ABIOGENIC OR BIOGENIC PETROLEUM*

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Abstract – Numerous observations have shown the wide prevalence of organic compounds in meteors, asteroids, comets, and planetary atmospheres (other than our own earth) for which the organic material must be classified as of abiogenic origin. The Western (W) hypothesis has generally favored the idea that petroleum on earth is a fossil fuel formed as the result of the deaths of early animal and plant life when the primordial seas dried up. This hypothesis is consistent with the idea that peak conventional petroleum productivity, followed by increasing costs and then lack of availability of transportation fuel, are likely near-term events (within about 20 years if we disregard the enormous supply opportunities associated with shale-oil recovery, oil from tar sands, and other not yet widely used supply sources). The opposing view to this scenario is now generally referred to as the Russian-Ukrainian (R-U) theory according to which chemical syntheses in the upper reaches of the earth's mantle have been and continue to be active locations where precursors of petroleum have been and continue to be formed. According to this theory, petroleum is not a fossil fuel but rather a renewable resource of great abundance at as of now difficult-to-reach or inaccessible depths. Some Western experts have attempted to make these two interpretations consistent in order to moderate the intellectual and practical impact of accepting mostly abiogenic petroleum formation by asserting that what we see at the surface is a little bit of abiogenic but more of the biogenic variety.

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1. History of Petroleum Discoveries and Uses (http://www.pafko.com/history/h_petro.html)

Petroleum derivatives and their applications have been recorded all over the world since the beginnings of human history. The following are representative examples.

Egyptians used pitch derived from petroleum to coat mummies and seal pyramids as preservatives.

Babylonians, Assyrians and Persians used pitch to pave streets, secure building structures and also to make boats on the Tigris and Euphrates water-tight.

Early use for heating by burning petroleum is recorded by Chinese historians.

According to the Old Testament, Noah used pitch to make his ark water-tight.

American Indians used petroleum as a fuel, as medicine and to make paints.

Nomads used petroleum to treat camels for mange (skin inflammations).

The Emperor Charles V swallowed petroleum to mitigate the severity of his gout attacks,

Until the end of the 19th century, petroleum was taken by many people in many lands as a universal “cure” or palliative for many ailments.

The modern petroleum industry began with the 1859 drilling of an oil well at Titusville, PA, by Edwin L. Drake. It flowed at the rate of 35 bbl/day and was valued at $20/bbl, which is an astronomical cost in terms of current dollars.

2. Western Wisdom ca 1770

Our source for the Western view about 235 years ago is the first edition of the Encyclopedia Britannica. The brief article on petroleum is interesting because it does not deal with the origin or resource base but rather with the appearance of petroleum and medical applications, which might now be called gross misuses. The paragraph in question is here reproduced.

Volume III of the first edition of the Encyclopedia Britannica, published in 1771, contains the following description of petroleum:

"Petroleum, also called rock oil, is an extremely subtle and penetrating fluid, and is much the thinnest of all native bitumens. It is very light and very pellucid; but though equally bright and clear under all circumstances, it is stable to a very great variety in its colour. It is naturally almost colourless, and in its appearance resembles the most pure oil of turpentine: this is called white petroleum though it has no more colour than water; it is sometimes tinged of a brownish, reddish, yellowish, or faint greenish colour; but its most frequent colour is a mixture of the reddish and blackish, in such a degree that it looks black when viewed behind the light, but purple when placed between the eye and a candle or window. It is of pungent and acrid taste, and of a strong and penetrating smell, which very much approaches to that of the distilled oil of amber. The white is most esteemed, it is so very inflammable, that while it floats on the surface of water, as it does in many parts of Italy, it takes fire at the approach of a candle.

Petroleum is found in rivers, in wells, and trickling down the sides of hills along with little streams of water. In short, it is the most frequent of all the liquid bitumens, and is perhaps the most valuable of them all in medicine. It is to be chosen the purest, lightest, and most pellucid that can be had, such as is of the most penetrating smell and is most inflammable.

It is principally used externally, in paralytic cases, and in pains of the limbs."

Encyclopedia Britannia 1958

I. Origin and Characteristics

"Most scientists believe oil was formed from the bodies of tiny plants and animals that lived in the sea hundreds of millions of years ago when the sea covered large areas of what are now land masses. The animals and plants lived and died by the billions, then sank to the bottom and mixed with mud and sand in layers called marine sediment.

Later, these sedimentary layers were covered by more mud and sand, which finally turned into rock. As ages passed, the sea withdrew, the earth's crust heaved and buckled and the heat and pressure caused by the overlying rock, together with decomposition of the organic life, is thought to have formed oil from the animals and plants in the deep-buried layers. Because of their mutual derivation from organic material, petroleum, natural gas and coal are known as fossil fuels.

Crude oil as it comes from the ground is a mixture of thousands of different chemicals, which range from extremely light gases to semisolid carbonaceous materials such as asphalt or paraffin wax. The gases are dissolved in the other components of the crude oil because of the extreme pressure to which petroleum is subjected in the ground.

Likewise, the paraffin wax is dissolved in the so-called paraffin crudes but can be removed by combinations of refrigeration and filtration or by selective solvents. As a liquid, petroleum may be as thick and black as melted tar, or as thin colourless as water, depending entirely upon the particular oil field from which it comes.

Chemically, crude oil is largely composed of hydrocarbons, compounds of hydrogen and carbon. In addition, crude oil often contains sulphur, either uncombined or present as a part of certain hydrogen-carbon-sulphur compounds."

In order to help us in maintaining an idea of the elapsed times, we reproduce in Table 1 a dictionary overview of geologic times.

Table 1. Geologic periods and their time frames; reproduced from a 1974 edition of Webster’s dictionary.

GEOLOGIC TIME AND FORMATIONS					
Eras	Periods and Systems	Epochs and Series	Approximate No. of Years Ago	Earliest Record of: Animals	Earliest Record of: Plants
Cenozoic	Quaternary	Holocene (Recent) Pleistocene (Glacial)			
	Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	70,000,000	mankind placental mammals	
Mesozoic	Cretaceous	Upper			
		Lower		birds	grasses and cereals
	Jurassic		160,000,000	mammals	flowering plants
	Triassic		230,000,000		ginkgoes
Paleozoic	Permian		230,000,000		cycads and conifers
	Pennsylvanian			insects	
	Mississippian			reptiles	primitive gymnosperms
	Devonian		390,000,000	amphibians	vascular plants: lycopodiums equisetums ferns, etc.
	Silurian				
	Ordovician		500,000,000	fishes	mosses
	Cambrian		620,000,000		
Proterozoic	not divided Into periods		1,420,000,000	invertebrates	spores of uncertain relationship marine algae
Archeozoic			2,300,000,000		

3. Formation of Abiotic Organic Compounds and the R-U Theory

Wherever we look, whether at comets, at asteroids or at planetary atmospheres other than that of the earth, where no plant life is known to have ever existed, we see an abundance of organic compounds. These cannot possibly be of plant origin because no plants have grown on asteroids, comets or planets other than our own in the solar system we inhabit. By definition, if the precursors of oil are not plants, then oil is not a fossil fuel and must have been produced by processes or reactions not involving plants.

Recent laboratory studies in the West have duplicated earlier work performed by Russian and Ukrainian scientists and have provided elaborations and laboratory verifications of the processes involved in the abiogenic formation of petroleum. After largely ignoring the R-U studies for more that 50 years, a major impetus for quantitative studies was provided for Western experts by a publication in English in the Proceedings of the U.S. National Academy of Sciences in August 2002 of an important review paper authored by J.F. Kenney (who is identified as associated with the Gas Resources Corporation in Houston, TX, as well as the Russian Academy of Sciences, RAS) and V.A. Kutcherov (RAS), N.A. Bendellani (Russian State University of Oil and Gas), and V.A. Alekseev (RAS).[1] The title of this paper provides a concise summary of its contents as follows: “The Evolution of Multicomponent Systems at High Pressures: VI. The Thermodynamic Stability of the Hydrogen-Carbon System: The Genesis of Hydrocarbons and the Origin of Petroleum.”

The 2002 paper was followed in 2004 by an independent experimental demonstration involving 7 authors (one of whom, Dudley R. Herschbach of Harvard University, is a Nobel Laureate in Chemistry) which confirmed the part of the R-U claims relating to methane formation at the conditions of high pressures (5 to 11 GPa) and temperatures (500 to 1000C) prevailing near the earth's mantle, a conclusion that is consistent with the thermodynamic analyses and experimental conditions presented in Ref. 1. The final sentence of the abstract of the 2004 article reads as follows: "The study demonstrates the existence of abiogenic pathways for the formation of hydrocarbons in the earth's interior and suggests that the hydrocarbon budget of the bulk earth may be larger than conventionally assumed."

If prestigious authors are required to turn the tide on a possible multi-generational blunder in the Western literature, we may also refer to a summary article by Roald Hoffmann (another chemistry Nobel Laureate) entitled “Old Gas, New Gas” which appeared[3] in the January-February 2006 popular science magazine entitled the “American Scientist.” Hoffmann provides the following brief overview of an example for abiogenic methane formation from which the mixture of HCs we associate with petroleum is readily formed.

Mantle rocks contain the minerals that make up olivine (e.g., Mg_2SiO_4, Fe_2SiO_4, etc.) which is changed to serpentine $(Mg, Fe)_3\ Si_2O_5\ (OH)_4$ plus brucite $[(Mg, Fe)\ (OH)_2]$ plus magnetite (Fe_3O_4) on reaction with H_2O at high temperatures and pressures while producing H_2. Schematically, the reaction is olivine + $H_2O \rightarrow$ serpentine + brucite + magnetite + H_2. Under appropriate pressure and temperature conditions and in the presence of CO_2, the widely used and well known Fischer-Tropsch synthesis occurs and leads to the formation of methane via

$$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O.$$

The subsequent formation of mixtures of higher hydrocarbons may then lead to abiogenic petroleum-like mixtures (see Sec. 5 of this paper). This mechanism also produces accessible NG responsible for the huge deposits (about 100 times greater than conventional NG resources) of methane hydrates (clathrates) known to be stored under high pressures and at depths.

4. Impacts on Petroleum Exploration of Divergent Russian-Ukrainian and Western Views

There is no fundamental difference in the methods of petroleum recovery. In either case, the resource is located somewhere in the fissures and cracks of depository structures at reachable depths, either as original deposit formations or else as trickle-up depositions originating from the "hot deep earth". There are excellent examples of refilling of oil-bearing strata from unknown sources as at Eugene Island, which provided a surprise for many Western observers but the existence of which is wholly consistent with the R-U view.

The following are some R-U comments on the R-U theory of deep, abiotic petroleum formation (see http://www.gasresouces.net/Home_body.htm): (i) The Modern R-U theory of deep, abiotic petroleum origin is recorded in thousands of articles published in mainstream Russian journals, books and monographs. (ii) Lack of familiarity with this body of work has allowed publication in the West of the unparalleled plagiarism involved in the book by Thomas Gold entitled "The Hot Deep Earth." (iii) One of the principal contributors to the R-U theory is Nikolai Alexandrovich Krayushkin, who is the author of more that 250 articles on modern petroleum geology and of several books. Krayushkin first described deep, abiotic petroleum formation in 1951. (iv) These original contributions made it possible to convert a petroleum-poor country (i.e. the USSR) in 1946 into one of the world's primary oil-exporting nations. Kundryavtsev's work motivated Emmanuil Bogdanvich Chekaliuk to apply the methods of statistical thermodynamics to the problem of deep, abiotic oil formation.

Table 2. Contrasting views of oil-deposit formations.

The Russian-Ukrainian View of J.F. Kenney et al	The Opposing Western View of Richard Heinberg
1. Thermodynamic constraints do not allow the formation of HCs at the T, p-conditions for the Earth's crust from plants. Petroleum is expected to enter biological systems as it trickles upward. The opposing view specified on the right-hand side amounts to the statement that ("Elephant tusks look like piano keys and must therefore be related to these.")	1. Some molecules found in petroleum look like molecules found in biological systems and must therefore come from these ("biomarkers").
2. Odd-even carbon-chain imbalances are all consequences of the structures of multicomponent fluids at elevated pressures (up to pressures for diamond formation) and support the idea that these compounds were formed at elevated pressures.	2. Odd-even carbon chain imbalance, carbon isotope ratios, optical activities of molecules are petroleum markers resembling those of biological systems.
3. Carbonaceous meteorites (especially chondrites) contain 0.1 to 6% of C, are 3 to 4.5 billion years old, and are certainly of abiotic origin. Their mineral structures require existence at very low temperatures. Hydrocarbons are present as both liquids and solids.	3. This statement is not controversial.
4. Porphyrins * are found in both biotic and abiotic systems. The same porphyrins have been found in petroleum and in the interiors of carbonaceous meteorites. They have been synthesized in the laboratory under abiotic conditions.	4. The presence of porphyrins in petroleum proves its origin from organic matter.
5. The C-13 to C-12 ratio is determined by the length of the path and by the nature of material involved before sampling because the C-12 species is generally more reactive than the C-13 species.	5. A small C-12 to C-13 ratio indicates biological origin of the material.
6. Hydrocarbons are found in all planetary atmospheres and meteorites; these cannot be of biogenic origin if no plant growths were co-located.	6. This statement is not controversial.

* Porphyrins are metal-free derivatives of pyrrole obtained especially from chlorophyll or hemoglobin.

5. The Key Scientific Issue

The key scientific issue is compatibility of the theory with the laws of thermodynamics. The compatibility of the R-U theory with abiogenic petroleum formation is illustrated quantitatively by Kenney et al in Ref. 1. No such analysis has been published for the biogenic production hypotheses of the W models. It is unlikely that such a model can be constructed without making the physical conditions in the W model like those in the R-U models, i.e. without arguing that pressures and temperatures near the earth's surface simulated those of the mantle as the result of tectonic upheavals. This type of subterfuge removes a controversy but does not contribute to our scientific understanding of petroleum formation.

6. Validity of the Claim of High Near-Term Peak Oil Production Followed by Resource Exhaustion

Even from the Western point of view, the notion of near-term petroleum exhaustion is not defensible without insertion of the qualifying adjective "conventional and using only currently developed and currently competitive technologies." The availability of potential liquid-fuel resources is very much greater than the availability of conventional petroleum resources. This fact has been known at least since the beginning of the 20th century when shale-oil recovery began in China under license from the precursor to the Chevron Corporation. During the Carter administration and for some years thereafter, the author served as Chair of the DOE "Fossil Energy Research Working Group" (FERWG), which included oil recovery from shale and tar sands. These processes were demonstrated at substantial scales in many parts of the world and the Canadian tar sands in Alberta remain economically competitive to this day with progressively increasing production levels. We may judge the magnitude of the propounded distortions by noting that resource assessments from the seventies and earlier years showed the potential shale-oil resources to exceed conventional petroleum resources by at least a factor of 100 and with suspected but not yet identified tar-oil resources perhaps equally large. Of course, in the R-U theory, the notion of "conventional" petroleum-resource exhaustion must be dismissed out of hand because petroleum is viewed as a renewable resource.

To repeat, the assertion of near-term petroleum-resource exhaustion involves total neglect of well known work on unconventional oil derived from oil-shale and tar-sand resources. For details concerning these huge resources, see, for example, the articles and monographs published by FERWG (US DOE Fossil Energy Research Working Group, S.S. Penner Chair) 1975-83 or Chapter 9 on "Oil Recovery from Tar Sands and Oil Shale" in S.S. Penner and L. Icerman, "Non-nuclear Energy Technologies," Volume II, pp. 1-64, Addison-Wesley Publishing Company, Inc. (1975), as well as numerous resource assessments dealing with the Athabasca tar sands, [e.g., D.C. Duncan and V.A. Swanson, "Organic-Rich Shales of the United States and World Land Areas, U.S. Geological Circular No. 523, Washington, D.C. (1965) or "U.S. Energy Outlook: Oil Shale Availability, National Petroleum Council, Washington, D.C. (1973), etc.]. Oil recovered from the Athabasca tar sands has been economically competitive for about 50 years, oil-shale recovery has been practiced commercially for more than a century in such diverse locations as China and the Baltic states and is expected to be competitive with conventional oil below currently elevated price levels after imposing proper controls for environmental impacts.

7. A 2002 Western View of Petroleum Geology

R. F. Broadhead of the New Mexico Bureau of Geology and Mineral Resources described oil formation and petroleum recovery as follows in 2002 (see New Mexico's Energy, Present and Future: Policy, Production, Economics, and The Environment, edited by B. S. Brister and L. G. Price, in New Mexico Bureau of Geology and Mineral Resources, 41 - 43 ((2002).

Recovery of oil and gas occurs from fields composed of reservoir rock holding sandstone and source rock such as shale, properly sealed to prevent escape, and capped by one or more traps where the resource has accumulated over time (see Fig. 1). The oil and gas were formed in quiet waters (e.g., swamps on land and both shallow and deep marine basins) from the remains of algae, wood fragments, land plants, and other organic materials over very long periods of time. These remains are covered by additional layers of sediments which cause the temperatures to rise above 120 C where millions of years of processing produce oil and gas that are appropriately described as thermogenic products. Wood fragments yield natural gas whereas algae and soft parts of plants yield both oil and natural gas. For deep burials, the temperatures may rise above 150 C and the organic materials form as much oil as possible before this is broken down into natural gas with still further heating.

Some sedimentary rock materials containing organic compounds may be broken down by bacterial processes labeled biogenic gas generation. These processes are believed to occur at depths of less than 2000 feet.

The reservoir rocks are porous, permeable, and interconnected by networks of microscopic pores or holes, thus allowing oil and gas to migrate from one reservoir rock to another. Migration ceases when the products encounter impermeable seals which are identified as being structural or stratigraphic and are formed over tens to hundreds of millions of years. Oil and gas move through these structures and fill available vacancies until movement is impeded by seals.

The specified mechanism is not supported by direct observations because no petroleum geologist was present over the postulated long periods of time required for processing of the precursor organic materials. It is not supported by analyses allowing for constraints imposed by fundamental physical and chemical laws, especially the second law of thermodynamics. The final observed structures and migrations of oil through stable or unstable rock formations are independent of the mechanisms of oil and gas formations. In the end, resource recovery depends only on locations of the oil and gas in accessible underground structures and is basically the same for biogenic or abiogenic oil production with one noteworthy exception. According to the Western view, oil and gas cannot be found in archaic rock structures that are more than a few billions of age whereas no such constraint exists with the abiogenic point of view. Furthermore, significant refilling of exhausted fields over relatively short periods of time is more obviously expected for the abiogenic than for the biogenic point of view. But, even with the abiogenic point of view, it is unclear how important new accessible fields may be found that were missed with the biogenic view of oil formation.

References

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R. Hoffman, “Old Gas, New Gas,” American Scientist 94, 16-18 (January-February 2006).

Appendix I: Alternative Oil Sources

The oil-shale, tar-sands and heavy-oil sources are widely distributed all over the globe and constitute as a whole hydrocarbon sources of such potentially usable magnitudes as to dwarf conventional petroleum supplies by very large margins.

Kerogen from oil shale is readily converted to oil as the result of pyrolysis. It has been used for centuries in many countries (Australia, Canada, the USA, Estonia, Brazil, Scotland, Russia, etc.) as a readily available fuel source in the same manner as coal. It probably represents the largest potential addition to the needed liquid- fuel supplies for transportation applications. Shale oil has been classified in the West as a biogenic fuel but may actually share abiogenic origin with all of the other liquid-fuel sources.

During the nineteen seventies and eighties, active recovery processes were under development in the USA, especially in the Piceance Basin of Colorado. Impressive in situ retorting was achieved by the precursor of Exxon Mobil Corporation (at a cost of about $2 billion at project termination), by Tenneco, Chevron, and other companies. These programs did not fail but were phased out when it became clear that abundant conventional petroleum supplies were being brought to the world markets at lower costs than could be accepted for retorted shale oil. Canadian recovery of oil from tar sands in Alberta has proceeded successfully to the present time although complete environmental impact restoration has not been achieved.

The net energy ratios (i.e., energy out divided by energy in) for in situ shale-oil recovery are in the range 1.2 to 1.4.

Among alternative oil sources, recovery from oil shale and tar sands have been noted as very large potential supplies. As with conventional oil, we must distinguish between relatively low-cost limited supplies available with tested technologies and very much greater potentially available supplies utilizing advanced technologies that may become commercially viable in the future. Significant R&D developments were recorded during the nineteen seventies and subsequent decades. Major obstacles to successful commercialization were both imaginary and actual environmental impacts, anticipated costs above then current but rapidly escalating costs of liquid petroleum supplies, and especially the recognition that these industries would become non-competitive with access to larger supplies of imported fuels recovered at reduced profit margins above very low original costs. For a mid-seventies overview of these potential oil supplies, reference may be made to Chapter 9 (pp. 1 to 68) in Volume II of the 3-volume series on “Non-nuclear Energy Technologies” (Addison-Wesley Publishing Company, Reading, Mass., 1975 and 1977 by S.S. Penner and L. Icerman).

From 1980 to 2006, the purchasing power of $100 declined to about $41.43. In 1980, refined shale oil was variously estimated to cost around $35/bbl. Hence, the 2006 cost (neglecting any technical process improvements during the intervening 26-year period) should be about $84/bbl. Oil from tar sands in 1980 was estimated to cost about $20/bbl; its 2006 production cost, again neglecting any technical process improvements during the intervening 26 years, should now be about $48/bbl, which is well below the maximum international crude price level of $75/bbl during April 2006. These rough estimates suggest that unconventional crude oil could supply a large part of the oil market beginning as of this year. In accord with these qualitative considerations, we find again reports of active shale-oil recovery processes from Texas (Ignis Petroleum recovering oil from Barnett shale), a lease by TBX Resources in the same region, natural recovery by Chesapeake Energy and natural gas extraction from Fayetteville (Arkansas) shale, a joint Shell and Jilin Quangzheng program to extract shale oil in the Jilin Province of China, an application from America Asia Petroleum to extract oil from Jordanian shale, etc.

Pessimistic cost projections for the future are mostly based on estimated high costs for required environmental remediation involving the newly built recovery systems.

From 1978 to 1982, the author served as chair of the DOE Fossil Energy Research Working Group (FERWG). References (1) through (10) are representative outputs from these studies.

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Appendix II. The Scientific Issue and Recovery of Abiogenic Petroleum at Depths

The scientific issue of abiogenic or biogenic origin of petroleum involves a straightforward application of the laws of thermodynamics, especially of the second law. Thermodynamics as a sound scientific discipline applicable to all equilibria following physical and chemical changes represents one of the crowning achievement of 19th century science to which important contributions were made during the 20th century by some of the world's most acclaimed scientists. No discrepancy to predictions based on competent applications of this discipline has ever been found.

The R-U theory, as applied by Kenney et al, meets the requirements that entropy changes for irreversible spontaneous chemical change from state A to state B must be greater than or equal to zero, that the free enthalpy must always be less for the final state B than for the initial state A, and that for all intermediate states the enthalpy must be less than for state A and greater than for state B. Furthermore, an inequality named after de Donder must be satisfied at all times. Beginning with this soundly based approach, Kenney et al were able to show that (a) methane is a stable hydrocarbon at atmospheric pressure and temperature and that stable formations of higher hydrocarbons from methane or the elements C and H require pressures of at least 25 kbar (1 bar = 10^6 dynes/cm^2 = 10^5 pascal (Pa) = 0.1 MPa $\cong$ 1 atm, atmospheric pressure = 14.7 lbs/square inch, 1 kbar = 10^3 bar $\cong$ one thousand atmospheres) at the supercritical temperature of 1000K. Furthermore, at pressures above 25 kbar, heavier HCs do not decompose into lighter HCs at temperatures up to 1000K and pressures above 25kbar.

The final section of the paper by Kenney et al deals with experimental demonstration of the formation of higher HCs at pressures up to 50 kbar and temperatures up to 1500°C, which are typical of mantle conditions. <u>The final conclusion is that depths of at least 100 km below the surface of the earth are required for petroleum formation form elementary carbon, hydrogen and oxygen.</u>

The final issue that must be addressed relates to the implications of the RU theory for future petroleum recoveries after drilling to depths of 100 km or more, which is well beyond currently existing capabilities. Progressively drilling deeper and deeper is a proper engineering challenge which may or may not be cost effective. Allowing natural processes to bring petroleum from lower depths to accessible levels will be as time consuming in the future as it has been in the past.

CONCLUDING REMARKS-----------A WESTERN VIEW

Reference:

http://www,cartage.org.lb/en/themes/Sciences/Earthscience/Geology/OilandGas/Hydrocarbon Occurrence

Petroleum discovery in source rock of Archaean age (i. e. rock formed more than about 2 billion years ago) was unexpected according to the classical theory that petroleum is of organic origin. Petroleum was considered unlikely to have survived the thermal stresses to which pre-Cambrian rocks (formed more than about 0.7 billion years ago) were subjected.

Proterozoic oil fields (formed from 1.0 to 1.5 b. y. a.) have been discovered in Oman, China and Siberia. Oil has been found in sandstone formed about 3 b. y. a. in the Kaapvaal craton of South Africa and the Lake Superior craton in Canada. Hydrocarbon-bearing mudstones have been found as source rocks.

Hydrocarbons continue to be found in asteroids and comets. Hydrocarbon "ice" in the Kuiper belt beyond Neptune indicates substantial amounts of extraterrestrial organic compounds.

Petroleum occurs in fluid inclusions lying within healed microfractures of individual quartz grains. In other words, oil is emplaced as the result of upwelling under pressure with the creation of fractures. Organically placed petroleum may have similarly migrated.

Australian oil in the Macarthur basin dates to 1.4 to 1.7 b.y.a., which coincides with the appearance of unicellular eukaryotes in accord with the organic theory of the origin of petroleum formation.