Hydrocarbon production from fractured basement formations

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The occurrence of naturally fractured basement reservoirs has been known within the hydrocarbon industry for many years. Generally regarded as non-productive, they have failed to draw the attention of the explorationist. Often passed over as 'of no economic potential', their investigation by exploratory drilling has been left to chance. Yet, they are commonly distributed in various petroliferous regions throughout the world. An attempt has been made in this article to understand hydrocarbon production in basement formations along with some examples.

RESERVOIRS in fractured basements, where the oil and gas in place may be held within an extensive fracture network on a variety of different scales rather than within the matrix porosity of the formation, present challenging problems to the petrophysicist and reservoir engineer. Fractured reservoirs are much more difficult and expensive to evaluate than the more conventional reservoirs[1–3].

A greater understanding of fracture distribution and connectivity within basement reservoirs using magnetic and seismic surveys may prove to be the key tool for improved exploration and management of this hidden resource. Commercial, naturally fractured basement oil deposits have been found largely by accident while looking for other types of reservoirs[4,5]. Landes *et al.*[5] postulated that basement rock-oil accumulations are not freaks to be found solely by chance, but are normal concentrations of hydrocarbons obeying the rules of origin, migration and entrapment. Therefore, in areas where the basement is not too deep, oil deposits should be sought with the same professional skill and zeal as accumulations in the overlying sediments.

According to Landes *et al.*[5], once the basement rock had been reached during drilling, it was thought that there was little or no chance for oil production. Even now many oil companies stop drilling operations as soon as basement rocks are intersected. Aguilera[6] suggests that drilling should be continued into the basement rocks for at least 300 m, especially if the basement is overlain by an oil-yielding formation. In the Western countries, all the oil fields that produce from crystalline basements were discovered by accident (Kenney, J. F., private commun., 1996). Most naturally fractured reservoirs (sandstones, carbonates, cherts, shales and not just basement reservoirs) were discovered by accident[6,7]. In Russia and the other countries of the former Soviet Union however, drilling into crystalline basements has been carried out intentionally (Kenney, J. F., private commun., 1996), although a literature search reveals that citations of producing fields in basement are actually few and far between. Many oil discoveries may have been missed because of inadequate exploration of the barely scratched basement by unsuccessful wildcats[5].

Definition of basement rocks

Many definitions of basement rocks exist. These have been discussed by several researchers[5,6,8–10]. The definition of a basement rock used here follows that of Landes *et al.*[5]. Here, basement rocks are considered as any metamorphic or igneous rocks (regardless of age) which are unconformably overlain by a sedimentary sequence.

P'an[8] in a major study of petroleum in basement rocks, considers two definitions. The first is where metamorphic and igneous rocks (regardless of age) are unconformably overlain by a younger oil-generating formation (source rock). However, if there is an extensive weathered zone, it may not be a strictly fractured zone. The oil, which is generated from the overlying sediments, is stored in the older metamorphic and igneous rocks. The second case considers any rocks that unconformably underlie oil-generating or oil-bearing formations as basement.

Aguilera[4,6] does not consider sandstones and carbonates as basement rock, even if they conformably underlie oil-bearing or oil-generating formations. North, however, has a different view towards defining basement rocks. Unlike Aguilera, North[10] considers basement rocks to include those of sedimentary origin, if they have essentially little or no matrix porosity. He states that 'basement' should not be compared with 'Precambrian' and that basement rock may have considerable fracture porosity due to deformation, weathering or both. This definition would be quite wide and would include fields hosted, for example, in the Cambro–Ordovician quartzitic sandstones of Algeria.

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Favourable conditions required in basement rock reservoirs

All basement reservoirs underlie a regional unconformity and almost all lie on an uplift or high. This uplift or high was generally continuously uplifted for long periods of geologic time and was subject to a long period of weathering and erosion. Younger sediments, which act as hydrocarbon sources, either flank or directly overlie the basement, providing an opportunity for entrapment of oil in the basement rock.

Structural highs in the basement are created by fault tectonics or by the submergence and subsequent covering with sediments of hills sculptured in the basement rock during its emergence. It is important that the reservoir is overlain by a seal and that oil from adjacent source rocks is able to migrate into this trap.

Unconformities can play an important role in basement reservoirs, as they can be the pathway for oil migration. The unconformity surface often provides evidence that the basement rocks have undergone weathering, erosion, solution and leaching for so long a time that porosity and permeability have increased greatly, facilitating accumulation of petroleum[8].

The usual ‘cap rock’ for basement accumulations is relatively tight (low permeability) sedimentary rock. However, a tight zone in the basement rock at the Mara field in Venezuela is barren and may act as the seal. At the other extreme is the situation in several California fields, where a thick oil column extends from an oil–water interface within the basement rock upward through a continuous reservoir, which includes such permeable materials as wash and basal sandstone, until a tight rock is reached somewhere above the base of the sedimentary section[5].

Most basement rocks are hard and brittle with very low matrix porosity and permeability. Consequently, reservoir quality depends on the development of secondary porosity. Secondary porosity may be divided into two main kinds by origin: (i) tectonic porosity (joints, faults, fractures, etc. at a range of scales from microfractures to seismic scale faults and their damage zones) and (ii) dissolution porosity (ranging from solution effects in weathering zones or fault zones to effects associated with hydrothermal circulation).

Aguilera[6] characterized fractured reservoirs based on porosity distribution between the matrix and the fracture system. In basement reservoirs, matrix porosity is effectively close to zero and most of the storage capacity and permeability is due to fractures. Study of intensity of fracture spacing suggests a favourable condition for a spacing of 0.4–1.1 m. The aperture width of fractures measured ranges from about 0.3 to about 8 mm. Reservoirs of this type[6] can be characterized by initially high production rates that decline to uneconomic limits in a short period of time.

However, exceptions to this have been worthy of their discovery and include the Edison and Mountain View Fields in the San Joaquin Valley, California; the El Segundo, Wilmington and Playa Del Rey Fields, Los Angeles Basin; the La Paz-Mara Fields, Venzuela; and the Amal Field, Libya. Major basement reservoirs are seen in Vietnam.

Source of oil in basement rocks

There are many possible sources for oil accumulation in basement reservoirs. However, three sources are referenced most commonly:

1. Overlying organic rock from which oil was expelled downward during compaction.
2. Lateral, off-the-basement, but topographically lower organic rock from which oil was squeezed into an underlying carrier bed through which it migrated up dip into the basement rock.
3. Lower, lateral reservoirs from which earlier trapped oil was spilled due to tilting or overfilling[5].

Mechanisms have been identified that could allow the downward migration of oil into fractured basement, when fracture dilation is caused during shearing in an anisotropic stress field. Dilatancy in the underlying reservoir rock reduces hydrostatic pressures in local areas of deformation. Pressure gradients are thereby established between the potential basement reservoir rocks and the overlying source and carrier beds containing oil, gas and water.

Basement reservoirs

Countries with hydrocarbon finds in basement reservoirs

This compilation has attempted to refer to hydrocarbon fields where production figures can be cross-referenced to published literature or traceable sources.

Algeria: Saharan plateau basaltic lavas are reported to contain hydrocarbons.

Argentina: Hydrocarbons are hosted in andesitic sills.

Brazil: Fractured volcanics (basalt) of the Badejo and Linguado fields (discovered in 1975) produce hydrocarbons[11]. These fields are located in the Campos Basin, offshore Brazil.

Canada: The Archaen 7-32-89-10 well at Fort McMurray yielded shows of high gravity oil, about 260 to 290 m below the top of granite.

Chile

Lago Mercedes Field: Lago Mercedes Well 1 was spudded on 17 January 1991. It was located to test a seismically defined structural culmination, located along a blind thrust near the deep foreland axis of the western Magallanes basin. The fault is responsible for a trap geometry that is genetically related to, but fundamentally different from, the numerous un-rooted Tertiary folds in the area[12]. Although the Lower Cretaceous Springhill Formation comprised the primary target, Dean *et al.*[12] anticipated that the geometry of the fold allowed for the possibility of several fractured intervals, including volcaniclastic rocks of the underlying Jurassic Tobifera basement sequence. The sequence was found to be productive elsewhere along the eastern platform of the basin. During the drilling of the well, promising gas and condensate shows were observed in several horizons. The most surprising of these shows later proved to be a Permo–Triassic granodiorite underlying the Tobifera. All the hydrocarbon-bearing intervals exhibited minimal matrix porosity, but varying degrees of fracturing. Testing of Well 1 yielded combined flow rates in excess of 12 MMCFD of rich gas and 1140 bbl/day of condensate. The most abundant zone corresponded to an intensely fractured and partially weathered interval. Additional testing was planned prior to any estimate of recoverable reserves.

China

Yaerxia Oil Field: The Yaerxia Oil Field in the Jiuxi Basin (western part of Jiuquan Basin) was the first basement reservoir in China[8,13]. Oil is produced from fractures in Palaeozoic metamorphic rocks. Oil production was to 1050 bbl/day at that time.

Discovered in 1959, the Yaerxia Basement Oil Field produces from the Quannaogou Formation, which consists of phyllite, slate and meta-sandstone. The rock is hard and compact. Because the joints, faults and fractures are well developed, production from some wells is quite high. Highly productive wells (such as 114, 514 and 519) are all situated in the vicinity of a fracture zone or at fault intersections.

During the period 1959–79, 24 wells penetrated the Silurian (which is more than 19,700 ft thick), 21 of which indicated oil and gas. The depth of the wells ranged from 8530 to 10,500 ft (2600 to 3200 m). Twelve wells had commercial value, six of which had initial production of less than 70 bbl/day and three wells produced 70 to 350 bbl/day of oil. Only two wells had initial production of 700 to 1050 bbl/day.

Xinglongtai Oil and Gas Field: The Xinglongtai Oil and Gas Reservoir is located in the middle of the west trough in the Lower Liaohe depression. The 26,300 ft (8000 m) deep Qingshui syncline is present to the south. The reservoir rock is composed of Archeozoic slightly metamorphosed granite, Mesozoic granitic breccia and extrusive rocks (andesite and basalt). Only Archeozoic granite is considered to be a basement rock here[8]. The source rock here is the Springhill Formation. By the end of 1976, eight productive wells had been drilled in the Xinglongtai Oil Field. A single well drilled to the Mesozoic volcanic rocks was producing approximately 756 bbl/day. Oil production from one particular well, which had been drilled into the granite and granitic breccia, was between 210 and 420 bbl/day. The Xinglongtai Basement Reservoir is a high-pressure, highly saturated reservoir with a hydrocarbon column of 2300 ft (700 m). The gas column is about 590 ft (180 m) with an oil column not less than 1640 ft (500 m).

Egypt

Hurghada Field: The Hurghada Field lies southeast of the Gemsah Field and close to the shore of the Gulf of Suez. It is a shallow, granite-buried hill. Wells drilled through Miocene and Cretaceous strata penetrated a granite core at depths of approximately 1670 ft to 2000 ft (510 to 610 m). Oil was found in the Cretaceous sandy shale, Nubian sandstone and in the weathered surface of the granite[8]. The Miocene strata are unconformable with the Cretaceous beds and are less folded. The Hurghada Field produces heavy oil (no production rates available).

Zeit Bay Field: The Zeit Bay Field is a northwest-southeast trending structure, which measures approximately 2.5 km by 4.5 km, located in the southwest corner of the Gulf of Suez. The field was discovered in 1981, when Well QQ 89-1 found gas in the basement. In October of the same year, the appraisal well, QQ 89-2, intersected a net 830 ft thick oil leg from Cretaceous and basement 2 km south of Well QQ 89-1. According to Zahran and Askary[14], the Zeit Bay Field fractured basement contains nearly one-third of the total oil in place for the field and the flow rates per well varied from 700 to 10,000 bbl/day, of which one third is from the basement. Due to its well-established production potential, 60% of the field's development wells were drilled down to the basement[14]. The Zeit Bay basement consists of granitic rocks of pegmatitic to coarse porphyritic texture. The reservoir in Zeit Bay is a hydraulically communicating sequence of Precambrian igneous and metamorphic rocks as well as sedimentary reservoirs.

India: In 1980, the Oil and Natural Gas Commission Ltd (ONGC) logged four productive gas wells in the PY-1 Field, including the PY-1-1 discovery well. Production tests of the wells reportedly ranged as high as 13 MMCF/

day. The PY-1 Field pay zone occurs in sections as thick as 200 ft and at depths of 5000 to 5500 ft[15]. The discovery is in the Cauvery offshore basin, about 100 miles south of Chennai in the Bay of Bengal.

An appraisal well was drilled in 1997 (Well PY-1-12) to confirm the significance of a 1980 gas discovery, reported by ONGC.

The reservoir, which is hosted in heterogeneous, Precambrian, weathered granite and sealed by Cretaceous to Eocene shales, lies on the crest of a northeast-southwest basement ridge known as the Portonovo high (Anon, 1995). The field lies beneath approximately 250 ft of water. It was estimated that PY-1 could yield as much as 250 BCF of gas and 1.16 M bbl of condensate in primary production. Process facilities were designed on flow rate criteria of 53 MM scf gas and 600 bbl condensate.

Indonesia

Sumatra – Beruk Northeast: The Beruk Northeast Oil Field of Central Sumatra was discovered in 1976 with the drilling of the Beruk Northeast Well No. 1 into a Pre-Tertiary basement. The oil field is located within the Central Sumatra BackArc Basin, one of a series of Tertiary basins oriented along the western and southern margin of the Sudan Craton. In addition to Beruk Northeast, only four other fields are reported by producing from Pre-Tertiary basement in Indonesia. Oil production from basement rocks is exceptional in Southeast Asia[9].

The Beruk Northeast Field is situated within a group of oil fields in the central area of the Pertamina–Calasiatic–Topoco Coastal Plains–Pekanaru Production Sharing Block. The basement rocks, which tested oil, consist of fractured metaquartzites, weathered argillites and weathered granite. Beruk Northeast Well No. 1 was drilled to a total depth of 1634 ft into the basement. An open-hole test of the basement flowed at 1680 bbl/day.

United Kingdom: Discovered in 1977, the Clair Oil Field lies 75 km west of the Shetlands, offshore UK, in waters of up to 150 m in Block 206. Clair comprises of an elongate NE–SW trending ridge of Lewisian basement and an associated roll-over (or terrace) containing a thick sequence of Devonian–Carboniferous continental red beds[16]. The first well drilled in 1977, Well 206/8-1A, tested oil at 1500 bbl/day from the red beds at the crest of the roll-over.

Well 206/7-1 followed, producing oil at 960 bbl/day from the fractured basement on the ridge, with the oil coming entirely through the fractures. Ten more wells drilled between 1977 and 1985 indicated oil in places measurable in billions of barrels. However, test results were disappointing. The success of the discovery wells (206/8-1A and 206/7-1) was never repeated and commercial test production rates were never achieved.

Two further appraisal wells were drilled in 1991. The first, a horizontal well in the fractured basement, tested at 2100 bbl/day after acid-wash stimulation. The second well tested the red beds on the flank of the roll-over and achieved sustained flow rates of 3000 bbl/day from two zones. An extensive fracture analysis was performed in the horizontal appraisal well. The objective of the well layout was to cross-cut the fracture zones located in the fractured basements which were believed to act as preferential drainage paths for the hydrocarbons situated in the overlying and adjacent red beds source rock[16].

Vietnam: Ongoing exploration activities (initiated in the 1970s) have proved the existence of oil and gas in basement reservoirs in the offshore area of South Vietnam. This has resulted in the discovery of several oil and gas fields, including White Tiger (Bach Ho), Dragon (Rong) and Rang Dong fields.

The oil company Vietsovpetro started working in offshore South Vietnam in 1981 and started to produce oil in 1986. By the end of 1991, about 100 wells had been drilled (85% of them by Vietsovpetro). Half the wells penetrated the basement, with basement cores recovered from 26 wells. The majority of these cores came from the White Tiger Field. By the mid-1990s, the company was producing 180,000 bbl/day. This production rate is likely to increase as White Tiger and Dragon fields are improved (both fields producing from the basement reservoirs). The basement capacity of Dragon Field was at 8000 bbl/day[17]. Vietnam's chief offshore asset is the White Tiger Field, which generated over 50 MM bbl in 1996[15]. The volume in place and, hence, the field's lifespan, remains unknown.

In 1988, while testing in the White Tiger Field (Well MSP-1-1), an oil flow of 1500 m^3/day was achieved. The basement was then identified as an oil reservoir of significant importance. Further drilling into the basement was undertaken, especially in the northern and central blocks of White Tiger. The White Tiger area is divided into three fault-bounded blocks; northern, central and southern. The basement was not penetrated in the southern block.

Traces of oil were also found in the basements of the Big Bear (South Con Son basin), Dragon and Bavi[18]. Granite constitutes the basement in the central part of White Tiger and predominate in the basement of the Dragon Field. It also occurs in the basement of the White Tiger northern block, together with microcline, hornblende–biotite and biotite–granodiorites. Microcline, hornblende–biotite and biotite–granodiorites also occur in the basement of the Bavi and Big Bear structures.

The basement rocks of the southern Vietnamese shelf contain very large oil accumulations. The White Tiger Oil Field is at a depth of 5000 m, of which 4000 m is fractured basement granite, with a pay zone interval of 1000 m and with 1992 oil production at a rate of more than 2000 m^3/day[18].

Challenges and achievements in basement reservoir mapping

In this article, it is brought out that basement discoveries are mostly accidental. However, with the advent of sophisticated instruments and integration of geological and geophysical techniques, the risk of drilling basement reservoirs was reduced considerably. Improvement in geological concepts, seismic survey designs, processing and interpretation, magnetic studies and integration of interpretations ensure minimum reservoir damage during drilling. In this article, a few recent advances are discussed in both geological and geophysical disciplines.

Studies of fractures and cores

Natural fractures in the subsurface can be detected and characterized with oriented and open-hole logging tools (acoustic, resistivity and televiewer). In wells where both core and fracture identification logs are available, the number of fractures identified by each method has comparable spacing, orientation and openness. However, the number of fractures detected in the core is usually greater than the number of fractures detected from well logs. Probably more fractures are identified in the core than by well logs, because with well logs, horizontal fractures are difficult to distinguish from bedding planes. Based on fracture spacing and aperture width measurements, it is found that northeast-southwest fracture set is associated with highest intrinsic fracture permeability.

Improved seismic methods for basement mapping

The standard seismic methods used for exploration of layered sedimentary rocks cannot be used for mapping of heterogeneity within the basement, because there are no traceable reflection horizons below the basement surface. The most probable irregular cellular model of basement structure looks like a random alternation of monolithic, impermeable zones of relatively high concentration of fractures and caverns. The physical characteristics of crystalline rocks ($r = 2.5$–3.0 g/cm^3, P-wave velocity from those of fluids filling the fracture and caverns ($r = 1.0$ g/cm^3, $V = 1.5$ km/s). Thus, the latter are relatively contrast microheterogenities (diffuse component). Their size (d) is several orders of magnitude less than the Fresnel zone.

The use of information contained in the diffuse component makes stringent requirements to the quality of seismic processing. The main requirements are as follows:

(a) Proper performance of all processing procedures after testing of processing parameters.
(b) Minimum data regularization and amplitude distortion.
(c) Application of the most effective procedures of suppression of low velocity multiples (Radon transform, etc.).
(d) Shift in the working portion of frequency spectrum towards higher frequencies without considerable loss of the S/N ratio.
(e) Precise determination of velocity model for effective migration.
(f) Prestack depth migration, which ensures best imaging of the earth's structure and minimum level of migration noise, provided the migration velocities are correct.

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