Origin of petroleum—the conundrum and the Indian scenario

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Abstract
Most geoscientists, worldwide, believe the origin of petroleum deposits found on the earth is biotic (organic) which is supported by scientifically proven facts and is based on the recognized model of the petroleum system. However, some scientists, mainly from Russia and Ukraine, disagree, and question the biotic origin. Arguing the contrarian views with supporting evidence they strongly believe the origin of petroleum is abiotic; its origin being primordial in the mantle, deep below in the earth. Proponents and opponents of the biotic and abiotic theories of origin have their arguments and counter arguments, each claiming the merits of their respective theories. The issue of origin holds enormous significance as it can impact the future energy scenario of petroleum resources of the planet. While the biotic origin foresees the petroleum reserves of the world as limited and exhaustible, the abiotic origin promises potentials of unlimited inexhaustible resources.

The biotic and the abiotic theories with their supporting and conflicting evidence/arguments are briefly mentioned. Some of the evidence is examined in the context of oil/gas occurrences in India which reveal certain interesting facts, inexplicable by either of the theories of the origin of petroleum.

Keywords: origin of petroleum, abiotic, primordial source, mantle, vertical migration, biotic origin, organic source, petroleum system

Introduction
Petroleum, a complex mixture of hydrocarbons, occurs on earth in liquid (crude oil), gaseous, or solid form (as bitumen in tar sands). However, the origin of crude oil and gas that is discovered on earth remains a debatable issue, about whether it is biotic (organic) or abiotic (inorganic). Deliberations on the origin of methane, the simplest form of hydrocarbon, are excluded here as it is unarguably formed by both biotic and abiotic sources.

The biotic origin of petroleum occurrences in conventional and unconventional reservoirs generated from organic rich sedimentary source rocks is commonly accepted and the process of accumulation of hydrocarbons is well expounded by the petroleum system and is recognized worldwide. However, some scientists, mostly from Russia and Ukraine, disagree, and argue otherwise questioning the biotic origin of petroleum. Backed by laboratory experiments as well as geological and geographical occurrences of hydrocarbons worldwide as evidence, they refute the biotic origin and strongly advocate for the abiotic origin of petroleum, a primordial

[Author’s note: Sometime back I was invited by a WhatsApp blog group to express my views on the origin of petroleum despite admitting upfront that I am unfamiliar with the topic. However, the invite prompted me to delve into some published literature on the topic which brought out a few interesting facts. Analysed in the context of some of the oil and gas occurrences in the Indian basins, some of them appear inexplicable by either theory on the origin of petroleum. This may provoke some of the readers to further reflect on the topic.]

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source deep inside the mantle. Many geoscientists have supported the presence of abiotic hydrocarbon fluids in the mantle of the earth from which the oil/gas is formed by inorganic processes. The abiotic theory of origin of petroleum is scientifically proven, backed by laboratory experiments and geologic evidence (Kutcherov and Krayushkin, 2010; Kutcherov, 2013; Gold, 1993). On the other hand, biotic theory, accepted by most in the world, is also regarded scientifically established based on synthesis studies of paleontology, geology, and chemistry (Walters, 2007). Both theories uphold their arguments and evidence leading to the conundrum about the origin of petroleum. This issue is important as it can have significant future ramifications in the energy scenario for our planet. This is because the abiogenic origin of hydrocarbons endorses the presence of enormous, inexhaustible resources of hydrocarbons whereas the biotic origin foresees the petroleum reserves of the world as finite and exhaustible.

The process by which petroleum can be formed synthetically is extensively researched with laboratory experiments and exhibits the complexity and complication of petroleum formation in nature. Without delving into the arguably complex and comprehensive chemical and geochemical processes entailed in the formation of petroleum in nature, in a simple way, I deliberate the issue of origin of oil and gas through a criterion of examining the geologic characteristics of some of the petroleum occurrences in the world. A brief review brings out that geologic evidence expounded by one theory can be annulled by the other. Beginning with a short description of each of the theories of origin of petroleum, the biotic and the abiotic, some of the important opinions and evidence advocated by the proponents of abiotic theory are taken up for discussion to adjudge the merits of the theories, particularly in reference to occurrence of some oil and gas fields of ONGC, India. The geologic characteristics of petroleum occurrences, though differ individually in field scale, bring out certain interesting and intriguing facts that are difficult to explain satisfactorily by either of the theories, leaving the riddle of the 'true' origin of petroleum to continue.

**Background**

**Biotic origin of petroleum**

The biotic theory expounds that when sedimentary rocks containing organic matter derived from biota, get buried to the required pressure and temperature, the kerogen in them gets transformed into oil and gas. The oil and gas from the source rock get expelled due to the overburden pressure, which then migrate horizontally and vertically through permeable beds and faults to porous reservoirs and accumulate in traps. The occurrences of oil and gas in conventional and unconventional reservoirs worldwide are reasonably well-explained, the process of formation and accumulation explicated by the principal elements of the petroleum system, namely the type and amount of organic matter in the source rock, the burial and thermal maturity, the porous reservoir rock, and the trap. Each type of source facies generates oil/gas with distinct chemical composition that reflects the biotic input, depositional setting, and thermal history. The theory that petroleum originates from sedimentary organic matter (that was once living organisms), is consistent with all natural observations, laboratory analyses and experiments, theoretical considerations, and with basin simulations which constitutes the petroleum system (Walters, 2007). Consequently, almost all exploration endeavours for discovery of oil and gas the world over are carried out based on estimating the potential of the elements of the petroleum system, founded on the doctrines of organic origin of petroleum.
Abiotic origin of petroleum

Abiotic origin, in contrast, essentially theorizes the origin of petroleum, as primordial and ‘abyssal’, generated deep inside the earth. Carbon and hydrogen atoms present at great depths, temperatures, and pressures, combine to form hydrocarbons, which migrate vertically through deep-seated faults and associated fractures and fissures to the surface of the earth (Figure 1). According to the proponents of the theory, the geochemical process of formation of petroleum deep inside the earth has been convincingly demonstrated in laboratory experiments (Kutcherov and Krayushkin, 2010). Many scientists have defended the synthesis of hydrocarbons formed from methane and inorganic minerals (serpentine) deep inside the earth proposing different geochemical processes (Scalera, 2011). The geologic and geographic patterns of widespread occurrence of petroleum and methane in tectonically active belts of earthquakes and volcanic arcs, related to deep-seated mega scale crustal features in the world is cited as one of the main pieces of evidence of abiotic origin of petroleum.

The principles of the theory of abiotic origin of petroleum being primeval, its process of generation in deep mantle conditions, the supporting experimental laboratory results and the surface evidence of pattern of geographical distribution and geologic characteristic of petroleum deposits worldwide are discussed in great detail in the seminal papers by Kutcherov and Krayushkin (2010) and Kutcherov (2013). Many giant and supergiant oil and gas fields across the world are comprehensively exemplified claiming that several questions raised on their geologic characteristics are incomprehensible as per the biotic theory but are explicable by the abiotic theory.

Figure 1: Schematic illustrating the genesis of natural gas and petroleum and its deposits (after Kutcherov, 2013). The origin of petroleum is abiotic with the primordial source located deep in the mantle from where it vertically migrates to earth’s surface through deep crustal faults and fractures.

With passage of time, more and more reported evidence of many compounds that are found in the oil reservoirs and elsewhere associated with abiotic origin of petroleum led to some western geologists admitting that some oil fields are of abiogenic nature (Scalera, 2011). The sedimentary source rock and lateral migration of
hydrocarbons, the two of the key elements on which the theory of biotic origin is found, are rejected. Gold (1993), an opponent of biotic theory, claimed that the so-called geochemical analysis of total organic carbon (TOC) in rocks such as shales does not refer to the organic carbon content of biological origin. Furthermore, the concept of lateral migration of oil and gas is opposed as not being consistent with the standpoint of the classic laws of physics that describe the relationship between capillary and buoyancy forces of oil and gas in the natural porous media (Kutcherov and Krayushkin, 2010). The denunciations, however, remain anathema to the believers of the theory of biotic origin. Interestingly, Gold (1993) suggested that one way of possible migration of oil and gas to the surface can be the ascent of fluids from the mantle due to the build-up of sufficient fluid pressure to fracture the rock and create pathways. Remarkably, this is a process envisaged similar to primary migration or expulsion of hydrocarbon from the shale source rock, supported in biotic theory.

**Evidence cited by proponents in support of abiotic origin**

Some of the evidence and observations advocated in support of the abiotic origin are listed below and deliberated, particularly from the perspective of oil and gas deposits of ONGC, India.

1. Mega scale geographical occurrences of oil/gas deposits in tectonically active belts of earthquakes and volcanic arcs worldwide indicate abyssal origin of petroleum that migrated vertically to the surface through deep crustal faults and fissures.

2. Presence of natural gas and petroleum fluids in the Precambrian crystalline basements all over the world with no sedimentary source rocks around, signify its abiotic source and vertical migration.

3. Misbalance between the amounts of assessed hydrocarbons generated from the volume of biotic sources identified and the estimated reserves for many giant and supergiant oil and gas fields in the world do not support biotic origin.

4. In regions where hydrocarbons are found at one level show occurrences in large or small quantities at all levels of different geological epochs down to and into the basement, known as “Kudryavtsev’s Rule”, suggestive of vertical migration of hydrocarbons from sources deep below.

5. Accumulations of gas in synclines in giant fields at Deep Basin, Alberta, Milk River, and San Juan, contradicts the biotic theory by which hydrocarbons are generated but not accumulated in synclines.

6. Replenishment of reservoirs after a period of decline suggests that it can only be possible from the huge abiotic source, deep below in the mantle.

**Deliberations**

1) **Mega scale geographical distribution of oil/gas deposits in tectonically active belts of earthquakes and volcanic arcs**

Gold (1993), a western scientist, supporting the ‘Russian-Ukrainian school’ of scientists opined that the mega scale geographic patterns of oil and gas accumulations in places related more to large scale deep-seated structural features of the crust is linked to abiotic origin as evidence. The circumpacific “belt of fire” is the most striking example of this and there are also many other tracks characterized by high heat flow and volcanic activity due to intense tectonic activities. But considering the phenomenal differences in the geologic characteristics involved in the scales of dimensions and types of hydrocarbon deposits all over the world, it seems incomprehensible to link the distribution and types of deposits to the origin of petroleum. For instance, the Himalayan Foreland basin in India, related to subduction tectonics with
attendant deep crustal faults, is a highly earthquake prone zone, yet several wells drilled so far have not discovered hydrocarbons. The burning of Jawalamukhi flame, considered as a potential lead, happens to be methane gas. The gases from the wells in the area on geochemical analysis were found to be methane-rich with small amount of nitrogen and are dry gases of thermogenic origin, which suggests a deep overmatured source (Mittal et al., 2006). Likewise, the fore-arc basin of Andaman Sea having the chain of volcanic islands and network of faults associated with subduction and seafloor spreading, has no hydrocarbon discovery so far except a gas show in one of the more than dozen wells drilled. According to abiotic theory, these are the most likely areas for oil/gas occurrences where charging is envisaged from the mantle source through deep crustal faults providing vertical migration pathways. However, the lack of success, as per biotic theory, is explained due to lack of matured source and reservoir rocks in the wells drilled in the Himalayan basin and the Andaman Sea respectively.

2) Presence of natural gas and petroleum fluids in the Precambrian crystalline basements with no sedimentary source around

Many occurrences of petroleum within the crystalline basement and often several feet deeper from the top of basement is deliberated in detail by Kutcherov (2013). There are no source rocks found around to account for the accumulation which suggests the origin is deep and abiotic. One of the most convincing examples cited is the northern flank of the Dnieper-Donets Basin (DDB), Ukraine (Kutcherov and Krayushkin, 2010), where oil pools are found in the crystalline fractured-basement. It is promoted as the best application of the theory of abyssal abiogenic origin helping in the successful exploration carried out in the DDB’s northern flank. Interestingly, the cap rock for the reservoirs in the Precambrian basement, is the impervious, non-fractured, essentially horizontal layer-like zones of crystalline rocks (Krayushkin et al., 2001).

Other examples supporting abiotic origin include the giant Precambrian fractured-basement oil field Bach Ho (White Tiger) in Cuu Long Basin, Vietnam and the La Paz oil field, onshore, Venezuela. The Precambrian granitic fractured -basement reservoir of the Bach Ho field is overlain by highly source-rich lacustrine Oligocene shales (Hung and Le, 2004) followed by drapes of Oligo-Miocene reservoir sands (Figure 2). But surprisingly, little oil is found in the overlying highly porous sands, while most of the oil is accumulated below, in the fractured basement (Koning, 2014). The implicit downward migration of oil from the source to the underlying basement reservoir, an unusual phenomenon, marks the Bach Ho field as remarkable. However, the opponents raised questions about this unique downward migration of oil from source and disbeliefed its origin as biotic. Furthermore, in the La Paz field, Venezuela, oil is found in the fractured-basement way down within the basement, the average depth being about 500 m below the top of basement (Koning, 2019) where no source rock is around. These facts are advocated as clear evidence of upward migration of oil from abyssal abiotic source.

Nonetheless, for most fractured-basement reservoirs in the world including those in India, source rocks are found present on the flanks accountable for generation and lateral migration of hydrocarbons. It is plausible the Bach Ho oil reservoir was charged from the Oligocene source at greater depth on the flank. The global phenomenon of presence of source-rich shales flanking fractured- basement reservoirs is unlikely to be linked to chance coincidence. Moreover, many fractured-basement oil and gas fields are found associated with multiple water contacts (Koning, 2019). In the Borholla field, Assam, India, oil water contacts are found at different depths in the wells which raises the question as wherefrom the water came into the fractured basement reservoirs if the source is presumed as abiotic and deep in the mantle.
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Figure 2: Geologic section of the giant Bach Ho fractured-basement oil field, Cuu Long Basin, Vietnam. (Modified after Koning, 2014). The Precambrian fractured-basement is overlain by source–rich Oligocene shales. Despite the presence of Oligo-Miocene good reservoir sands draping the source, most of the oil was found accumulated in the underlying basement reservoir implying downward migration, making the field unique. Proponents of biotic origin question the downward migration of oil and cite this as an example of oil migrating vertically from the deep source below through faults and fractures.

3) Misbalance between assessed volumes of oil/gas generated from identified volume of source and the estimated field reserves

One of the most formidable pieces of evidence mentioned against biotic oil is the deficiency of the volume of identified matured source to account for the recoverable reserves of several giant/supergiant oil fields. According to calculations shown by Kutchev and Krayushkin (2010), many big and giant oil and gas fields in the oil-rich Arabian Basin show a huge imbalance between calculated volumes of hydrocarbons generated from the tiny percentage of kerogens present in the total carbon content (TOC) part of the source and the proven oil reserves of the fields. Examples given include the giant and supergiant fields such as the Ghawar oil field in Saudi Arabia and many others in the Middle East, the Orinoco heavy oil and the Athabasca bitumen/oil sands belt. The super-giant bituminous/oil sand belt of Athabasca, Canada, with enormous quantities of bitumen/oil in the sands would have required immense amount of source rocks for generation which is not present (Kutchev and Krayushkin, 2010). This fact counters the origin of source as biotic and instead claimed as strong evidence of massive abiotic sourcing from the mantle to account for these prolific fields. Moreover, citing inclusions of bitumen and petroleum fluids in natural diamonds and kimberlites as evidence of mantle hydrocarbons, the bitumen/oil sands of Athabasca are convincingly argued as of abyssal abiotic origin. Although the origin of the oil sands remains disputable, most petroleum geologists believe that the Athabasca deposit was formed in much the same way as the other fossil fuels, the oil, natural gas and humic coal, form from the biogenic source.

In the case of the giant Mumbai High field in western offshore basin, India, there seems to be uncertainty about the source that charged the Miocene micritic limestone oil reservoirs that directly overlie the Deccan Trap basement. With no significant thickness of source-rich shales near to account for the giant oil and gas reserves, the sourcing is believed by long distance migration from the Panna formation (Paleocene-Eocene)
either in the northeast Surat depression or in the southwest Murad depression formation (Eocene) where it is considerably thick. The very long-distance migration, however, is not quite appealing as several structures on the migration corridor remain without getting charged. Alternatively, if the giant field is believed to be charged from the mantle abiotic source by migration through deep faults, the fractured basement would have had oil accumulation. But no commercial accumulation so far is found in the basement although several wells were drilled.

4) Mode of oil/gas occurrences and Kudryavtsev’s Rule

Kudryavtsev’s Rule of abiotic origin states any region in which hydrocarbons deposits are found at one level will be seen to have hydrocarbons in large or small quantities, but at all levels down to and into the basement rock (Gold, 1993; Glasby, 2006). The Lost Soldier field in Wyoming is quoted as example where oil is found in the Precambrian crystalline basement and the overlying sedimentary rocks ranging from Cambrian to Tertiary age. However, the adjoining Wertz field, separated by a low, is a gas field and furthermore the oil prone district in general does not uniformly have oil and gas bearing strata at all localities (Fath and Moulton 1924).

In the Indian scenario, the Kudryavtsev’s Rule seems applicable in the Lakwa-Lakhmani field in the Upper Assam shelf where oil and gas is found in formations of all ages from Paleocene to Pliocene ages. However, the two major fields nearby, the Rudrasagar and the Geleki, and many other smaller fields in the highly petroleum-rich Upper Assam shelf do not comply with the rule. The Kudryavtsev’s Rule also seems not complied in other highly petroliferous basins in India such as the Cambay and the western offshore basins.


Figure 3: Geologic section of Deep Basin showing gas sands in the syncline (after Kutcherov and Krayushkin, 2010). Accumulation of gas in syncline instead of migrating upward to a structurally higher place is cited as evidence against biotic origin.

The Deep Basin gas field in Alberta, Canada is promoted as an example to challenge the biotic theory. The field consists of multiple stacked gas-bearing reservoir sandstones found in the basinal syncline downdip
of the strati graphically equivalent water-bearing zones, updip on the shelf (Figure 3). The proponents of abiogenic theory question the lateral migration and accumulation of hydrocarbons in a syncline that contradicts the biotic theory where it is recognized to be generated in synclines (kitchens) but not accumulated (Kutcherov and Krayushkin, 2010).

The Deep Basin consists of two basic reservoir types, conventional and unconventional tight reservoirs of low-permeability fine-grained tight sandstones (McMaster, 1981). The field, in fact, can be subsumed under unconventional reservoirs, as ‘Basin centered gas accumulations’ (BCGAs), also called ‘tight gas sands’ and ‘deep basin gases. In his seminal paper, Law (2002) emphasizes that though BCGAs are unconventional reservoirs, they have all the components of a petroleum system similar to that of conventional reservoirs and deals exhaustively with the mechanism and process of formation of BCGAs.

6) Refilling of reservoirs during depletion

Promoters of abiogenic oil say that hydrocarbon reservoirs get refilled regularly and as example they cite the Middle Eastern oil fields, that were anticipated to run dry in the 1970s, but continue to produce more and more oil. Other examples are the reservoirs in the Romashkinokoye supergiant oilfield in Russia, the Prudhoe Basin, North Slope, Alaska, and the Eugene Island, Block 330, Gulf of Mexico, USA, where recoverable reserves are found higher than the proven reserves. This is claimed as evidence of continuing refill of the reservoirs from the mantle abiogenic source (Kutcherov 2013).

Reserves of fields are estimates that can vary with time depending on several factors including geological, engineering, financial, political, and environmental. Use of advanced seismic and engineering technologies leading to drilling of more wells in the field can result in surprising and serendipitous finds of new and/or thicker oil pays, not anticipated earlier that can upscale the initial estimates. For instance, in the Eugene field in Gulf of Mexico, continuing geologic, geophysical, and engineering studies have led to increased reserves by re-evaluating and defining the newly discovered deltaic prospects (Holland, et.al., 1999). Nearer home, there are the examples of the giants Mumbai High, Gandhar and the Ankleshwar oil and gas fields where unanticipated new and thicker reservoirs with better recovery factor were discovered through drilling additional wells that lead to more recoverable reserves requiring upward revision of initially estimated reserves.

On the other hand, evidence against the ‘filling theory’ can be seen in the failure of commercial production from the fractured basement in Dai Hung (Big Bear) offshore field, Vietnam. The Dai Hung setback in Cuu Long Basin is strange as it has similar tectonic and structural setting and basement characteristics as of the giant Bach Ho offshore oil field (White tiger) in the same basin. The Dai Hung field estimated to produce 250,000 BOPD only produced 25,000 BOPD and despite attempts by several operators the field could not produce economically and was abandoned (Koning, 2019). Furthermore, the giant prolific producer ‘White tiger’ with thick oil columns up to 1500 m got depleted rapidly in 20 years with wells cutting water heavily (Koning, 2014). If recharging from the deep abiogenic source is envisaged, will these fields be recharged and if so, when? Yet, another example refuting the proposition of massive source of mantle hydrocarbons refueling can be the Surakahany ‘fire of temple’ in Azerbaijan, Alpine fold belt, where the gas flames continuing for centuries, presumably fed from deep veins, have since stopped.
The Indian scenario, some imponderables

Exhaustive analysis of oil/gas reservoirs are likely to show their individual characteristics dissimilar, as varied as the human characters. The geologic attributes of the reservoirs can be uniquely diverse, some of these inexplicable by either of the theories of origin. Of many such instances three examples are cited. In the giant Gandhar oil and gas field in Cambay basin, drilling results show layers of oil-bearing sands overlain and underlain by water-bearing sands belonging to the same stratigraphic unit. This preferential filling of oil in the sands in the wells raises questions about the migration process and charging mechanism. Other instances are the offshore Plio-Pleistocene oil and gas sands on the east coast, KG Basin, and the Oligocene sands of the Narimanam oil field in Cauvery onland basin. In the KG offshore fields, channel sands at similar structural and stratigraphic levels have shown varying fluid saturations of oil, gas, and water. In onland Narimanam field, Cauvery basin, the producing Oligocene prograding toe-sands are believed to be sourced by the Cretaceous shales as the immediately underlying thick Eocene shale is ranked immature. With no seismic evidence of faults connecting the Cretaceous source to the Oligocene reservoirs it is difficult to comprehend the actual migration pathway. Interestingly, drilling of a contiguous updip stack of the same prograding Oligocene sequence proved the sands water bearing. Neither of the theories can explain the migration process and the accumulation phenomena satisfactorily.

Where does it all lead to?

Lack of explanation of the geologic facts of a particular field by one theory cannot be taken as the other theory being correct. The above instances show there is something more than that meets the eyes and needs more understanding of the vagaries of nature. However, with more and more evidence coming up, many scientists believe that some petroleum deposits are of biotic origin while some may be from abiotic sources. Progressively, numerous evidence supporting the abiogenic origin of many compounds found in the oil reservoirs, the western geologists today are admitting that some oil fields are of abiogenic nature because of the undeniable co-presence of both biogenic and abiogenic signatures in various degrees in most hydrocarbon fields (Scalera, 2011). Robinson (1966), the 1947 Nobel Prize winner in chemistry, proposed a duplex origin of petroleum in which biogenic processes were dominant in the formation of younger oil, but were virtually absent in the formation of older crude oil. Is then the ‘true’ origin of petroleum a mix of both theories (balanced theory)? No one has witnessed or can witness the truth, for sure, detailing the exact process the petroleum originated, migrated, and accumulated in the traps where it is discovered. There are several things unknown to us, the ‘unknown unknowns’ and nature's mystery remains.

All that being said, why determination of the exact origin of petroleum matters so much? As mentioned earlier, the upshot is that biotic origin limits the resources to end up in a few decades, whereas, the abiotic origin opens up huge scope for quasi-non ending supply of oil and gas. But the fly in the ointment is where and how to explore for it to discover commercial reserves? Is there a doable and economically viable exploration template suggesting how and where to look for these hidden giant petroleum deposits of abiotic origin? While the strategy for exploration of biotic oil has been systematic, organized, and practiced for centuries, there seems to be no such comparable approach for exploring abiotic oil. If searching for oil by current strategies based on biotic concepts discovers oil that is considered of abiotic origin, so be it.

Seismic is an indispensable tool used the world over for imaging the subsurface earth for exploration of biotic oil. The explorationist analyses from the images the geology of the sedimentary sections and the basement and evaluates the hydrocarbon potential of the area based on the ‘petroleum system’ approach of the biotic
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Origin. This helps make decisions on planning and strategizing exploration ventures with its attendant economic risks. However, exploration for oil/gas deposits of abiotic origin believed to be favorable in the tectonically active zones can be difficult, uneconomical, and frustrating. This is because reliable subsurface images of the complicated tectonic zones with associated fault systems in the lithosphere, many kilometers down the earth, are beyond the scope of today’s seismic technology and particularly on land. Suggestions of the existence of massive oil/gas fields in tectonized hot spots, subduction and seafloor spreading zones on mega scale are too nebulous to attract exploration ventures. Without a priori geological knowledge of the subsurface, speculative drilling to unknown targets several kilometers down the crust can be a highly risky and commercially unfeasible proposition.

Gold (1993) suggested that surveying for methane seepage could work as clue to oil/gas deposits below. In Mumbai offshore basin for several years ‘sniffer surveys’ for detecting gas seepages were carried out in conjunction with marine seismic acquisition and there was no correlation between the positive spots mapped by sniffer survey and the oil/gas finds. Surface indications of hydrocarbon seepages can be from areas distant, faraway and not from vertically below and in fact, it can be important evidence of lateral migration of hydrocarbons, a process unacceptable in abiotic theory. However, a few facts drawn from Indian scenario are listed which do not seem to favor the abiotic theory.

a) If abiotic oil/gas migrates from deep mantle through faults to the sedimentary reservoirs, why basements with faults and fractures are by-passed with no hydrocarbon shows?

b) According to Kutcherov and Krayushkin’s (2010) abiotic oil/gas from mantle is deposited in any kind of rock including crystalline basement and in any kind of structural position. But evidence shows wells drilled only on top of basement/sedimentary highs find hydrocarbons while the sidestepped wells on the flanks encounter water.

c) Basement rocks are often overlain by several layers of thick impermeable rocks such as shales and limestones. Presuming vertical migration, how would oil charge the shallower reservoirs with no evidence of faults on seismic and drilled well data?

d) The abiotic theory asserts vertical migration of oil/gas through deep seated faults, several tens of kms from the mantle to the surface for oil/gas accumulation. Do the roots of the crustal faults always extend deep enough to the mantle? Structural geologists often model these deep-seated faults as listric faults dying down in the compliant basaltic layer below. Moreover, compressional faults in subduction zones may not necessarily continue deep enough as in skin-tectonics.

e) Many reservoirs including the basement are filled with oil/gas in the top few meters with water contacts below indicating lean source. If oil is believed sourced from the mantle on a regional and mega scale can the abyssal source be so lean in this part of the Indian crust?

f) Can there be a resource estimate of abiotic oil in mantle and recoverable reserves in the crustal traps analogous to that for biotic oil for economic risk analysis in exploration ventures?

Conclusions
From the above deliberations, the balance of probability, however, seems to tilt more in favor of biotic origin. The biotic process of formation of oil/gas, its accumulation and distribution on the surface has led to convincing and conveniently acceptable templates for strategizing the gamut of exploration and has thus gained much
acceptance in the world for centuries at the cost of the abiotic origin. Exploring for biotic oil is likely to continue till an alternate blueprint of doable, robust, and economically viable strategy to search for abiotic oil is offered. **Caveat:** It would be remiss of me if I did not mention the caveat in reaching the above conclusions. The above discussion and imponderables are based on my past experience and knowledge that runs back about three decades. Many of the discussed issues may have changed or been solved in the light of the latest information assimilated from data obtained through the drilling of thousands of new wells during this time. However, I am not informed of any such development.

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Thereafter, as a freelance petroleum geophysicist, his involvement in the hydrocarbon upstream industry continues, building more than six decades of varied experience in diversified geologic basins, both in India and abroad. He has been a consultant to many E&P companies in India such as, Essar Oil, Mumbai, Hardy oil, Chennai, BPCL, New Delhi, GSPCL, Ahmedabad, and Germi, Gandhinagar. He has also been a member of the Advisory Council of KDMIPE, ONGC, Dehradun.

Apart from consulting, Shri Nanda has been a visiting faculty to the Delta Institute, Andhra University, Visakhapatnam, and MS University, Baroda, where he taught classes on interpretation and evaluation of seismic data to post-graduate students of exploration geophysics and petroleum geology. He has conducted several training courses and workshops in seismic interpretation for industry professionals at different work centres of ONGC, GERMI, Gandhinagar and at Society of Petroleum Geophysicists (SPG) biennial international conferences.

In 1987, he was honoured with the National Mineral Award by the Government of India for his pioneering contribution in the field of reservoir seismic. He received an Honorary Life Membership from SPG, India, in 2006 and an outstanding geophysicist award from GEOINDIA in 2008. In 2013, he was awarded the B. S. Negi gold medal for lifetime contribution in petroleum geophysics by SPG, India.

He has published several papers and authored a book entitled “Interpretation and evaluation of seismic data for hydrocarbon exploration and production—a practitioner’s guide”, published by Springer in March 2016. A second edition of this book containing additional topics, including “Exploration and exploitation of unconventional reservoirs – role of seismic” was published by Springer in April 2021.