REVIEW ARTICLE

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Exploring in Asia, Africa and the Americas for oil & gas in naturally fractured basement reservoirs: best practices & lessons learned

T. Koning
Calgary, Canada
E-mail: tako.koning@gmail.com

Abstract. Oil and gas occurs in basement reservoirs in many parts of the world. The reserves of basement fields are as small as one or two million barrels of oil or gas-equivalent to as much as almost 2.0 billion barrels of oil as in Libya's Auguila-Naafora field. Exploration for oil and gas in basement has been remarkably successful in the past decade with important discoveries in basement in Indonesia, United Kingdom, Norway, Chad, and Argentina. In order to successfully develop basement oil and gas fields and also to avoid costly mistakes, all available geological, geophysical, reservoir engineering and economic data must be closely studied. Also, it is very important to study analogues of basement oil and gas fields worldwide in order to understand why some fields are very successful and others turn out to be failures.

Keywords: crystalline basement, oil and gas fields, fractured reservoirs, weathered rocks, world best practices, exploring, developing

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Introduction

Basement rocks are important oil and gas reservoirs in a number of basins in the world including Asia (Indonesia, China, Viet Nam, & India), Russia, Middle East (Yemen), Africa (Algeria, Libya & Egypt), South America (Venezuela & Brazil), USA (California, Kansas, Oklahoma & Texas), and the North Sea (UK West of Shetlands & Norway) (Fig. 1). The basement reservoirs include fractured and weathered granites, quartzites, metamorphics and volcanics.

The basement oil and gas play has intensified in the past decade with significant basement discoveries in the United Kingdom (Lancaster and Lincoln oil fields), Norway (Rolvsnes oil field), in Chad (central Africa), Argentina, and in 2019 a major gas discovery was made in basement in Indonesia.

The author has followed this subject closely for over 35 years since being involved in 1982 with the development of the Beruk Northeast basement oil pool in Indonesia. He has also been involved with evaluating basement oil discoveries in Angola and Uganda. He hereby shares his knowledge and experience.

This paper provides a technical review of select basement oil and gas fields in Asia, Africa and the Americas. Also reviewed is "best practices" for exploring and developing basement fields. Although this paper reviews mostly "success stories" there are also failures since basement reservoirs can be very complicated and unpredictable. Accordingly, two basement fields which proved to be economic failures, Dai Hung (Big Bear) in Viet Nam and Beruk Northeast in Indonesia, are also reviewed.

The biggest oil and gas fields among the basement fields occur within basement which is heavily naturally fractured. The opinion of this author is that the best rock types are fractured quartzites or granites since they are brittle and thus fracture optimally (Koning, 2019).

Fractured gneisses are poorer reservoirs since they can be massive, dense or slabby with open fractures parallel to the direction of foliation.

Rocks such as gneisses and schists are ductile and tend to "smear" and not fracture when subjected to tectonic stress.

Phyllites and slates are the least attractive since such rocks are not brittle, rather they are thinly bedded, fissile and ductile and fracture poorly.

Weathered granitic basement can also be an excellent reservoir such as in the Auguila-Naafora oil field in Libya as described later in this paper.

The following is the preference scale for basement reservoir rock types:

Fig. 1. Global distribution of oil & gas fields in basement reservoirs

- Fractured quartzites (*most preferred rock type*);
- Fractured granites;
- Fractured carbonates;
- Weathered granites;
- Fractured gneisses;
- Weathered gneisses;
- Fractured schists;
- Weathered schists (*least preferred rock type*).

Oil and gas fields in basement require the same geological criteria as conventional oil and gas fields which includes reservoir rocks (fractured or weathered basement), oil & gas source rocks adjacent to or overlying basement, structural closure, and cap rocks which seal off the basement reservoirs.

ASIA BASEMENT OIL & GAS FIELDS

VIET NAM

The largest oil field in Viet Nam is the giant-size Bach Ho (White Tiger) basement oil field. Other basement oil fields include the Dai Huang (Big Bear), Ca Ngu Vang (CNV), Rong (Dragon), Rang Dong, Ruby and Su Ten Den fields with oil reserves ranging from 100 to 400 million barrels of oil (Koning 2019, Chung-Hsiang P'An, 1982).

Bach Ho (White Tiger) Oil Field

This is a giant oil field with estimated reserves of 1.0 to 1.4 billion barrels recoverable (Hung & Le, 2004). The field was discovered in Viet Nam's Cuu Long Basin by Mobil in 1975 with oil found in Oligocene sediments draping a major basement structural high (Fig. 2). Due to the political situation, Mobil, a USA oil company was not able to develop the field and exited from Viet Nam. However, in 1988 VietSovPetro discovered oil in the underlying fractured and weathered Precambrian granite basement. Oil production peaked at about 280,000 barrels of oil per day in 2005. The oil production is 95 % from the basement reservoirs and 5 % from the Oligocene sediments. Bach Ho's production declined to 140,000 barrels of oil per day in 2009 and has continued to decline to 65,000 barrels of oil per day in 2018.

The oil is stored in macrofractures, microfractures, and vuggy pores within the fractures. Matrix porosity within the granite is negligible. Most of the fractures inside basement are at high dip angles of 40-75 degrees. Porosity in the fractures is only 2-3 % but permeabilities are excellent at ten to thousands of millidarcies. Flow rates have been measured at up to 14,000 barrels of oil per day per well. Bach Ho's giant-size reserves are due to the oil column having a very significant thickness of 1,500 meters.

Dai Hung (Big Bear) Oil Field

A contrast to the success of Bach Ho is provided by the development and production history of the Dai Hung Field where oil and gas is hosted in a similar granite-granodiorite matrix. In 1993, Australia's BHP led a consortium that won the bid to develop this field and predicted the field would produce 250,000 barrels of oil per day. A full-scale production platform was installed but very disappointingly by the mid-1990's the field was producing only 25,000 barrels of oil per day and output declined rapidly and in 1997 BHP left the consortium announcing the field was not profitable.

Malaysian state oil company, Petronas took over as operator but failed to raise the output beyond

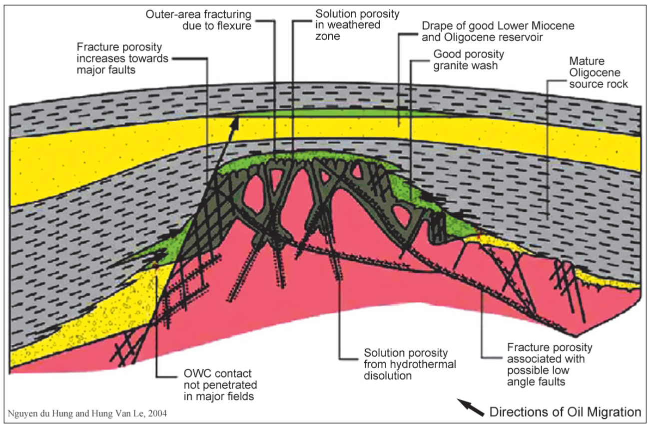


Fig. 2. A two-dimensional model of the play concept for the Cuu Long Basin, Viet Nam (Hung & Le, 2004)

10,000-15,000 barrels of oil per day and left in 1999. In 2000, VietSovPetro, operator of the Bach Ho and Rong fields became operator of Dai Huang but was only able to produce about 5,400 barrels of oil per day. The "lessons learned" from Dai Huang is that it is very important to fully understand the geological, geophysical and reservoir complexities of such a basement field prior to embarking on full-scale production.

Ca Ngu Vang (CNV) Oil Field

The CNV Field was discovered in 2002 and is the deepest oil-bearing structure in the Cuu Long Basin with the top of basement at a depth of 3,700 meters. CNV is a buried hill field as is the Bach Ho Field and produces from fractured Precambrian granites. The operator of the field is United Kingdom-based SOCO International. The CNV-3 well was the longest measured depth well in Viet Nam at 6,123 meters with over 2,000 meters of basement penetrated in a near-horizontal well bore (Fig. 3). The well tested both oil and gas at a rate of 13,040 barrels per day of oil & gas equivalent.

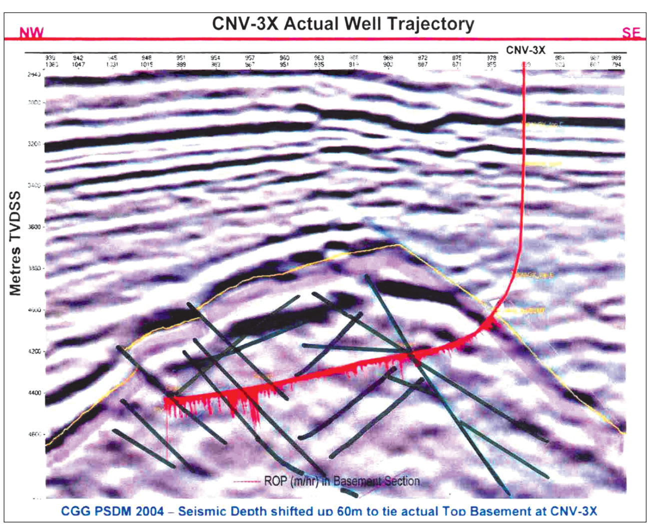


Fig. 3 Seismic section and CNV-3 well trajectory through CNV Field, Viet Nam (SOCO Int. website, 2011)

INDONESIA

Suban Gas Field, South Sumatra

The Suban gas field was discovered in 1999 by drilling deep into basement. Approximately 5 TCF (trillion cubic feet) of gas was discovered in fractured granites. Highly prolific gas wells were drilled on the basis of the wells being highly deviated and oriented perpendicular to the dominant fracture system. The success of Suban has led to further successful exploration for gas in basement in Sumatra due to the need for more gas as the Indonesian economy continues to expand. Gas from the Suban Field has been pipelined to the huge Duri heavy oil steam flood project in Central Sumatra as well as to Singapore for electricity generation. The American oil company ConocoPhillips is the operator of the field.

Kali Berau Dalam Gas Discovery, South Sumatra

In 2019 the Spanish oil company Repsol announced that their Kali Berau Dalam-2 exploration well had made a major gas discovery in fractured pre-Tertiary basement rocks. This discovery extends the basement gas play 150 kilometers to the northwest of the Suban Field. The well was reported too have flowed at a rate of 45 million cubic feet of gas per day.

Repsol mentioned that the discovery found at least 2 trillion cubic of gas. On an oil equivalency basis this equals 330 million barrels of oil. For Indonesia the Kali Berau Dalam discovery is very significant since it is the largest oil or gas discovery in Indonesia in the past 18 years since the Cepu discovery in 2001. Indeed, petroleum industry analysts have stated that this discovery is one of the ten biggest discoveries in the world in the last 12 months.

Beruk Northeast Oil Pool, Central Sumatra

This basement pool appeared to be very promising based on the flow rate of 1,680 barrels of oil per day from the discovery well, Beruk Northeast-1 drilled in 1976 (Koning & Darmono, 1984) (Fig. 4, 5). The oil-bearing reservoir drilled by the discovery well was a fractured quartzite and radiometric age dating established a Permian age for the quartzite. The discovery was followed up by four development wells, none of which were drilled deep into basement thus the operator Caltex (Chevron-Texaco) did not know about the presence of multiple shallow underlying oil-water contacts. The field produced only 2 million barrels of oil when rapid water influx terminated the life of the field and rendered it noncommercial.

The "lessons learned" was that wells need to be drilled sufficiently deep into the basement rather than simply touching or "tagging" into the top of the basement.

Tanjung Oil Field, Kalimantan

The largest oil accumulation in basement in Indonesia is the Tanjung Field in the Barito Basin,

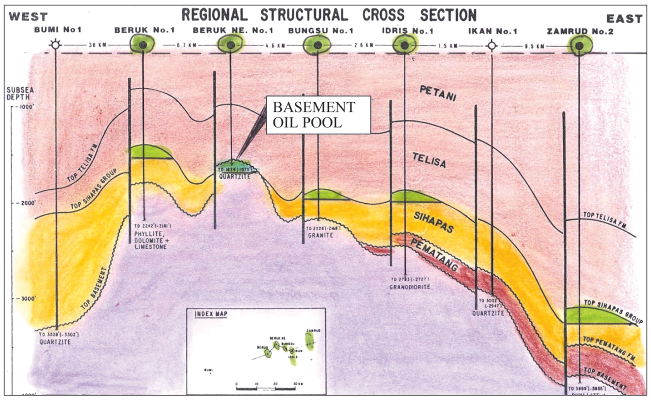


Fig. 4. Regional cross-section through the Zamrud-Beruk area, Central Sumatra basin. The Sihapas is a Tertiary-age sandstone which produces oil throughout this area. The Sihapas pinches out onto basement at Beruk Northeast where the Telisa shale provides a top seal to the underlying fractured basement of the Beruk Northeast oil pool (Koning & Darmono, 1984).

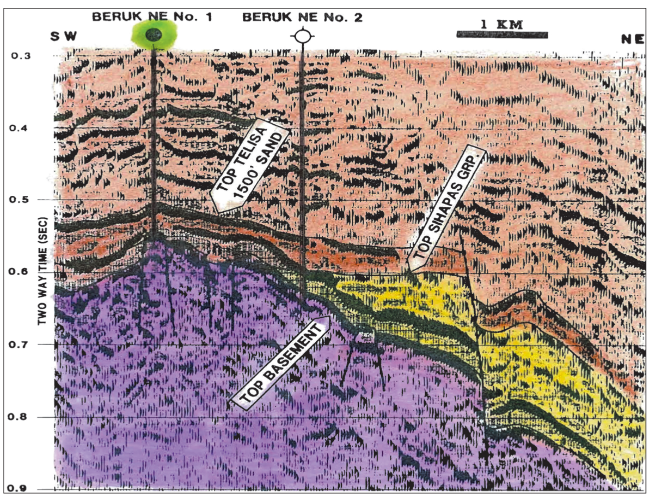


Fig. 5. Seismic line across the Beruk Northeast oil pool. Note the Sihapas sandstones pinch-out on the flank of the basement high. Accordingly, the oil-bearing basement high is capped and sealed by Telisa Formation marine shales (Koning & Darmono, 1984)

southern Kalimantan. This field has produced over 70 million barrels of oil from Eocene sandstones and conglomerates overlying a faulted basement high and it has also produced over 20 million barrels of oil from basement rocks including volcanics, pyroclastics and metasediments.

CHINA

Yaerxia Oil Field

The Yaerxia Field is an onshore oil field discovered in 1959 and is the first basement "buried hill" field ever discovered in China. The oil is produced from Paleozoic phyllites, slates, and meta-sandstones. The wells are moderately productive with 12 wells producing less than 70 barrels of oil per day, 3 wells producing at 200 barrels of oil per day and 2 wells producing at 875 barrels of oil per day. The wells are not highly productive since the phyllites and slates do not naturally fracture optimally. Similarly, phyllites and slates do not produce good reservoirs when they are weathered.

Dongshenpu Oil Field

This field is located onshore central China and like the Yaerxia oil field is an example of a Chinese "buried hill" basement oil field. The Dongshenpu oil field was discovered in 1983 and the reservoir consists of Precambrian granites, granulites, diabases, and hornblende gneisses. The rocks have no primary porosity but porous reservoirs were developed by weathering and natural fracturing. The discovery well tested at 1,570 barrels of oil per day and subsequent development drilling has found the oil column to be 400 meters thick. The reserves in this field were estimated at approximately 190 million barrels of oil.

MALAYSIA

Adang Utara Oil Field

Malaysia's first basement oil discovery occurred in 2005 with the drilling by Petronas of Adang Utara-1 in the southern Malay basin, offshore Terengganu. The well was drilled to a total depth of 2,610 meters including 120 vertical meters of basement penetrated. The flow rate of the discovery well is not available. However, 6 appraisal and development wells have been drilled. Flow rates from basement were as low as 159 barrels of oil per day to as high as 2,116 barrels of oil per day. The flow rates are much dependent on the wells optimally intersecting the oil-bearing basement fractures. No reserves information has been published on Adang Utara.

INDIA

India is the third largest consumer of crude oil in the world, after USA and China. India's oil and gas demand has significantly outpaced its domestic production. In India, basement exploration is not a new concept with established oil production from fractured and weathered basement in the Assam and Assam Arakan Basin, as well as in the Mumbai, Krishna Godaveri, Cauvery, and Cambay Basins. With the gradual decrease in large, easy-to-find oil pools, there is a shift in the focus of exploration from conventional sedimentary reservoirs to exploration in basement.

An example of an Indian basement field is the Mumbai High which is located offshore from India's west coast. This field was discovered in 1976 and produces from both basal sands and fractured Precambrian granites. Wells in basement have produced at rates of 465 to 2,575 barrels of oil per day.

Another example of an Indian basement field is the onshore Padra Field which produces oil from Deccan Traps volcanic basement. This consists of layered basalts laid down by episodic lava flows which occurred in the Upper Cretaceous-Paleocene time period. The fractured and weathered basalts contain oil columns of up to 300 meters in thickness. The Borhalla oil field in northeastern India in the Assam Arakan basin produces from fractured basemen and is another example of a basement oil field in India.

AFRICA BASEMENT OIL & GAS FIELDS

LIBYA

Major reserves of oil occur in basement in Libya. The Auguila-Naafora Field is a multi-billion barrels accumulation discovered in the mid-1960's in the Sirte Basin. The reservoir consists of hydrothermally altered fractured and weathered Precambrian granite. The field is a prominent horst block created at the onset of rifting in Middle to Upper Cretaceous time (Harding, 1984) (Fig. 6). The discovery well which found oil in basement was tested at 7,627 barrels of oil per day. Thick excellent oil source rocks onlap the basement high and also act as the ultimate seal to the accumulation. The source rocks are Cretaceous-age basinal marine dark shales.

Primary porosity in the granite is low (2-3 %) but hydrothermal alteration and weathering have led to about 6 % porosity in the weathered zone and a maximum of about 11 %. The weathering at the top of basement varies from as little as 5 meters to as much as 200 meters. There are sufficient open fractures in the basement structure to ensure effective fluids communication throughout the accumulation and to guarantee good production rates.

Reserves are estimated at 9.0 billion barrels of oil in place of which 90 % occurs within basement and 10 % in the overlying sediments. Production by 1984

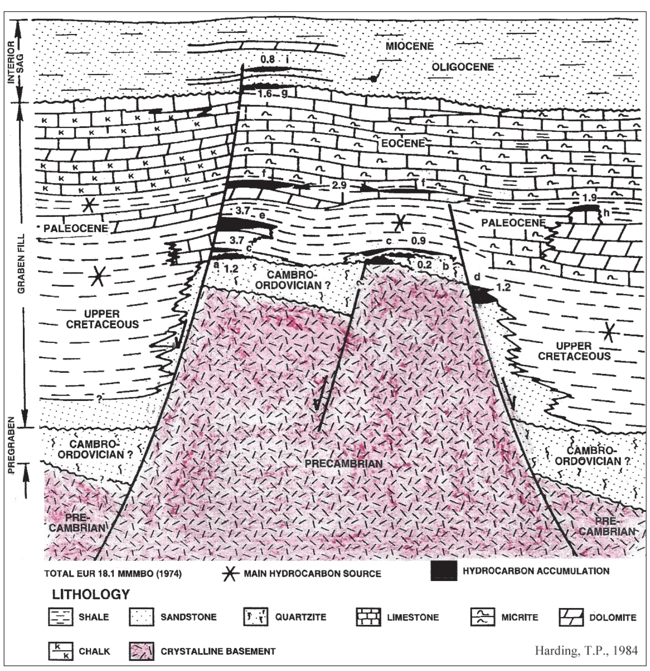


Fig. 6. Typical horst structure, Sirte Basin, Libya (Harding, 1984)

was 820 million barrels of oil. The field is estimated to have ultimate production of 2.0 billion barrels, which is equivalent to a 22 % recovery factor. Basement's share of the production is estimated to be 1.8 billion barrels of oil.

Accordingly, in the view of this author, Auguila-Naafora is the largest basement oil field in the world and is the prime analogue for geoscientists who are searching for major oil or gas accumulations in basement.

EGYPT

The Zeit Bay basement oil field is located in the offshore Gulf of Suez and was discovered in 1981. The initial discovery well had an oil column of 260 meters. Approximately 1/3 of the field's reserves are in basement and 2/3's in the overlying sediments. Basement consists of granites, meta-volcanics, meta-sediments and dykes. Flow rates in basement vary from 700 to 9,000 barrels of oil per day.

SOUTH SUDAN

About 40 wells were drilled in the Melut Rift Basin of which two wells flowed oil from basement at undisclosed flow rates. The reservoirs are granites and granitic gneisses. The Lower Cretaceous Renk formation is the major source rock in this basin. There is little public domain information on South Sudan's petroleum geology but based on regional geology one would expect that there is a high potential for oil and gas in basement in South Sudan's rift basins.

CHAD

In 2013 the China National Petroleum Company (CNPC) made the Lanea-1 oil discovery in the Bogor Basin in granite basement in a buried hill structure with 1,000 meters of relief. This has been followed up by 5 more oil and gas discoveries in buried hills. The reservoirs are fractured granite and hydrothermally leached granite, the latter being the best reservoir facies. The source rocks and top seals are Early Cretaceous lacustrine shales. The oil column is 1,500 meters thick and the average well productivity is 1,500 barrels of oil per day. The reserves have been estimated at approximately 100 million barrels of which 70 % is in basement and 30 % in the overlying granite wash.

ANGOLA

In 1968, USA's Gulf Oil Corporation drilled and completed Angola's first basement oil discovery, well 61-1 in the onshore area of Angola's province of Cabinda (Koning, 2014) (Fig. 7, 8). The well flowed 600,000 barrels of oil on an extended flow test. Additional development drilling proved that 61-1 is a one well pool. A second basement oil discovery was made by Gulf at 37-3 which tested up to 60 barrels of oil per day from basement. Neither of the Cabinda discoveries were

Fig. 7. Intensely fractured Precambrian granite in a fracture corridor in the interior of Angola. This potentially would be an excellent basement reservoir (Koning, 2014).

Fig. 8. Precambrian age granitic gneiss in the interior of Angola. Note the vertical and oblique orientation of the fractures which indicates this would be a complicated potential oil-producing reservoir. Note also that it is not intensely fractured like the granite in Fig. 7. Accordingly, this reservoir would be inferior in comparison to the reservoir which outcrops in Fig. 7 (Koning, 2014).

commercial. However, no oil company has deliberately searched in Angola for oil in basement and the basement oil play remains totally under-evaluated.

NORTH AMERICA

CANADA

Canada is the world's four largest oil producer with production of 4.5 million barrels of oil per day. The world's top oil producer is the USA with production of 12.6 million barrels of oil per day, followed by Saudi Arabia at 11.8 million barrels of oil per day, followed by Russia at 11.4 million barrels of oil per day.

In view of Canada having such prolific petroleum geology, it is anomalous that there is no production from basement anywhere in Canada. This may be attributable to the absence in Canada of good oil or gas source rocks overlying basement which would feed oil or gas into basement. In addition, in Canada the basement oil and gas play is poorly understood thus there has never been a deliberate, highly-focused effort to explore for oil and gas in basement. Also, in Saudi Arabia there is no oil or gas production from basement. The absence of basement oil and gas production in Saudi Arabia may be due to the same reasons as in Canada.

CALIFORNIA

The state of California produces currently about 0.5 million barrels of oil per day. This production is almost entirely from Tertiary Miocene age sandstones and conglomerates except for the following fields which produce from basement reservoirs:

1. Playa de Rey Field, Santa Monica area. Production from fractured Jurassic schists.
2. Santa Maria Field, Santa Barbara area. Production from fractured Jurassic sandstone basement.
3. Willmington Field, Long Beach area. Production of 22 million barrels of oil from fractured Jurassic schists.
4. Edison Field, Bakersfield area. Production of 20 million barrels of oil from fractured Jurassic schists.
5. El Segundo Field, western Los Angeles area. Reservoir is fractured Jurassic schist in the west half of the field and fractured Jurassic schist conglomerate in the eastern half with oil tested up to 4,500 barrels of oil per day from the basement at a depth of about 2,150 meters.

KANSAS

Oil is produced in the state of Kansas from the top of fractured Precambrian quartzites which occur in buried hills. The oil source rocks are the overlying Pennsylvanian age shales which also form the cap rock. Kansas has approximately 10 small pools which produced about 150,000 barrels of oil per well. An example is the Orth pool which produced about 1 million barrels of oil from 15 wells.

The production of oil from these small pools is commercially viable since the shallow depth of the basement reservoirs results in modest drilling costs. The area where these basement pools occur is an area with extensive oil production from conventional oil fields and related existing oil production infrastructure including pipelines and oil gathering stations. Accordingly, connecting the basement wells into the existing oil infrastructure is not expensive.

OKLAHOMA

The 15-kilometer diameter Ames structure in northwestern Oklahoma is a meteor impact structure created when a meteor struck in Middle Ordovician time. Oil and gas production is obtained from the brecciated Precambrian granite as well as from the overlying Cambro-Ordovician Arbuckle dolomite.

TEXAS

In northern Texas in the Panhandle-Hugoton area, oil is produced in the Anadarko Basin from fractured Precambrian rocks (Manwaring & Weimer, 1986). These oil pools, including the Apco Field, consist of basement highs which resulted from structural deformation and paleo-weathering. The oil is believed to have migrated from the Devonian Woodford Shale into basement along ubiquitous fractures, and accumulated in open fracture zones associated with faults.

The depth of production averages 1,060 meters. Basement oil production ranges from as low as 1 barrel of oil per day to as high as 700 barrels of oil per day. Drilling within a fault zone does not assure basement production. Other geological factors are equally important to basement oil accumulations and production which includes fault orientation, fracture type, mineralization within the fractures, degree of weathering, basement subcrop elevation, lithology, fault intensity, and proximity to fault-associated fracture zones. Proper drilling methods into basement is equally important as well as appropriate treatment of the basement reservoir during the completion of the well.

SOUTH AMERICA

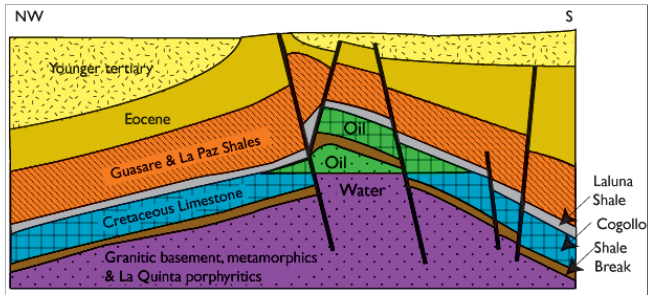
VENEZUELA

The giant-size La Paz oil field is located in the Maracaibo Basin in the interior of Venezuela. The field was discovered in 1944 and up to the year of 1992 has produced 830 million barrels of oil from the La Luna limestones and 325 million barrels from the underlying fractured basement reservoir (Landes et al., 1960, Talukdar et al., 1994, Koning, 2003, Koning, 2018). After the discovery of the field, due to the strong production performance of the La Luna reservoir, the geoscientists and reservoir engineers speculated that the reservoir was obtaining production support from a deeper reservoir. Accordingly, 30 years after the discovery of the field a well was drilled into the underlying basement and discovered the La Paz basement field.

The discovery well produced at a rate of 1,000 barrels of oil per day from the La Luna limestone. Basement wells have had initial production rates of up to 11,500 barrels of oil per day but the average initial production rate is 3,500 barrels of oil per day (Fig. 9).

BRAZIL

The only field in Brazil which has produced oil or gas from basement is the Carmopolis Field in the onshore Sergipe sub-basin. This field has produced oil from Cretaceous sandstones and the underlying basement. The depths of all reservoirs are very shallow, ranging from depths of 400 to 800 meters. The oil gravity ranges from 24 to 30.5 degrees API. Approximately 85 % of the oil production is from the overlying sediments and



Vertical section through the **La Paz field, onshore Venezuala**. Aprox 830 MMbls oil produced from low porosity Cretaceous limestones and 325 MMbls produced from fractured granite basement. Maximum IP of basement wells was 11,500 BOPD average IP of 3,600 BOPD. Average penetration into basement is 500 meters (1,700 feet). Source rock is the Laluna shale which is also the cap rock for the limestone reservoir.

Fig. 9. Vertical section through the La Paz field, onshore Venezuala (Landes et al., 1960, Talukdar & Marcano, 1994, modified by Koning, 2000).

15 % from basement. Approximately 35 million barrels of oil has been produced from basement.

ARGENTINA

The Octogono Field is the only field in Argentina to have produced oil or gas from basement. This field was discovered in 1918 in the onshore Neuquen basin and produced oil from the sediments overlying basement. Deeper drilling almost a century later focused on the basement and resulted in oil discovered in basement which in 2015 provided oil production of 3,000 barrels per day (Velo et al., 2014).

The primary source rock in the Neuquen basin is the organically-rich Vaca Muerta Formation (Spanish for Dead Cow) which is of Late Jurassic to Early Cretaceous in age. In the Octogono Field, the primary basement lithology is Paleozoic granite. All permeability and storage has resulted from fracturing and alteration. Fracturing in basement resulted from the uplift of basement more than 1,000 meters above the ground rocks. Six alteration zones corresponding to differential weathering has been identified.

The recovery factor in basement is estimated at 25 % due to expansion of a 300 meters gas cap. The oil column in basement is 300 meters. The discovery of oil in basement and the ongoing development of the basement reservoir has given new life to the Octogono Field.

EUROPE

It is beyond the scope of this paper to review in detail recent significant successes in Europe exploring for oil and gas in basement. Hurricane Energy, based in the UK, has made significant oil discoveries in the offshore West of Shetlands area. The reservoirs are fractured Precambrian granites. Flow rates of up to 9,800 barrels of oil per day was obtained in 2019 from the Lincoln discovery. The Lancaster Field commenced production in June, 2019 and is producing 17,000 barrels of oil per day from 2 production wells.

In recent years, oil has been discovered in basement in Norway. An example is the Rolvsnes field which will soon be placed on production with the oil being produced from fractured and weathered Precambrian granites.

Best practices for discovering and producing oil from fractured & weathered basement reservoirs

Exploration wells should be drilled highly deviated rather than vertical in order to optimally intersect the dominant fracture system. Production wells should be drilled perpendicular or near-perpendicular to the dominant fracture system.

Highly focused 3 dimensional (3D) seismic such as CGG – Veritas' CBM (Controlled Beam Migration) is needed to define the fracture systems in basement oil & gas fields.

Coring in fractured basement is difficult and not welcomed by the drilling engineers. Nonetheless, extensive core is needed to provide critically important information on the lithologies and reservoir parameters. Some of the cores should also be radiometrically age dated in order for the geoscientists to understand the complexities of the reservoir.

Development wells should be drilled sufficiently deep to fully drain the reservoir. For example, in the La Paz basement oil field, Venezuela, wells are typically drilled 500 meters into basement. In China's Dongshenpu "buried hill" basement field, the oil column is 400 meters thick and development wells typically are drilled through most of the reservoir.

Exploration wells should not just "tag" the top of basement since this will not allow for full evaluation of the basement and could result in an important discovery being "left behind". Indeed, the Suban gas field, South Sumatra was not discovered in the mid 1980's by Caltex (Chevron-Texaco) despite a major exploration program since the wells were drilled through the sedimentary section and then merely tagged into basement. The underlying giant basement gas field (5 trillion cubic feet of gas) was subsequently discovered in 1999 by Gulf Canada and Canada's Talisman Energy by drilling deep into basement.

There are a number of cases worldwide, such as the giant-size La Paz Field in Venezuela where oil in the basement was discovered much later (30 years) in the life of the field with the attention initially focused on producing oil from the overlying sedimentary reservoirs. A second example of this is the Octogono oil field, Neuquen Basin, Argentina which was discovered in 1918 and produced oil from shallow sediments overlying basement. Finally, almost a century later, basement was drilled and evaluated and now provides reserves and production upside. Production in 2015 from basement averaged 3,000 barrels of oil per day and continues to increase and has given a new life to this aging field. The La Paz and Octogono fields highlight that operators of oil & gas fields producing from sediments draped over basement highs should consider drilling a well down into the basement. High resolution 3D seismic will help with defining the best location to optimally intersect the fractured or weathered basement.

Weathered "rotten" granites can also be excellent reservoirs as one can observe in outcrops in tropical areas where heavy rainfall can leach out feldspars and less resistant minerals and leave behind an excellent reservoir. The high mafic minerals in schists, phyllites and slates negates the creation of secondary porosity by weathering. Likewise, granites and quartzites are more likely to produce attractive, highly porous "granite wash" sands whereas eroded schists and gneisses do not produce such good reservoirs.

Geologists, geophysicists, reservoir engineers, and economists must study proven analogues of basement oil and gas fields worldwide in order to fully understand any basement discoveries they are attempting to develop.

Conclusions

In the past, oil and gas fields in basement were discovered mostly by accident. The conventional way of thinking in the past was that basement is mostly tight and did not warrant exploring. However, today there are a few companies who are highly basement-focused and have been especially successful in finding oil in basement. They are SOCO International in Viet Nam & Yemen and Hurricane Exploration in the United Kingdom's West of Shetlands area. Hurricane's recent successes can be viewed as a "basin revival play" for the mature North Sea basin.

Basement reservoirs are very unusual in comparison to conventional sedimentary rock oil and gas reservoirs since the basement reservoirs are in crystalline rocks. Accordingly, to successfully work with basement rocks, a special "mind set" is required which is open to all of the complexities associated with crystalline rocks.

This author believes that significant oil and gas fields remain to be found in Asia, Africa, the Americas and worldwide. Unconventional geological thinking and risk-taking has led to many of the world's major oil and gas discoveries and such strategies will reward the explorers searching for oil and gas in basement.

Understanding basement reservoirs is not only important for oil and gas, but this knowledge is also very relevant to the need to reduce the world's Green House Gases (GHG). Carbon dioxide (CO_2) can be captured an injected into fractured or weathered basement and thereby can be safely and permanently stored. Also, a commodity which is increasingly in short supply in the world is helium. Economic helium is derived from the radioactive decay of uranium and thorium in basement rocks and granite washes. In Canada's province of

Saskatchewan, significant programs have commenced exploring for helium in basement reservoirs.

Lastly, the reader is referred to one of the first papers published on oil and gas in basement which was the classic paper by K.K. Landes et al. in 1960 in which it was states: "*Commercial oil deposits in basement rocks are not geological "accidents" but are oil accumulations which obey all of the rules of oil sourcing, migration and entrapment; therefore in areas of not too deep basement, oil deposits within basement should be explored with the same professional skill and zeal as accumulations in the overlying sediments*".

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About the Author

Tako Koning – Senior Geologist, Independent Consultant, Calgary, Canada

E-mail: tako.koning@gmail.com

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