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Analogue Outcrops Study of the Weathered Crystalline Crust Benefits for Basement Reservoirs Exploration in Ukraine

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Summary

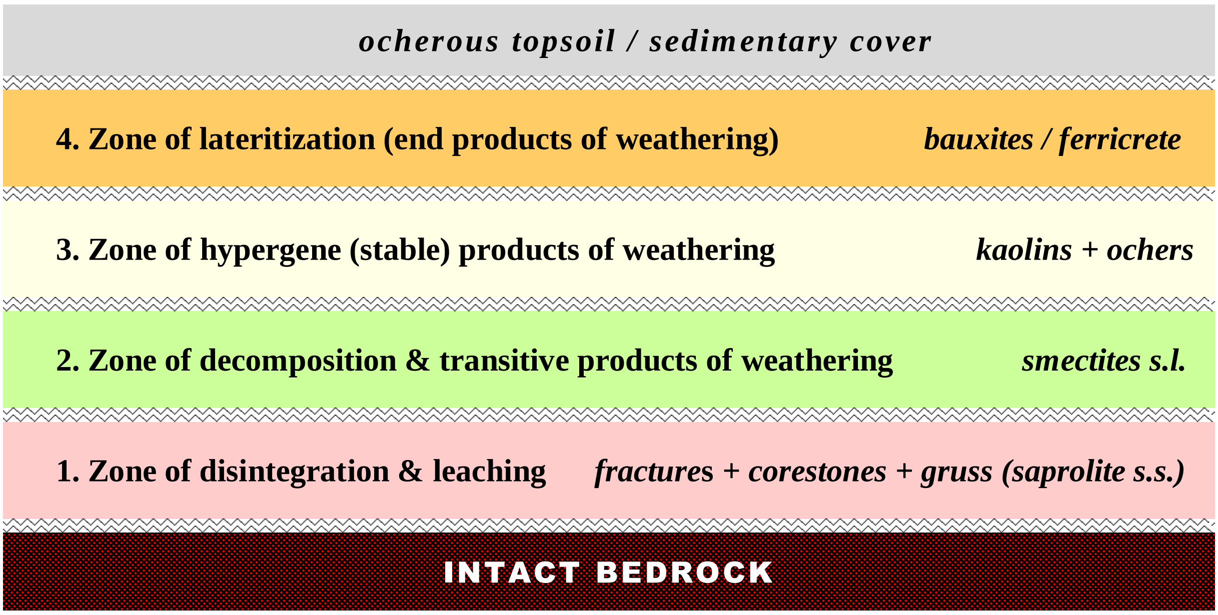
Hydrocarbon exploration targeting basement reservoirs is a challenging issue for the fundamentals of petroleum geology and routine industrial practices. By now, commercial production of hydrocarbons from fractured crystalline basement is well documented in the petroleum basins across the globe hosting weathered, fractured and/or altered basement fields. Understanding of the weathering processes producing disintegration, leaching and decomposition of the crystalline rocks is a key factor to predict commercial hydrocarbon potential in the basement reservoirs. Analog outcrops study conducted across the Ukrainian Crystalline Shield (UCS) and description of different weathering profiles developed upon its igneous and metamorphic rocks provides basic knowledge for predicting of basement reservoirs occurrence in the slopes of the late Devonian Dnieper-Donets basin that separate the UCS from the Voronezh Crystalline Massif in the northwest of Ukraine. More than dozen hydrocarbon fields like Khukhra-Chernetchyna, Yuliivka, Gashynivka and so on are discovered in weathered, fractured and altered basement rocks in the Northern Flank of that basin to the date. New technique developed at DEPROIL Ltd (Ivano-Frankivsk) to explore basement reservoirs applying joint inversion of seismic and gravity data demonstrates good practical results.

Intro

The Ukrainian Crystalline Shield (UCS) is one of the best-outcropped Precambrian terrains with world-class weathered crystalline crust (WCC) 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. 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.

WCC development in the UCS

The thickness of WCCs depends on composition of the parent 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 are not distinct so their recognition is a conditional to some extent. WCC zonation is stipulated by different degree of original minerals transformations and their substitution with hypergene products. Upon this feature in a WCC profile one can recognize four mineral-geochemical zones (going upward), corresponded to the mineral-geochemical zones of disintegration, leaching (initial decomposition), clay minerals (spotty hydromicaceous zone of dominated hydrolysis), oxides and hydroxides (final hydrolysis and oxidation):



The weathered crust is developed almost everywhere upon the crystalline basement rocks of the UCS. Its areal distribution is controlled by ancient topography of the basement and recent relief features. However, within ancient and some present-day river valleys the weathered crust is completely eroded. Upon the morphology and character the weathering profiles, and sometimes, due to their thickness, two types of WCC are recognized, the areal and linear (fractured) one. The latter is developed very locally and attributed to weak dilation zones of some faults. In some cases it is possible to recognize the mixed type of WCC, a linear-areal one (cellular or blocky). We studied different WCC profiles developed upon acid, basic and ultrabasic rocks (of ocherous and nontrotinic types), metamorphic ferruginous quartzites, etc.

Basement hydrocarbon reservoirs as an ultimate exploration frontier

Hydrocarbon exploration targeting basement reservoirs is a challenging issue for the fundamentals of petroleum geology and routine industrial practices. Till the 80's of the last century the discoveries of commercial oil and gas in the crystalline basement were made accidentally or upon exploration mistake and often treated as a curiosity. By now, commercial production of hydrocarbons from fractured crystalline basement is well documented, with petroleum basins across the globe hosting weathered, fractured and/or altered basement fields. To present time more than 450 oil and gas fields in 54 countries and more than 100 sedimentary basins (Gavrilov *et al.*, 2010) with commercial productivity of the crystalline basement are known worldwide over all continents except Antarctica (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), Carmopolis (Sergipe-Alagoas), Augila-Nafoora (Sirte), Oymasha (Manghyshlak), NE Beruk (Sumatra), White Tiger, Black Lion and Ruby (offshore Vietnam), and other hydrocarbon unique HC accumulations. The notion 'basement' includes as true crystalline basement as so-called intermediate (or acoustic) basement represented by folded metamorphic (weathered and fractured) rocks prospective for hydrocarbons (e.g. West Siberia).

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' of Bohai Bay basin, etc.), the UK and Norway in the Atlantic frontier and North Sea (Trice, 2014; Lie *et al.*, 2016) and so on. Some of highly elevated basement horst affected by tectonic rejuvenation and hydrothermal alteration (Gavrilov *et al*., 2010) are characterized very high initial flow rates of oil, absence of OWC and consequently waterless production, and even dead oil saturation of the basement rocks below the horst toe (Gavrilov et al., 2010). To understand the nature of hydrothermally impacted basement reservoir one can consider hydrothermal alteration as kind of upward 'hypabyssal weathering' producing additional porous volume in the buried but elevated basement rock domain.

Three basic types of basement reservoirs are recognized in practice as following:

- weathered crystalline crust (WCC) ones resembling sedimentary reservoir rocks (disintegration zone of full weathering profile) sealed by the non-reservoir rocks of kaolinization / hydromication zones
- fractured and hydrothermally altered reservoirs produced by tectonic dilation and/or mineral transformations of the bedrock
- vein-like (or fault-related) reservoirs hosting hydrocarbon accumulations of a complex morphology

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 uplifting. For deep-seated basement hydrocarbon reservoirs it is necessary to suppose an occurrence of internal intra-basement sources of hydrocarbons (for example metamorphic rock with residual generation potential or crustal or even upper mantlean sources for dry gas). Ones believe 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 basement. Therefore petroleum geoscientists need to answer where the lowermost limit of petroleum column is. This study supports an idea about association of ultradeep oil and gas reservoirs in the basement with crushed and mylonitized zones of wrench faults.

Basement HC discoveries in Ukraine

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. 1.

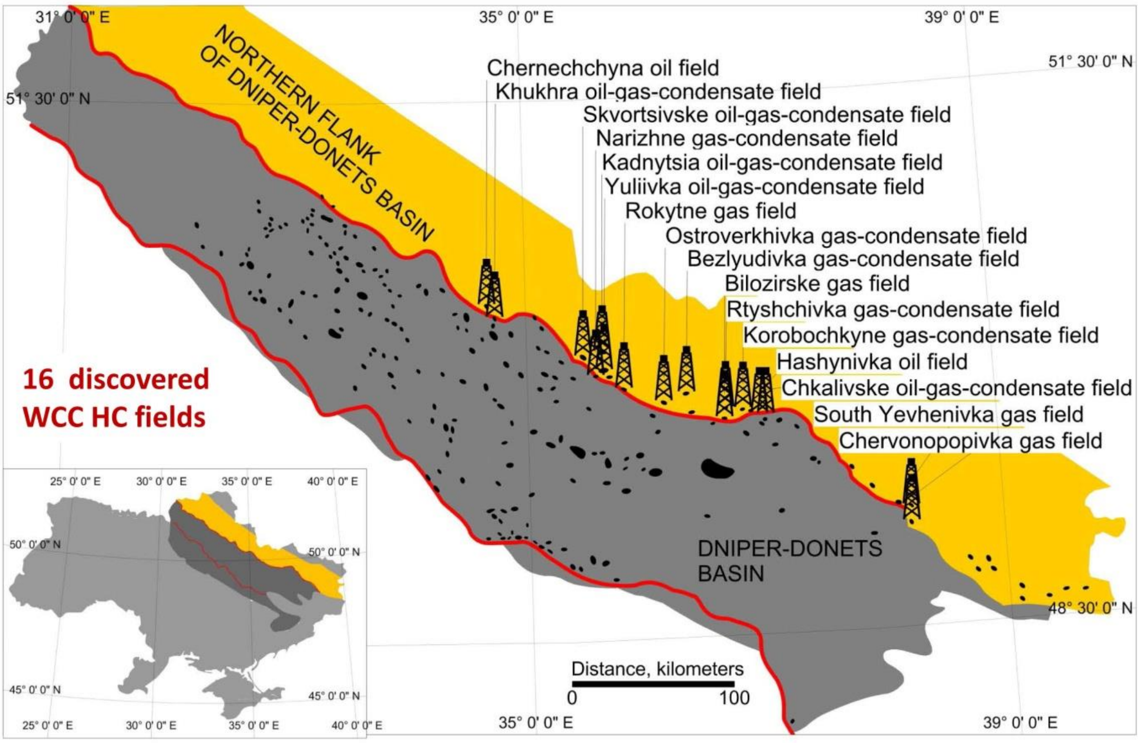


Figure 1 Basement-reservoired HC fields discovered in the WCC of the Dnieper paleorift Northern Flank.

Most of them are related to the structural traps for quite continuous and up to 150 m thick quasi-stratified and complex reservoir made by the pre-Visean WCC disintegration zone developed upon different Precambrian crystalline rocks of the paleorift faulted margin, though some pay zones occur much deeper (for example, 200 m and more below the basement top in the fractured and mylotinitized hornblendites in Yuliivka oil/gas condensate field).

A sophisticated new technique developed at *DEPROIL Ltd* (Petrovskyy *et al.*, 2016) applying 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 reservoirs. 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, see an example in Fig. 2.

Conclusions

1. 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.
2. Middle/Late Devonian to Pre-Early Carboniferous WCCs controls occurrences of basement hydrocarbon accumulations in the Northern Flank of DDB.
3. 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.

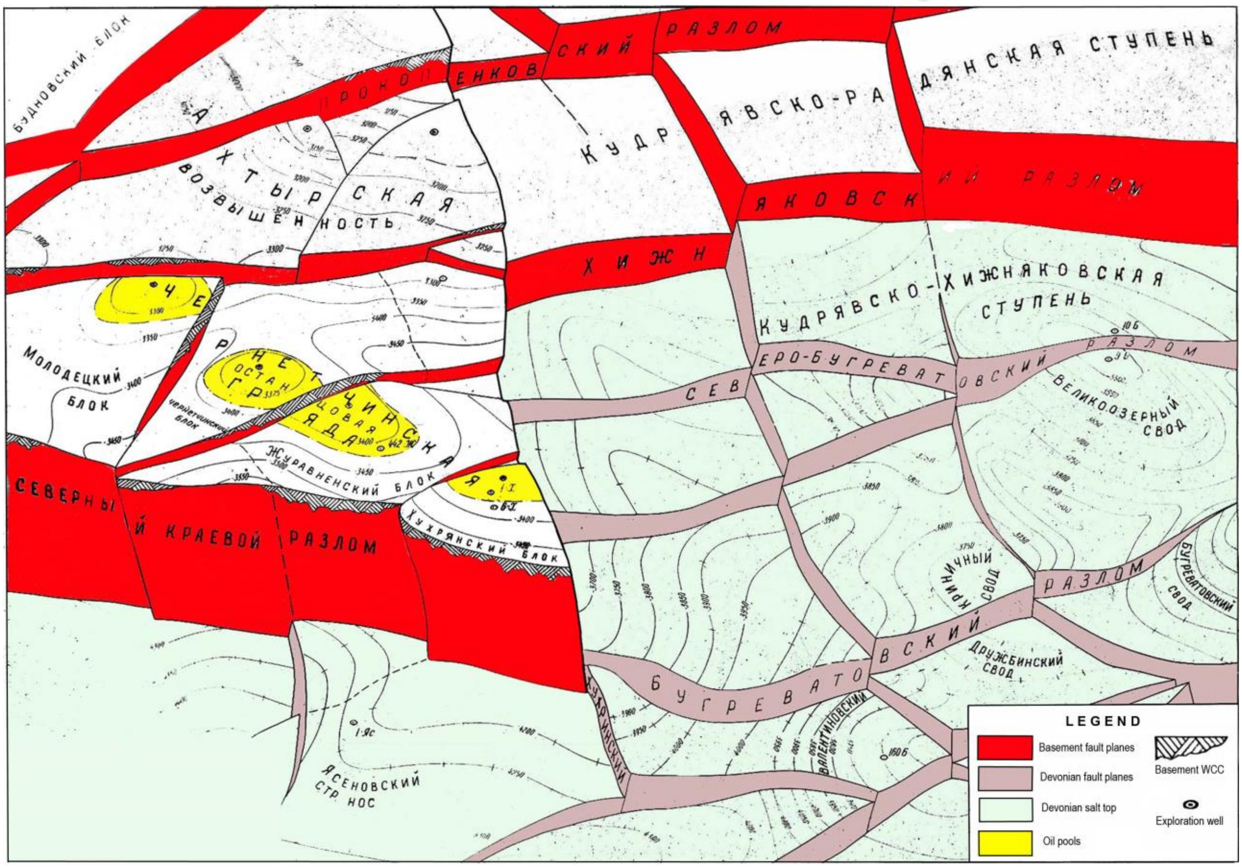


***Figure 2** 3D view of Khukhra-Chernetchyna basement oil field, Northern Flank of the Dnieper basin.*

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.

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