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Development of oil formation theories and their importance for peak oil

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ABSTRACT

This paper reviews the historical development of both biogenic and non-biogenic petroleum formation. It also examines the recent claim that the so-called "abiotic" oil formation theory undermines the concept of "peak oil," i.e. the notion that world oil production is destined to reach a maximum that will be followed by an irreversible decline. We show that peak oil is first and foremost a matter of production flows. Consequently, the mechanism of oil formation does not strongly affect depletion. We would need to revise the theory beyond peak oil only for the extreme — and unlikely — hypothesis of abiotic petroleum formation.

1. Introduction

The finite nature of oil resources is the origin of the "peak oil" theory, which states that the world's oil production will reach a maximum value when approximately half of the existing resources have been extracted. Peak oil doesn't mean "running out" of oil, as it is sometimes wrongly stated. It simply means that the yield of extraction, in economic and energy terms, gradually declines to the point that it is not convenient any longer to invest the huge amounts of financial resources that would be needed to keep production increasing.

The concept of peak oil is often regarded as controversial but it is a direct consequence of the fact that it is impossible to extract larger amounts of crude oil than Nature has created. The exact date of the world peak is obviously uncertain, although the available data indicate that the peak of production for conventional oil may have been passed in 2005. Despite this uncertainty, peak oil a major challenge for the future of our hydrocarbon-based society.

Nevertheless, not everyone agrees that oil is a finite resource. These speculations are often based on the so-called "abiotic" oil formation theory. Historically, crude oil has been found by empirical methods in subsurface reservoirs and other underground formations. Two geological explanation models have attempted to explain how petroleum was formed. These two theories can be called the biogenic and the abiotic (alternatively abiogenic or non-biogenic) models for petroleum formation. The biogenic theory states that petroleum originates from remains of biological matter, while the abiotic theory claims that petroleum derives from non-biological processes. Although scientific evidence and supporting observations can be found for both models, the amount of evidence for a biogenic origin is overwhelming in comparison to that for the abiotic theory. However, there is nothing that prevents both theories from being true thus allowing petroleum to be both generated from biological matter as well as non-biological matter (Robinson, 1966).

The genesis of petroleum is an important topic in oil exploration, as noted by Peters et al. (2005). This article will review the development of oil formation theories, the ways which scientists have tried to explain and understand how petroleum is created by nature and how these theories have affected the search for crude oil all over the world. The debate on this point has been ongoing in the scientific literature as well as in the press, with several claims that the "abiotic" theory puts to rest all worries related to oil depletion. Kenney (1996) boldly states that abiotic petroleum gives "no reason to worry about, and even less to plan for, any predicted demise of the petroleum industry based upon a vanishing of petroleum reserves." Odell (1999) later mentions how abiotic oil could lead to

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an increasing or potentially everlasting availability of petroleum. Tsatskin and Balaban (2008) even claim that the present peak oil debate is underpinned by a biogenic paradigm of oil formation.

In contrast, Bardi (2004) concluded that abiotic oil formation is irrelevant to the peak oil debate unless it occurs at extremely rapid rates, much faster than conventional oil creation theory would dictate. The rate of formation compared to extraction is essential for future production projections and, as long as the extraction process is significantly faster than the creation process, fossil fuels must be categorized as non-renewable and subject to depletion — regardless of their biogenic or abiotic origin.

So far, there have been no discussions in the scientific literature on how the concept of abiotic oil, and the related claims of great abundance, affects the concept of peak oil. The present paper will examine this point in detail, showing that the mechanism of oil formation affects the future production trends only in an extreme — and unlikely — hypothesis.

2. Historical development of oil formation theories

Petroleum and other hydrocarbons have been known to mankind since the dawn of civilization. The word petroleum derives from the Latin words petra, meaning rock, and oleum, denoting oil, which combined literally means rock-oil. This term was first used by the German mineralogist Georgius Agricola (1546a) in the treatise De Natura Fossilium. The ancient Greek word naphtha was often used to describe any petroleum or pitch-like substance. In older texts naphtha was often used as a synonym for petroleum, but this has now been phased out in English language. However, some languages, such as Russian or Arabic, still use variants of naphtha as the word for petroleum.

Often petroleum was treated as a curiosity without any serious use to society, although it was widely used in some parts of the world prior to industrialization. The eternal fires of Kirkuk, consisting of burning oil seepages, and the use of oil and natural bitumen in ancient Middle East has been studied by Beydoun (1997). The Roman Empire has been known to use coal for household heating in Britannia (Dearne and Branigan, 1995). The dreaded Greek fire, an early incendiary weapon used by the Byzantine Empire, is believed to have been partly based on petroleum or naphtha (Partington and Hall, 1999). Speight (2007) covers the history of petroleum utilization and terminology in greater detail.

In many places all over the world where oil seepages occurred, local inhabitants drilled or dug surface wells and shafts to increase flow rate for collection purposes (Hunt, 1979). These were the first hint of what would become the great rush for petroleum of modern times. In these early days, how petroleum was formed was not known and the knowledge of geology was far from sufficient to propose reasonable theories. However, scholars and philosophers nevertheless tried to explain the genesis of petroleum.

2.1. Early ideas about petroleum formation

The ancient Greeks were familiar with the existence of petroleum and some of their natural philosophers discussed its origin. Aristotle and other Greek philosophers proposed a theory based on the idea that that everything was made up from four different elements; earth, air, water and fire. Since petroleum seeped out of the ground and was very flammable, it was thought to be connected to fire and earth. Consequently, Aristotle thought that ores, minerals and hydrocarbons were the result of exhalations from the deep of the earth (Walters, 2006). His followers suggested that the foul smell that was typical for many forms of petroleum indicated that it was related to sulphur in some way.

Medieval development was chiefly driven by Arabic science. Several important developments in chemistry and alchemy were done by Arabian and Persian scholars. In the 8th century, a Arabian polymath, Abu Musa Jabir ibn Hayyan al Azdi, developed the foundation of chemistry and paved the way for many subsequent alchemists and scientists (Derewenda, 2008). Abu Bakr Muhammad ibn Zakariya Razi was the first to distil petroleum and produce kerosene around 9th century (Gutierrez et al., 2000). These experiments later inspired many European alchemists and scholars as manuscripts and books reached the Medieval Europe.

Alembics, retorts and primitive chemical analysis were used by many alchemists to uncover the secrets of nature and provide better understanding of the world. However, few references to petroleum and its origin can be found in the literature from this time. Roger Bacon (1258) even made remarks about the inability of Aristotle and other Greek natural philosophers to adequately explain the origin of petroleum in his treatise Opus Tertium.

It was not until the Renaissance that the first modern theories about the origin of hydrocarbons were developed. In 1546, Georgius Agricola (1546b) in his manuscript De Natura eorum quae Effluunt ex Terra expanded on Aristotle's ideas about exhalations from deep underground and proposed that bitumen is a condensate of sulphur. Andreas Libavius in his chemistry textbook Alchemia of 1597 proposed that bitumen was formed from resins of ancient trees (Walters, 2006). These texts may be seen as the origin of the modern theories about oil formation.

The Russian universal genius Lomonosov proposed and demonstrated in his book On the Strata of the Earth from 1763 (Peters et al., 2005) the idea that petroleum and natural bitumen originates from transformation of coal and plant remnants due to subsurface heat and pressure. Already by 18th century, fossil evidence had indicated that coal and peat was related and that both originate from preserved vegetation remains. Remains of leaves and plant parts can actually be seen in certain coal and peat samples. Today, it is commonly accepted that coal has a biogenic origin and the modern coal geology is well documented, for instance, in Thomas (2002).

Whereas the origin of coal can be considered a settled question already in 18th century, the origin of petroleum remained an open debate for a long time. More detailed hypotheses and different versions of the biogenic origin of petroleum were created during the 19th century. Several studies claimed that oil originated directly from organic remains or was created in a distillation process (Dott, 1969). Hunt (1863), Lesquereux (1866) and Newberry (1873) studied Palaeozoic rocks in North America and found that oil seemingly originated from ancient marine sediments.

Meanwhile, the first seeds of the abiotic oil formation theory were planted in Europe. A French chemist, Marcellin Berthelot, described how hydrocarbon compounds could be created from the acid dissolution of steel (Walters, 2006). In Russia, the famous scientist Mendeleev (1877, 1902) proposed that petroleum was created in the depths of the Earth from chemical reactions between water and iron carbides in the hot upper mantle. This theory was largely ignored and its supporters dwindled under the mounting evidence of biogenic petroleum creation at this time.

2.2. Modern development of biogenic oil formation theories

The beginning of the 20th century marks the development of modern petroleum geology. Early European studies of organic-rich rocks supported the biogenic origin of oil (Pompeckj, 1901; Schubert, 1915). Similar studies by the US Geological Survey (USGS) showed that Californian oil originated from organic-rich shale (Arnold and Anderson, 1907; Clarke, 1916). Snider (1934) implied that organic matter seemed to be almost universally buried in argillaceous mud and to a lesser extent in calcareous mud and marls, while coarse sands, gravels and very pure calcareous deposits generally lacked organic content.

Engler (1913) showed a connection between thermal properties in the ground and petroleum, when he managed to produce hydrocarbons by heating organic matter. White (1915) introduced the carbon-ratio theory, which implies that petroleum occurrence is limited by the thermal history of a region. In essence, studies now started to connect petroleum generation to some naturally occurring distillation process of organic-rich sediments.

The birth of more advanced chemical analysis led to many new discoveries and shed additional light on the origin of petroleum. Treibs (1934, 1936) established a link between chlorophyll in living organisms and porphyrin pigments, a class of nitrogen compounds that originates from mainly chlorophylls, in petroleum, shale and coal. Oakwood et al. (1952) showed that oils retain fractions that are optically active, just like biological matter. This was later confirmed by Whitehead (1971). Eglinton and Calvin (1967) showed that oil contains many chemical fossils and biomarkers, besides porphyrins, that could be traced to biological predecessors. Tissot and Welte (1978;1984), sometimes seen as the fathers of modern geochemistry, expanded the analysis with geochemical fossils, allowing further comparison of structurally similar organic compounds in sediments and oil with their precursors in living organisms. A more comprehensive overview of the development of petroleum chemistry can be found in Hunt et al. (2002) or Durand (2003).

The introduction of mass spectroscopy allowed new types of analyses that could identify differences in isotopic composition. Stable carbon isotope compositions in oil were found to be in line with biogenic origin (Craig, 1953) as living organisms favour certain carbon isotopes more than others. Silverman and Epstein (1958) applied carbon isotope studies to both petroleum and sedimentary organic materials, confirming their biogenic origin. Fuex (1977) summarizes the application of stable isotope analysis in petroleum exploration. Clayton (1991) and Tang et al. (2000) presents more detailed modelling data for stable carbon isotopes.

Geological field studies provided important knowledge and valuable information relevant to petroleum genesis. Hydrocarbons were found to be abundant in ancient marine shales and limestones, whilst they were uniformly absent in recent muds from a variety of environments (Erdman et al., 1958). Forsman and Hunt (1958) studied rock samples from a wide variety of ages, lithologies, environments and depositions, arriving at the conclusion that the absolute concentration of hydrocarbons was greater in ancient rocks than in younger sediments. The findings showed the important role of kerogen in petroleum generation (Abelson, 1963; Durand, 1980). Philippi (1965) discovered that hydrocarbon yield from source rocks increases with time and temperature. From these studies came the understanding of the geologic zone of intense oil generation, now commonly known as the oil window (Hunt et al., 2002).

Winters and Williams (1969) and Jobson et al. (1972) showed how microorganisms could alter petroleum and cause biodegradation, resulting in heavy oil. Demaison (1977) points out the importance of this process and relates it to the discovered quantities of heavy oil prior to 1980. Ahsan et al. (1997) provide additional information on biodegradation. Theories and models on degradation and alteration could now explain the formation of all forms of petroleum within the biogenic framework.

2.3. Modern abiotic oil formation theories

Starting in the 1950s, Kudryavtsev (1951) and other subsequent publications proposed a modernised version of Mendeleev's theory, relying on thermodynamic equilibrium for chemical reactions that only allows spontaneous formation of methane at high temperature and pressure, comparable to those of the upper mantle region. Rudakov (1967) gave a summary of the early developments of abiotic oil formation.

The authors favouring the abiotic theory claim that the hydrogen-carbon system generates hydrocarbons under pressures found in the mantle of the Earth and at temperatures consistent with that environment (Kenney et al., 2002). There exists experimental proof that, in some conditions of high pressure and temperature (e.g. under a diamond anvil) it is possible to combine carbon and hydrogen to generate hydrocarbons (Kenney et al., 2002). Also the Fischer and Tropsch (1930) process – developed in the 1920s – is proof that it is possible to create long-chain, petroleum like, hydrocarbons starting from inorganic reactants.

Because many of the Russian-Ukrainian works were never translated and spread among western scientists, perhaps the most well known promotion of recent abiotic theory is the work of Thomas Gold (1985, 1992, 1999). J.F. Kenney, who also served as the drilling manager of Gold's Siljan Ring project, has also made significant efforts to spread the abiotic theory of petroleum formation. Kutcherov and several other Russian scientists have co-authored many papers with Kenney in their attempts to revitalize the Russian-Ukrainian theory and spread it within the scientific establishment. The Russian-Ukrainian theory, Gold's ideas and some other contributors have been reviewed in greater detail by Glasby (2006).

The proponents of the abiotic theory have also often claimed that hydrocarbons cannot be produced near the surface due to chemical constraints imposed by the second law of thermodynamics. However, this claim ignores the fact that all life is in thermodynamic disequilibrium with its environment (Walters, 2006). In some cases it was claimed that carbohydrates could be used as precursors being "typical biotic reagents" Kenney et al. (2002), even though others stated that neither proteins nor carbohydrates have been thought to have a role in petroleum formation for the last 40 years (AAPG Explorer, 2002). Kenney and Dieters (2000) also attempted to explain how optical activity can be formed in abiotic processes.

Astronomers have been frequent proposers of the abiotic petroleum theory in recent decades. Carbonaceous chondrites and other planetary bodies, including asteroids, comets, and moons, have been shown to contain hydrocarbons and other organic compounds while no biological life is present (Cronin et al., 1988). Fred Hoyle (1955) theorized that since the Earth was formed from similar materials, there should be vast amounts of abiotic hydrocarbons residing somewhere. The abundance of methane in the outer planets of the solar system is frequently used as an argument for abiotic oil origin.

The astronomer Thomas Gold (1985) was influenced by Hoyle's idea and developed his own model. Gold stated that mantle methane is continuously injected into the crust of weak areas such as the lithosphere's plate boundaries, ancient suture zones, and meteorite-impact sites. Under conditions of slow upward migration and cooling, some of this methane is assumed to polymerize and react in Fischer-Tropsch-analogous reactions resulting in longer hydrocarbon chains and crude oil of higher molecular weight. Szatmari (1989) and Potter et al. (2004) gives an overview of Fischer-Tropsch synthesis related to abiotic petroleum. Schoell (1988) and Wang et al. (1997) provides an overview of abiogenic natural gas. Gold (1992, 1999) later modified his hypothesis and suggested that coal and crude oil originate from mantle gas flows that feed bacteria living at extreme depths.

In 1980s, Gold managed to convince the Swedish government to test the abiotic theory by drilling ultra deep boreholes near in the granite formations of an old impact crater, the Siljan Ring, in northern Sweden. These drillings are the most serious attempt to test the abiotic oil formation theory. The drillings failed to locate any recoverable amounts of hydrocarbons. Evidence of even trace amounts of hydrocarbons has been deemed controversial (Kerr, 1990). The oily black paste that was found was shown to be derived from the mud, lubricants and organic additives of the drilling process (Jeffrey and Kaplan, 1988, 1989; Castano, 1993).

Nevertheless, Gold and other supporters of abiotic theory viewed the drillings as a scientific success. As of 2009, permission for new drillings in the Siljan area was given to a company in collaboration with the researcher V.G. Kutcherov to test their improved version of the abiotic oil formation theory and where commercial amounts of abiotic petroleum could be located (Orsa Tidning, 2010). To date, no results are reported for these new drillings.

Giardini and Melton (1981) and Giardini et al. (1982) should also be mentioned for their work. Studies of rocks from many places of the world have shown that mantle hydrocarbons can be found widely, although the content of such hydrocarbons in mantle-derived rocks are extremely low (Sugisaki and Mimura, 1994). Hulston et al. (2001) reached a similar conclusion from an investigation of the Taranaki Basin in New Zealand. Globally significant amounts of abiotic oil in the crust can be ruled out (Sherwood Lollar et al., 2002). Other studies have managed to discover or produce trace amounts of abiotic oil (Sherwood Lollar et al., 1993; McCollom and Seewald, 2001; Potter and Konnerup-Madsen, 2003; McCollom, 2003; Kolesnikov et al., 2009).

From this review of the situation we can conclude that it is possible to create abiotic oil in some laboratory conditions of high pressure and temperatures and that minor amount of abiotic hydrocarbons may be created in the mantle. However, commercially interesting accumulations have never been found (Walters, 2006). Nor has any oil ever been reported along major faults in continental shield areas where sedimentary rocks are not present (Peters et al., 2005). Jenden et al. (1993) concluded that the abiotic content of commercial natural gas is less than 200 ppm and that little confidence should be placed on the resource potential of abiotic natural gas.

2.4. Concluding remarks on oil formation theories

Durand (2003) highlights how proponents of abiotic petroleum were generally chemists with very little geological knowledge. One example is how the Russian-Ukrainian school saw evidence of their theory in the fact that some oil reservoirs exist in non-sedimentary rocks such as granite, metamorphic or porous volcanic rocks. However, all the studies conducted by geologists demonstrated that these rocks served as reservoirs for oil expelled from a sedimentary source rock not far away through common migration or re-migration mechanisms. Somehow those results were never integrated into the abiotic theory. Durand (2003) also points to the media as a factor behind the apparent popularity of abiotic petroleum theories in public debates, despite the underlying shortcomings and lack of holistic treatment.

Kutcherov (2008) claims that there are a number of geological data, such as the giant and super-giant petroleum deposits, can't be satisfactory explained in the established biogenic petroleum theory. Based on a hydrocarbon habitat estimate from Ayres et al. (1982), Kutcherov (2008) reaches the conclusion that only 6% of the Saudi in-place reserves could have originated from a migration from the petroleum source rock. Barkey and Dickey (1984) suggested that there were more source rocks than only the one of Callovian-Oxfordian age used by Ayres et al. (1982). However, both those studies were based on obsolete practices for estimating the amount of oil generated by a source rock. The introduction of Rock-Eval methodology and new studies, such as Demaison and Huizinga (1991) or Laherrere et al. (1994) arrived as significantly higher estimates. The source rocks in the petroleum system have generated more than 70 times the known in-place reserves of Saudi-Arabia, with very large amounts dispersed in the sediments compared to the recoverable resources. In other words, no abiotic oil is needed to explain the in-place discoveries in Saudi-Arabia if recent and updated geological studies are acknowledged. Indeed, it is surprising to see Kutcherov (2008) refer to an old paper from 1982, when there are many more recent papers.

A second argument presented by Kutcherov (2008) and other proponents of abiotic petroleum origin is the occurrence of petroleum deposits at great depths. A number of oil discoveries have been made at depths of 5000–10 000 m, but the vast majority has been located been located less deep. The world inventory of oil fields, excluding USA and Canada, is about 14 000 fields with total reserves of 2000 billion barrels. Only less than 500 of them are located deeper than 5000 m (Fig. 1). It is clear from the empirical discovery data that less oil has been found in deep horizons. This is also as expected from the studies on temperature and its importance for oil occurrence.

Tissot et al. (1987) found that temperature is the most sensitive parameter in hydrocarbon generation. About 90% of the world's oil and gas are found between the 60 °C and 120 °C isotherms, i.e. the golden zone, a clear trends show decreasing reserves with increasing reservoir temperature (Statoil, 2005). The maximum temperature where oil can be found is also an important topic. The geochemical approach of the 1980s were based on vitrinite reflectance and found that around 200 °C was the maximum temperature for oil to be preserved and not transformed into gas. Isaksen (2004), Hao et al. (2008), Mankiewicz et al. (2009) all showed how oil was cracked into natural gas at temperatures greater than 200 °C, which typically occurred at depths greater than 5000 m. However, there are also recent claims that oil can be stable up to temperatures of 240°–260 °C (Domine et al., 2002), which can explain occurrence of oil at more extreme places than previously thought possible.

Scientific support can be found for both the biogenic and abiotic theory of petroleum formation. However, theoretical studies, laboratory verification and discoveries of trace amounts of abiotic oil do not imply the existence of commercially significant deposits. The observations and actual discoveries made by geological studies must be integrated in any sound theory of petroleum formation. One cannot chose to disregard certain "*inconvenient*" details or fail to integrate new results in a theory.

Petroleum geology and exploration is an empirical and pragmatic field, which has evolved by trial and error. Geologists and oil companies have learned where to drill and where not to drill, and thus, developed a theoretical model that works and corresponds to reality. That model is consistent with the biogenic theory of oil creation, which can be read in more detail in AAPG (1994), Hunt (1995) or Selley (1998).

In the real world, the "truth of the borehole" speaks louder than any theory, since it provides actual production flows. Needless to say, the drilling done in line with the biogenic theory of oil formation has resulted in a vast amount of oil that has been of benefit to mankind since the beginning of the oil era. This has been verified by geochemical and geological studies that are accepted by a broad majority of researchers and experts within the scientific establishment and the petroleum industry.

Modern petroleum geology does not deny the existence of commercial amounts of abiotic oil. The abiotic theorists would surely win more credibility if big oil fields could be found supporting their theory. Glasby (2006) highlights how researchers have been unable to cite any commercial occurrence of abiotic petroleum, despite a long list of promising places such as the Siljan

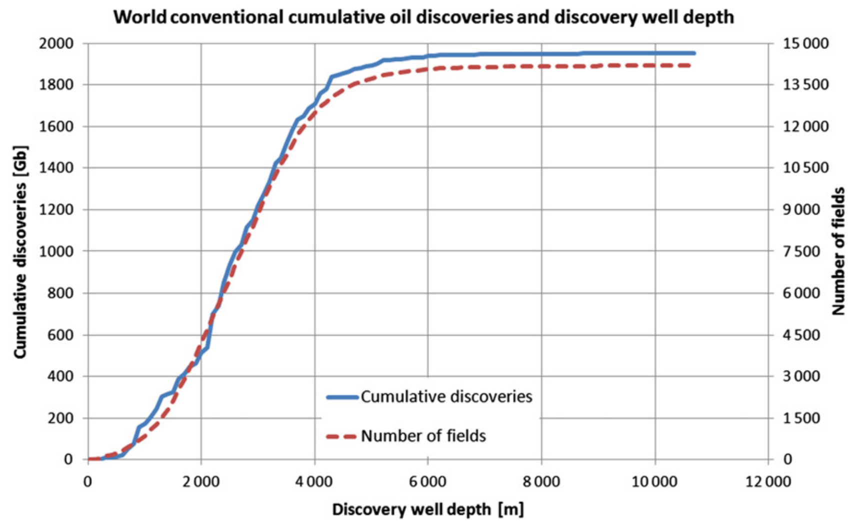

Fig. 1. World inventory of discovered oil fields outside the USA and Canada. Most discoveries have been done below 5000 m and only relatively minuscule additions have been provided by deeper wells. Data provided by Laherrere, 2010 (personal communication).

Ring, offshore Vietnam, Eugene Island in the Gulf of Mexico or the Dnieper-Donets Basin. In fact, the petroleum resources of those regions can be explained entirely within the biogenic framework (Vlierboom et al., 1986; Parnell, 1988; Roberts, 2001; Ulmishek, 2001; Bojesen-Koefoed et al., 2009; Coung and Warren, 2009). The abiotic theory of oil creation can be summarized as a question: if abiotic petroleum exists in large commercial amounts, where is it hiding?

3. Peak oil and oil formation theories

It commonly claimed that peak oil, i.e. the concept that oil production will reach a maximum level, is only about geology. We rather state that peak oil is the result of a complex series of forces which include economics and the physics of oil wells. On this point, we quote a famous passage from Newton (1726), reflecting the heart of natural science: "For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction."

Empirical observations and quantitative studies show that all oil fields and petroleum producing regions sooner or later "peak," that is, reach a maximum in oil production and then decline. There is no reason why world oil production and the physical laws that ultimately govern it should be different from those that govern the USA, various North Sea offshore fields or any other post-peak region. Many observations and historical experiences show how regions and fields reach a peak and begin to decline. In total, over 50 countries have passed their maximum production. Consequently, historical phenomena support the peak oil theory.

However, there are those who claim that the obvious physical limitations of the earth do not imply an economic limitation (Simon, 1998), or that natural resources are not needed for economic growth (Solow, 1974) or even that human ingenuity can overcome all possible physical limitations (Radetzki, 2007). However, neoclassical economy and its promises of perpetual increase in global oil production (which can be seen as just another region) is not supported by any phenomenological data, reducing it to a hypothesis based on metaphysical or occult qualities as Newton would have stated.

Peak oil is a theory backed by phenomenological evidence, including geology, reservoir physics, fluid mechanics, statistical physics, economics, and actual observations. This is different from some peak oil disbelievers, who seemingly argue for the hypothesis where natural laws can be bent or broken if the monetary price is high enough or if sufficiently strong political reasons exist. An overview of various oil forecasting methodologies has been done by Bentley and Boyle (2007), where it was concluded that quantitative studies of oil production are the most realistic.

Claims about a non-geological production peak due to lack of investments, lack of access or similar factors can and should only be seen as agreement with the peak oil theory, because peak oil it is about production flows not being able to meet demand, regardless of what the cause may be. Naturally, it can be discussed when in time the peak will arrive, but the important concept is the inescapable arrival of a production peak sooner or later. Having this understanding is vital for planning and necessary in order to tackle the challenges that nature imposes on future development.

3.1. Production patterns due to the finite nature of a resource

Before going into details about what peak oil theory actually claims, it is necessary to define certain parameters. The term "*finite resource*" is frequently used but few people seem to ponder what it actually means. When it comes to natural resources, we argue that production limits are determined by the extraction and creation rates. If extraction of a resource is faster than replenishment rate the resource will be "finite" in the sense that it will eventually be exhausted.

For instance, whales and their blubber oil were a finite resource. The whales were on the verge of becoming extinct despite their "renewable" nature prior to the use of crude oil (Bardi and Yaxley, 2005; Bardi, 2007). The case of whaling in 19th century is an excellent illustration of a complete Hubbert cycle, where a resource has been extracted at a much faster rate than it could be replaced. Whale oil and whale bone production show a very clear "bell shaped" curve (Fig. 2). The main species being exploited at the time (right whales) was reduced to nearly complete extinction, with an estimate of only 50 females left alive in the ocean. One could even

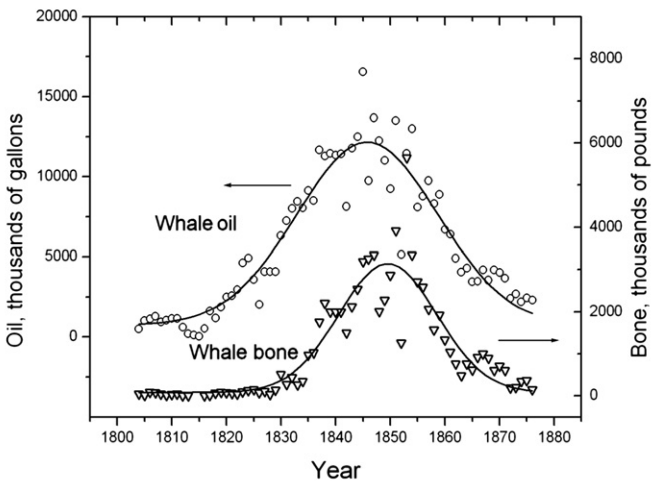

Fig. 2. Bell shaped production behavior or whale oil and whale bone, despite the renewable nature of whales. Adapted from: Bardi (2007).

claim that whales were saved by the discovery of oil and the switch to petroleum-derived products.

In addition, forests can be "renewable" if the annual outtake is no more than the annual growth. There are examples of how over-extraction of wood fuels have turned renewable forests into finite resources that resulted in eroded, deforested areas without any usable wood fuel production, effectively depleting the resource (Johansson, 2007). Peat and coal are also finite resources as they call for thousands or millions of years to generate layers of only a few millimetres, while extraction can cut layers of many meters per day. Uranium is also a finite resource as it is originally created from the ashes of supernovas (Burbidge et al., 1957), requiring many millions or billions of years to accumulate commercially interesting concentrations (World Nuclear Association, 2006). According to the standard, biogenic oil formation theory, millions of years are required for source rocks to be transformed into petroleum and accumulate in reservoirs (AAPG, 1994) while the reservoirs are drained in just a few years or decades in most cases.

An American geologist, M.K. Hubbert, is often seen as the father of peak oil theory. Hubbert (1956) proposed a model for the extrapolation of finite resource production curves into the future. His model assumes that production levels begin at zero, before the production has started, and ends at zero, when the resource has been exhausted. In between, the production curve passes through one or several maxima. The actual shape of the production curves may vary, but they are ultimately limited by the recoverable amounts of the finite resource. Naturally, recoverability is influenced by technology, accessibility, restrictions and economics as well as geology. It is impossible to extract more petroleum than geologically available. Constraints imposed by technology, economics and other factors will in practice make far less than all the geologically available volumes available for production.

Hubbert (1956) initially proposed a bell shaped curve for idealized production behaviour, representing various stages of maturity, without giving any exact mathematical description for it. Later, Hubbert (1959) used the simple logistic function due to its mathematical tractability as well as simplicity. Bardi (2005) subsequently showed that mineral production always results in a generally bell shaped curve except for very special assumptions — but the shape was not necessarily symmetric. Asymmetric models have been used for petroleum forecasts in many cases (Moore, 1966; Fitzpatrick et al., 1973; Feng et al., 2008).

Peak oil theory does not say that decline will necessarily be exponential or symmetric (as logistic curves do). In fact, Peak oil theory is a wide family of methods and curves for forecasting future production where the core is analysis of production flows and whether supply can meet a given demand. Cambridge Energy Research Associates (CERA) and their discussion of an undulating plateau instead of a distinct peak is still a case of "peak oil theory," although somewhat more concealed behind veils of accessibility and economical terms.

Colin Campbell and the Association for the Study of Peak Oil & Gas (ASPO), uses the following definition: "the term peak oil refers to the maximum rate of the production of oil in any area under consideration, recognising that it is a finite natural resource, subject to depletion." It does not state anything about which specific oil formation theory that is used nor does it imply that only geological constraints are regarded or that future production is supposed to follow the Hubbert curve (i.e. the derivative of the logistic function). Finiteness is the key factor and it is a function of the extraction rate compared to the generation rate — nothing else.

Formation of a commercially interesting oilfield requires petroleum generation, migration, accumulation and entrapment — processes that take much longer time altogether compared to the extraction of the recoverable oil by human activities. In a broader context, resources that are consumed faster than they are replenished will evidently be subject to depletion. Depletion and peaking can be modelled in many ways but the fundamental property is that there is some form of limitation on production imposed by nature.

Bardi and Lavacchi (2009) have explained the peak phenomenon on the basis of a simple theory based on the well known Lotka–Volterra biological model. The basis of the theory is that, initially, the extraction of an abundant and cheap resource leads to economic growth and to increasing investments in further extraction. Gradually, however, the cheap resources are depleted and extraction costs become higher because of the need to extract lower quality deposits. In time, investments cannot keep pace with these rising costs; the growth slows down and, eventually, production starts declining. Here, "costs" are to be understood in monetary terms as well as energy costs, which grow for physical reasons related to the lower concentration and or lower quality of the resource. In other words, what creates the bell curve for an energy resource like oil is the variation with time of the net energy of extraction, also known as Energy Return on Energy Investment (EROEI). In the case of oil, the EROEI effect is enhanced also by physical factors related to the fall in reservoir pressure and also with the fact that less and less oil-bearing reservoir is in touch with the wells as the oil is progressively extracted (Höök, 2009; Bardi, 2009). The theory developed by Bardi and Lavacchi (2009) is compatible with the experimental data, as shown in Fig. 3. It shows the historical trends of oil production in the US 48 lower states fitted with the theoretical Lotka–Volterra model. The agreement shows that simple concepts from biological systems, such as predator-prey-relations without reproduction of the prey, can explain peaking behaviour in natural resource extraction.

3.2. Abiotic oil theory and its implications for peak oil

How can abiotic oil formation theory change the practical finite nature of petroleum and the behaviour that leads to production peaks? We can see two possible cases: a "weak" and a "strong" abiotic petroleum theory (Bardi, 2004).

- The "weak" abiotic oil theory: oil is abiotically formed at rates not higher than those that petroleum geologists assume for oil formation according to the conventional biogenic theory.
- The "strong" abiotic theory: oil is formed at a speed sufficient to replace the oil reservoirs as we deplete them, that is, at a rate something like 10 000 times faster than known in conventional

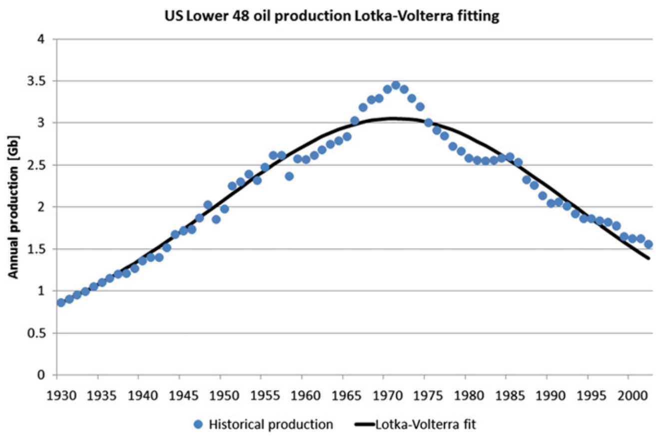

Fig. 3. Historical trends of oil production in the 48 US lower states fitted with the model developed by Bardi and Lavacchi (2009).

petroleum geology. In some cases, this version of theory claims that there exist true "oceans of oil" deep within the earth.

The weak abiotic theory does not change the fact that we are extracting oil much faster than it is being generated. For this reason, it does not change the fundamentals of peak oil theory. Nor does it remove the concept of a production peak at some point. In fact, one can easily swap biogenic petroleum formation theory for weak abiotic oil genesis and still derive the same type of arguments for a coming peak since it is production flows that matter. Mankind is still using oil much faster than it is regenerated by nature and sooner or later the oil reserves will be depleted and force the onset of decline and peak production, regardless of biogenic or weak abiotic oil formation theory.

Strong abiotic oil genesis is a completely different topic, as it would imply that oil is created naturally at least as fast as we are currently extracting it or even faster. In the most convenient (from a human viewpoint) version of the theory, the wells being exploited today are connected to ultra deep reservoirs that slowly (or rapidly) refill them. In this version, the theory allows for a virtually endless plateau production at some level of oil consumption. However, at some point production will eventually match the creation rate and, consequently, limit oil utilization. Therefore, the arrival of a maximum sustainable production level is still valid but it would be a plateau rather than a peak. This occurrence would likely postpone the "end of oil" far into the future and cause it to occur only when futuristic energy sources ought to have been invented.

It goes without saying, however, that even the most enthusiastic supporter of the abiotic oil theory cannot show any evidence for the "strong" version of the theory, at least in the papers published in scientific journals. It is another matter in the popular press, where wild claims have often been made. Such claims are more the result of wishful thinking than any quantitative evaluation based on scientific methodology.

4. Discussion

Discoveries of significant abiotic oil reserves would naturally postpone the global oil peak, if they can be put into production fast enough. However, the important point is whether those hypothetical undiscovered abiotic oil formations can be drilled and emptied fast enough to replace the decline from depleting fields currently in production, as peak oil is about flows.

The decline in existing oil production has been determined to be about 6% (Höök et al., 2009), being equivalent to a new annual production requirement of 4–7 Mb/d just to keep current production levels constant. These are figures that are well established from observations and widely spread within the petroleum industry and related agencies and organisations. Such numbers put certain perspectives on the flows that are needed for sustaining world oil production. A hypothetically vast reserve base has little to do with the likelihood of significant future production since production is dependent on many more factors than just geological availability. It is the size of the tap that matters, not the size of the reserves.

For example, vast and already discovered accumulations of non-conventional oil (oil sands, oil shale, etc.) exist and can be used to attenuate decline in existing production after peak oil. However, even with the most optimistic assumptions, a sustained growth rate of more than 10% for non-conventional oil production over the next two decades would be required (de Castro et al., 2009) to make up for the decline of conventional oil. Growth rates higher than 6–7% for non-conventional oil are not expected by either IEA (2008) or EIA (2009) in their outlooks to 2030 and even those rates are probably optimistic.

In comparison, vast abiotic oil accumulations have not been discovered yet and would likely require super and/or ultra deep drillings, which are expensive and take time. Kelessidis (2009) gives an overview of the challenges that deep drilling campaigns must overcome. A major and rapid development of potential abiotic oil formations deep within the crust or even deeper down near the mantle do not seem as a realistic alternative to quickly offset the decline in existing production. Whether hypothetically massive amounts of abiotic petroleum can be brought on stream and reach the world market in time can only be seen as questionable.

There is little doubt that drillings will be done to greater depth in the future but the important question is perhaps how fast such drilling methods can be developed and how cheap they can become. Even if there were sufficiently large abiotic oil reservoirs at great depth, producers must be able to tap those formations and make some kind of profit by selling the extracted oil. Without profit, they will simply become an untapped resource due to technological and/or economical obstacles.

The spectacular claims of the strong abiotic oil theory, that it is capable of refilling existing fields with hundreds of thousands of barrels per day, cannot be seen as anything other than cornucopian fairy tales, at least until they have been supported by observations. Consequently, the burden of proof rests with the proponents of such fabulous pronouncements. We wonder if anyone is prepared to back up such bold claims with any evidence.

5. Conclusions

Petroleum formation has been discussed since prehistoric times to the present day. In many ways, the current biogenic and abiotic theories may be seen as greatly improved and rigorous versions of their historical predecessors. Concepts and explanations have matured over hundreds of years and been continuously strengthened by new scientific investigations. Scientific support and theoretical arguments can be derived for both biogenic and abiotic oil. From a production perspective, it is the commercially extractable amounts of oil that matter. Biogenic petroleum geology has been superior in terms of locating reservoirs, which has given rise to the oil era and the present petroleum-powered society.

In comparison, abiotic theory has not been able to provide vast amounts of commercial reserves. The Siljan Ring drillings failed at finding a commercially interesting deposit, even though new attempts are going to be made in the future. Abiotic theory sometimes claims success in-places such as Vietnam, Dniepr-Donets Basin and Eugene Island, but those deposits can also be explained by biogenic petroleum geology. The lack of a clear and irrefutable success in locating abiotic petroleum in commercial quantities is problematic. Until such examples are found, abiotic petroleum will likely remain a relatively ambiguous concept. However, certain groups do not agree and claim that commercial accumulations have nothing to do with fossil remains (Kenney et al., 2001).

Abiotic petroleum formation theories are largely irrelevant to the debate about peak oil, unless it is assumed that the most extreme version of the abiotic oil theory, namely the "strong one" is a reality. However, such spectacular claims necessitate comprehensive and convincing evidence. In what might be a reasonably realistic version of the abiotic theory, massive abiotic oil discoveries and their rapid development would be able, at most, to postpone the date of the peak by some years or decades in the weak case, but it would not be able to remove the notion of an ultimate production peak at some time. Peak oil is a matter of extraction rates and flows, not oil formation theories. People that do not understand this difference should not be allowed to advice policy makers or plan for the future in the light of peak oil and the importance of natural resources for the continued well-being of mankind.

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References

AAPG, 1994. The petroleum system – from source to trap. AAPG Memoir 60, 655.
AAPG Explorer, 2002. To be (abiogenic), or not to be. http://www.aapg.org/explorer/2002/11nov/abiogenic.cfm November 2002,.
Abelson, P.H., 1963. Organic geochemistry and the formation of petroleum. Sixth World Petroleum Congress Proceedings, Section 1, pp. 397–407.
Agricola, G., 1546a. De Natura Fossilium. Dover Publications, Mineola, 256 pp.
Agricola, G., 1546b. De Natura Eorum Quae Effluunt Ex Terra. SNM, Bratislavae, 487 pp.
Ahsan, A., Karlsen, D.A., Patience, R.L., 1997. Petroleum biodegradation in the Tertiary reservoirs of the North Sea. Marine and Petroleum Geology 14 (1), 55–64.
Arnold, R., Anderson, R., 1907. Geology and oil resources of the santa maria oil district, Santa Barbara County, California. USGS Bulletin, report 322, 161.
Ayres, M.G., Bilal, M., Jones, R.W., 1982. Hydrocarbon habitat in main producing areas, Saudi Arabia. AAPG Bulletin 66 (1), 19.
Bacon, 1258 Bacon, R., 1258. Fr. Rogeri Bacon Opera Quædam Hactenus Inedita, edited by John Sherren Brewer. Longman, Green, Longman and Roberts, London, 577 pp.
Bardi, U., 2004. Abiotic Oil: Science or Politics?. see also: From the Wilderness Publications http://www.fromthewilderness.com/free/ww3/100404_abiotic_oil.shtml.
Bardi, U., 2005. The mineral economy: a model for the shape of oil production curves. Energy Policy 33 (1), 53–61.
Bardi, U., Yaxley, L., 2005. How general is the Hubbert curve? The case of fisheries. Presented at the Fourth International Workshop on Oil and Gas Depletion (IWOOD 4), 19–20 May, Lisbon, Portugal. See also: http://www.cge.uevora.pt/aspo2005/abscom/Abstract_Lisbon_Bardi.pdf.
Bardi, U., 2007. Energy prices and resource depletion: lessons from the case of whaling in the nineteenth century. Energy Sources Part B, Economics, Planning and Policy 2 (3), 297–304.
Bardi, U., Lavacchi, A., 2009. A simple interpretation of Hubbert's model of resource exploitation. Energies 2 (3), 646–661.
Bardi, U., 2009. Peak oil: the four stages of a new idea. Energy 34 (3), 323–326.
Barkey, C., Dickey, P.A., 1984. Hydrocarbon habitat in main producing areas, Saudi Arabia; discussion. AAPG Bulletin 68 (1), 108–109.
Bentley, R., Boyle, G., 2007. Global oil production: forecasts and methodologies. Environment and Planning B: Planning and Design 34 (4), 609–626.
Beydoun, Z.R., 1997. Prehistorical, ancient and medieval occurrences and uses of hydrocarbons in the Greater Middle East Region. Journal of Petroleum Geology 20 (1), 91–95.
Bojesen-Koefoed, J.A., Nytoft, H.P., Nguyen, T.D., 2009. Petroleum composition in the Cuu long Basin (Mekong Basin) offshore southern Vietnam. Marine and Petroleum Geology 26 (6), 899–908.
Burbidge, E.M., Burbidge, G.R., Fowler, W.A., Hoyle, F., 1957. Synthesis of the elements in stars. Reviews of Modern Physics 29 (4), 547–650.
Castano, J.R., 1993. Prospects for commercial abiogenic gas production: implications from the Siljan Ring Area, Sweden. In: Howell, D.G. (Ed.), The Future of Energy Gases. U.S. Geological Survey Professional Paper 1570, pp. 133–154.
de Castro, C., Miguel, L.J., Mediavilla, M., 2009. The role of non conventional oil in the attenuation of peak oil. Energy Policy 37 (5), 1825–1833.
Clarke, F.W., 1916. Data of Geochemistry, third ed. US Geological Survey Bulletin, 616 pp.
Clayton, C., 1991. Carbon isotope fractionation during natural gas generation from kerogen. Marine and Petroleum Geology 8 (2), 232–240.
Coung, T.X., Warren, J.K., 2009. Bach Ho field, a fractured granitic basement reservoir, Cuu Long Basin, Offshore SE Vietnam: a "buried-hill" play. Journal of Petroleum Geology 32 (2), 129–156.
Craig, H., 1953. The geochemistry of the stable carbon isotopes. Geochimica et Cosmochimica Acta 3 (2–3), 53–92.
Cronin, J., Pizzarelo, S., Cruikshank, D.P., 1988. Organic matter in carbonaceous chondrites, planetary satellites, asteroids, and comets. In: Kerridge, J.F., Matthews, M.S. (Eds.), Meteorites and the Early Solar System. University of Arizona Press, pp. 819–857.
Dearne, J., Branigan, K., 1995. The use of coal in Roman Britain. The Antiquaries Journal 75, 71–105.
Demaison, G.J., 1977. Asphalt sands and supergiant oil fields. American Association of Petroleum Geologists Bulletin 63, 1950–1961.
Demaison, G.J., Huizinga, B.J., 1991. Genetic classification of petroleum systems. AAPG Bulletin 75 (10), 1626–1643.
Derewenda, Z.S., 2008. On wine, chirality and crystallography. Acta Crystallographica Section A 64, 246–258.
Domine, F., Bounaceur, R., Scacchi, G., Marquaire, P.-M., Dessort, D., Pradier, B., Brevart, O., 2002. Up to what temperature is petroleum stable? New insights from a 5200 free radical reactions model. Organic Geochemistry 33 (12), 1487–1499.
Dott, R.H., 1969. Hypotheses for an organic origin. In: Dott, R.H., Reynolds, M.J. (Eds.), Sourcebook for Petroleum Geology, Part 1 – Genesis of Petroleum. American Association of Petroleum Geologists, Tulsa, pp. 1–244.
Durand, B., 1980. Kerogen-insoluble Organic Matter from Sedimentary Rocks. Editions Technip, Paris, 519 pp.
Durand, B., 2003. A history of organic geochemistry. Oil and Gas Science and Technology – Revue de IFP 58 (2), 203–231.
Eglinton, G., Calvin, M., 1967. Chemical fossils. Scientific American 216, 32–43.
EIA, 2009. International Energy Outlook 2009. World unconventional liquids production by region and country, Table G3. http://www.eia.doe.gov/oiaf/ieo/index.html see also:
Engler, K.O.V., 1913. Die Chemie und Physik des Erdöls (in German). S. Hirzel, Leipzig, 855 pp.
Erdman, J.G., Marlett, E.M., Hanson, W.E., 1958. The occurrence and distribution of low molecular weight aromatic hydrocarbons in recent and ancient carbonaceous sediments. Presented before the Division of Petroleum Chemistry, 134th Meeting, American Chemical Society, Chicago, Illinois, 7–12 September 1958.
Feng, L., Junchen, L., Pang, X., 2008. China's oil reserve forecast and analysis based on peak oil models. Energy Policy 36 (11), 4149–4153.
Fischer, F., Tropsch, H., 1930. US Patent 1746464, "Process for the production of paraffin hydrocarbon with more than one carbon atom", http://www.fischer-tropsch.org/primary_documents/patents/US/us1746464.pdf [accessed Feb 2010].
Fitzpatrick, A., Hitchon, B., McGregor, J.R., 1973. Long-term growth of the oil industry in the United States. Mathematical Geology 5 (3), 237–267.
Forsman, J.P., Hunt, J.M., 1958. Insoluble organic matter (kerogen) in sedimentary rocks of marine origin. In: Weeks, L.G. (Ed.), Habitat of Oil: a Symposium. American Association of Petroleum Geologists, Tulsa, pp. 747–778.
Fuex, A.N., 1977. The use of stable carbon isotopes in hydrocarbon exploration. Journal of Geochemical Exploration 7, 155–188.
Giardini, A.A., Melton, C.E., 1981. Experimentally-based arguments supporting large crustal accumulations of non-biogenic petroleum. Journal of Petroleum Geology 4 (2), 187–190.
Giardini, A.A., Melton, C.E., Mitchell, R.S., 1982. The nature of the upper 400 km of the earth and its potential as the source for non-biogenic petroleum. Journal of Petroleum Geology 5 (2), 173–190.
Glasby, G.P., 2006. Abiogenic origin of hydrocarbons: an historical overview. Resource Geology 56 (1), 85–98.
Gold, T., 1985. The origin of natural gas and petroleum and the prognosis for future supplies. Annual Review of Energy 10, 53–77.
Gold, T., 1992. The deep, hot biosphere. Proceedings of the National Academy of Sciences of the United States of America 89 (13), 6045–6049.
Gold, T., 1999. The Deep Hot Biosphere. Copernicus, New York, 235 pp.
Gutierrez, J.M., Mamuscai, D., Mohr, K.S., 2000. Upgrading petroleum Terminal Separators using Coalescing Plates. Proceedings of the Water Environment Federation, Industrial Wastes, 585–591.
Hao, F., Guo, T., Zhu, Y., Cai, X., Zou, H., Li, P., 2008. In: Evidence for Multiple Stages of Oil Cracking and Thermochemical Sulfate Reduction in the Puguang Gas Field, 92. AAPG Bulletin, Sichuan Basin, China, pp. 611–637. 5.
Hoyle, F., 1955. Frontiers of Astronomy. Heineman, London, 360 pp.

Hubbert, M.K., March 7–9 1956. Nuclear Energy and the Fossil Fuels. Presented before the Spring Meeting of the Southern District. American Petroleum Institute, Plaza Hotel, San Antonio, Texas. http://www.hubbertpeak.com/Hubbert/1956/1956.pdf.
Hubbert, M.K., 1959. Techniques of Prediction with Application to the Petroleum Industry. Shell Development Company, Dallas, 43 pp.
Hulston, J.R., Hilton, D.R., Kaplan, I.R., 2001. Helium and carbon isotope systematics of natural gases from Taranaki Basin. New Zealand. Applied Geochemistry 16 (4), 419–436.
Hunt, T.S., 1863. Report on the geology of Canada. Canadian Geological Survey Report: Progress to 1863, Canadian Geological Survey.
Hunt, J.M., 1979. Petroleum Geochemistry and Geology, first edition. Freeman, New York, 617 pp.
Hunt, J.M., 1995. Petroleum Geochemistry and Geology, second edition. Freeman, New York, 743 pp.
Hunt, J.M., Philp, R.P., Kvenvolden, K.A., 2002. Early developments in petroleum geochemistry. Organic Chemistry 33, 1025–1052.
Höök, M., Hirsch, R., Aleklett, K., 2009. Giant oil field decline rates and their influence on world oil production. Energy Policy 37 (6), 2262–2272.
Höök, M., 2009. Depletion and Decline Curve Analysis in Crude Oil Production. Licentiate thesis from Uppsala University. http://www.tsl.uu.se/uhdsg/Personal/Mikael/Licentiat_Thesis.pdf.
IEA, 2008. World energy outlook 2008. see also: http://www.worldenergyoutlook.org/.
Isaksen, G.H., 2004. Central North Sea hydrocarbon systems: generation, migration, entrapment, and thermal degradation of oil and gas. AAPG Bulletin 88 (11), 1545–1572.
Jeffrey, A.W.A., Kaplan, I.R., 1988. Hydrocarbons and inorganic gases in the Gravberg-1 well, Siljan ring, Sweden. Chemical Geology 71 (1–3), 237–255.
Jeffrey, A.W.A., Kaplan, I.R., 1989. Drilling fluid additives and artifact hydrocarbons shows: examples from the Gravberg-1 well, Siljan Ring, Sweden. Scientific Drilling 1, 63–70.
Jenden, P.D., Hilton, D.R., Kaplan, I.R., Craig, H., 1993. Abiogenic hydrocarbons and mantle helium in oil and gas fields. In: Howell, D.G. (Ed.), The Future of Energy Gases. USGS Professional Paper 1570, pp. 31–56.
Jobson, A., Cook, A.D., Westlake, D.W.S., 1972. Microbial utilization of crude oil. Applied Microbiology 23, 1082–1089.
Johansson, K., 2007. Energy System in the Loess Plateau – a Case Study of Changes during the Rehabilitation Period. see also:. Project report from Uppsala University http://www.tsl.uu.se/uhdsg/Publications/Loess.pdf.
Kenney, J.F., 1996. Considerations about recent predictions of impending shortages of petroleum evaluated from the perspective of modern petroleum science. Energy World 240, 16–18.
Kenney, J.F., Dieters, U.K., 2000. The evolution of multicomponent systems at high pressures, Part IV: the genesis of optical activity in high-density, abiotic fluids. Physical Chemistry Chemical Physics 2 (14), 3163–3174.
Kenney, J.F., Shnyukov, A.Y.E., Krayushkin, V.A., Karpov, V.G., Kutcherov, V.G., Plotnikova, I.N., 2001. Dismissal of the claims of a biological connection for natural petroleum. Energia 22 (3), 26–34.
Kenney, J.F., Kutcherov, V.A., Bendeliani, N.A., Alekseev, V.A., 2002. 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. Proceedings of the National Academy of Sciences 99 (17), 10976–10981.
Kerr, R.A., 1990. When a radical experiment goes bust. Science 247 (4947), 1177–1179.
Kelessidis, V.C., 2009. Challenges for very deep oil and gas drilling – will there ever be a depth limit? Third AMIREG International Conference: Assessing the Footprint of Resource Utilization and Hazardous Waste Management, 7-9 September 2009, Athens, Greece
Kolesnikov, A., Kutcherov, V.G., Goncharov, A.F., 2009. Methane-derived hydrocarbons produced under upper-mantle conditions. Nature Geoscience 2, 566–570.
Kudryavtsev, N., 1951. Against the organic hypothesis of the origin of petroleum (in Russian). Petroleum Economy [Neftianoye Khozyaistvo] 9, 17–29.
Kutcherov, V.G., 6 June 2008. Theory of Abyssal Abiotic Petroleum Origin: Challenge for Petroleum Industry. AAPG European Region Newsletter. http://www.aapg.org/europe/newsletters/2008/06jun/06jun08europe.pdf.
Laherrere, J., Perrodon, A, Demaison, G., 1994. Undiscovered petroleum potential. Petroconsultants report, 383 pp.
Laherrere, J., 2010. Personal Communication.
Lesquereux, L., 1866. In: Worthen, A.H. (Ed.), Report on the Fossil Plants of Illinois, 2. Palaeontology. Geological Survey of Illinois, pp. 425–467.
Mankiewicz, P.J., Pottorf, R.J., Kozar, M.G., Vrolijk, P., 2009. Gas geochemistry of the Mobile Bay Jurassic Norphlet Formation: thermal controls and implications for reservoir connectivity. AAPG Bulletin 93 (10), 1319–1346.
McCollom, T.M., 2003. Formation of meteorite hydrocarbons from thermal decomposition of siderite ($FeCO_3$). Geochimica et Cosmochimica Acta 67 (2), 5078–5097.
McCollom, T.M., Seewald, J.S., 2001. A reassessment of the potential for reduction of dissolved CO_2 to hydrocarbons during serpentinization of olivine. Geochimica et Cosmochimica Acta 65 (21), 3769–3778.
Mendeleev, D., 1877. second series. L'Origine du pétrole, vol. VIII. Revue Scientifique, pp. 409–416.
Mendeleev, D., 1902. The principles of chemistry. In: Second English Edition, Translated from the Sixth Russian Edition, Volume 1. Collier, New York, 552 pp.
Moore, C.L., 1966. Projections of U.S. Petroleum Supply to 1980, with Annex Entitled: the Gompertz Curve for Analyzing and Projecting the Historic Supply Patterns of Exhaustible Natural Resources. Office of Oil and Gas, Washington, DC, Technical report, 47 pp.
Newberry, J.S., 1873. The General Geological Relations and Structure of Ohio, Ohio Geological Survey Report 1, Part 1. Division of Geological Survey, Columbus, Ohio.
Newton, I., 1726. Philosophiae Naturalis Principia Mathematica, General Scholium. page 943 of I. Bernard Cohen and Anne Whitman's 1999 translation, third ed. University of California Press. 974pp.
Oakwood, T.S., Shriver, D.S., Fall, H.H., McAleer, W.J., Wunz, P.R., 1952. Optical activity of petroleum. Industrial and Engineering Chemistry 44, 2568–2570.
Odell, P.R., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 737–742.
Tidning, Orsa, 2010. Where cracks meet, it is advisable to drill [in Swedish]. http://www.orsatidning.net/?p=1637 Local newspaper reportage from the Siljan region in Sweden.
Parnell, J., 1988. Migration of biogenic hydrocarbons into granites: a review of hydrocarbons in British plutons. Marine and Petroleum Geology 5 (4), 385–396.
Partington, J.R., Hall, B.S., 1999. A History of Greek Fire and Gunpowder. JHU Press, Baltimore, 381 pp.
Peters, K.E., Walters, C.C., Moldowan, J.M., 2005. The Biomarker Guide, second edition. Cambridge University Press. 1155pp.
Philippi, G.T., 1965. On the depth, time and mechanism of petroleum generation. Geochimica et Cosmochimica Acta 29 (9), 1021–1049.
Pompeckj, J.F., 1901. Die Juraablagerung zwischen Regensburg und Regenstauf. Geologisches Jahrbuch 14, 139–220.
Potter, J., Konnerup-Madsen, J., 2003. A Review of the Occurrence and Origin of Abiogenic Hydrocarbons in Igneous Rocks. In: Geological Society, London, Special Publications, vol. 214 151-173.
Potter, J., Rankin, A.H., Treloar, P.J., 2004. Abiogenic Fischer–Tropsch Synthesis of Hydrocarbons in Alkaline Igneous Rocks; Fluid Inclusion, Textural and Isotopic Evidence from the Lovozero Complex, vol. 75. Lithos, N.W. Russia (3–4), 311–330.
Radetzki, M., 2007. Råvarumarknaden (in Swedish). SNS Förlag, 312 pp.
Roberts, S.J., 2001. Fluid flow in the South Eugene Island area, offshore Louisiana: results of numerical simulations. Marine and Petroleum Geology 18 (7), 799–805.
Robinson, R., 1966. The origins of petroleum. Nature 212, 1291–1295.
Rudakov, G., 1967. Recent developments in the theory of the non-biogenic origin of petroleum. Chemical Geology 2, 179–185.
Schoell, M., 1988. Multiple origins of the methane in the earth. Chemical Geology 71 (1–3), 1–10.
Schubert, C., 1915. The conditions of black shale deposition as illustrated by Kuperschiefer and Lias of Germany. Proceedings of the American Philosophical Society 54, 259–269.
Selley, R., 1998. Elements of Petroleum Geology, second edition. Academic Press, San Diego, 470 pp.
Sherwood Lollar, B., Frape, S.K., Weise, S.M., Fritz, P., Macko, S.A., Whelan, J.A., 1993. Abiogenic methanogenesis in crystalline rocks. Geochimica et Cosmochimica Acta 57 (23–24), 5078–5097.
Sherwood Lollar, B., Westgate, T.D., Ward, J.A., Slater, G.F., Lacrampe-Couloume, G., 2002. Abiogenic formation of alkanes in the Earth's crust as a minor source for global hydrocarbon reservoirs. Nature 446 (6880), 522–524.
Silverman, S.R., Epstein, S., 1958. Carbon isotopic composition of petroleums and other sedimentary organic materials. AAPG Bulletin 42, 998–1012.
Simon, J., 1998. The Ultimate Resource 2, Revised Version. Princeton University Press, New Jersey, 778 pp.
Snider, L.C., 1934. Current ideas regarding source beds for petroleum. In: Rather, W.E., Lahee, W.E. (Eds.), Problems of Petroleum Geology. AAPG Memoir 1. American Association of Petroleum Geologists, pp. 51–66.
Speight, J.G., 2007. The Chemistry and Technology of Petroleum, fourth edition. CRC Press, Boca Raton, 945 pp.
Statoil, 2005. Distribution of Hydrocarbons in Sedimentary Basins – the Importance of Temperature Research and Technology Memoir 7. August 2005.
Solow, R., 1974. The economics of resources or the resources of economics. The American Economic Review 64 (2), 1–14.
Sugisaki, R., Mimura, K., 1994. Mantle hydrocarbons: abiotic or biotic? Geochimica et Cosmochimica Acta 58 (11), 2527–2542.
Szatmari, P., 1989. Petroleum formation by Fischer-Tropsch synthesis in plate tectonics. AAPG Bulletin 73 (8), 989–998.
Tang, Y., Perry, J.K., Jenden, P.D., Schoell, M., 2000. Mathematical modeling of stable carbon isotope ratios in natural gases. Geochimica et Cosmochimica Acta 64 (15), 2673–2687.
Treibs, A., 1934. The occurrence of chlorophyll derivatives in an oil shale of the upper Triassic. Justus Liebigs Annalen der Chemie 517, 103–114.
Treibs, A., 1936. Chlorophyll and hemin derivatives in organic materials. Angewandte Chemie 49, 682–686.
Thomas, L., 2002. Coal Geology. John Wiley & Sons Ltd., Chichester, 384 pp.
Tissot, B.P., Welte, D.H., 1978. Petroleum Formation and Occurrence — a New Approach to Oil and Gas Exploration. Springer, Berlin, 538 pp.
Tissot, B.P., Welte, D.H., 1984. Petroleum Formation and Occurrence, Second Revised and Enlarged Version. Springer, Berlin, 699 pp.

Tissot, B.P., Pelet, R., Ungerer, P., 1987. Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. AAPG Bulletin 71 (12), 1445–1466.
Tsatskin, A., Balaban, O., 2008. Peak oil in the light of oil formation theories. Energy Policy 36 (6), 1826–1828.
Ulmishek, G.F., 2001. Petroleum Geology and Resources of the Dnieper-Donets Basin. U.S. Geological Survey Bulletin, Ukraine and Russia. http://pubs.usgs.gov/bul/2201/E/ 2201–E.
Vlierboom, F.W., Collini, B., Zumberge, J.E., 1986. The occurrence of petroleum in sedimentary rocks of the meteor impact crater at Lake Siljan, Sweden. Advances in Organic Geochemistry 10 (1–3), 153–161.
Walters, C.C., 2006. The origin of petroleum. In: Hsu, C.S., Robinson, P.R. (Eds.), Practical Advances in Petroleum Processing. Springer, pp. 79–101.
Wang, X., Li, C., Chen, J., Xia, X., Guo, Z., Xie, H., 1997. On abiogenic natural gas. Chinese Science Bulletin 42 (16), 1327–1337.
Winters, J.C., Williams, J.A., 1969. Microbiological alteration of crude oil in the reservoir. Symposium on Petroleum Transformation in Geologic Environments, American Chemical Society, Division of Petroleum Chemistry, Paper PETR 86, p. E22-E31.
White, D., 1915. Geology: some relations in origin between coal and petroleum. Journal of the Washington Academy of Science 5 (6), 189–212.
Whitehead, E.V., 1971. Chemical clues to petroleum origin. Chemistry and Industry 27, 1116–1118.
World Nuclear Association, 2006. The cosmic origins of uranium. http://www.world-nuclear.org/info/inf78.html See also: