

DEEP-SEATED ABIOGENIC ORIGIN OF PETROLEUM: FROM GEOLOGICAL ASSESSMENT TO PHYSICAL THEORY

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Abstract

[1] The theory of the abyssal abiogenic origin of petroleum is a significant part of the modern scientific theories dealing with the formation of hydrocarbons. These theories include the identification of natural hydrocarbon systems, the physical processes leading to their terrestrial concentration, and the dynamic processes controlling the migration of that material into geological reservoirs of petroleum. The theory of the abyssal abiogenic origin of petroleum recognizes that natural gas and petroleum are primordial materials of deep origin which have migrated into the Earth's crust. Experimental results and geological investigations presented in this article convincingly confirm the main postulates of the theory and allow us to reexamine the structure, size, and locality distributions of the world's hydrocarbon reserves.

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Index Terms: 1025 Geochemistry: Composition of the mantle; 1038 Geochemistry: Mantle processes (3621).

1. INTRODUCTION

[2] The main goal of this article is to summarize the conclusions of modern petroleum science dealing with the generation, structure, size, and location of the world oil and gas potential resources and to provide convincing arguments from both laboratory experiments and geological data supporting the theory of the abyssal abiogenic origin of petroleum. This paper is organized as follows: [Section 2](#) describes the principles of the theory of the abyssal abiogenic origin of petroleum, including the possibility of hydrocarbon generation in mantle conditions as confirmed by distribution characteristic of petroleum and by experimental results obtained. [Section 3](#) provides evidence contradicting the lateral migration of oil and gas at their deposit formation. [Sections 4–14](#) give geological data (structure, size, and location of the

world's hydrocarbon reserves) which cannot be explained by the biotic hypothesis of petroleum origin but can be explained by the theory of the abyssal abiogenic origin of petroleum. In [section 15](#), considerations regarding the petroleum potential of the Earth's mantle are presented confirming the inexhaustible nature of the hydrocarbon resources of our planet.

[3] For the historical perspective on the debate surrounding the theory, we refer the interested reader to [Glasby \[2006\]](#). Our review aims to support the theory of the abyssal abiogenic petroleum origin. Opposing arguments are presented by [Clark \[1934\]](#) and [American Association of Petroleum Geologists \[1971\]](#).

2. PRINCIPLES OF THE THEORY OF ABYSSAL ABIOGENIC ORIGIN OF PETROLEUM AND ITS EXPERIMENTAL CONFIRMATION

2.1. Theory

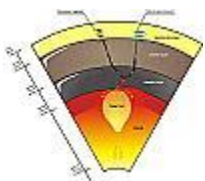


Figure 1. A scheme of petroleum deposit formation.

[4] The theory of the abyssal abiogenic origin of petroleum is an extensive body of scientific knowledge which covers the subjects as follows: (1) chemical genesis of the hydrocarbon molecules, (2) physical processes leading to their terrestrial concentration, (3) dynamic processes placing hydrocarbons into geological reservoirs of petroleum, and (4) the location and commercial production of petroleum. The theory of the abyssal abiogenic origin of petroleum recognizes that petroleum is a primordial material of deep (mantle) origin. This theory, which has been developed in the last 50 years in Russia and Ukraine, explains that hydrocarbon compounds generate in the mantle of the Earth and migrate through the deep faults into the crust of the Earth. There they form oil and gas deposits in any kind of rock (crystalline basement, volcanic, and volcanogenic sedimentary rocks) and in any kind of structural position. Thus, the accumulation of oil and gas is considered as a part of the natural process of the Earth's outgassing, which was, in turn, responsible for the creation of its hydrosphere, atmosphere, and biosphere ([Figure 1](#)) [[Kudryavtsev, 1951](#); [Kropotkin and Shakhvarstova, 1959](#); [Porfir'ev, 1974](#); [Krayushkin, 1984, 1989](#); [Chebanenko et al., 2005](#)].

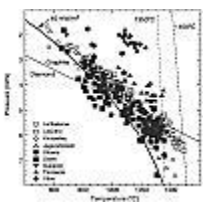


Figure 2. Thermobaric conditions in a variety of continental areas [[Ionov et al., 1993](#); [Rudnick and Nyblade, 1999](#)]. The straight line is the diamond-graphite phase boundary [[Kennedy and Kennedy, 1976](#)], and the short-dashed and long-dashed lines show the positions of adiabats for potential temperatures of 1350°C and 1400°C, respectively [[Rudnick and Nyblade, 1999](#)]. From [Carlson et al. \[2005\]](#).

[5] Until recently, the obstacle to accepting the theory of the abyssal abiogenic origin of petroleum was the lack of reliable and reproducible experimental results confirming the possibility of the synthesis of complex hydrocarbon systems under the conditions of the upper mantle of the Earth. According to this theory the following conditions are necessary for the synthesis of hydrocarbons: (1) adequately high pressure and temperature, (2) donors/sources of carbon and hydrogen, and (3) a thermodynamically favorable reaction environment.

Theoretical calculations based on methods of modern statistical thermodynamics have established that (1) polymerization of hydrocarbons takes place in the temperature range 600°C–1500°C and at pressures ranging from 20 to 70 kbar [Kenney *et al.*, 2002] and (2) these conditions prevail deep in the Earth at depths of 70–250 km [Carlson *et al.*, 2005] (Figure 2).

[6] Donors/sources of carbon and hydrogen are the following: (1) carbon dioxide (CO₂), graphite, magnesite (MgCO₃), and calcite (CaCO₃) for carbon and (2) water as supercritical fluid and hydroxyl group in some minerals (biotite and muscovite) for hydrogen. All the above mentioned substances are present in the mantle in sufficient amounts [Murakami *et al.*, 2002; Isshiki *et al.*, 2004], although quantitative estimates of their abundances vary.

[7] Thermodynamically favorable reaction environment (reducing conditions) could be created by a presence of FeO. The presence of FeO in basic and ultrabasic rocks of upper mantle is documented [Anderson, 1989].

[8] Thus, abiogenic synthesis of hydrocarbons can take place in the basic and ultrabasic rocks of the upper mantle in the presence of FeO and donors/sources of carbon and hydrogen. The possible reaction of synthesis in this case could be presented as follows: (1) reduced mantle substance + mantle gases → oxidized mantle substance + hydrocarbons or (2) combination of chemical radicals (methylene (CH₂) and methyl (CH₃)). Different combinations of these radicals define all scales of oil and gas hydrocarbons and also cause analogous properties and genetic similarity of oils from different deposits of the world.

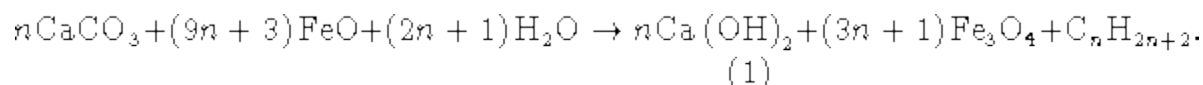
[9] In the theory of the abyssal abiogenic origin of petroleum the generation of petroleum accumulations/deposits occurs in four steps as follows: (1) hydrocarbon fluids are generated in the upper mantle; (2) where and when overlying rocks of the Earth's crust break up/fracture, petroliferous fluids rise from the mantle through the deep faults and their feather joints or fissures; (3) the tremendous pressure injects the petroliferous fluids from the faults and feathers into any rock with porous (sedimentary rocks) or fractured (basement rocks) pore space; and (4) the petroliferous fluids flood the reservoir. (For details, see section 3.) These favorable conditions for deep hydrocarbon generation are not available everywhere in the mantle. This explains the nonuniformity of spatial accommodation of hydrocarbon deposits on the Earth.

2.2. Laboratory Experiments

[10] Since petroleum is generated at high pressures and high temperatures, a special high-pressure apparatus which permits investigations at pressures to 50 kbar and temperatures to 1200°C has been designed. The challenge was to establish the above mentioned conditions in high-pressure equipment that is capable of preventing contamination by air, is fully sealed for several hours at pressures of 50 kbar and temperatures of 1200°C, and also allows a rapid drop

of temperature while maintaining high pressures. To be able to examine the spontaneous reaction products the system must be rapidly quenched to “freeze in” its high-pressure, high-temperature distribution. (Such a mechanism is analogous to that which occurs during eruptive transport processes responsible for the stability and occurrence of diamonds in kimberlite ejecta in the crust of the Earth.) The high-pressure chamber that was used in the experiments is described by [Nikolaev and Shalimov \[1990\]](#). Both stainless steel and platinum reaction cells with a volume of 0.6 cm³ were used. All were constructed to prevent contamination by air and to provide impermeability during and after each experimental run. The reaction cell with initial components was placed into the high-pressure chamber and was brought from 1 bar to 50 kbar gradually, at a rate of 2 kbar/min, and from room temperature to the elevated temperatures of investigation at the rate of 100°C/min. The reaction cell and high-pressure chamber were held for at least an hour at each temperature for which measurements were taken in order to allow the hydrocarbon system to come to thermodynamic equilibrium. The samples were thereafter quenched at the rate of 900°C/s to 200°C and from 200°C to room temperature over several minutes, while maintaining the high pressure of investigation. The pressure was then reduced gradually to 1 bar at the rate of 1 kbar/min. For analyses of reaction products the standard mass spectrometer and chromatograph with a connected desorber were used. Chromatographic analyses were carried out simultaneously with two detectors and three chromatograph columns at the temperatures of desorption from 150°C to 850°C.

[11] Experiments to demonstrate the high-pressure genesis of petroleum hydrocarbons have been conducted using 99.9% pure, solid iron oxide, FeO, and marble, CaCO₃, wet with double-distilled water. There were no biotic compounds or hydrocarbons admitted to the reaction chamber. At pressure of 50 kbar with a temperature of 1200°C, the synthesis is due to the reaction as follows:



Most of the experiments were performed with initial mixtures for which the reagent abundances had been calculated to provide the maximal output of condensed hydrocarbon phases. All experiments were carried out twice and repeated 6 months later to confirm their reliability and reproducibility. Results of chromatographic analyses [[Kutcherov et al., 2002](#)] shown in [Table 1](#) indicate that the mixtures of the initial members of alkanes, alkenes, and aromatic hydrocarbons throughout have been obtained as a result of chemical reactions in the system $\text{CaCO}_3\text{-FeO}$ at pressures of 30–50 kbar and at temperatures of 900°C–1200°C. (Characteristics for gas-liquid inclusions of granitoid rocks from the White Tiger oil field (Vietnam) [[Areshev et al., 1997](#)] presented in [Table 1](#) show that during high-pressure experiments the system spontaneously evolved hydrocarbon mixtures in distribution characteristic of natural petroleum.)

[12] Part of our experimental results were confirmed by experiments conducted by [Scott et al. \[2004\]](#). The authors have presented in situ observations of hydrocarbon formation via carbonate reduction at upper mantle pressures and temperatures. They have shown that methane was formed from FeO, CaCO₃-calcite, and water at pressures between 50 and 110 kbar and temperatures ranging from 500°C to 1500°C.

[13] In our new experiments the following suggestions were checked: (1) The hydrocarbon synthesis under mantle conditions does not depend substantially on the form in which carbon participates in a reaction. (2) A cooling rate during high-pressure experiments influences significantly the content of the products of the reactions.



Figure 3. General view of BARS apparatus.

[14] In the new series of experiments, carbon, iron, and distilled water were used as initial substances. Experiments were done using the large-volume multianvil press apparatus BARS [Pal'yanov *et al.*, 1990]. A general view of the apparatus is shown in Figure 3. *Chepurov et al.*'s [1999] method of high-pressure experiments was similar to the method which we used for the ring anvil (CONAC)-type chamber. The cell and reaction chamber were held for 30 min at pressure of 50 kbar and temperature of 1200°C. The samples were then cooled at different rates (several seconds, 2 h, and 4 h) to room temperature, while maintaining the high pressure of investigation. The pressure was then reduced gradually to 1 bar. The reaction cell was then gently placed in the chromatograph for analysis. The chromatographic analysis was carried out at temperature of 150°C. Besides hydrocarbons, a content of H₂O, CO₂, and CO was determined. The results of chromatographic analysis of the products of reactions for three experiments made at different cooling rates are shown in Table 2. The new results presented confirm that hydrocarbon synthesis does not depend on the type of carbon donor. A drop of the cooling rate leads to formation of heavier hydrocarbons and increases the amount of saturated hydrocarbons detected in the reaction products. The experimental results obtained by independent groups of researchers in the different laboratories discussed above confirm one of the main postulates of the theory of the abyssal abiogenic origin of petroleum: complex hydrocarbon systems could be spontaneously generated deeply in the Earth under the upper mantle conditions.

3. FORMATION OF OIL AND GAS FIELDS IN LIGHT OF ABIOGENIC ORIGIN OF PETROLEUM

[15] The theory of the abyssal abiogenic origin of petroleum denies the lateral migration of oil and gas in their reservoirs unless a hydrodynamic (hydraulic) fluid movement exists. Capillary forces which are related to the pore radius and to the surface tension across the oil-water (or gas-water) interface (the process is described by Laplace's equation) are, generally, 12–16 thousand times stronger than the buoyancy forces of oil and gas (according to the Navier-Stokes equation) in the natural porous, permeable media of the subsurface. This was confirmed by the respective modeling experiments [Krayushkin, 1967, 1989]. In these experiments, natural gas was injected in the bottom part of water-saturated sands placed in a transparent tank, a model of a gas bed. In all experiments, injected gas remained in the bottom part of the

tank. Updip gas migration was never observed. Change of sand porosity in a wide range did not influence the results of the experiments. This was also supported by the practice of subsurface gas store building in the tilted or horizontal water-saturated sands and sandstones. Natural gas that was injected in the gas store remained around an injected well. Updip gas migration was never observed in this case also. According to the theory of the abyssal abiogenic origin of petroleum, oil and gas fields are born as follows. Rising from subcrust zones through the deep faults and their feather joints or fissures, the petroliferous fluid of the mantle is injected under high pressure into any rock and distributed there. The hydrocarbon composition of oil and gas accumulations formed this way depends on the cooling rate of the fluids during their injection into the rocks of the Earth's crust. When and where the further supply of injected hydrocarbons from the mantle stops, the fluids do not move further into any forms of the Earth's crust (anticline, syncline, and horizontal and tilted beds) without the restart of the injection of the abyssal petroliferous fluids.

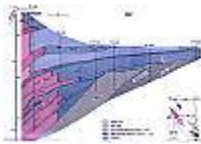


Figure 4. Cross section of Alberta showing gas-saturated sands of Deep Basin [from [Masters, 1979](#)]. Gas is concentrated in the tight impermeable sand, which is transformed progressively and continuously updip into the coarse-grained, highly porous, and highly permeable sand saturated by water.

[16] The most convincing evidence of the above mentioned mechanism of oil and gas deposit formations is the existence of such giant gas fields as Deep Basin ([Figure 4](#)), Milk River, and San Juan. They are located in Alberta, Canada, and Colorado, United States. The formation of these giant gas fields questions the existence of any lateral migration of oil and gas during the oil and gas accumulation process. Those giant gas fields occur in synclines where gas must be generated but not accumulated, according to the hypothesis of biotic petroleum origin and hydrodynamically controlled migration. The giant gas volumes ($12.5 \times 10^{12} \text{ m}^3$ in Deep Basin, $935 \times 10^9 \text{ m}^3$ in San Juan, and $255 \times 10^9 \text{ m}^3$ in Milk River) are concentrated in the very fine grained, tight, impermeable argillites, clays, and shales and in tight sandstones and siltstones. These rocks are usually accepted as source rocks and caprocks/seal rocks in petroleum geology but by no means are universally recognized reservoir rocks of oil and natural gas. All the gas-saturated tight rocks here are graded updip into coarse-grained, highly porous, and highly permeable aquifers with no visible tectonic, lithological, and stratigraphic barriers to prevent updip gas migration. Therefore, the tremendous gas volumes of the above mentioned gas fields have tremendous buoyancy, but it never overcomes capillary resistance in pores of the water-saturated reservoir rocks.

[17] Existence of the above mentioned giant gas fields indicates the following:

[18] 1. The models of lateral migration of oil and gas at their deposit formation are not consistent with the standpoint of the classic physics laws describing the relation between capillary and buoyancy forces of oil and gas in the natural porous media. A mechanism of the separation of the phases and undeniable presence of fluid contacts is caused by the capillary phenomena. This is a subject of petroleum engineering, which is why we did not consider this mechanism in detail in our paper.

[19] 2. These fields were formed as a result of the migration of the mantle petroliferous fluid from the depths to the surface of the Earth.

4. NATURAL GAS AND OIL IN THE RECENT SEAFLOOR SPREADING CENTERS

[20] Petroleum of abyssal abiogenic origin and its emplacement into the crust of the Earth can occur in the recent seafloor spreading centers in the oceans. Igneous rocks occupy 99% of the total length (55,000 km) of them, while the thickness of sedimentary cover over the spreading centers does not exceed 450–500 m [Rona, 1988]. Additionally, subbottom convectional hydrothermal systems discharge hot (170°C–430°C) water through the sea bottom's black and white “smokers.” Up to now, more than 100 hydrothermal systems of this kind have been identified and studied in scientific expeditions using submarines such as *Alvin*, *Mir*, *Nautila*, and *Nautilus* in the Atlantic, Pacific, and Indian oceans. Their observations pertaining to the deep abiogenic origin of petroleum are as follows:

[21] 1. The bottom smokers of deepwater rift valleys vent hot water, methane, some other gases, and petroleum fluids. Active “plumes” with heights of 800–1000 m venting methane have been discovered every 20–40 km between 12°N and 37°N along the Mid-Atlantic Ridge (MAR) over a distance of 1200 km. MAR's sites, trans-Atlantic geotraverse (TAG) (26°N), Snake Pit (23°N), Logatchev (14°45'N), Broken Spur (29°N), Rainbow (37°17'N), and Menez Gwen (37°50'N), are the most interesting.

[22] 2. At the Rainbow site, where the bottom outcrops are represented by ultramafic rocks of mantle origin, the presence of the following substances was demonstrated (by chromatography/mass spectrometry): CH₄, C₂H₆, C₃H₈, CO, CO₂, H₂, H₂S, and N₂ as well as petroleum consisting of *n*-C₁₆–*n*-C₂₉ alkanes together with branched alkanes and diaromatics [Charlou and Donval, 1993; Charlou *et al.*, 2002]. Contemporary science does not yet know any microbe which really generates *n*-C₁₁–*n*-C₂₂ alkanes, phytan, pristan, and aromatic hydrocarbons.

[23] 3. At the TAG site, there were no bottom sediments, sedimentary rocks [Simoneit, 1988; Thompson *et al.*, 1988], buried organic matter, or any source rocks. The hydrothermal fluid is too hot (290°C–321°C) for any microbes. There are the Beggiatoa mats, but they were only found at some distances from smokers.

[24] 4. Active submarine hydrothermal systems produce the sulfide metal ore deposits along the whole length of the East Pacific Rise (EPR). At 13°N the axis of EPR is free of any sediment, but here aliphatic hydrocarbons are present in hot hydrothermal fluids of black smokers. In the sulfide metal ores here the methane and alkanes higher than *n*-C₂₅ with prevalence of the odd number of carbon atoms have been identified [Simoneit, 1988].

[25] 5. Oil accumulations have been studied by the *Alvin* submarine and by the deep marine drilling in the Gulf of California (the Guaymas Basin) and in the Escanaba Trough in the Gorda Ridge [Gieskes *et al.*, 1988; Koski *et al.*, 1988; Kvenvolden and Simoneit, 1987; Lonsdale, 1985; Peter and Scott, 1988; Simoneit, 1988; Simoneit and Lonsdale, 1982;

Thompson et al., 1988] of the Pacific Ocean. These sites are covered by sediments. However, petroleum fluids identified there are of hydrothermal origin according to *Simoneit and Lonsdale* [1982], and no source rocks have yet been identified there.

[26] 6. As for other sites around the globe, scientific investigations with submarines have established that methane plumes occur over sea bottom smokers or other hydrothermal systems in the Red Sea, near the Galapagos Isles, in the Mariana and Tonga deepwater trenches, in the Gulf of California, etc. [*Baker et al.*, 1987; *Blanc et al.*, 1990; *Craig et al.*, 1987; *Evans et al.*, 1988; *Horibe et al.*, 1986; *Ramboz et al.*, 1988]. Nonbiogenic methane (10^5 – 10^6 m³/yr) released from a submarine rift off Jamaica [*Brooks*, 1979] has been also known. A recent investigation along the Mid-Atlantic Ridge 2300 miles east of Florida confirms that the hydrogen-rich fluids venting at the bottom of the Atlantic Ocean in the Lost City Hydrothermal Field were produced by an abiotic synthesis of hydrocarbons in the mantle of the Earth [*Proskurowski et al.*, 2008]. Quantitatively speaking, the seafloor spreading centers may vent 1.3×10^9 m³ of hydrogen and 16×10^7 m³ methane annually [*Welhan and Craig*, 1979].

[27] Data discussed in this section confirm the following: (1) source rocks accounting for the volume of the petroleum venting described are not available and (2) the natural gas and petroleum fluids in the recent seafloor spreading centers can be explained as a result of the vertical migration of mantle fluids.

5. NATURAL GAS AND PETROLEUM FLUIDS IN THE PRECAMBRIAN CRYSTALLINE SHIELDS

[28] Additional evidence confirming the abyssal abiogenic petroleum origin is an abundant presence of natural gas and petroleum fluids in the Precambrian crystalline shields (African, Baltic, Canadian, Greenlandian, Sino-Korean, and Ukrainian shields) with no source rocks around as follows.

5.1. Africa



Figure 5. (a) Geological map of the Albert Graben and its commercial petroleum fields. Data are from *Oil and Gas Journal* [2006]. (b) Generalized structural section, Alberta Graben. Data are from *Patton et al.* [1995]. Patterns are as follows: 1, gneisses and granite gneisses; 2, crystalline schist; 3, granites; 4, volcanic; 5, sand; 6, fault.

[29] An abundant presence of natural gas in the Precambrian igneous and crystalline metamorphic rocks of the Caapvaal Craton, South Africa, has been observed. In many gold mines of the Witwatersrand mining district, natural gas is abundantly detected to occur in Archean crystalline rocks filling an ancient graben. Till 1958, more than 190 explosions of hydrocarbon gas were registered in only one of the mines mentioned above. The total quantity

of methane produced through the ventilation system of these mines exceeds 5×10^8 m³/yr [Hugo, 1963]. In 2004–2006 the oil fields Kingfisher, Mputa, and Waraga were discovered on the eastern coast of Lake Albert in Uganda (Figure 5). “In-place” oil resources of these oil fields are 210×10^6 t [Patton et al., 1995]. There are only Precambrian crystalline rocks and Quaternary clays surrounding Lake Albert.

5.2. Baltic Region

[30] In the Baltic Shield, 240 km northwest of Stockholm, oil was discovered at the depth of 2883 m in the 1 Stenberg well and at the depth of ~6800 m in the 1 Gravberg well. Both of these wells were drilled in the Precambrian granites only [Aldhous, 1991; Brown, 1991]. All Precambrian igneous rocks in the Kola segment of the Baltic Shield contain from 90 to 110 g/t of Vaseline-like bitumen consisting of n -C₂₇– n -C₃₁ alkanes (32% of mass) as well as cycloalkanes and arenes [Petersilje et al., 1967]. The 3-SG-Kola ultradeep well penetrating Precambrian rocks discovered the same oil-saturated igneous rocks at the depth range of 7004–8004 m [Oil and Gas Journal, 1991, 1992a; Krayushkin, 2000].

5.3. Canada

[31] The pulse influx of methane along with chloride-saturated solution under the abnormally high pressure (8.1 MPa at the depth of 510 m) was met in the Precambrian shield crystalline rocks during the work to increase the depth of the Underseal Mine. This mine is very rich in native copper which occurs in the voids, interstices, and fractures of the Precambrian crystalline rocks near Lake Superior, Ontario, Canada. In the adjacent Central Patricia Mine, which is also rich in commercial copper ores, the methane emissions from the Archean crystalline rocks were very abundant: 135 flashes and explosions of methane were registered in both mines during 1940–1950 [Tigert, 1951]. In the White Pine mining district that is situated on the Michigan shore of Lake Superior, Precambrian crystalline rocks comprising copper ores in commercial grade and quantity are impregnated with liquid crude oil. This crude seeps from fractures, fissures, and caverns in the face, top, and walls of the copper mine and consists of the full and typical petroleum spectrum hydrocarbons including the optically active alkanes, porphyrins, phytane, and pristane [Barghoorn et al., 1965; Kelly and Nishioka, 1985].

5.4. Greenland

[32] In western Greenland near Peninsula Nuussuaq the Precambrian crystalline rocks of the Greenlandian shield are dissected with numerous faults and intruded with the Tertiary age plateau basalts. Having a total thickness of more than 6500 m they overlap regionally in the shield's rocks. In 1993 one exploration well was drilled to a total depth (TD) of 448 m. This well penetrated to a series of porous zones in basalt and indicated the presence of liquid petroleum down to the depth of 90 m in basalt. In eastern Greenland, where the Paleocene plateau basalts overlap the Precambrian crystalline rock mass of the shield, the liquid bitumen was found in 1992 as an active natural seepage of heavy viscous oil/bitumen. It seeps from the Tertiary plateau basalts exposed near a base of the Paleocene lava pillow. All the interstices, voids, and vugs of lava and basalt are filled fully with bitumen in the area of ~1 km along the

strike and of several hundred meters capwise [*Schiener and Leythaeuser, 1978; Requejo et al., 1989; Oil and Gas Journal, 1993a*].

5.5. Sino-Korean Region

[33] In northern China the Yanshan aulacogen is filled predominantly with the Middle and Later Proterozoic crystalline limestones, dolomites, and marbles. Their total thickness exceeds 9000 m. The isotopic age of carbonates varies from 800 to 1850 Ma. Here 65 native liquid oil and solid bitumen shows have been mapped in outcrops of Tilin and Vumishan crystalline carbonates, whereas the Lontangchou lenticular bituminous basal quartzite (the isotopic age is 1000 Ma) occurs on the more ancient crystalline rocks of the aulacogen. In this quartzite the concentration of bitumen varies from 8% to 15% of mass. The host rock of the bituminous quartzite (Zyamalyang Formation) was intruded with the gabbro-diabase sills (the isotopic age is ~763 Ma). The bitumen of the above mentioned quartzite is considered to be a residue or remnant of an ancient oil accumulation which has undergone a thermodestruction during the early Riphean time [*Wang, 1991*].

5.6. Ukraine

[34] Covered predominantly with the Tertiary and Quaternary beds and being exposed in the deep entrenched river valleys and ravines, the Ukrainian Precambrian shield with its surface area of 200,000 km² is an uplifted geologically complex crystalline basement of the East European Platform. The Archean rock mass of that shield consists of amphibolites, apophyrites, calciphyres, crystalline schists, diorites, ferrikerous quartzites, gneisses and graphitic gneisses, granites, marbles, metaconglomerates, metasandstones, and quartzites intruded with the Proterozoic igneous rock bodies such as the Korosten, Korsun-Shevchenko, near-Azov Sea, and Novomirgorod plutons. The Proterozoic crystalline complex of the shield is distributed broadly and comprises amphibolites, gabbro, gabbro-norites, labradorites, norites, gneisses and graphitic gneisses, granites, diabases, carbonatites, calciphyres, crystalline schists, ferrikerous quartzites, felsites, leptites, marbles, metasandstones, tuffs, and alkali ultrabases. Both the Archean and the Proterozoic rocks here do have petroleum fluid indications over large areas. Liquid crude oil was observed in fissures and fractures of amphibolites and granite core samples recovered from several boreholes at the depth of 380–900 m in the northeast area of the Ukrainian shield [*Porfir'ev et al., 1977*]. As indicated by gas chromatography of gas mixture samples from pulverized Precambrian rocks of the Ukrainian shield, they contain 0.001–0.204 cm³/g of methane [*Semenenko et al., 1985*].

5.7. Conclusions

[35] Examples discussed in sections 5.1–5.6 indicate that (1) petroleum shows/deposits have been found in Precambrian crystalline shields all over the world, (2) presence of oil and gas deposits in the Precambrian crystalline shields without sedimentary rocks cannot be explained from the traditional biotic petroleum origin point of view, and (3) petroliferous fluid of the mantle could be the only possible source of petroleum deposits in the Precambrian crystalline shields.

6. PETROLEUM FLUID INCLUSIONS IN MINERALS OF IGNEOUS AND OTHER CRYSTALLINE ROCKS

6.1. Victoria, SE Australia

[36] The Pleistocene alkali basalts of Victoria (SE Australia) are found at the southern termination of the Mesozoic-Recent basaltoid belt. They contain mantle xenoliths. These are the spinel lherzolites with numerous primary fluid inclusions which contain up to 6 g/t of aliphatic hydrocarbons with measured $\delta^{13}\text{C}$ values of -28.9‰ [*Sugisaki and Mimura, 1994*].

6.2. Russia and Ukraine

[37] Lherzolites from the recent Baikal Rift belt are rich in primary fluid inclusions, the methane concentration of which was reported at the level of 3 g/kg (V. S. Zubkov, Heavy hydrocarbons in mantle fluid of the Earth, synopsis of thesis prepared by Dr. Ph., A. P. Vinogradov Institute of Geochemistry, Russian Academy of Sciences, Irkutsk, 2005). $\text{C}_1\text{-C}_6$ alkanes with concentrations from 4.09 to 63.35 L/t were found in primary fluid inclusions of albite, apatite, nepheline, sphene (titanite), aegirine, and eudialite from the olivine-titanium-augite gabbro and urtites in east Siberia [*Petersilje et al., 1967*]. In the Pamir Mountains bitumen was found in the mantle xenoliths embedded in igneous rocks. Here also primary fluid inclusions occur in xenoliths of the garnet pyroxenites (the mantle rocks), explosion pipe rocks and dykes of fergusonite-porphyrates or tinguaites (derivatives of mantle magma), amphibolites, granites, hyperbasites, charnockites, basic granulites, and eclogites (granulite-basite layer). The average petroleum fluid concentration of the primary fluid inclusions varies in the range of 6–8 g/t, decreasing regularly in the direction from the Earth's mantle to the granite/gneiss layer. This is evidence of the abyssal nonbiogenic origin of bitumen [*Mogarovski et al., 1980*]. In Ukraine, primary fluid inclusions of pegmatite quartz comprise $n\text{-C}_1\text{-}n\text{-C}_4$ alkanes in the Proterozoic age Korosten, Korsun-Shevchenkovo, and Novomirgorod plutons of the Ukrainian shield (Z. I. Kovalishin, Geochemical investigations of the abyssal origin gases on inclusions in minerals, synopsis of thesis prepared by Dr. Ph., Institute of Geology and Geochemistry of Combustible Minerals, Lvov, Ukraine, 1986).

6.3. Antarctica

[38] The Shackleton Ridge of eastern Antarctica is rich in Precambrian supracrustal volcanogenic sedimentary rocks and their zonal metamorphic forms (kyanite-sillimanite facial series). Primary fluid inclusions of 13 garnet crystals samples from parametamorphites of the Shackleton Ridge comprise methane and heavy hydrocarbons [*Prasolov et al., 1986*]. Mantle xenoliths found in the Quaternary lavas of Mount Erebus Volcano [*Sugisaki and Mimura, 1994*] (Ross Island, East Antarctica) are dunites, garzburgites, and pyroxenites. Gas content of their primary fluid hydrocarbon fluid inclusions is 0.2–1.0 g/t.

6.4. Africa

[39] Primary petroleum fluid inclusions (PFI) are frequently reported in the Precambrian shield rocks of southwest Africa. PFI of quartz contain CH_4 , C_2H_6 , C_3H_8 , CO , CO_2 , H_2O , H_2 , N_2 ,

and Vaseline-like heavy crude oil [*Kvenvolden and Roedder, 1971; Walter et al., 1996*]. This oil is geochemically prominent because it has an extraordinarily high concentration of isoprenoidic hydrocarbons. Primary fluid inclusions of this oil comprise identical quantities of hydrocarbon molecules with their odd and even carbon atom numbers as well as the noncyclic isoprenoids, pristane, phytane, and pharnesane.

6.5. Brazilian Shield and Baltic Shield

[40] Mesozoic age basalts breaking through the Precambrian crystalline rocks of the Brazilian shield (Santa Catarina) are unweathered; poor in fractures; and rich in geodes, voids, and interstices filled with liquid crude oil [*Powers, 1932*]. Something similar was also found in the Baltic Shield, Sweden. Although there are no sedimentary rocks in or around the Arendal area, the dolerite (crystallization temperature is more than 1000°C–1200°C) dykes intersecting the Archean gneisses have many interstices and amygdaloidal voids filled with liquid petroleum of $n\text{-C}_{10}\text{--}n\text{-C}_{22}$ alkanes with some admixture of isoprenoid hydrocarbons. *Evans et al. [1964]* have concluded that this petroleum doubtlessly is of nonbiogenic origin.

6.6. United States

[41] *Matson and Muenow [1984]* studied the volatiles in amphiboles from the mantle xenoliths, Vulcan's Throne, Grand Canyon, Arizona, United States. The amphiboles there contain CH_4 , C_2H_4 , C_3H_8 , and the heavier hydrocarbons. Methane concentrations vary from 200 to 500 g/t. The above mentioned hydrocarbons have $\delta^{13}\text{C}$ equal to $-26.0\text{‰} \pm 0.5\text{‰}$ that is typical for the noncarbonate carbon in ultramafic igneous rocks where $\delta^{13}\text{C}$ varies from -22.2‰ to -27.1‰ . According to experiments, amphibole-bearing xenoliths crystallize at the depth of 65 km.

[42] *Sugisaki and Mimura [1994]* carried out the most extensive study of petroleum presence in pores, vugs, voids, interstices, caverns, fractures, fissures, and primary fluid inclusions which occur within basalts, gabbro, granites, peridotites, and their mantle xenoliths. A collection of those rocks consisted of 227 samples from all over the world. All samples contain CH_4 , while ultramafics also contain $n\text{-C}_{14}\text{--}n\text{-C}_{33}$ alkanes with total concentrations of 0.1–2.3 g/t and $\delta^{13}\text{C} = -23\text{‰}$ to -28.9‰ .

6.7. Conclusions

[43] The examples shown in sections 6.1–6.6 show the following: (1) The petroleum fluid content of mantle rocks including primary inclusions was formed in the conditions of the mantle of the Earth. (2) The presence of complex hydrocarbons in mantle rocks confirms that abiogenic abyssal origin of hydrocarbons is a reality. (3) The content of CO , CH_4 , and other hydrocarbons in the amphibole-bearing xenoliths indicates that in certain parts of the upper mantle, favorable reduction conditions necessary for nonabiotic synthesis of hydrocarbons could take place [*Matson and Muenow, 1984*].

7. BITUMEN AND HYDROCARBONS IN NATIVE DIAMONDS, CARBONADO, AND KIMBERLITES

[44] A presence of bitumen and hydrocarbons in native diamonds, carbonado, and kimberlites could be taken into consideration as evidence confirming the abyssal petroleum origin. Studying the native diamonds, carbonado, and kimberlites under the microscope, many scientists from several countries have found numerous primary fluid inclusions which have been opened due to the specific methods. Fluid contents of primary fluid inclusions have been recovered without any contamination and studied by mass spectrometry/gas chromatography. Results of such investigations carried out on the samples from Africa, Asia, Europe, and North and South America can be summarized as follows.

[45] The well-known diamond-producing mines such as the Dan Carl, Finsh, Kimberley, and Roberts Victor mines are located in the kimberlite pipes of South Africa. There the African shield is characterized by the remarkable disjunctive dislocations and nonorogenic magmatism which has produced a great number of the carbonatite and kimberlite intrusions and explosion pipes in the area around Lake Tanganyika, Lake Malawi, and Lake Victoria between 70 and 3000 Ma [*Irvine, 1989*]. These lakes are in the Great East African Rift Valley. The valley's margins and disjunctive edges consist of the African shield crystalline rocks. Two hundred and fifty-eight samples of diamonds from this area have been investigated under the microscope [*Deines et al., 1989*]. The investigation has shown the presence of primary fluid inclusions in all samples investigated. These samples have been disintegrated into small particles in a vacuum of $\sim 1.3 \times 10^{-6}$ Pa and 200°C. The gas mixture from each sample was received. Mass spectrometric/gas chromatographic studies of the mixtures are shown in [Table 3](#). The same hydrocarbons and gas mixtures were detected in natural diamonds from Congo, Brazil [*Melton and Giardini, 1974*], and Zaire [*Giardini et al., 1982*] ([Table 3](#)).

[46] The composition of the primary fluid inclusion composition has been studied by mass spectrometry in seven native Arkansas diamonds. The result of the investigation has confirmed the presence of different kinds of hydrocarbon in all samples ([Table 3](#)) [*Melton and Giardini, 1974*].

[47] In a Brazil, carbonado primary fluid inclusions comprise a set of heavy hydrocarbons ([Table 3](#)). Pyrope ($\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$) and olivine, which were recovered from diamond crystals and kimberlites of the Mir, Ruslovoye, and Udatchnoye Eastern diamond-bearing pipes, east Siberia, Russia, contain a number of different hydrocarbons ([Table 3](#)) [*Kulakova et al., 1982; Kaminski et al., 1985*].

[48] According to *Makeev and Ivanukh [2004]*, 9–27 forms of metallic films were found and studied upon the crystal faces of diamonds from Brazil and from the Middle Timan, Ural, and Vishera diamonds in the European part of Russia. These films consist of aluminum, cadmium, calcium, chrome, cerium, copper, gold, iron, lanthanum, lead, magnesium, neodymium, nickel, palladium, silver, tin, titanium, ytterbium, yttrium, zinc, zirconium, and precious metals including even Au_2Pd_3 . The thickness of these films is from fractions of a micrometer to several micrometers. These films are the evidence for the growth of diamonds from carbon dissolved in the melt of gold and palladium [*Makeev and Ivanukh, 2004*]. The coarseness of the diamond crystals in kimberlite and lamprophyre pipes depends on the sizes of precious metal droplets in the respective zone, in the Earth's upper, transitional, and lower mantle.

[49] Investigation of primary fluid inclusions in diamonds has shown a presence of bitumen in diamonds. The primary inclusions preserved in natural diamonds are bitumen inclusions and contain mantle hydrocarbons. This is evidence that the source materials for the abyssal, natural synthesis of diamonds were the hydrocarbon fluids which have saturated the outgassing mantle and enabled mantle silicates to be reduced to native metals. The Brazil natural diamonds were sampled from the Juine kimberlite pipe field of Mato Grosso, Brazil. The Juine Later Cretaceous kimberlites contain five mineral associations related to the different facies and depths which are reflected in Table 4. One of the Juine diamonds sampled near Sao Luis Creek was the lower mantle diamond and comprised the primary fluid inclusions with the lower mantle bitumens [Makeev and Ivanukh, 2004].

[50] Values of $\delta^{13}\text{C}$ for 213 diamonds from the different pipes were analyzed. The $\delta^{13}\text{C}$ values ranged from -1.88‰ to -16‰ [Deines et al., 1989]. The chemical and isotope peculiarities of natural diamonds reflect the different mantle media and environments. Diamonds with $\delta^{13}\text{C}$ from -15‰ to -16‰ come from the region at a lower depth than the natural diamonds with $\delta^{13}\text{C}$ from -5‰ to -6‰ .

[51] From this section, we conclude the following: (1) There is no doubt that diamonds, carbonado, and kimberlites are formed at great depths. (2) Presence of the inhibited primary hydrocarbon inclusions in diamonds, carbonado, and kimberlites testifies that hydrocarbon mantle fluids were a material for synthesis of these minerals in the mantle. (3) Presence of abiotic hydrocarbon fluids in the mantle of the Earth is scientifically proven evidence.

8. PETROLEUM IN METEOR IMPACT CRATERS

[52] Petroleum reserves in meteor impact craters possess great potential. At the present moment, there are ~170 meteor impact craters identified on all continents and in the world ocean bottom. Among them there are giants with diameters of several hundred kilometers. Impact fracturing can occur to depths of 35–40 km and penetrate into the Earth's mantle. The parameters of the biggest meteor impact craters are shown in Table 5 [Masaitis et al., 1980; Carter and Campbell, 1990; Hildebrand and Boynton, 1990; Kerr, 1990; Donofrio, 1998; Oil and Gas Journal, 2006f].

[53] The impact fractures are the result of impacts of asteroids, bolides, and comets on the Earth. When a massive cosmic object impacts the Earth surface with velocity in the range from 15 to 70 km/s, it is accompanied by an explosion. A meteorite with a density of 3500 kg/m³, mass of 2.5×10^{14} g, velocity of 20 km/s, and diameter of 500 m during the moment of impact releases 5×10^{19} J of kinetic energy. That is the equivalent to an explosion of 12×10^9 t of TNT. Such a meteorite impact generates an impact crater of 10–15 km in diameter [Masaitis et al., 1980; Donofrio, 1981; KYTE et al., 1988; Margolis et al., 1991]. According to experiments devoted to mechanisms and models of cratering in the Earth media, the hyperfast impact creates temperature of 3000°C and pressure of 600–900 kbar in rocks of different compositions and generates their disintegration, pulverization, vaporization/exhalation, oxidation, and hydrothermal transformation. As the result of the above mentioned events and processes the meteorite (comet) impact transforms any nonreservoir rock into a porous and permeable reservoir rock [Curran et al., 1977; Masaitis et al., 1980; Donofrio, 1981].

[54] Petroleum reserves were found in onshore and offshore meteor impact crater carbonate, sandstone, and granite rocks over the world [Donofrio, 1998; *Oil and Gas Journal*, 2006f] (Table 5). Granites compose the crystalline basement of meteor impact craters, whereas the carbonates and sandstones compose the sedimentary infill of the crater. Their producing depth is determined from 61 to 5185 m; the total production is from 4.8 to 333,879 m³/d of oil and from 7363 m³/d to 39.6×10^6 m³/d of gas; and the total proven reserves are from 15,899 m³ to 4770×10^6 m³ of oil, 48×10^6 m³ of condensate, and from 56.6×10^6 to 424.8×10^9 m³ of gas [Donofrio, 1998].

[55] The richest petroleum meteor impact crater, Cantarell, is in Mexico. Its cumulative production exceeds 1.1×10^9 m³ of oil and 83×10^9 m³ of gas. The current remnant recoverable reserves are equal to 1.6×10^9 m³ of oil and 146×10^9 m³ of gas in three productive zones. They produce currently 206,687 m³/d of oil, and 70% of it is recovered from carbonate breccia only. (Note that a current petroleum engineering study indicates significantly lower remaining reserves than calculated earlier.) Its porosity is 8%–12%, and the permeability is 3000–5000 mdarcy. Occurring at the Tertiary-Cretaceous boundary, this breccia is genetically related to the Chicxulub impact crater, the diameter of which is now measured to be 240 km [Grajales-Nishimura *et al.*, 2000].

[56] Calculating with an average porosity, permeability, and water saturation of the over-crater breccia and fractured bedrocks of the undercrater crystalline Earth crust together with the rocks which surround the crater, the petroleum potential of a single meteor impact crater having a diameter of 20 km can exceed the total proven oil and gas reserves of the Middle East [Donofrio, 1981]. Donofrio [1981] also estimates that during the last 3000 Myr the meteorite-comet bombardment of the Earth must have created 3060 onshore meteor impact craters of similar diameters. Krayushkin [2000] calculates that 7140 submarine meteor impact craters can be equal to $\sim 12 \times 10^{14}$ m³ of oil and 7.4×10^{14} m³ of gas. The oil and gas in the meteor impact craters cannot be biogenic since (1) any intercrater source rocks are destroyed, disintegrated, melted, and pulverized together with all the other rocks at the site of the meteorite impact [Masaitis *et al.*, 1980] and (2) after the impact any lateral petroleum migration from the noncrater zones into the crater through concentric ring uplifts of 100–300 m high and concentric ring trenches of 100–300 m deep which surround the central uplift of the crater is not enabled.

9. COMMERCIAL PETROLEUM POTENTIAL OF VOLCANIC AND VOLCANO-SEDIMENTARY ROCKS

[57] Commercial oil and gas deposits are found not only in sedimentary rocks. In this section the commercial significance of petroleum accumulations in volcanic rocks and volcano-sedimentary bed complexes is discussed. These petroleum accumulations could be divided into two groups: deposits in buried volcanoes and accumulations that occur in the buried layers of volcanic agglomerates. There are 46 oil- and gas-producing buried volcanoes around the world (Table 6). But more often, the commercial oil and gas accumulations occur in the buried layers of volcanic agglomerates, ashes, lapilli, andesites, basalts, dolerites, and other volcanites as well as in the rock masses consisting of sedimentary beds which intercalate with volcanic rocks. They were found in 79 sedimentary basins of 38 countries around the world. Among

those accumulations, there are 35 giant and supergiant ones, including eight gas fields, four gas and oil fields, and 23 oil fields. Brief information about these giant deposits is presented in Table 7.

[58] The data are taken from *Powers and Behre* [1932], *Waldschmidt* [1948], *Kertai* [1959], *Belov et al.* [1961], *Pletikapić et al.* [1964], *Bagiryan et al.* [1965], *Brognon and Verrier* [1966], *Wopfner* [1966], *Vysotski* [1968a, 1968b], *Lindtrop et al.* [1970], *Pippin* [1970], *Vercellino and Rigo* [1970], *Williams et al.* [1975], *Oil and Gas Journal* [1971], *Oilweek* [1971], *Gas World* [1971], *Nesterov et al.* [1971], *Čverčko and Rudinec* [1972], *Rudinec and Tereska* [1972], *Janků* [1972], *Karović et al.* [1973], *Soeparjadi and Slocum* [1973a, 1973b, 1973c], *Soeparjadi et al.* [1975], *Hopkinson and Nysaether* [1975], *Krayushkin* [1975, 1984, 2000], *Selley* [1975], *Watson and Swanson* [1975], *Alekseeva et al.* [1976], *McCaslin* [1976], *Vysotski* [1976a, 1976b], *Zhuravlev et al.* [1973], *Porfir'ev et al.* [1977], *Porfir'ev and Klochko* [1982], *Katz* [1979], *Scott* [1979], *Sanford* [1980], *P'an* [1982], *Zhabrev* [1983], *Tappmeyer* [1985], *Lindner* [1985], Y. G. Shakhghildyan (Geological principles of development for the volcanogenic type reservoir rocks in the Samgori-Patardzeuli and Muradkhanly fields, synopsis of thesis prepared by Dr. Ph., Institute of Geology and Development of Combustible Minerals, Moscow, 1985), Z. R. Gajiev (Petroleum potential evaluation in the Eocene beds of the Yevlakh-Agjabedin Depression, synopsis of thesis prepared by Dr. Ph., Institute of Geological Sciences, Baku, Azerbaijan, 1986), *Pieri and Mattavelli* [1986], *Maksimov* [1987a, 1987b], *Xiaojun* [1987], *Ovanesov et al.* [1988], *Taylor et al.* [1991], *Hunt et al.* [1992], and *Rach* [2005].

[59] Proven reserves of the giant and supergiant petroleum fields mentioned in Table 7 are equal to a total of 4.1×10^{12} m³ of natural gas and 10.6×10^9 t of oil. Those compose ~6% of the total world proven reserves of oil (180.5×10^9 t as of 1 January 2007, according to *Oil and Gas Journal* [2006m]) and 2.4% of the total world proven reserves of natural gas (175×10^{12} m³ as of 1 January 2007, according to *Oil and Gas Journal* [2006m]).

[60] In the volcanic and volcano-sedimentary sequences, commercial oil and gas deposits are found at depths ranging from 187 m (Chapman, Texas, United States) to 4000 m (Muradkhanly oil field, Azerbaijan) [*Sellards*, 1932; *Ovanesov et al.*, 1988]. The reservoir rocks are andesites, basalts, dolerites, and other volcanic rocks with flow rates varying from 0.13 to 1500 t/d of oil and from 1000 to 500,000 m³/d of natural gas. Oil with a density of 820–893 kg/m³ has been produced from serpentinite which filled the crater of buried volcanoes in petroleum fields such as, e.g., Bacuranao, Guanabo, Jaruco, and Santa Maria in Cuba [*Powers and Behre*, 1932; *Oil and Gas Journal*, 2006c]. Porosity of rocks in these petroleum fields ranges from a tenth of a percent to 22%–36%, permeability ranges from several m² to 2.0×10^{12} m², and thickness of petroleum pay zones ranges from 1 to 600 m.

[61] There are also the territories where petroleum shows are frequently observed in the volcanic rocks exposed on the Earth surface. In the coastal plain of Gulf of Mexico, in the rich petroliferous region of Tampico-Tuxpam (Mexico), there are tens of thousands of active natural seepages of oil and asphalt in andesites, basalts, dolerites, and other exposed volcanic rocks. It is also known that the oil accumulation is associated with andesite and basalt stocks or dolerite sills in oil fields such as Alamo, Chapopote, Ebano, Furbero, Casiano, Los Naranjos,

Panuco, Tlacolula, etc. Since 1 January 1976, Mexico's Poza Rica giant oil and gas field has already produced more than $330 \times 10^6 \text{ m}^3$ of oil and $\sim 106 \times 10^9 \text{ m}^3$ of natural gas from lower Eocene and Cretaceous beds which had been intruded with Mecatepec Plato basalts. Generally, basalts are extensively present within the Old Gold Belt, the oldest petroleum-producing district of Mexico.



Figure 6. The commercial oil and gas fields in the volcanic rocks at the Etna volcano, Sicily. Produced by V. Krayushkin with data from *Vercellino and Rigo [1970]* and *Pieri and Mattavelli [1986]*. Regions are as follows: 1, Pliocene hollow Trapani; 2, Miocene foothill belt; 3, metamorphic basement complex; 4, central Pliocene hollow; 5, platform Ibleo.

[62] *Vercellino and Rigo [1970]* and *Pieri and Mattavelli [1986]* reported nine commercial gas fields around the Etna volcano, Sicily, Italy. Bronte, Casalini, Feudo Grande, Miraclia, and Rizzo gas fields (*Figure 6*) have supplied natural gas to Catania, Cisina, Palermo, and other towns and settlements in Sicily during more than 30 years [*Vercellino and Rigo, 1970; Pieri and Mattavelli, 1986*]. As for oil, oil shows are regularly associated with basalts, dolerites, and pyroclastites (Francavilla, Kozzo Grillo, Likodia Evbea, Modjio, Passero, Paterno, Scikli, and Vizzini, near the Etna volcano). A commercial quantity of oil is predominantly produced from the Triassic-Jurassic carbonates intruded with numerous dykes and veins of basalt, gabbro, or other volcanic rocks. Sometimes, the intrusive igneous bodies themselves are reservoir rocks, e.g., as in the Raguza oil field [*Kafka and Kirkbride, 1961; Vercellino and Rigo, 1970*].

[63] It was commented above that the Earth's mantle gases escape through the serpentinites in the recent spreading centers and axes at the sea bottom of the world ocean. Similar ultrabasics related to outgassing can be observed at three sites within Turkey as follows:

[64] 1. On the Mediterranean shore, 25 km southwest of Iskenderun, in the village of Ekber and around the high mountains which are composed of serpentinites, the serpentinite is heavily fractured, and the fractures/fissures exhale combustible gases that have been burning for many centuries.

[65] 2. Farther in Turkey, the ophiolite massif of the eastern Taurus Mountains is also petroliferous near Van Lake. Five kilometers south of the village of Kurzot the great body of serpentines is exposed between volcanic breccia, dark-colored effusives, recrystallized limestones, and crystalline schists. In a tunnel driven in 1919, crude oil has been produced in enough quantities to supply the entire boat fleet on Van Lake with the extracted fuel.

[66] 3. One of the most intensive outgassings of the Earth's mantle has been detected in the seashore of Antalya Bay, ~ 40 km south of the Antalya mountain. Here the natural gas proceeds come from serpentinites. This gas contains 83% of methane and 14% of ethane and has been known to burn uninterruptedly for 2500 years. All attempts to extinguish the flame have proved unsuccessful. The temperature of serpentinites around the burning gas gusher is very high, and this is why even if the fire was somehow extinguished, a spontaneous inflammation renewed the fire [*Powers, 1932; Tasman, 1959; Dott and Reynolds, 1969; Owen, 1975*].

[67] As for recent volcanoes, *Markhinin* [1985] established the presence of petroleum in extrusive products of recent active volcanoes in Kamchatka and on the Kurile Isles, Russia (Avatcha, Bezimyanny, Klyutchevskoy, Shivelutch, Tolbatchik, Uzon, Alaid, and Tyatya), as well as on the island of Bali, Indonesia (Agung volcano). All samples of volcanic ashes, bombs, and slags cut without any outside contamination from the above mentioned volcanoes contained n -C₁₅– n -C₃₆ alkanes, C₁₈–C₂₆ iso-alkanes, cycloalkanes, and monocyclic and polycyclic aromatic hydrocarbons [*Markhinin*, 1985].

[68] Numerous petroleum shows/indications were also registered in kimberlite of the Udachnaya diamond-bearing pipe (Siberia, Russia) and in its encompassed sedimentary rocks (the Middle and Upper Cambrian). Here the petroleum is present in the form of yellowish liquids, black malphas, and asphalt. The kimberlite body is also intensively saturated with heavy oil and bitumen, which occur in the fractured and brecciated zones of the kimberlite body. This oil contains n -alkanes, 12- and 13-methyalkane, porphyrin complexes, etc. [*Safronov et al.*, 2005]. It was estimated that the sedimentary rocks which composed the Udachnaya diamond-kimberlite pipe must have contained $\sim 3.4 \times 10^9$ t oil before being degraded [*Budanov et al.*, 1986]. According to *Goldberg and Makarov* [1966] the zones which were exposed to a thermal action of the kimberlite melting had not contained bitumen but had been rich in liquid oil. Therefore, *Goldberg and Makarov* [1966] are convinced that there were not any oil shows in the kimberlite field area until the formation of the pipe: oil and other hydrocarbons migrated there during the post–Later Devonian to pre–Later Permian time; that is, the oil and gas that accumulated there after the kimberlite explosion are not of biotic origin and migrated from a distance into the fractured reservoir space generated by the explosion.

[69] The presence of oil and gas deposits in volcanic and volcano-sedimentary rocks can support the abiogenic origin of petroleum where there is no geochemical evidence confirming genetic connection between the oil and gas in volcanic and crystalline rocks and corresponding source rocks. It is highly probable in areas where petroleum accumulated in volcanic rocks exposed on the Earth's surface with no potential source rocks around.

10. OIL AND GAS FIELDS IN THE PRECAMBRIAN CRYSTALLINE BASEMENT OF SEDIMENTARY BASINS

[70] The crystalline crust of the Earth is the basement of 60 sedimentary basins with commercial oil and gas deposits in 29 countries of the world. Additionally, there are 496 oil and gas fields in which commercial reserves occur partly or entirely in the crystalline rocks of that basement. Fifty-five of them are classified as giant fields (>500 megabarrels (Mbbls)) with 16 nonassociated gas, 9 gas-oil, and 30 undersaturated oil fields among them (Table 8). They contain 9432×10^9 m³ of natural gas and $32,837 \times 10^6$ t of crude oil, i.e., 18% of the total world proven reserves of oil and $\sim 5.4\%$ of the total world proven reserves of natural gas (as of 1 January 2007).

[71] In the crystalline basement the depths of the productive intervals vary from 900 to 5985 m. The flow rates of the wells are between 1–2 and 2400 m³/d of oil and 1000–2000 and 2.3×10^6 m³/d of gas. The pay thickness in a crystalline basement is highly variable. It is 320 m in the Gomez and Puckett fields, United States; 680 m in Xinglontai, China; and 760 m in the

Dnieper-Donetsk Basin (DDB)'s northern flank. The petroleum saturated intervals are not necessarily right on the top of the crystalline basement. Thus, oil was discovered at a distance of 18–20 m below the top of the crystalline basement in the La Paz and Mara fields (western Venezuela) and 140 m below the basement's top in Kazakhstan's Oimasha oil field. In the Baltic Shield, Sweden, the 1 Gravberg well produced 15 m³ of oil from the Precambrian igneous rocks of the Siljan Ring impact crater at the depth of 6800 m. In the Kola segment of the Baltic Shield several oil-saturated layers of Precambrian igneous rocks were penetrated by the Kola ultradeep well at the depth range of 7004–8004 m.

[72] One of the most successful stories of the practical application of the theory of the abyssal abiogenic origin of petroleum in exploration is the exploration in the DDB, Ukraine [*Chebanenko et al., 2002*]. It is a cratonic rift basin running in a NW–SE direction between 30.6°E and 40.5°E. Its northern and southern borders are traced from 50.0°N to 51.8°N and 47.8°N to 50.0°N, respectively. In the DDB's northern, monoclinal flank the sedimentary sequence does not contain any salt-bearing beds, salt domes, or stratovolcanoes and contains no source rocks. Also, this flank is characterized by a dense network of numerous synthetic and antithetic faults. These faults create the mosaic fault block structure of the crystalline basement and its sedimentary cover, a large number of fault traps (the faulted anticlines) for oil and natural gas, and alternation uplifts (horsts) and troughs (grabens). The structure of the DDB's northern flank excludes any lateral petroleum migration across it from either the Donets Foldbelt or the DDB's Dnieper Graben.

[73] Consequently, the DDB's northern flank was qualified earlier as not a prospect for petroleum production due to the absence of any “source rock of petroleum” and to the presence of an active, highly dynamic artesian aquifer. However, after a while the prospectivity of this area was reinterpreted and reexamined in compliance with the theory of the abyssal abiogenic origin of petroleum starting with the detailed analysis of the tectonic history and geological structure of the crystalline basement in the DDB's northern monoclinal flank. Subsequently, respective geophysical and geochemical prospecting programs were accepted primarily for exploring deep-seated petroleum.

[74] In the late 1980s to early 1990s, 61 wells were drilled in the DDB's northern flank. Thirty-seven of them proved commercially productive (the exploration success rate is as high as 57%), discovering commercial oil and gas strikes in the Khukhra, Chernetchina, Yuliyevka, and other areas. A total of 12 oil and gas fields was discovered, worth \$4.38 billion in the prices of 1991 and \$26.3 billion in the prices of 2008. For the discovery of these new oil and gas accumulations, I. I. Chebanenko, V. A. Krayushkin, V. P. Klochko, E. S. Dvoryanin, V. V. Krot, P. T. Pavlenko, M. I. Ponomarenko, and G. D. Zabello were awarded the State Prize of Ukraine in the Field of Science and Technology in 1992 [*Chebanenko et al., 2002*].

[75] The geochemical peculiarity of the DDB's northern flank petroleum province is that oil and gas are accompanied by unusually high quantities of helium, which is most abundant in natural gas and crude oil from the crystalline basement. For example, the Yuliyevskoye giant oil and gas condensate field contains not less than 180×10^6 m³ of helium. Helium is understood to generate radiogenically from the crystalline crust in the granitic composition and can be transported to significant distances in the Earth's crust by a carrier fluid only

(hydrocarbons, carbon dioxide, and nitrogen). To accumulate $180 \times 10^6 \text{ m}^3$ of helium in the Yuliyevskoye field, natural gas and crude oil must come upward the long way through the crystalline Earth's crust of the DDB's northern flank.



Figure 7. Geological cross section of lower portion of the Chernetchinskoye (left and middle blocks denoted by the dashed lines) and Khukhrinskoye oil fields, the Dnieper-Donets Basin, Ukraine. Patterns are as follows: 1, oil; 2, crystalline basement granites; 3, basement crust of weathering; 4, fault.

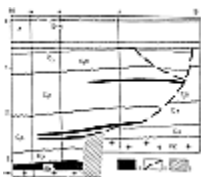


Figure 8. Transversal geological section of the Yevgeniyevskoye gas fields, the Dnieper-Donets Basin, Ukraine. Patterns are as follows: 1, natural gas; 2, fault; 3, deep fault zone.

[76] Today there are 50 commercial gas and oil fields known in the DDB's northern flank. Data obtained from drilling in many of these areas show that the crystalline basement of the northern flank consists of amphibolites, charnockites, diorites, gneisses, granites, granodiorites, granito-gneisses, migmatites, peridotites, and schists. Thirty-two of the commercial fields have oil and/or gas accumulations in sandstones of the Middle and Lower Carboniferous age. Sixteen other fields contain reservoirs in the same sandstones but separately from them, in amphibolites, granites, and granodiorites of crystalline basement as well (Table 9 and Figures 7 and 8). Two fields contain oil pools in the crystalline basement only.

[77] An exploration drilling in the DDB's northern flank has discovered five petroleum reservoirs in the Precambrian crystalline basement rock complex at depths ranging from several meters to 336 m below the top of crystalline basement. Gas and oil shows have been found in the Precambrian crystalline basement rocks as deep as 760 m below the top of the crystalline basement. The seal rocks for the reservoirs in the Carboniferous period sandstones are shallower shale formations. This is typical for petroleum pools in sedimentary beds. The caprock for the reservoirs in the Precambrian crystalline basement is the impervious, nonfractured, essentially horizontal, layer-like zones of crystalline rock which alternate with the fractured, uncompacted, bed-like zones of granite, amphibolite, and the other crystalline rocks mentioned above [Krayushkin *et al.*, 2001].

[78] The exploration drilling in the DDB's northern flank is still in progress and continues to yield success in the $100 \times 600 \text{ km}$ petroliferous strip of the DDB's northern flank. Its proven petroleum reserves are already equal to $289 \times 10^6 \text{ t}$ (\$230 billion at 50 U.S. dollars/bbl oil prices). The DDB's northern flank is even more attractive with its total prospective in-place petroleum resources which amount to $\sim 13,000 \times 10^6 \text{ t}$ ($\sim 80,000 \text{ bbls}$) of oil equivalent in an area of $48,000 \text{ km}^2$. The petroleum potential of the DDB's southern flank should not be neglected either, with total in-place prognostic petroleum resources of $\sim 6000 \times 10^6 \text{ t}$ of oil equivalent in an area of $22,000 \text{ km}^2$. Here several promising leads with oil shows can be found in the crystalline basement and its sedimentary cover [Chebanenko *et al.*, 1996].

[79] The data are taken from Powers [1932], *American Association of Petroleum Geologists Bulletin* [1953], Beach [1948], Eggleston [1948], Walters and Price [1948], Walters [1953], Travis [1953], Hubbert and Willis [1956], Smith [1956], Sproule [1957, 1962], Landes et al. [1960], Merriam et al. [1961], Rogers [1961], Khaimov [1963], Khamrabayev et al. [1964], Wopfner [1966], Vysotski [1968a, 1968b], Mikić et al. [1969], Vujkov [1969], Agutenkov [1970], Lindtrop et al. [1970], Pippin [1970], Klimushina et al. [1971], Nesterov et al. [1971], Williams [1972], Janků [1972], Zhuravlev et al. [1973], Janković et al. [1974], Durica [1974], Soeparjadi et al. [1975], Vasquez [1975], Babikov et al. [1976], Vysotski [1976a, 1976b], McCaslin [1976], Deroo et al. [1977], Porfir'ev et al. [1977, 1978], Porfir'ev and Klochko [1982], Clement and Mayhew [1979], Towar and Taruno [1979], Brown [1980], Stuart-Gordon [1980], Klimenko et al. [1981], Durkee [1982], Gerhard et al. [1982], Gorin et al. [1982], Guangming and Quanheng [1982], P'an [1982], Koning and Darmono [1984], Krayushkin [1984, 1999], Krayushkin et al. [2000], Carter et al. [1986], Hallett et al. [1985], Loucks and Anderson [1985], Yarbrough [1985], Alsharhan and Kendall [1986], Popkov et al. [1986], Wiman [1987], Maksimov [1987a, 1987b], Xiaojun [1987], Ullah et al. [1988], Walrond and Clare [1988], Zahran and Askary [1988], Chen [1989], Misra [1990], Zhang [1990], Zhukov et al. [1990], Taylor et al. [1991], Areshev et al. [1992], Aguilera [1993], Khalil and Pigant [1991], *Oil and Gas Journal* [1993b, 1995b], Morissey [1996], Chebanenko et al. [1996, 2002, 2005], Roux [1997], *Oil and Gas Journal* [1999b], Kochetkov et al. [2000], *Oil and Gas Journal* [2000b], Krayushkin et al. [2001], *Oil and Gas Journal* [2001], Young [2001], Abraham [2004], Areshev et al. [2004], Fischer [2004, 2005], Danilkin [2005], Rach [2005], and *Oil and Gas Journal* [1993c, 2005f, 2006k].

[80] Abyssal abiogenic petroleum has been discovered in China as well: the giant Xinjiang gas field contains $\sim 400 \times 10^{12} \text{ m}^3$ of abiogenic natural gas [Zhang, 1990]. Chinese petroleum geologists estimated this quantity in volcanic island arcs, transarc zones of mud volcanism, transarc rift basins, transarc epicontinental basins, deep fault zones, and continental rift basins.

[81] In conclusion, (1) according to the traditional biotic petroleum origin hypothesis the DDB's northern flank was qualified as possessing no potential for petroleum production. (2) Based on the theory of the abyssal abiogenic origin of petroleum, 50 commercial gas and oil deposits were discovered in this area; this is the best evidence confirming the theory.

11. PETROLEUM PRESENCE IN DEEP AND ULTRADEEP SEDIMENTARY ROCKS

[82] In this section we discuss how far the distribution, location, and reservoir conditions in the deep and ultra-deep petroleum deposits can be explained by the traditional biotic petroleum origin. The key points are as follows:

[83] 1. Deep and ultra-deep petroleum fields are below the main zone of petroleum formation determined by the traditional biotic petroleum origin hypothesis, i.e., the depth of 2–4 km and in exceptional cases, down to the depth of 6 km.

[84] 2. Reservoir temperature of these fields is much higher than the optimal temperature range of the traditional biotic hypothesis of petroleum formation.

[85] 3. The biotic hypothesis suggests that with growing depth and temperature, hydrocarbons are destroyed and reservoir rock porosity drops; thus, petroleum reserves should be significantly reduced. A presence of more than 1000 petroleum deposits at the depth 5–10 km all over the world contradicts these points, as seen in [sections 11.1–11.4](#).

[86] There are more than 1000 commercial petroleum fields producing oil and/or natural gas from sedimentary rocks at the depths of 4500–10,428 m. These fields were discovered in 50 sedimentary basins around the world.

11.1. Russia

[87] A number of oil and gas fields have been discovered at the depth of 4000–4600 m in Russia. The cumulative production of these fields is equal to 421×10^6 t of oil, 45.5×10^9 m³ of the associated oil gas, and 641×10^6 m³ of natural gas. Although these fields are not “ultradeep” reservoirs, they are interesting from our point of view: they are associated with deep faults intersecting the whole sedimentary rock sequence. The “roots” of these deep faults extend underneath the basement part of the lithosphere. The roots form vertical columns (“pipes”) of high permeability/petroleum saturation, and chains of oil and gas accumulations are connected to them. It was established that the traces of petroleum migration are entirely absent outside of anticline crests [*Istratov, 2004*].

11.2. Ukraine

[88] Seventeen giant and supergiant gas fields were discovered in the Lower Carboniferous age sandstones of the Dnieper-Donets Basin at the depth range of 4500–6287 m. At these depths, the total proven reserves of natural gas is 142.6×10^9 m³. The total recoverable reserves of condensate is 2.3×10^6 t [*Gozhik et al., 2006*].

11.3. North Sea Basin

[89] Commercial gas, condensate, and oil fields have been found at the depth of 4880–5760 m in the Jurassic sandstones of the North Sea Basin. All these deposits have anomalously high reservoir temperatures of 200°C–340°C [*Lasocki et al., 1999; Knott, 1997*].

11.4. United States

[90] In the United States more than 7000 boreholes with TD deeper than 4575 m were drilled between 1963 and 1979. Recent discoveries Jack-1 and Jack-2 in Walker Ridge, Gulf of Mexico, confirm the presence of commercial oil reservoirs as deep as 8000–9000 m [*Choudhury and Borton, 2007*]. In the Mesozoic-Cenozoic rift system of the Gulf of Mexico a region of deep to ultradeep (the Upper Cretaceous) sands has been observed. With a width of 32–48 km and a length of 520 km this trend extends along the Gulf of Mexico from New Orleans to the borderline between Louisiana and Texas. Many oil and gas fields were found in this formation over the area indicated at the depths of 4500–6100 m. Most of them have anomalously high reservoir temperatures (Freeland field, 232°C) that are much higher than the optimal temperature of petroleum formation from ancient organic materials. The total proven

reserves of natural gas in the Tuscaloosa trend is equal to $170 \times 10^9 \text{ m}^3$, but there is an opinion that only the central portion of it contains potential resources, as much as $850 \times 10^9 \text{ m}^3$ of natural gas and $240 \times 10^6 \text{ m}^3$ of condensate [King, 1979; Matheny, 1979; Pankonien, 1979; Sumpter, 1979].

[91] In the deepwater portion of the Gulf of Mexico, United States, 20 ultradeep oil and gas fields have been found at the depth of 7300–10,500 m (Table 10). Their reservoirs are predominantly Oligocene, Eocene, and Paleocene turbidites. The petroliferous area is equal to $40 \times 10^3 \text{ km}^2$ with recoverable reserves of oil from 1430×10^6 to $2385 \times 10^6 \text{ m}^3$. This is 42%–70% of the total recent proven oil reserves in the United States (1 January 2007). Data are taken from following sources: McCaslin [1976], Grow [1998], Henderson [1998], Fischer [2001, 2004, 2005], *Oil and Gas Journal* [2002a, 2004a, 2003, 2004b, 2005a, 2006h], Ashcroft and Schmidt [2005], *Oil and Gas Journal* [2005b, 2005c, 2006a], Meyer et al. [2005], Rach [2005], *Oil and Gas Journal* [2005d, 2005e, 2006b, 2006c, 2006d, 2006e, 2006g, 2006i, 2006j, 2006m, 2007a], and Choudhury and Borton [2007].

[92] A total of 40 giant and supergiant petroleum fields was discovered at the depths of 4500–10,500 m over the world (Table 10). The data are taken from the following sources: McCaslin [1976], Masters [1979], Zhabrev [1983], Loucks and Anderson [1985], Wiman [1987], Maksimov [1987a, 1987b], *Oil and Gas Journal* [1987], Carnevali [1988], Snyder [1973], Petzukha [1990], Anderson [1993], Heafford and Lichtman [1993], *Oil and Gas Journal* [1995a, 1996a, 1996b, 1998, 1999a, 1999d], Connell et al. [2000], *Oil and Gas Journal* [2000a], Fischer [2002, 2003, 2006], *Oil and Gas Journal* [2002b], Meyer et al. [2005], Rach [2005], and *Oil and Gas Journal* [2005e, 2006b, 2006c, 2006g, 2006i, 2006j, 2007a].

12. SUPERGIANT OIL AND GAS FIELDS IN LIGHT OF THE PETROLEUM ORIGIN THEORIES

[93] One of the main problems of the traditional biotic petroleum origin hypothesis is the identification of biotic sources and material balance of the hydrocarbon generation for most supergiant oil and gas fields.

12.1. Middle East

[94] In the Middle East, proven recoverable reserves are equal to $101 \times 10^9 \text{ t}$ of oil and $73.5 \times 10^{12} \text{ m}^3$ of gas as of 1 January 2007 [*Oil and Gas Journal*, 2006m]. Saudi Arabia's proven reserves are $36 \times 10^9 \text{ t}$ of oil and $7 \times 10^{12} \text{ m}^3$ of natural gas [*Oil and Gas Journal*, 2006m]. Most of these reserves are located in ten supergiant gas and oil fields (Table 11) [McCaslin, 1976; Alhajji, 2001; Foreign Policy, 2006].

[95] These giant oil fields give oil production from the Jurassic-Cretaceous granular carbonates. All these crude oils have very similar composition referring to a common source. Such a source is the Jurassic-Cretaceous thermally mature, thin-bedded organic rich carbonate sequence (3–5 mass %). Organic material is concentrated in dark, 0.5–3.0 mm thin beds alternating with the lightly colored, similarly thin beds poor in organics. Let us make a calculation of the oil that might have been generated inside the basins of Saudi Arabia with an

estimated original oil in place (OOIP) of $127 \times 10^9 \text{ m}^3$ [*Oil and Gas Journal*, 2006m]. Areas within the sedimentary basins where the kerogen is mature (i.e., H/C ratio is 0.8–1.3) were mapped [*Ayres et al.*, 1982] and multiplied by the thickness of the source zones. This simple calculation gives a volume of petroleum source rocks as high as 5000 km^3 . If we accept that (1) the volume of kerogen is equal to 10% of the petroleum source rock volume, (2) the coefficient of transformation of kerogen into bitumen is equal to 15%, and (3) 10% of this bitumen can migrate out of the petroleum source rocks, we come to the conclusion that only $7.5 \times 10^9 \text{ m}^3$ of oil could migrate out of the petroleum source rocks. This is <6% of Saudi Arabia's estimated in-place oil reserves. Note that if the kerogen transformation parameters are twice as high as taken here (i.e., 20%, 30%, and again 20%), the OOIP is still $60 \times 10^9 \text{ m}^3$, i.e., half of the booked value.

[96] Where did 94% of Saudi Arabia's recoverable oil come from? This question is not a rhetorical one because any other sources of beds of petroleum are absent in the subsurface of Saudi Arabia as well as of all countries mentioned above, according to *Ayres et al.* [1982] and *Baker and Dickey* [1984]. Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, and Yemen reside in the same sedimentary basin, the Arabian-Iranian Basin, where *Dunnington* [1958, 1967] established the genetic relationship, i.e., the single common source of all crude oils.

12.2. Canada

[97] The west Canadian sedimentary basin attracts great attention also. There is the unique oil/bitumen belt extended as the arc-like strip of 960 km length from Peace River through Athabasca (Alberta) to Lloydminster (Saskatchewan). This belt includes such supergiant petroleum fields as Athabasca (125 km width and 250 km length), Cold Lake (50 km width and 125 km length), Peace River (145 km width and 180 km length), and Wabaska (60 km width and 125 km length). Here the heavy ($946.5\text{--}1.029 \text{ kg/m}^3$) and viscous (several hundred to several million centipoises) oil saturates the Lower Cretaceous sands and sandstones. These fields contain in-place oil reserves equal to 92×10^9 to $187 \times 10^9 \text{ m}^3$ in Athabasca, 32×10^9 to $75 \times 10^9 \text{ m}^3$ in Cold Lake, 15×10^9 to $19 \times 10^9 \text{ m}^3$ in Peace River, and 4.5×10^9 to $50 \times 10^9 \text{ m}^3$ in Wabaska and 2×10^9 to $5 \times 10^9 \text{ m}^3$ of oil/bitumen in Lloydminster, totaling 170×10^9 to $388 \times 10^9 \text{ m}^3$ [*Vigrass*, 1968; *Wennekers*, 1981; *Seifert and Lennox*, 1985; *Oil and Gas Journal*, 1992b; *Warters et al.*, 1995].

[98] The conventional understanding is that the oil of Athabasca, Cold Lake, Lloydminster, Peace River, and Wabasca generated from dispersed organic matter buried in the argillaceous shales of the Lower Cretaceous Mannville Group only. It is underlain by the pre-Cretaceous regional unconformity, and its thickness varies from 100 to 300 m. Its total volume is $\sim 190 \times 10^3 \text{ km}^3$ with a 65% shale content. From the data of the total organic carbon concentration, the hydrocarbon index, constant of transformation, and all other values from the accepted geochemical model of the oil generation from the buried organic matter dispersed in clays and argillites, it was concluded that the Mannville Group could only give $71.5 \times 10^9 \text{ m}^3$ of oil. This is several times less than the total quantity of oil (see above) estimated before 1985 in Athabasca, Cold Lake, Lloydminster, Peace River, and Wabasca oil sand deposits [*Moshier and Wapples*, 1985].

[99] If we accept other estimations of the volume of oil/bitumen in place in the Athabasca, Wabasca, Cold Lake, and Peace River area ($\sim 122,800 \text{ km}^2$) conducted by Alberta Energy Utilities Board (AEUB) and the National Energy Board (NEB), Canada, the gap between the booked and organically generated quantities is even wider (Table 12). AEUB estimated $270 \times 10^9 \text{ m}^3$ of bitumen in place, while NEB estimated $397 \times 10^9 \text{ m}^3$.

[100] In the above mentioned area, there are additionally 200×10^9 to $215 \times 10^9 \text{ m}^3$ of heavy ($986\text{--}1030 \text{ kg/m}^3$) and viscous (10^6 cP under 16°C) oil at the depth range of $75\text{--}400 \text{ m}$ in the Upper Devonian carbonates (Grosmont Formation). They occur in the area of $70 \times 10^3 \text{ km}^2$ beneath the Athabasca, Cold Lake, Lloydminster, Peace River, and Wabasca oil sand deposits [Wennekers, 1981; Seifert and Lennox, 1985; Hoffmann and Strausz, 1986].

[101] The total estimated reserves of bitumen in place in the above mentioned area is between 370×10^9 and $603 \times 10^9 \text{ m}^3$. If there is no any other petroleum source rock besides the Mannville clays and shales, which could give only $71.5 \times 10^9 \text{ m}^3$ of oil, where is a biotic source for the remaining 82%–88% of oil in this area?

[102] Downdip of Athabasca oil sand deposits, there is the Deep Basin natural gas accumulation (original gas in place of $12.5 \times 10^{12} \text{ m}^3$) which occurs at the depth of $1068\text{--}6100 \text{ m}$ in Upper Cretaceous–Permian beds with a maximum pay gas thickness of 3050 m . This supergiant multilayer gas accumulation of 670 km length and 170 km width extends from southeast to northwest, parallel to the Rockies and subparallel to the Athabasca oil sand area [Masters, 1979]. If there is no other petroleum source rock besides the Mannville clays and shales, where did $12.5 \times 10^{12} \text{ m}^3$ of the Deep Basin natural gas come from?

[103] The western termination of the Deep Basin gas accumulation is conjugated with a deep fault, which is the tectonic boundary between Rockies and the west Canadian basin [Masters, 1979]. According to Tilley *et al.* [1989] the natural gas saturates pores, the walls of which are strewn with numerous druses of hydrothermal ($170^\circ\text{C}\text{--}195^\circ\text{C}$) quartz crystals. These crystals contain the primary fluid inclusions comprising methane, ethane, and propane, which are the main components of the Deep Basin natural gas as well. The thermal history of the Deep Basin provides evidence that the hot fluids migrated up the dip on permeable conglomerates and on fractures along bedding. The obvious relationship of the hot fluids to the western part of the Deep Basin area indicates that the hydrothermal convective heat and mass transfer can act throughout only tens of kilometers in the Lower Cretaceous rocks and can be provided with the hefty influx of fluids from only the deep fault.

12.3. Venezuela

[104] Something similar can be observed in the Bolivar Coastal oil field in Venezuela. According to Bockmeulen *et al.* [1983] the source rock of petroleum here is the La Luna limestone of Cretaceous age. The estimated oil reserves are equal to $4.8 \times 10^9 \text{ m}^3$ [Foreign Policy, 2006] with an oil density of $820\text{--}1000 \text{ kg/m}^3$. The same kind of calculations that were done for Saudi Arabia in section 12.1 give us the following result. One cubic meter of the oil-generating rock contains $2.5 \times 10^{-2} \text{ m}^3$ of kerogen, which can generate $2.5 \times 10^{-3} \text{ m}^3$ bitumen, giving $1.25 \times 10^{-4} \text{ m}^3$ of oil within the accepted geochemical model of biotic petroleum origin.

Having this oil-generating potential and the $4.8 \times 10^9 \text{ m}^3$ of estimated oil reserves of the Bolivar Coastal field as a starting point, the necessary volume of oil source rock would be equal to $3.84 \times 10^{13} \text{ m}^3$. This is consistent with the oil-generating basin area of 110 km across if the oil source rock is 1000 m thick. The average thickness of La Luna limestone is measured as only 91 m [Bockmeulen *et al.*, 1983]. The diameter of the oil-generating basin would be therefore equal to 370 km, and the area of this basin would equal ~50% of the territory of Venezuela, which is geologically highly improbable.

[105] The geological data mentioned above confirm the following: (1) A sufficient biotic source for most giant and supergiant petroleum deposits is unknown. (2) Sedimentary basins of the above mentioned areas are located on the crystalline basement, which is dissected by a network of deep faults and cracks. (3) Oils in the frame of each area mentioned above are genetically similar, i.e., from a single common source. (4) A presence of deep faults under giant and supergiant petroleum deposits and the genetic relationship of petroleum correspond to the theory of the abyssal abiogenic origin of petroleum: mantle fluids migrated through deep faults and cracks in the crystalline basement, penetrated the sedimentary rocks, and created giant and supergiant petroleum deposits.

13. GAS HYDRATES: GREATEST SOURCE OF ABIOGENIC HYDROCARBONS

[106] Gas hydrates are clathrates. They look like ice and consist of gas and water where the molecules of hydrate-forming gas (e.g., Ar, CH₄, C₂H₆, C₃H₈, iso-C₄H₁₀, Cl, CO, CO₂, He, H₂S, and N₂) are squeezed under pressures of 25 MPa and more into the interstices of the water (ice) crystalline cage without any chemical bonding between molecules of water and gas. As a result, thawing 1 m³ of gas hydrate at the sea level produces 150–200 m³ of gaseous methane and 0.87 m³ of fresh water. Naturally, the formation of gas hydrates takes place under a great velocity of fluid movement and under a certain combination of pressure and temperature. For example, methane hydrate arises under conditions of –236°C and 2×10^{-5} MPa and 57°C and 1146 MPa [Klimenko, 1989; Makogon, 1997; Lowrie and Max, 1999; Makogon *et al.*, 2005]. There are also data showing that the formation of gas hydrate from the CH₄-C₃H₈-CO₂-H₂O-H₂S mixture proceeds under such a high temperature increase and such a high pressure decrease that a gas hydrate of one of the above mentioned compositions arises and exists mainly in sea bottom sediments where the depth of the sea is only 50 m, e.g., in the Caspian Sea [Lowrie and Max, 1999].

[107] Visually, the gas hydrates (“combustible ice”) are the aggregate growths of transparent and semitransparent white, gray, or yellow crystals. They can partially or entirely saturate the natural porous media, adding mechanical strength and acoustic hardness to sediments and sedimentary rocks. Boreholes and seismic surveys have established that methane hydrates occur in the polar regions of Asia, Europe, and North America and in 93%–95% of the world ocean where the combustible ice is always underlaid with natural gas [Trofimuk *et al.*, 1975; Panaev, 1987; Collet, 1993; Dillon *et al.*, 1993; Kvenvolden, 1993].

[108] Gas hydrates represent a huge unconventional resource base: it may amount to $113 \times 10^{17} \text{ m}^3$ of methane according to the U.S. Geological Survey [Oil and Gas Journal, 1999c]. The

global resources of natural gas which underlay the combustible ice were not known for a long time. Recently, they have been evaluated because of data from the Outer Blake Ridge (U.S. Atlantic offshore) and from the Messoyakha gas and gas hydrate field (west Siberia, Russia). The Outer Blake Ridge contains $56.1 \times 10^{12} \text{ m}^3$ of methane, including $36.8 \times 10^{12} \text{ m}^3$ of hydrate methane and $19.3 \times 10^{12} \text{ m}^3$ of the free natural gas underlaying the methane hydrate [Makogon *et al.*, 2005]. In the Messoyakha field the cumulative gas production is equal to $12.2 \times 10^{12} \text{ m}^3$ of methane, including $6.5 \times 10^{12} \text{ m}^3$ of gas hydrate methane and $5.7 \times 10^{12} \text{ m}^3$ of free natural gas.

[109] Thus, the share of methane hydrate is equal to 66% while the share of free natural gas below the methane hydrate equals 34% in the Outer Blake Ridge. In the Messoyakha field the same ratio is 53.5% (share of methane hydrate) and 46.5% (the underlaying free natural gas). Applying these ratios to the global resources of methane hydrate ($113 \times 10^{17} \text{ m}^3$ of methane), the global resources of free methane underlaying the methane hydrate layer could be in the range from 40×10^{17} to $53 \times 10^{17} \text{ m}^3$ of methane. The global resources of methane hydrate and free natural gas underlaying the methane hydrate are equal to 152×10^{17} to $166 \times 10^{17} \text{ m}^3$ of methane.

[110] There is another aspect concerning the origin of the tremendous global resources of gas hydrates, mode of their migration, and time of accumulation. The global amount of noncarbonate carbon is as follows: (1) the organic matter of the atmosphere is $\sim 3.6 \times 10^9 \text{ t}$, (2) the organic matter of marine biota is $3 \times 10^9 \text{ t}$, (3) the organic matter of land biota is $830 \times 10^9 \text{ t}$, (4) detrital organic matter is $60 \times 10^9 \text{ t}$, (5) the organic matter of peat is $500 \times 10^9 \text{ t}$, (6) the organic matter dissolved in waters is $980 \times 10^9 \text{ t}$, (7) organics of soil are $1400 \times 10^9 \text{ t}$, and (8) recoverable and nonrecoverable fossil fuels (coal, oil, and gas) are $5000 \times 10^9 \text{ t}$, i.e., totaling $\sim 8800 \times 10^9 \text{ t}$. The dispersed organic carbon such as kerogen and bitumen equals nearly 1000 times the total amount mentioned above [Kvenvolden, 1993] and together with the above sum is equal to $8.8 \times 10^{15} \text{ t}$.

[111] The atomic mass ratio between carbon and hydrogen in the molecule of methane is 0.75. With such a ratio the global reserves of carbon in the global resources of gas hydrate and underlaying free gas will be equal to 114×10^{17} to $124 \times 10^{17} \text{ t}$. In other words, the amount of carbon in the gas hydrates and underlaying free natural gas is 1300–1400 times higher than the global quantity of the organic carbon concentrated in the atmosphere, land and marine biota, detrital organics, peat, soil, water, recoverable and nonrecoverable fossil fuels, and dispersed organics such as kerogen and bitumen combined. Therefore, it is clear that the Earth's organics cannot be the source material of the world reserves of gas hydrate and underlaying free gas.

[112] The top of the supergiant gas hydrate and free natural gas accumulations occurs at a depth of 0.4–2.2 m below the sea bottom in the Recent sediments of the world ocean. The bottom of these accumulations is subparallel to the sea bottom surface and intersects beds with anticlinal, synclinal, and tilted forms. This geometry, the geographical distribution of hydrates over 93%–95% of the world ocean, their Recent to Pleistocene age, and the freshwater nature of combustible ice could not be explained by terms (source rocks; diagenesis and katagenesis/metagenesis of any buried, dispersed organic matter; and lateral migration of natural gas) used in the traditional biotic petroleum origin hypothesis.

[113] According to the theory of the abyssal abiogenic origin of petroleum all gas hydrate and free natural gas accumulations were formed because of “one worldwide act,” i.e., an upward vertical migration of abyssal abiogenic mantle fluid through all the faults, fractures, and pores of rocks and sea bottom sediments. In that time, not more than 200 kyr ago, those faults, fractures, and pores were transformed by a supercritical geofluid (mixture of supercritical water and methane) into a conducting/accumulating/intercommunicating media. Acting as natural “hydrofracturing,” the abyssal geofluid has opened up cavities of cleavage and interstices of bedding in rocks and sediments as well. According to *Dillon et al. [1993]* the vertical migration of natural gas still takes place today on the Atlantic continental margin of the United States. Along many faults there the natural gas continues to migrate upward through the combustible ice as through a “sieve” that is distinctly seen as torch-shaped vertical strips in the blanking of seismographic records.

[114] The proven natural gas reserves of the world are equal to $175 \times 10^{12} \text{ m}^3$ [*Oil and Gas Journal, 2006m*]. This is 85,000–95,000 times less than the global resources of methane hydrate and its underlaying free natural gas. In 2006 the annual world production of natural gas was equal to $2836 \times 10^9 \text{ m}^3$ [*Oil and Gas Journal, 2007b*]. So the global reserves of methane hydrate together with the global reserves of free natural gas underlaying the methane hydrate will be enough for the next 5–6 Myr if consumption is kept at the present rate.

14. ETHANE AND PROPANE ACCUMULATIONS IN SEDIMENTARY ROCKS

[115] There are some new discoveries which could be taken into consideration as evidence for the theory of the abyssal abiogenic origin of petroleum. One of the most interesting pieces of evidence is a discovery of ethane and propane accumulations in sedimentary rocks and sediments. So due to the Ocean Drilling Program [*Fischer, 2006*] the drill cores were taken off the Peruvian coast in the 396.5 m deep sediment using the research drilling vessel *JOIDES Resolution*. A team of researchers has found ethane and propane accumulations in the core samples. The carbon isotope compositions are markedly different from the thermogenic gases formed at high temperatures [*Fischer, 2006*].

[116] An ethane deposit was also found in the sedimentary rocks of the Ross Sea, Antarctica. In the deep (400–1000 m) water part of the sea there are three great sedimentary basins: Eastern, Central, and Victoria Land. They strike from the north to the south and are related to the tensional deformation belt between East and West Antarctica. This belt comprises the Upper Cretaceous and younger sedimentary rocks in a total thickness of 5–6 km. In the deeper parts these three basins are separated from each other with the uplifted and eroded ridges of basement rocks. In the Ross Sea region the crude oil is not known, but the well drilled here under the auspices of the Deep Sea Drilling Project has flowed with ethane [*Cooper and Davey, 1986*]. A pure ethane deposit might not be generated from the organic materials. Where did it come from? Scientists from the Minnesota State University established that methane, ethane, and some higher hydrocarbons can be naturally and nonbiogenically generated below the sea bottom along the mid-ocean ridges. There are numerous hot hydrothermal vents flowing with superheated fluids into seawater along the Mid-Atlantic Ridge. The hydrocarbons (methane, ethane, and propane) can arise to the surface of minerals rich in iron and chrome,

according to the $\text{CO}_2 + \text{H}_2$ reaction at a temperature of more than 371.4°C and pressure of 41.5 MPa [*Fischer, 2005*].

15. PETROLEUM POTENTIAL OF THE EARTH'S MANTLE

[117] How large are the petroleum resources of the Earth's mantle? *Giardini et al. [1982]* studied primary fluid inclusions and solid mineral inclusions in natural diamonds of Africa, Brazil, and Arkansas, United States, and arrived at the following conclusions:

[118] 1. About 52% of the gas phase volume in those inclusions consists of petroleum-forming materials such as H_2O , CO_2 , CO , CH_4 , etc.

[119] 2. The average composition of the gas phase of primary fluid inclusions in diamonds from Zaire (% mass) is as follows: H_2O , 69.6; CO_2 , 20.5; CH_4 , 4.7; CO , 3.0; Ne, 1.2; H_2S , 1.0; and Ar, 0.2, as well as traces of C_2H_4 , C_3H_6 , C_4H_8 , and C_4H_{10} .

[120] 3. The carbon isotope composition of diamonds and CO_2 in the primary fluid inclusions indicates that diamonds and hydrocarbon substances are the products of transformation of the C-H-O system in the Earth's mantle. The depth of diamond formation varies from 70 to 370 km, while the diamond formation media are partially the melted silicates containing H and C. Petroleum source materials are supposed to be concentrated in the topmost part of the Earth's upper mantle.

[121] 4. For the last 3 Myr, $\sim 3 \times 10^6$ t of nonbiogenic hydrocarbons have been outgassed through every square kilometer of the Earth's surface. As a result, the Earth's abyssal interior has lost 10^{16} t of hydrocarbons, while its residual resources of nonbiogenic petroleum are equal to 10^{15} t in the Earth's subcrustal region [*Giardini et al., 1982*].

[122] The data published by *Giardini et al. [1974, 1982]*, *Giardini and Melton [1975]*, *Melton and Giardini [1974, 1975]*, *Mitchell and Giardini [1977]*, and *Musatov and Mezhelovski [1982]* indicate that the African, Arkansas, and Navajo kimberlites contain 2356–9187 g/t of hydrocarbons. According to *Harris et al. [1997]* and *Makeev and Ivanukh [2004]*, there are diamonds in the Earth's lower mantle too.

[123] It is possible to consider that the whole mantle of the Earth is a diamond-bearing and petroliferous substance. The mass of the mantle according to *Markhinin [1985]* is 4.05×10^{21} t. So looking at the total concentration (2356–9187 g/t) of hydrocarbons in kimberlites, the petroleum potential of the Earth's whole mantle is measured to be in the range of 95×10^{17} to 372×10^{17} t. This result corresponds to the data from U.S. Geological Survey [*Oil and Gas Journal, 1999c*], where it was estimated that the global resources of methane are equal to 113×10^{17} m³ in the shallow gas hydrate body of the Earth only.

16. CONCLUSIONS

[124] Geological data presented in this paper do not respond to the main questions related to the hypothesis of biotic petroleum origin. Only the theory of the abyssal abiogenic origin of

petroleum gives a convincing explanation for all of the above mentioned data. The experimental results discussed in the paper confirm that the $\text{CaCO}_3\text{-FeO-H}_2\text{O}$ system spontaneously generates the suite of hydrocarbons characteristic of natural petroleum. Modern scientific considerations about the genesis of hydrocarbons confirmed by the results of experiments and practical results of geological investigations provide the understanding that part of the hydrocarbon compounds could be generated at the mantle conditions and migrate through deep faults into the Earth's crust, where they form oil and gas deposits in any kind of rock and in any kind of structural position. The experimental results presented place the theory of the abyssal abiogenic origin of petroleum in the mainstream of modern physics and chemistry and open a great practical application. The theory of the abyssal abiogenic origin of petroleum confirms the presence of enormous, inexhaustible resources of hydrocarbons in our planet and allows us to develop a new approach to methods for petroleum exploration and to reexamine the structure, size, and location of the world's hydrocarbons reserves.

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