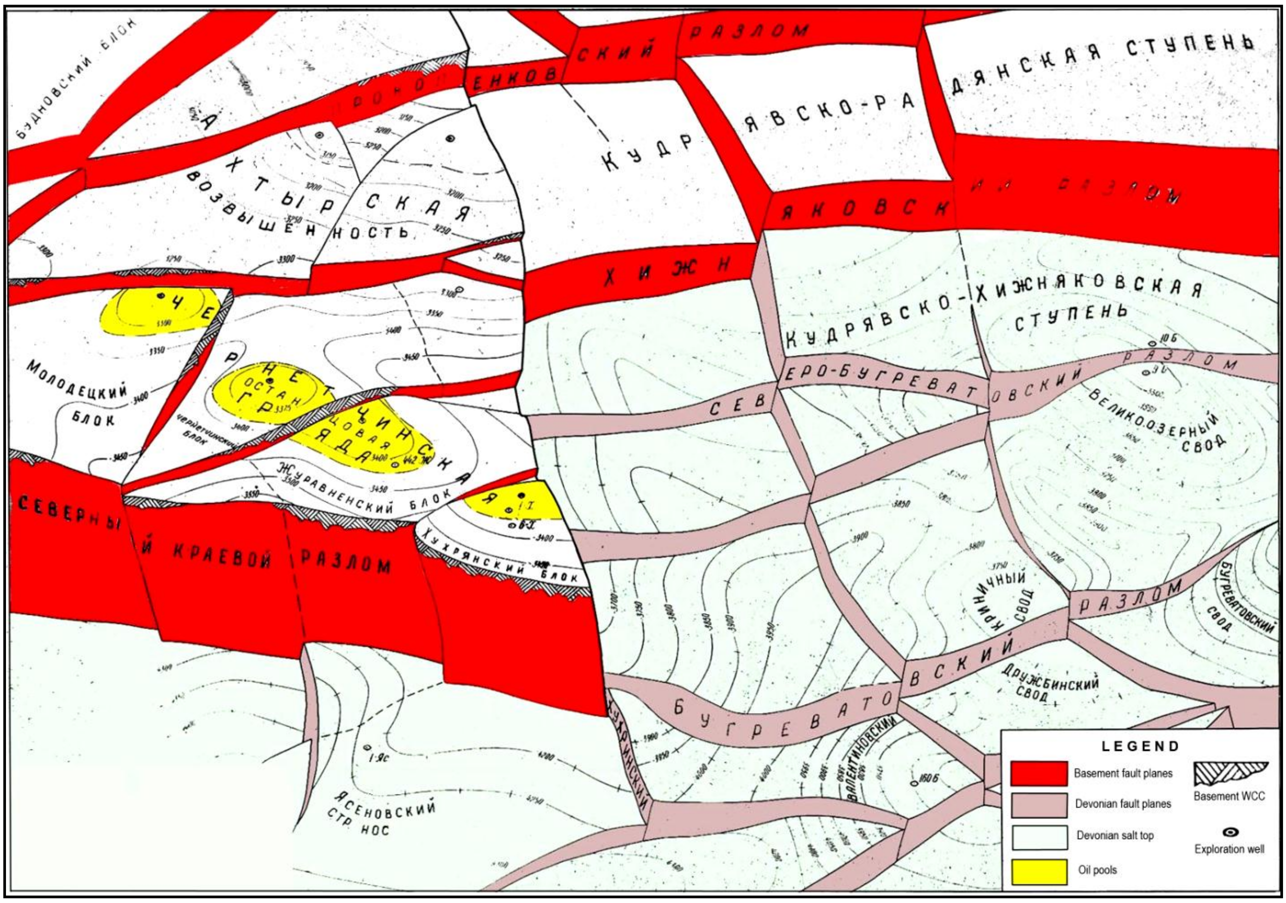


Fig. 16. Perspective view of the Okhtyrka promontory of the Precambrian basement at the conjugation of the Marginal Fault of the Dnieper paleorift Northern Flank and Verkhivtsevo-Lgov transversal deep fault, compiled by A.A. Kitchka, 1987 (Demidenok et al., 1987). Khukhra-Chernetchyna erosional ridge with WCC oil pools (shown in yellow) at its axis striking NNW.

The schematic cross-section of the Khukhra and Chernetchyna oil fields with well testing results is shown in Fig. 17 and demonstrates that upper kaolinization zone of the WCC makes the seal for oil accumulation in the basement. To map the basement decompaction zone (i.e. WCC) the CDP seismic data were processed using a pseudosonic logging based on the well data set acquired in the Yuliivka-2 well that made a commercial discovery in the Precambrian basement within the Yuliivka prospect.

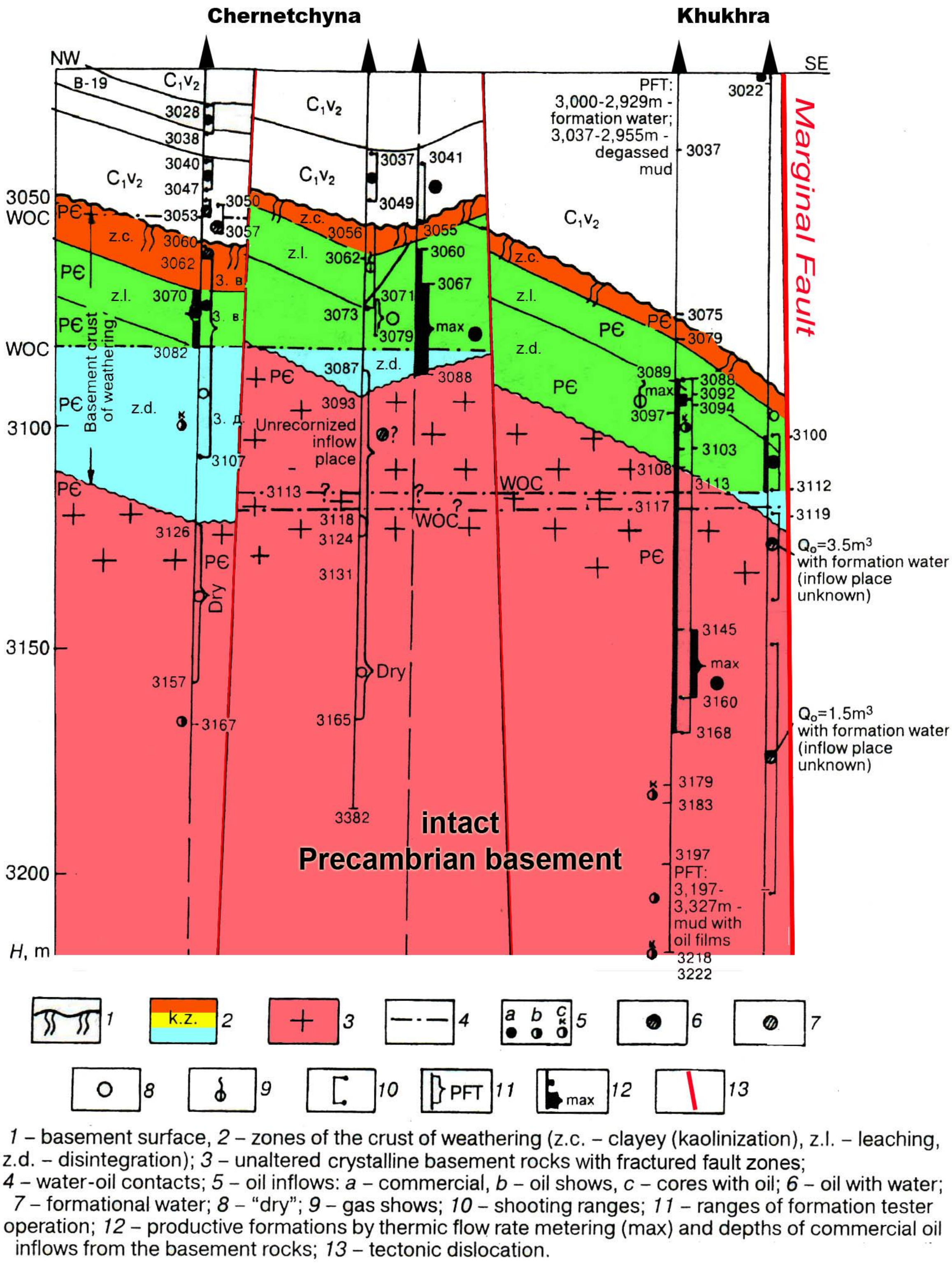


Fig. 17. Geological cross-section of Chernetchyna and Khukhra oil fields with testing results (oil pools in the Visean reservoirs are not shown), Discoveries…, 2005.

Flow rate thermal metering has recognized in several of the pay zones in the crystalline basement rocks revealed by well Yuliivka-2.

The parameters of the gas from the pay zone of 3636-3800 m depth is as follows: the hydrocarbon gases make 96.54 % of its production including methane (87.5 %), ethane (5.56 %), propane (1.85%), butane – (0.04%), isobutane (0.04 %), isopentane (0.02 %), hexane and higher gases (0.81 %) in total. Also the gas contains non-hydrocarbon gases: 3.14% of nitrogen; 0.40% of CO_2, 0.000059% of H_2S, and 0.23% of helium (that is 5 times greater than its conventional commercial concentration). Such a composition is characteristic of gas condensate accumulations.

The cross-section of the Yuliivka horst is shown in Fig. 18. It can be seen that the VII horizon is displaced by the reverse fault controlling the trap in the weathered basement. The higher concentration of gas condensate in the bottom of the basement accumulation may reflect a partial degassing and formation pressure drop due to migration of hydrocarbons upward along faults and formation new pools in the sedimentary cover.

In the frame of state-funded "Comprehensive Program for Exploring Oil and Gas Potential of the Crystalline Basement at the Northern Flank of Dnieper-Donets Basin in 1989-1995 the aforesaid data were applied to be built the series of structural maps along the VII horizon. It was traced at a depth of 100-200 m beneath the basement top and related to decompacted basement zones. (Demianchuk et al., 1989).

A wide range of exploration wells was drilled employing this information and a series of oil and gas discoveries was made in the crystalline basement as well as in the overlying sedimentary cover.

It is necessary to mention that Precambrian basement of the Northern Flank is composed of heterochronous and heterogeneous (of different age of consolidation and petrology) crustal blocks (Kolosovskaya, 1994).

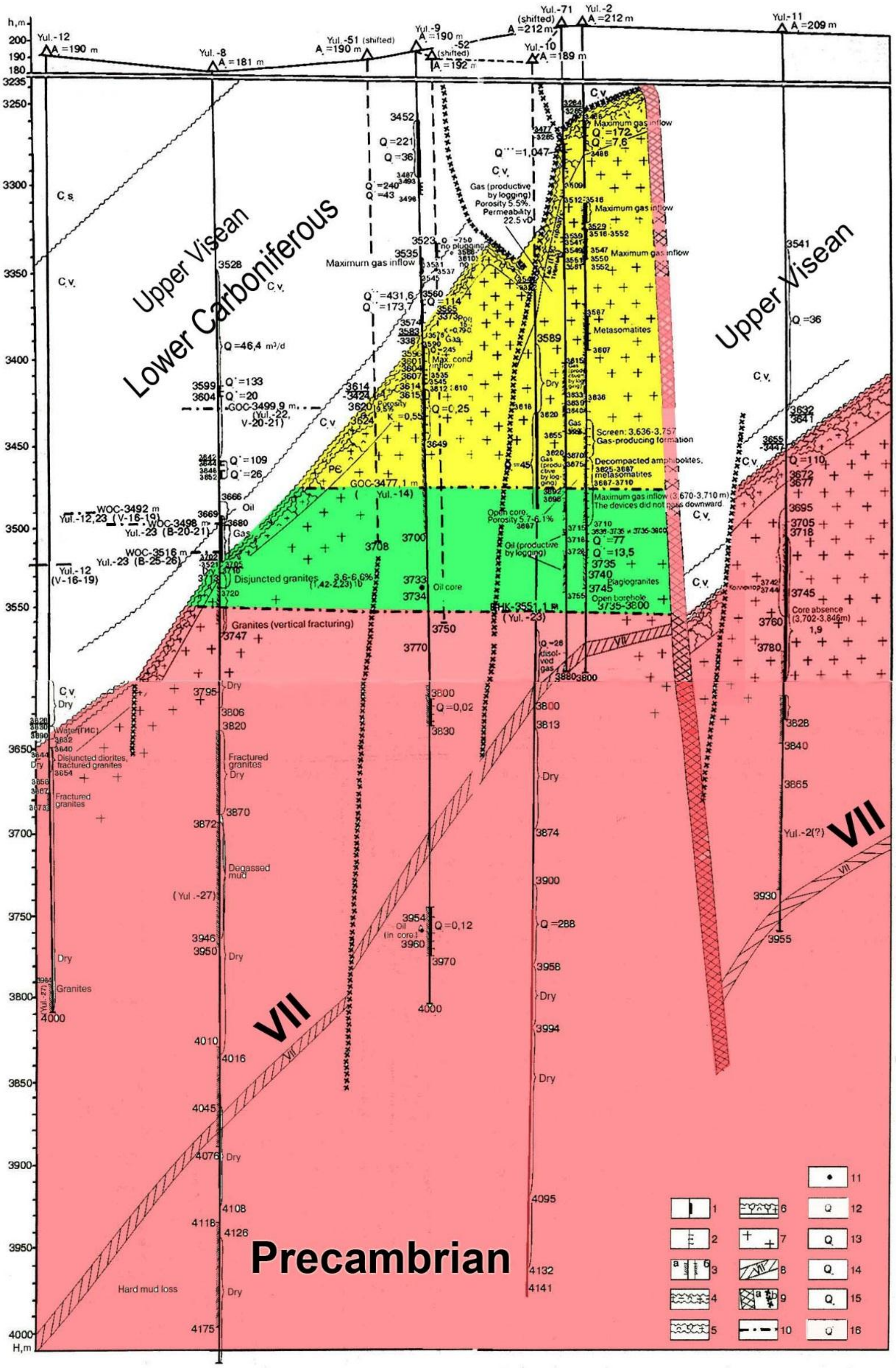


Fig. 18. Geological cross-section of the Yuliivka oil-gas-condensate field with well testing results. The gas-saturated basement reservoir is shown in yellow, while oil saturated zone (upon cores) is shown in green, based on the testing results and interpretation of well-logging data. VII – reflection CDP horizon below the WCC/sedimentary cover interface, possible basal platform of the weathering paleo-

front. The vertical scale is exaggerated. Hydrocarbon pools in the sedimentary cover are not shown. The legend is the same as for Fig. 17 (Discoveries…, 2005).

Their petrology have influenced formation of WCCs of different type and secondary processes of rock transformations like metasomatosis that developed additional porosity of slightly weathered but heavily fractured basement rock in the disintegration and leaching zone of the WCC.

An example of different basement rock types is shown in Fig. 19.

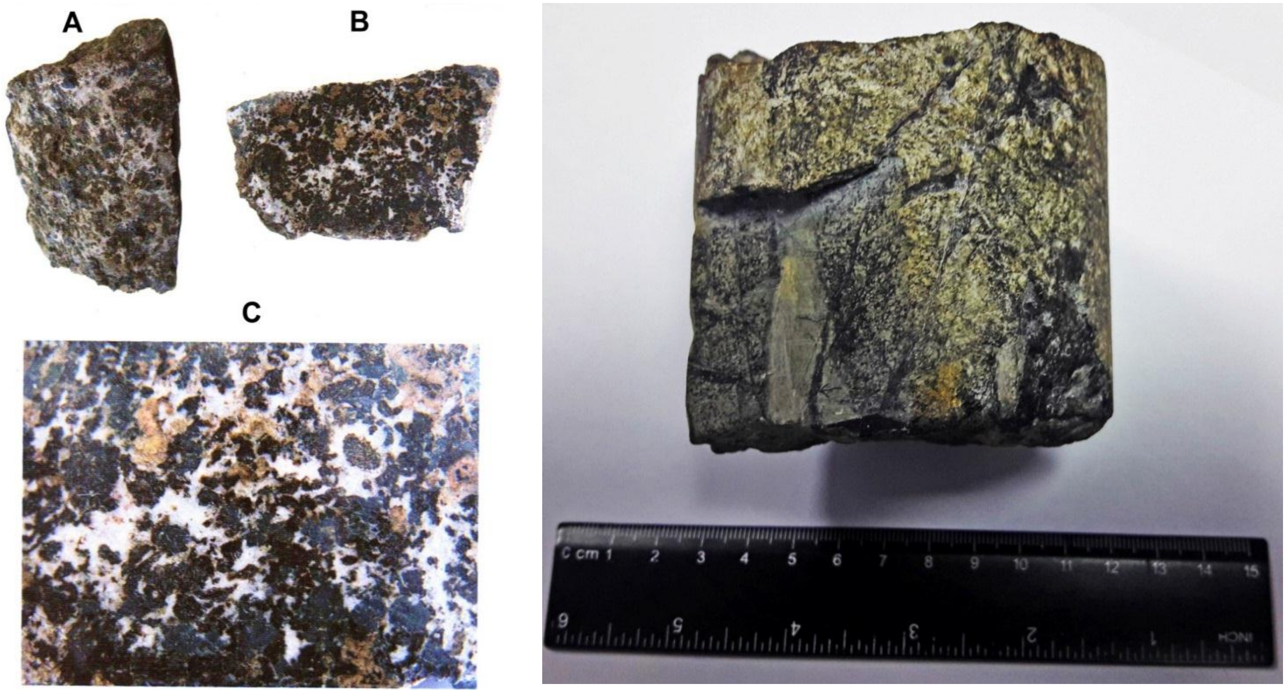


Fig. 19. Basement core samples: Yuliivka-2 well, core sample #25 (depth interval 3772–3776 m) - metasomatites in a plagioclase amphibolite (left) by Lebed & Rakovska (2014), and Chernetchyna-1 well - seprentinized ultrabasites (right).

The permeable fractured and hydrothermally altered zones in the crystalline basement of the Northern Flank are revealed by many exploration wells and some of them have produced commercial flow rates of gas while initial testing, Fig. 20.

To correlate porous intervals in the weathered basement from well to well the researchers from NADRA Group have elaborated an approach helping to distinguish the type of reservoir depending on the petrology of the primary rock using gamma-ray logging (Fig. 21). Decreasing of gamma-ray intensity of the rocks at the top of crystalline basement is caused by leaching of U and Th from the upper parts of the WCC (Kolisnichenko & Kashuba, 2005).

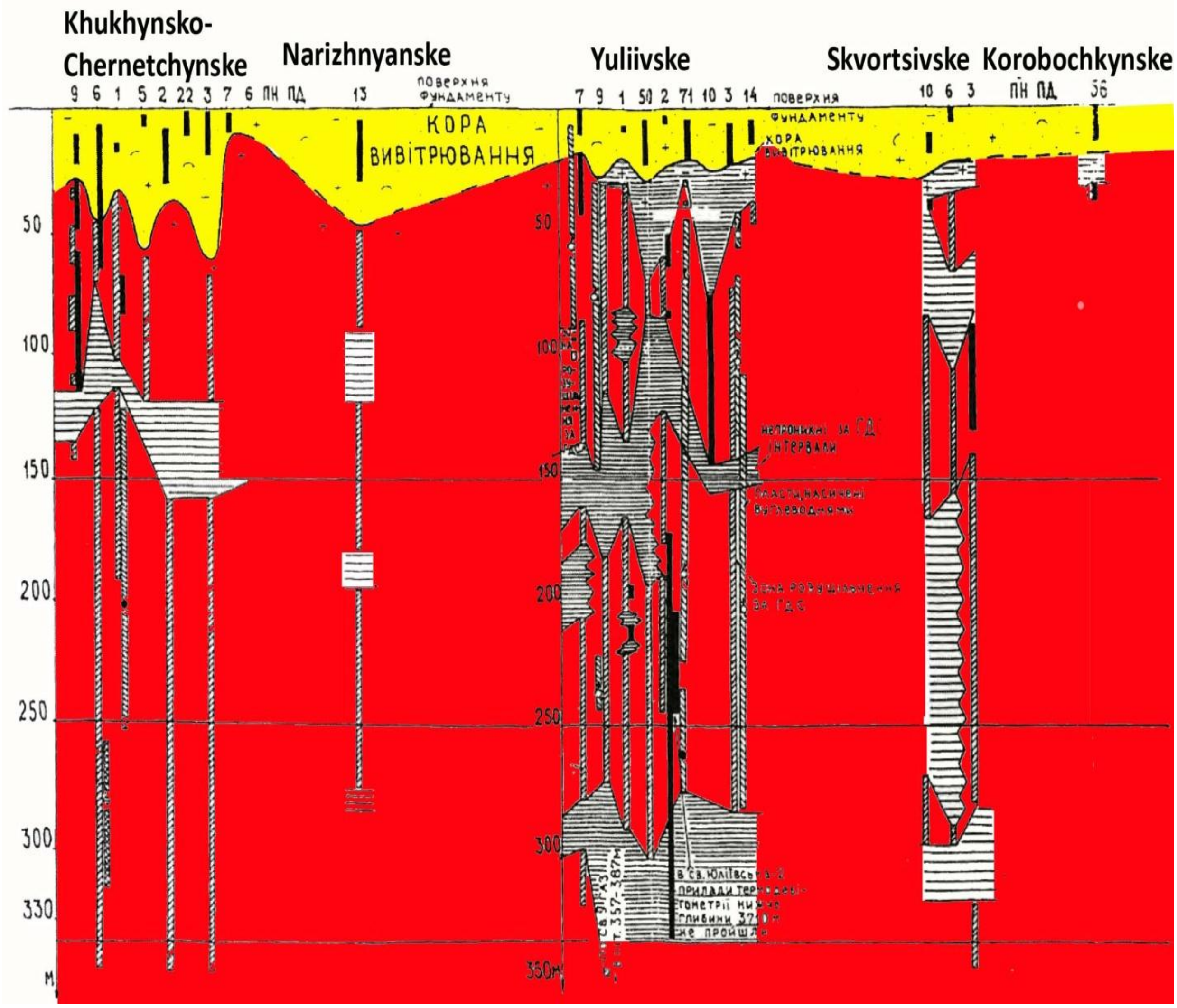


Fig. 20. Hydrocarbon WCC reservoir (yellow) and permeable (water of hydrocarbons) fractured zones (shaded) in the Precambrian basement of the DDB Northern Flank, after Kolos, (2003) and cited by Vysochansky (2013).

The well-to-well correlation of different WCC zones along the Northern Flank from west to east is shown in Fig. 22. It is clearly seen from that chart that in some localities the upper zones of WCC are eroded in some localities and the thickness of the disintegration zone can vary within a very broad range. A slightly different correlation chart is compiled by well-log data available from SE Naukanaftogaz that features only smectitization zone of 5-7 to 25-30 m thick that is quite continuous along the Northern Flank of the DDB (Fig. 23).

Applied assessment methodology

A sophisticated new technique developed at *DEPROIL Ltd* applying a joint inversion of seismic and gravity data and adjusted by other geological and production data allows a confident delineation of prospective basement reservoirs and build a geodensity model of a WCC reservoir. It also was found that rocks of the second zone of (hydromicaceous) and sometimes material of the third zone of WCC profile (residual kaolins and ochers) represent an impermeable formation of up to 10-30 m thick for effective sealing of commercial hydrocarbon accumulations in the weathered, fractured and altered basement reservoirs of 17-36% porosity in the Northern Flank of DDB.

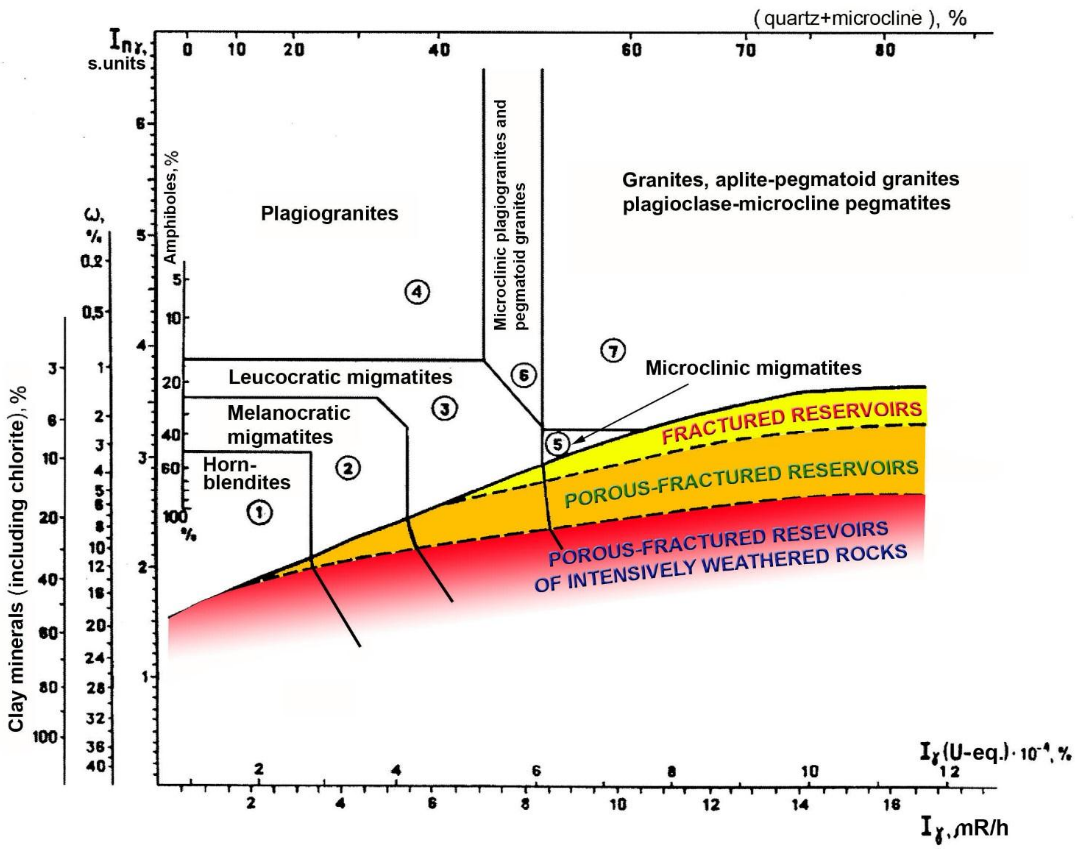


Fig. 21. Discrimination of WCC reservoir type rocks using radioactive well logging (Kolisnichenko & Kashuba, 2005).

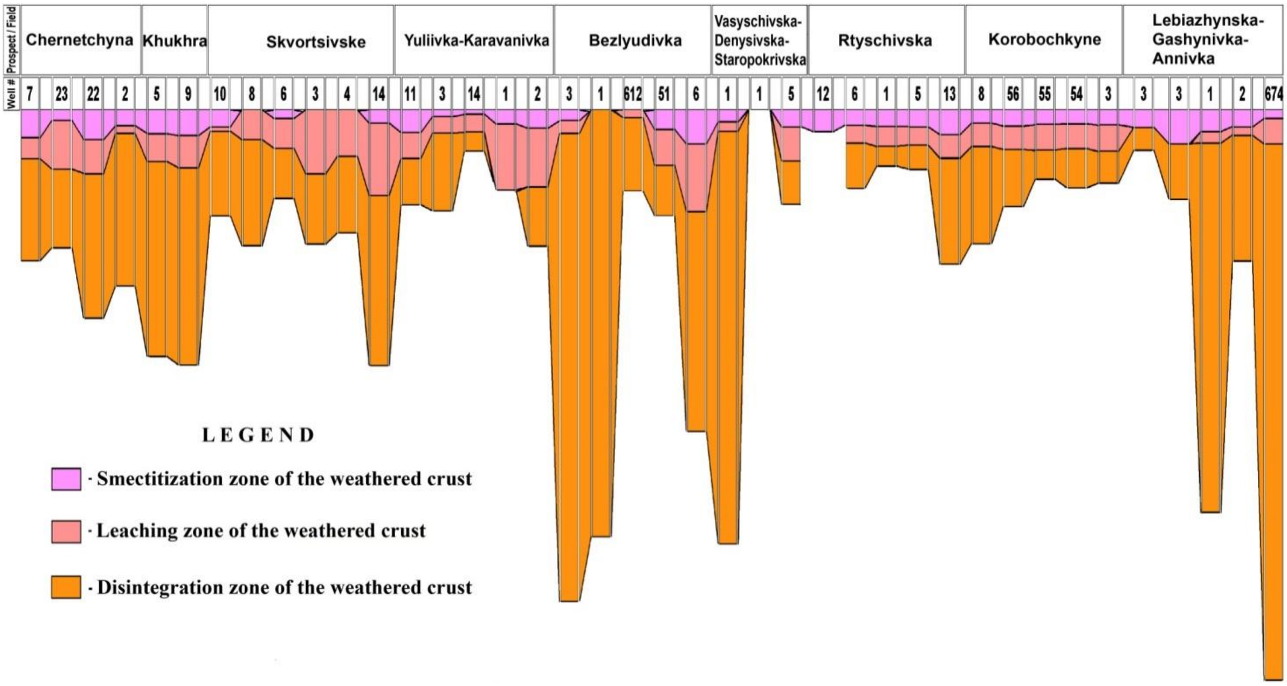


Fig. 22. West-east WCC correlation chart along the DDB Northern Flank (Kosachenko et al., 2008).

The complex structure and geometry of reservoirs in crystalline basement rocks make exploration extremely challenging, and require supplementing of seismic and well information with additional geophysical data in order to reduce exploration risks. The proper technologies of integrated geophysical interpretation play the key role, allowing the fully benefit from available data set by applying joint geophysical inversion to build a single and integrated 3D model combining all available geological and geophysical information.

In Ukraine this kind of approach is implemented in the Technology of Integral Interpretation of Seismic, Well and Gravity Data for Oil & Gas Exploration (Petrovskyy O. P., 2003; Petrovskyy O. P., 2005), which is based on the methods of forward and inverse geophysical modeling. Specific features of the Technology providing high geological efficiency applicably for oil and gas exploration are the following:

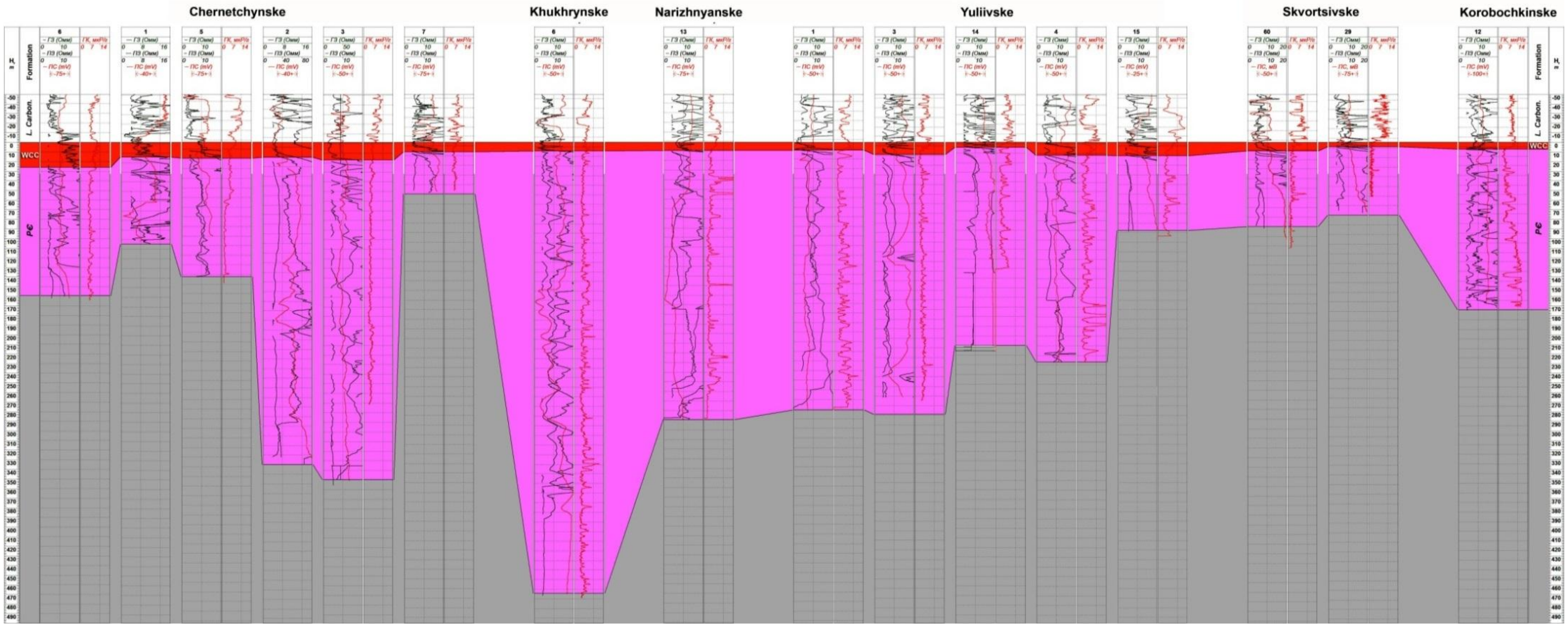


Fig. 23. West-east correlation chart for the WCC smectitization zone along the DDB Northern Flank.

- Gravity data are inverted together with seismic, well, petrophysical and geological information.
- Inversion based on Tikhonov's regularization proved to provide stable, but unmeaningful solutions because of the exotic properties of the harmonic function for the natural uniqueness class of linear inverse solution. Thus, in the applied technology the inverse problem was redefined because the inversion is not only constrained by the prior information, but is driven by it. In this way additional geological information is used as a guiding rule to select the single geologically meaningful model from the space of possible solutions, corresponded to the observed gravity field.
- The 3D density model is built for the full depth range from the surface to basement or Moho for basin scale.
- The 3D structural and / or property inversion is run depending on geology and uncertainty of geophysical data.
- Real densities are used to build the 3D density model.
- Inversion is quantitatively parameterized and constrained through quantifying uncertainties, variability, constraints for all the geological sequence, involving structure by seismic, petrophysics, well-logging data, taking into account a provisional layering according to expected stratigraphy.
- Inversion is run for the full observed gravity field.

Case study: Gashynivka oil field

One of the successful applications of the above technology is the development of Gashynivka oil field. It is located in the Shevchenkivsky District of the Kharkiv Oblast and situated within the south-eastern part of the Northern Flank of the DDB. It is confined to the tectonically screened uplifted block. Due to the intense basement faulting a thick weathered crust (up to 87 meters) was formed, representing a potential trap for hydrocarbon accumulations. The first wildcat well Gashynivka-1 was drilled in 2000 and discovered the oil pool in the basement below the lowermost clear seismic reflector confined to the base of the sedimentary cover. As previously mentioned, the basement is usually poorly depicted by seismic data along the Northern Flank, thus making it impossible to determine the reservoir extension from the first discovery oil well Gashynivka-1. Therefore, the integrated geo-modeling technique of joint seismic, well log and gravity data inversion was applied to map reservoirs in WCC and disintegration zones in the basement and to predict the extension of oil pool.

The following initial geological and geophysical data were available for the interpretation:

- 2D seismic sections T_0;
- gravity field (500 m spacing between gravity stations, accuracy 0.07 – 0.15 mGal);
- velocity information;
- generalized data about rock density by core analysis of wells from the Gashynivka prospect and in nearby areas;
- well logging data for three wells.

For the Gashynivka prospect the technology of joint inversion of seismic and gravity data includes the following stages:

1. Iterative refinement of the structural model, based on the solution of the inverse kinematic structural problem with consideration of wave refraction on all intermediate boundaries of the seismic model.

2. Iterative inverse structural problem solution of gravity.

3. Structural inversion for seismic and gravity fields is run applying the fixed formation velocities and densities, producing geological macro-model that fit with predetermined accuracy to registered travel times by seismic data and to observed gravity field.

4. Prediction of heterogeneous distribution of density properties on the basis of gravity linear inversion aiming full fit between measured and calculated gravity fields.

Detailed analysis of the obtained density model has revealed the presence of a low-density zone in the proximity of well Gashynivka-1 at the depth from -3285 to -3585 m, which corresponds to the upper part of the crystalline Archean-Proterozoic basement. The area of the lowest density includes well Gashynivka-1 and extends to the north, thus outlining the area of the oil pool in the weathered crust. Location of planned new appraisal wells 2, 3, 4 to the east and west of well #1 was characterized as a denser one compared to the producing well in the inverted density model. As a result we interpreted these areas to either have poor reservoir properties or be water-saturated. In addition, WCC reservoir discovered by well #1 was interpreted to be lithologically screened and not controlled by the structural closure. Posterior appraisal drilling fully proved the validity of the density model in weathered crystalline rocks. Wells 2 and 4 were dry, and testing of well 3 proved water saturation of the WCC reservoir Fig. 24.

Later to the south-west from the Gashynivka structure, new exploration well Chkaliv-1 was drilled within the isolated low-density area (Fig. 24). The well has discovered the new field with oil and gas pools in the weathered basement crust and Lower Carboniferous reservoirs. Following seismic study has proved that Chkaliv structure is an isolated block, separated from the Gashynivka field with the discordant fault. Separate position of two oil pools within the structure is clearly seen in the density model by higher-density arch-zone separating low-density anomalies. Thus, density model of WCC reservoirs within the Gashynivka field built in the result of integral interpretation of seismic, well and gravity data has been proved by posterior drilling of the four wells.

Conclusions

1. Basement reservoirs including WCCs are the final frontier for hydrocarbon exploration in sedimentary basins and can host very prolific oil and gas fields.
2. Hundreds of commercial HC fields are discovered in the weathered, fractured, and hydrothermally altered basement reservoirs to the date but the techniques to recognize basement reservoirs should be improved.

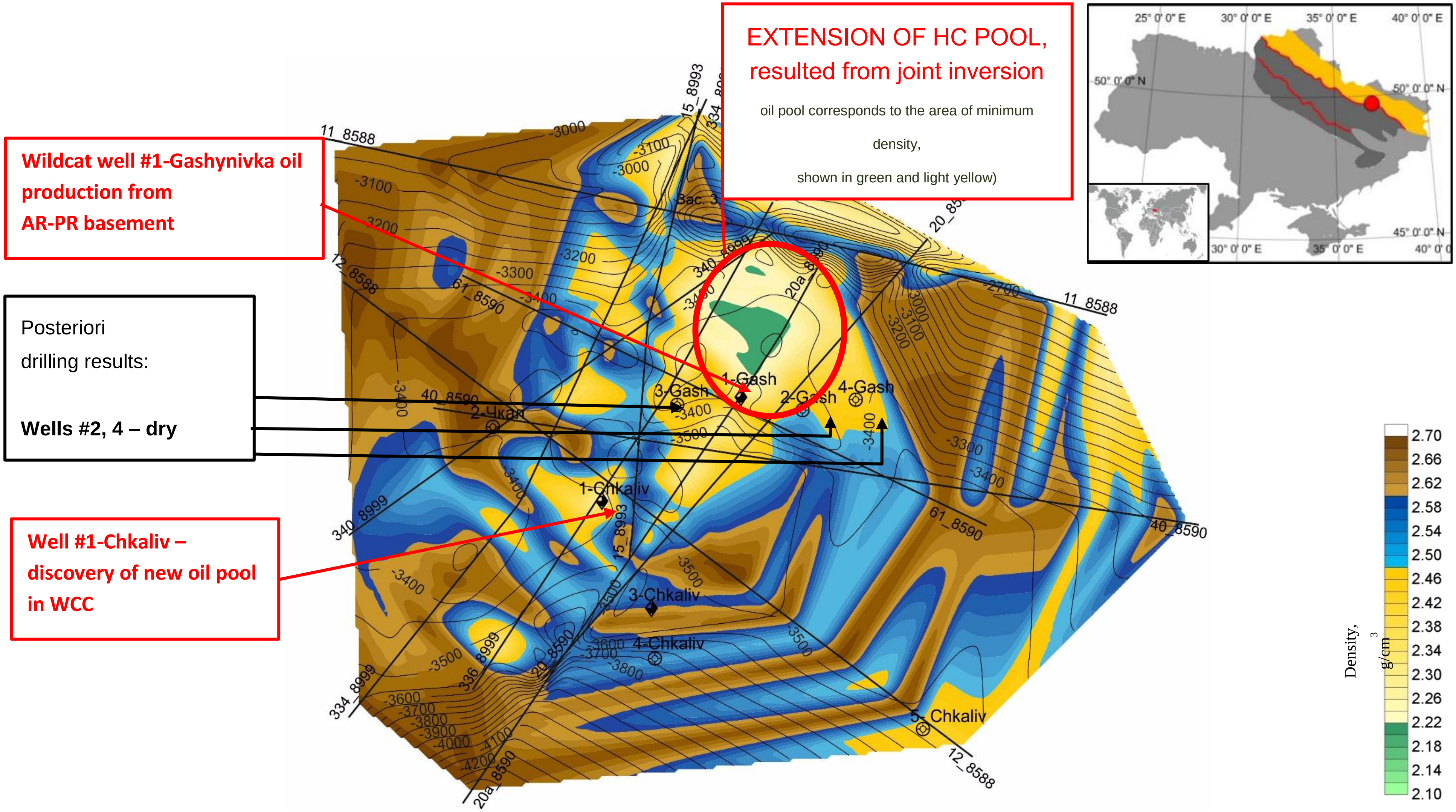


Fig. 24. Gashynivka field. Density of the weathered crust by joint seismic, well and gravity inversion (interpretation based on 2D data). Local areas of the lowest density indicate hydrocarbon-saturated reservoirs.

3. The UCS and its slopes is one of the best world's geological terrains to study development of WCC profiles and related deposits of useful minerals and basement hydrocarbon accumulations.Middle/Late Devonian to Pre-Early Carboniferous WCCs controls occurrences of basement hydrocarbon accumulations in the Northern Flank of DDB.
4. Neither interface between the crystalline basement and sedimentary cover nor upper zones of the WCC profile are properly illuminated by seismic methods.
5. The seismic horizon mapped by reflection and refraction studies in the flanks of the Dnieper-Donets basin that mimics the true basement / sedimentary cover interface and lowering basinward can be interpreted as the surface of deep weathering paleo-front or so-called basal platform (aquitard for paleo-groundwater flow) where precipitation of some soluble minerals of the WCC have occurred.
6. Magnitude of gravity anomalies associated with WCC reservoirs and disintegration zones in the basement are enough intensive to be used for their mapping via joint inversion of seismic and gravity data.

Acknowledgements

This study was partly carried out within the framework of Phase III of "Crustal Onshore-Offshore Correlation Project" that was funded by the Geological Survey of Norway (NGU) under the contract #20150901.

References

1. Areshev E.G., Dong T.L., San N.T. & Schnip O.A. 1992. Reservoirs in fractured basement on the continental shelf of Southern Vietnam. Jour. of Petroleum Geology 15.P. 451-464.
2. Blackbourn G. 2014. Petroleum geology of the Pre-Jurassic. ROGTECH Magazine. 6. P. 58-69.
3. Cuong T.X. & Warren J.K. 2009. Bach Ho field, a fractured granitic basement reservoir, Cuu Long Basin, offshore SE Vietnam: A "buried-hill" play. Jour. of Petroleum Geology 32(2), P. 29-155.
4. Demianchuk V.G., Krot V.V., Klochko V.P. et al. 1989. Search for hydrocarbons in the crystalline basement rocks in the Northern Flank of the Dnieper-Donets depression. Comprehensive Program for Exploring Oil and Gas Potential of the Crystalline Basement in the Northern Flank of Dnieper-Donets Basin in 1989-1995. Preprint IGS NAS Ukraine P. 89-11. (in Russian)

5. Demidenok L.G. et al. 1987. Basement exploration program for the Ochtyrka petroleum-producing district. Report on Theme # 86.01.87, UkrGIPRONIIneft Res. Inst., USSR Ministry of Petroleum Industry. Kiev. (in Ukrainian)
6. Discoveries of commercial petroleum accumulations in the Precambrian basement of the Dnieper-Donets basin. 2005. In: Petroleum in the basement of sedimentary basins. Krayushkin V.A. (ed.). Kiev. *EKMO Publ.* P. 69-97.
7. Entin V.A., Gintov O.B., Mychak S.V. & Yushin A.A. 2015. The structure of the Moldovsky iron ore deposit (The Ukrainian Shield) according to geological-geophysical data and its possible endogenous nature. Geophysical Jour. no. 4. vol. 37. P. 3-18 (in Russian)
8. Gavrilov V.P., Gulev V.L., Kireev F.A. 2010. Granitoid reservoirs and petroleum potential offshore the South Vietnam: GazpromZarubezhNeftegaz STL. *2*. Moscow: *Nedra* Publ. 293 p. (in Russian)
9. Guariguata R.C. & Richardson J.A. 1959. El Basamento en el Oeste del Lago de Maracaibo: III Congreso Geológico Venezolano, Caracas, Venezuela, 28 pp.
10. Gutmanis J., Batchelor T., Doe S., Pascual-Cebrianet E. et al. 2015. Hydrocarbon Production from Fractured Basement Formations, Ver. 11: GeoScience Ltd., 45 pp.
11. Kheraskov N.P. 1963. Geological types of the weathered crust and regularities of their spatial development. Moscow. Proc. GIN USSR. Issue 77. (in Russian)
12. Kitchka A. 1997. Oil and Gas Traps in the Crystalline Basement: Evidence for Wrench Tectonics. AAPG Search and Discovery Article, 90942. Abs. 1997 AAPG Int. Conf and Exhibition. Vienna. Austria.
13. Kolisnichenko V.G., Kashuba G.A. 2005. Study of the Dnieper-Donets basin basement by well-logging data interpretation. NADRA Group Presentation.
14. Kolosovskaya V.A. 1994. The study of crystalline basement of the Dnieper-Donets basin Northern Flank to evaluate its hydrocarbon potential in 1990-1993. Kiev. SGE Geoprognoz Report. 128 pp.
15. Kolos V.Ya. 2003. Pecularities of the geological structure and petroleum potential of the Okthtyrka hydrocarbon-prodicing region. PhD Thesis. Ivano-Frankivsk. 221 pp.
16. Koning T. 2014. Global Accumulations of Oil and Gas in Fractured and Weathered Basement: Best Practices for Exploration and Production. AAPG Search and Discovery Article 20281. 4 p.
17. Kosachenko V.D., Burmanova S.N., Kvitchenko T.N. 2008. Study of physical properties of the crystalline basement rocks of the Northern Flank of the Dnieper-Donets depression. Kyiv, UkrSGPI Publ. 79 pp.
18. Kostenko M.M., 2015. Regarding geotectonic zoning of crystalline basement of the Ukrainian Shield. Mineral Resources of Ukraine Jour. 4. 7-13. (in Ukrainian)
19. Lebid V.P., Rakovska O.L. 2014. Analysis of oil and gas shows in Precamprian crystalline basement of Dnieper-Donets Depression to predict hydrocarbon prospects. Collected Papers of UKRDGRI. 2014. 2. P. 61-75. (in Ukrainian)
20. Lie J.E., Nilsen E.H., Grandal E., Grue K. & Sørlie R.A. 2016. Successful geophysical prediction of fractured porous basement reservoir - Rolvsnes Oil Discovery 2015, Utsira High: Ext. Abs. 78^{th} EAGE Conf. Vienna. 4 p.
21. Morariu D. 2012. Contribution to hydrocarbon occurrence in basement rocks. Negtegazovaya geologia. Teoria i practica, 7(3), 17 pp. (in Russian)
22. Petrovskyy O.P., Kobrunov O.I., Gangenko N.S., Sujatinov V.M. 2003. Automated system of quantitative complex interpretation of geophysical data GCIS as absis of technonology of integral interpretation of G&G data for oil and gas exploration. Geoinformatics. 2. P. 25-23. (in Russian)
23. Petrovskyy O.P. 2005. Mathematical model of integral interpretation of geological and geophysical data. Geoph. Jour. NASU. 27. 900-904.

24. Rabasso J. 2010. Gondwana Paleolandscapes: Long-term landscape evolution, genesis, distribution and age. UNESP, Geociências 29. 4. P. 541-570.
25. Small R. 1978. The study of landforms. A textbook of Geomorphology. 2nd edition. Cambridge University Press, 502 pp.
26. Stovba S.M., Stephenson R.A. 2003. Style and timing of salt tectonics in the Dniepr-Donets Basin (Ukraine): implications for triggering and driving mechanisms of salt movement in sedimentary basins. Marine and Petroleum Geology. 1. P. 1169-1189.
27. Stovba S.N., Maystrenko Yu.P. 2001. Late Devonian crustal extension as one of the factors of formation of inhomogeneities yn the crystalline rocks of the marginal parts of the Dnieper-Donets basin. Geophysical Jour. NASU. 23. 6. P. 67-74. (In Russian)
28. Trice R. 2014. Basement exploration, West of Shetlands: progress in opening a new play on the UKCS. In Cannon, S. J. C. & Ellis, D. (eds): Hydrocarbon Exploration to Exploitation West of Shetlands. Geological Society, London, Special Publications. 397. P. 81-105.
29. Ulmishek G.F. 2001. Petroleum Geology and Resources of the Dnieper-Donets Basin, Ukraine and Russia. U.S. Geological Survey Bulletin 2201-E, Version 1.0. 13 pp.
30. Vysochansky I.V. 2013. Geological factors of on non-anticlinal traps formation in the atypical zones of hydrocarbon accumulation of the Dnieper-Donets aulacogene. Visnyk of Kharkiv Univ., 1084, Series Geology-Geography-Ecology, Issue 39. P. 45-65.
31. Walter B., Géraud Y. & Diraison M. 2015. Role of the Inherited Structure and the Paleo-Weathered Surfaces on the Reservoir Quality within the Basement. Proc. World Geothermal Congress, Melbourne, Australia, 19-25 April 2015. 6 pp.
32. Wyns R., Baltassat J.M., Lachassagne P., Legtchenko A. and Vairon J. 2004. Application of proton magnetic resonnace soundings to groundwater reserves mapping in weathered basement rocks (Brittany, France). Bulletin de la Société Géologique de France, 175(1). P. 21-34.
33. Zhuravliov E.G., Oblekov G.I. 2000. Hypergenetic gas-bearing formation of Novoprtovskoe Field Basement. Geology of Oil & Gas. 2000. 5. P. 39-43. (in Russian).