HYDROCARBON PRODUCTION FROM FRACTURED BASEMENT FORMATIONS

INTRODUCTION

This is a compilation of public-domain information about commercial hydrocarbon reservoirs in fractured crystalline basement formations from approximately 30 different countries. Although basement reservoir plays have been exploited for decades, since the mid-90's there has been increasing interest and exploitation due to a number of factors working together. These include the impetus derived from major discoveries in Vietnam and Yemen; the advent of new downhole tools (especially borehole image logs and full waveform sonic logging), seismic techniques (eg shear-wave attributes) and sophisticated drilling methods; and the arrival of elevated oil prices to allow re-appraisal of basement projects previously discounted as difficult or 'uneconomic'.

Perhaps the best known basement reservoir examples are offshore Vietnam, where the Cuu Long Basin comprises 95% of the country's hydrocarbon production and 85% of this value comes from the fractured granitic basement, and in the Yemen (e.g. DNO in Block 43, Nexen in Block 14, Total in Block 10, and OMV in Block S2). Other significant discoveries have been made in Argentina at the Cuyo Field and the Neuquen Field, both producing from fractured volcanics.

There is one company (Hurricane Exploration) specifically set up recently to appraise and develop basement plays, and they are having success on the UK Continental shelf West of Shetland (see Trice, 2014).

By definition (see below), this review concentrates only on those reservoirs found in igneous, metamorphic and volcanic rocks. Although largely a historical review we have tried to make new information available on a regular basis, and we are currently at Version 11 of an evolving document started in the mid-90's. It is made available for personal interest and education only and should not be republished or distributed in any way. Data has not been cross-checked in detail against multiple references so use with care. In addition, some of the information, for example on production, will be out of date since it is based on historical sources.

Information updates, corrections and comments are welcome. We know from our own work that there are several fields that are not included here because no information has been released in the public domain. If you can provide information or examples that we can use in the compilation we will be delighted to continue developing the resource.

Compiled by Jon Gutmanis, Tony Batchelor, Suzie Doe, Enric Pascual-Cebrian and colleagues at GeoScience Limited.

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FRACTURED BASEMENT RESERVOIRS - DEFINITION AND HISTORICAL BACKGROUND

A large proportion of the world's proven oil reserves have been found in reservoir rocks that are naturally fractured (**Waldren & Corrigan, 1985; Nelson, 1985; Aguilera, 1995; Nelson**, **2001). Nelson (2001)** listed some 370 fields where natural fractures are important for production, a significant proportion being in basement settings, and also stated that "...in BP Amoco alone, current and future fields in various types of fractured reservoirs are estimated to account for some 21 billion barrels of oil equivalent (BBOE)".

Basement reservoirs are a subset of naturally fractured reservoirs, and various definitions of 'basement rocks' exist (see for example **Landes et al 1960, P'An 1982, Koning & Darmono 1984, Aguilera 1995c and North 1990**)**.** The definition that we think is most appropriate in the context of hydrocarbon exploration is that of **Landes et al (1960**):

> *any metamorphic or igneous rock (regardless of age) which is unconformably overlain by a sedimentary sequence*

North (1990) however took a different view, considering basement rocks to include those of sedimentary origin if they have little or no matrix porosity. This definition would be quite wide including fields hosted, for example, in the Cambro-Ordovician quartzitic sandstones of Algeria.

Basement reservoirs have been known about for decades but were often passed over as 'of no economic potential'. Yet they are commonly distributed in hydrocarbon regions of the world. As early as 1948, **Eggleston (1948)** reviewed oil production from basement rocks in California and found that 15,000 bpd were in production, representing about 1.5% of total Californian production at the time. Soon afterwards **Hubbert and Willis (1955)** produced a comprehensive list of fractured reservoirs in the United States.

Landes (1959) speculated that many oil discoveries had been missed because of inadequate exploration of the barely scratched basement by unsuccessful wildcats. According to **Landes et al (1960),** about 100 million bbl had been produced by that time from various basement formations worldwide, with initial productions being as high as 17,000 bpd. In their view basement hydrocarbon accumulations were not freaks to be found solely by chance but normal concentrations of hydrocarbons obeying the rules of origin, migration and entrapment and should be explored for with the same professional skill and zeal as accumulations in the overlying sediments. They suggested that the potential offered by fractured basement plays was of sufficient magnitude to justify attempts to discover them by design rather than by the previous situation of discovery by ‘accident’ (drilling too deep).

Kenney (1996) noted that all the oil fields in the West that produce from crystalline basements were discovered by accident whereas in Russia and some of the other countries of the Former Soviet Union (FSU) drilling into crystalline basements has been carried out intentionally (although a literature search reveals that citations of producing fields in basement are actually few and far between). Until more recent years perhaps, many oil companies stopped drilling as soon as basement rocks were intersected. **Aguilera (1995a)** suggested drilling at least 300m into basement especially if the cover rocks contain oil and believed that fractured reservoirs contain significant volumes of undiscovered hydrocarbons which may have been missed by a failure to intersect the mainly vertical to sub-vertical fracture system (**Aguilera 1996).**

BASEMENT RESERVOIR CHARACTERISTICS

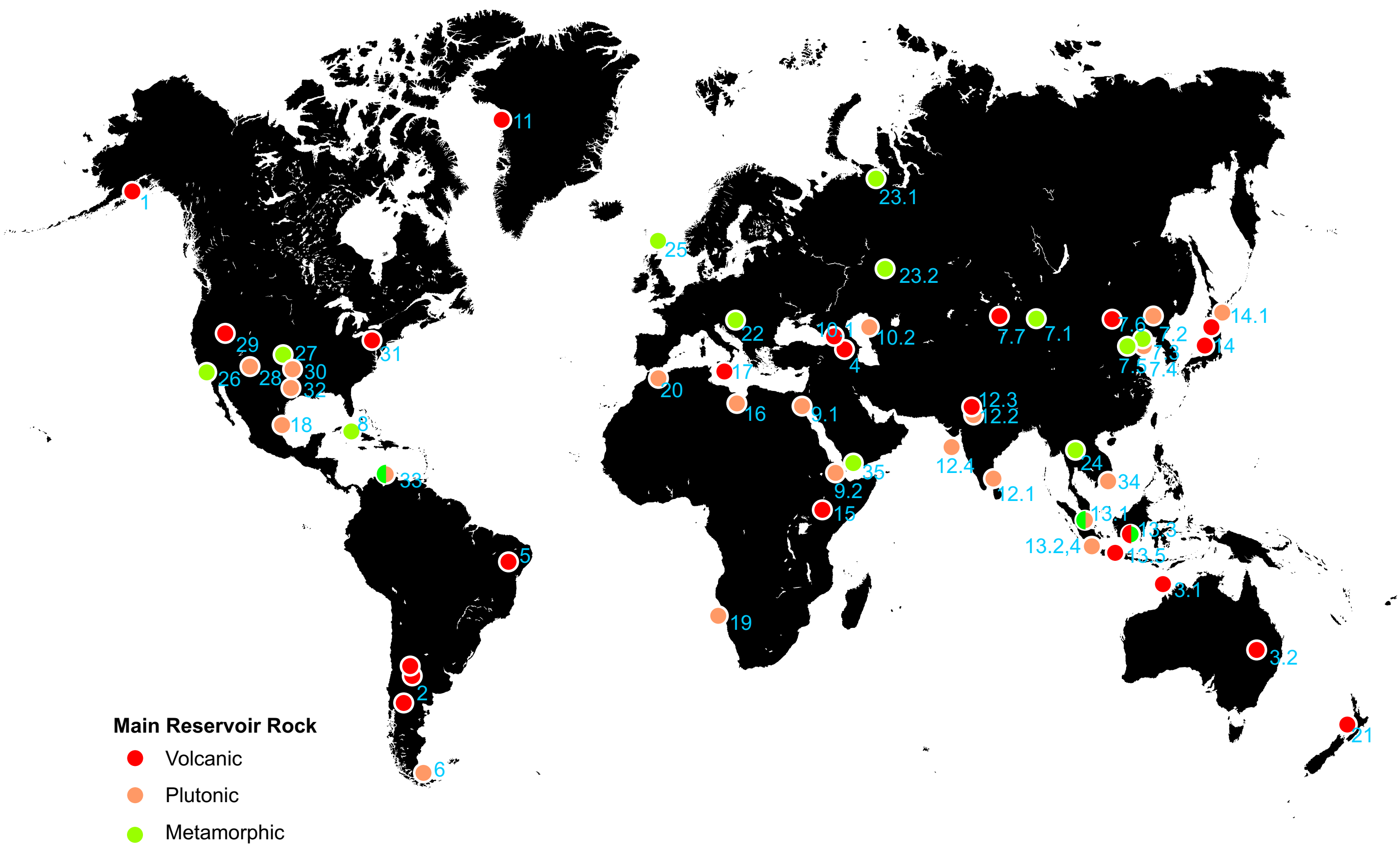
A GeoScience review of the geology and production characteristics of basement reservoirs was presented at the International Petroleum Technology Conference (IPTC) in Qatar (December 2009). Based on many reservoir appraisal and development projects carried out by GeoScience as well as a large volume of published information, the review contains a summary of possible charging mechanisms, methods of reservoir characterisation, controls on reservoir quality as well as some case histories and proposed development strategies.: It can be found on our Downloads page.

Some key points made in the IPTC presentation are:

- Basement charging is most commonly thought to result from up-dip / lateral migration from an adjacent kitchen area into structural highs (either fault blocks or buried hills). But other mechanisms are distinctly likely to operate as well, such as downward migration due to differential stresses between overburden and basement; and long-distance lateral migration through active faults (which may explain oil seeps found at depth within the Hercynian granite plutons of Cornwall for example)
    - *How was your basement reservoir charged?*
- As a result, hydrocarbon charge distributions in basement may be ‘unusual’, (e.g. the Lancaster discovery West of Shetland, see below) especially if sealing horizons are present such as poorly fractured or highly mineralised layers. In addition, the OWC is very often hard to establish
    - *Do you concur with this comment?*
- Reservoir quality and production from basement plays usually relies on the presence of a connected open fracture network because matrix porosity and permeability are generally very small (typically < 0.5%) except perhaps in localised weathered zones (which may be 5 to 10%). Bulk fracture porosity values of between 0.1 and 1% are typical for fractured reservoirs including basements (Nelson 2001, Narr et al 2006, GeoScience unpublished review) and production usually depends on features offering enhanced permeability such as fault damage zones, fracture corridors or extensive weathered zones at top basement or within faults.
    - *But not all of them! It’s important to identify the subset of dynamically active and connected fractures*
- Lithology is also often an important control on reservoir quality, perhaps surprisingly in what are normally assumed to be fairly uniform basement rocks. However there is growing evidence that granitic lithologies offer better prospects because they tend to have better connected fracture systems compared to layered metamorphics which have more limited fracture dimensions (see Figure 5 in the IPTC download).
    - *Don’t assume all basements are granitic – metamorphic formations especially when altered may be distinctly tight*

- Tectonic and fracture history are almost always a crucial factor because fracture porosity and permeability may be focussed on the youngest structures, and also on those which are in a state of critical shear within the current stress field (see Figure 3 in the IPTC download).
    - *Bring in the geomechanics people to look at in-situ stress!*

Figure 1: Oil and Gas Geographical Distribution in Basement Rocks



1 Alaska
2 Argentina
3 Australia
4 Azerbaijan
5 Brazil
6 Chile
7 China
8 Cuba
9 Egypt
10 Former Soviet Union Countries
11 Greenland
12 India
13 Indonesia
14 Japan
15 Kenya
16 Libya
17 Malta Offshore & Sorrounding Regions
18 Mexico
19 Namibia
20 Morocco
21 New Zealand
22 Pannonian Basin, Europe
23 Russia
24 Thailand
25 United Kingdom
26-32 United States
33 Venezuela
34 Vietnam
35 Yemen

COUNTRIES WITH HYDROCARBON FINDS IN BASEMENT RESERVOIRS

Examples of producing basement reservoirs covering many countries throughout the world have been documented within the public domain. This compilation has attempted to refer to hydrocarbon fields where production figures can be cross-referenced to published literature or traceable sources.

Alaska

The McArthur River field (Fig. 1, Location 1), Cook Inlet, is producing hydrocarbons from Jurassic tuffites and volcanic sands (Aguilera, 1998. Pers. Comm.).

Algeria

Saharan plateau basaltic lavas are reported to contain hydrocarbons.

Argentina

Cuyo Field

Permian volcanics are found to host hydrocarbons (Fig. 1, Location 2) generated from the lacustrine shales of the Upper Triassic Cacheuta Formation. The volcanics consist of andesite sills, and serve as a secondary hydrocarbon producer to the overlying Triassic alluvial sandstones (Mosquera, 2004)

Nirihuao

Although this area is currently lacking the identification of a viable source rock, geochemistry demonstrates a potential for oil generation. Possible reservoir units at this location include Eocene and Miocene volcanics, along with Palaeogene to Recent clastics and carbonates (Jacques, 2003).

Neuquen

Drilling at the Neuquen field discovered hydrocarbons in the Permo-Triassic basement. Source rocks were identified as the Upper Jurassic black shales of the Vaca Muerta Formation, along with Jurassic calcareous mudstones and Lower Cretaceous mudstones. The target horizons were Miocene carbonates and sandstones, however hydrocarbons were also found to be contained within a Miocene volcanic series (rhyolites, tuffs and tuffaceous sandstones), along with the Permo-Triassic basement. Production from these units was 11000 bo/d in 1980 (Aguilera, 2000). Moreover, commercial oil has been produced from laccoliths (Delpino and Bermudez, 2008).

Australia

The Browse Basin (Fig. 1, Location 3.1) contains volcanic interbeds in the Jurassic with good reservoir characteristics. The Scott Reef Volcanic oil/gas field possesses the largest reserves in the basin (3877×10^8 m^3 gas; 1795 10^4 tons oil). In Scott Reef Field, the reservoir lies between ~4000-4695m.

The Scotia gas field, located in the Bowen Surat basin (Fig. 1, Location 3.2), has a production of 17.8 10^4 m^3/day. The reservoir rock consists of fractured andesite (Zou et al., 2013). The production started in 2002, and the gas field is owned and operated by Santos Limited (Baker and Slater, 2008)

Azerbaijan

Oil was discovered during the 1970s in **the** Kula Basin **(Fig. 1, Location 4)** where oil is mainly located **above** a buried hill within volcanic rocks. The Muradkhanli oil field has five reservoirs; one of **which** consists of andesite, basalt and porphyrite. The porosity of the eruptive rock varies from 10% to 16% and is controlled by well-developed fractures. Each well has different production profiles due to heterogeneous fracture distribution (Zou et al., 2013).

Brazil

The Carmópolis Field (state of Sergipe, Fig. 1, Location 5) is an important oil reservoir that consists of fractured phyllites and schists of Precambrian age (Milani and Medeiros de Araújo, 2003). The Sousa basin in the central Borborena Province also presents oil accumulations in gneisses (Carvalho et al., 2013), where porosity is the result of fluid flow, tectonics, and hydrothermal alteration. Fractured volcanics (basalt) of the Badejo and Linguado fields (discovered in 1975), located in the Campos Basin (offshore Brazil) are also known to produce hydrocarbons (Nelson, 2001).

Canada

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

Chile

<u>Lago Mercedes Field</u>

Lago Mercedes Well 1 was spudded on 17th 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 (Fig. 1, Location 6). 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 (Dean et al, 1993).

Although the Lower Cretaceous Springhill Formation comprised the primary target, Dean et al 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 (Dean et al, op cit).

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 grano-diorite 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 1,140 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 Field, Yumen

The Yaerxia oil field (Fig. 1, Location 7.1) in the Jiuxi Basin (western part of Jiuquan Basin) was the first basement reservoir in China (Guangming & Quanheng, 1982; P'An, 1982). Oil is produced from fractures in Palaeozoic metamorphic rocks. Oil production was up to 1,050 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 to 1979, 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 8,530 ft to 10,500 ft (2,600 m to 3,200 m). Twelve wells had commercial value, six of which had initial production of less than 70 bbl/day, and three wells produced 70 bbl/day to 350 bbl/day of oil. Only two wells had initial production of 700 bbl/day to 1,050 bbl/day.

Xinglongtai Oil and Gas Field

The Xinglongtai oil and gas reservoir (Fig. 1, Location 7.2) is located in the middle of the west trough in the Lower Liaohe depression. The 26,300 ft (8,000 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 the Archeozoic granite is considered to be a basement rock here (P'An, 1982).

By the end of 1998, 16 productive wells had been drilled in the Xinglongtai oil field (Luo et al., 2005). 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 bbl/day and 420 bbl/day. The Xinglongtai basement reservoir is a high pressure, highly saturated reservoir with a hydrocarbon column of 2,300 ft (700 m). The gas column is about 590 ft (180 m) with an oil column not less than 1,640 ft (500 m).

Dong Sheng Pu Buried Hill Field

The Dong Sheng Pu Buried Hill reservoir located in Xin Min County, Liaoning Province (Fig. 1, Location 7.3) is a fractured, metamorphic basement rock. The structural location of the Buried Hill reservoir is the centre of the Da Ming Tun Depression with a minimum burial depth of 2,600 m (Ullah et al, 1988).

Exploratory drilling began in October 1982 based on seismic data. In January 1983, Well 3, located above the crest of the Buried Hill, tested oil at a rate of 183.8 tons/day. By December 1987, there were 14 active producers and one observation well with cumulative volumes of oil and gas of 1,050,000 tons and 65,500,000 m^3 respectively. Water injection was initiated in

October 1986 through four injectors with a cumulative volume of 290,000 m^3 (Ullah et al, 1988).

During late 1985 and early 1986, a detailed reservoir study was conducted to determine the most appropriate method of developing and operating the field. Ullah et al state that a water flooding scheme would produce the most efficient method of oil recovery compared to natural depletion and gas injection. With water injection, oil production rates varied between 1,163 m^3/day and 1,838 m^3/day which relates to an estimated cumulative oil production, at the end of the field's production life, of 25,390,000 m^3.

Production from granites and gneisses has also been reported at Bohai Bay Basin (Kaijun et al., 2012), and hydrocarbon shows have also been reported in the Upper Basement in the Beibu Gulf (Roc Oil press-release, 03/05/04).

Other

Production has also been reported from fractured basement consisting of PreCambrian gneiss at Wangzhuang field in China (Fig. 1, Location 7.4). Also from volcanics at Dujiatai, Qija, Shijutuo and Shuguang (Lee, 1989), and from metamorphics at Jinganpa.

Hydrocarbon exploration from volcanic formations in China has expanded in the last 50 years and increased tenfold since the beginning of the 21st century. There are obvious differences between hydrocarbon reservoirs in the east and west of China (Cai-neng et al., 2008). Hydrocarbon reservoirs in the east are composed of Mesozoic-Cenozoic intermediate acidic rocks, often forming a major source kitchen from a single eruption phase. Whereas, hydrocarbon reservoirs in the west are formed from multi eruptional stages of intermediate basal volcanics from Palaeozoic intracontinental rifts or island arcs. In 2013, PetroChina Company Limited had proven oil reserves of 6 x 10^8 tons and proven natural gas reserves of 4700x10^8 m^3 in volcanic reservoirs.

Volcanic reservoirs in China are successful because of 3 main factors: 1) they have a good source-reservoir-cap rock association with near source (often vertical) migration and accumulation. 2) The compaction resistance of the reservoirs is strong and 3). The source rock is mainly composed of coals with a “high evolution degree” (Wenzhi, Z et al., 2009).

Bohai Bay Basin-Metamorphic field of JZ25-1S

JZ25-1S oilfield is an Archean buried hill reservoir in the Liaoxi low bulge, Bohai Sea (Fig. 1, Location 7.5). Fractured reservoir systems are found throughout the Archean migmatization granitic gneiss, an example of a metamorphic basement reservoir with potential. The best reservoir properties are located in the semi-weathered crust (Kaijun et al., 2012).

Songliao Basin

The Songliao basin is situated in the East of China (Fig. 1, Location. 7.6) and is composed of lower Cretaceous source rocks from the Shahezi formation, volcanic reservoir rocks from the Yingcheng formation and a mudstone cap rock from the Donglouku formation. There are 2 productive layers in the basin, a shallow middle layer hosting the Daqing Oilfield and a deeper layer containing mainly gas. This deeper layer is riddled with large fault depressions (up to 1000km^2) 6 of which are producing commercial amounts of oil and gas. Xushen 1 was the first well to be sunk in the Songliao for volcanic gas exploration; it produced 54 x 10^4 m^3 from the Yincheng formation of which there is an estimated 286.8 BCM of gas reserves remaining in the field (Wen-zhi, 2008).

Junggar Basin

This is an extensive basin located in the Uygur Autonomous Region of Xinjiang (Fig. 1, Location 7.7), northwestern China with Carboniferous-Permian volcanic reservoirs formed during an intracontinental rift phase related to collision. Hydrocarbons are accumulated in the weathered crust and little is found below it. 38 oil/gas reservoirs have been discovered in the Junggar Basin (Hui et al., 2009).

Cuba

The Jatibanico Pool reserve of Cuba has over 1200 hydrocarbon producing wells penetrating fractured serpentinites (Oil and Gas Journal, 14th July, 1945, Vol3. 44, p.92).

Hydrocarbons are also observed in the Pina reservoir, producing from Upper and Lower Cretaceous tuffites (Villavicencio et al, 1994).

Exploration for oil in basement reservoir rocks in Cuba peaked in the 1920's. Serpentine was the predominant reservoir rock in the area (Fig. 1, Location 8), with oil seeps following cracks and fissures made by dykes of diorite (in Habana) or obsidian (in Motembo), these fissures are thought to be Eocene in age (Lewis, 1932). There were two main production fields within Cuba:

1) The Motembo field, situated on a serpentine highland with a vertical height of 325 feet and a diameter of 3 miles. By the 1930's this field had produced 5000 barrels of oil and was semi-commercial.
2) The Bacuranao field, discovered in 1915, 10 miles east of Habana. By the 1930's, 40 wells had been drilled in an area of 160 acres. These wells were owned by the Union Oil Company and produced 30 barrels per day.

Asphalt from serpentine country rocks was also mined in large quantities. Particularly lustrous wells included the Santa Eloisa (500 tons), La Esperansa and Chambas (Lewis, 1932).

Egypt

The basement oil fields of Egypt are located approximately 196 km southeast of Suez on the west shore of the Gulf of Suez. Oil is produced mainly from the Hurghada and Gemsah fields. The Gemsah oil field is located on a granite buried hill. Oil is found in a coral reef that lies above the granite ridge and is probably of Miocene age. However, it is not a basement reservoir and has not been included in this compilation. The oilfields at the entrance to the Gulf have been described by Salah & Alsharhan (1998). Basement fracture analogues for the offshore oilfields have been described by Younes et al (1998).

The Gulf of Suez contains many recently discovered basement reservoirs, such as the Zeit Bay field and the offshore Ashrafi field. These produce approximately 25, 000 barrels of oil per day and are found in fractured basement reservoir rocks of granite and granodiorite intrusions. Two fault sets are associated with the basement rocks, contributing to the increased porosity and permeability of the reservoirs. The first fault set is parallel to the rift (310-330°) creating oblique and dip-slip normal faults, the second fault set strikes across the rift at 055-065° and is related to block rotation (Younes et al., 1998).

Hurghada Field

The Hurghada field (Fig. 1, Location 9.1) 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 1,670 ft to 2,000 ft (510 m to 610 m). Oil was found in the Cretaceous sandy shale, Nubian sandstone and in the weathered surface of the granite (P'An, 1982). The Miocene strata are unconformable with the Cretaceous beds and are less highly folded. The Hurghada field produces heavy oil (no production rates available).

Zeit Bay Field

The Zeit Bay field is a northwest-southeast trending structure (Fig. 1, Location 9.2) which measures approximately 2.5 km by 4.5 km located in the southwest corner of the Gulf of Suez (Khalil & Pigaht, 1991). The field was discovered in 1981 when well QQ 89-1 found gas. In October of the same year, the appraisal well, QQ 89-2, intersected an 830 ft thick oil leg 2 km south of well QQ 89-1.

According to Zahran & Askary (1988), 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 bbl/day to 10,000 bbl/day. Due to its well established production potential, 60% of the field's development wells were drilled down to the basement (Zahran & Askary, 1988). 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 (Khalil et al, 1993; El Hamalawy et al, 1993). The 830 ft thick oil column covers the total reservoir sequence. The field commenced production in 1984 reaching approximately 80,000 bbl/day (Salah Alsharhan, 1998) and by 1991 it was estimated that 65% of the recoverable oil had been produced (Khalil & Pigaht, 1991).

A significant proportion of early production was from basement wells with individual flow rates of up to 10,000 bbl/day being recorded. Pressure maintenance by gas injection was implemented in 1987. Out of 36 production wells drilled in the Zeit Bay field, 24 wells penetrated the fractured basement, 14 of these were completed as openhole basement producers.

The Zeit Bay field basement can be classified into five rock types:

- Basement wash (this overlies the basement rock; composed of granite, feldspar, chlorite and clay)
- Fractured granite
- Meta-volcanics (composed of hornblende, magnetite, apatite and chlorite)

- Meta-sediments
- Dykes

Former Soviet Union Countries

There are said to be numerous fields in the FSU producing from fractured basement reservoirs (Kenny, 1996), but very little detail has been published in the West. Kenny (1996) states that more wells have been drilled into crystalline basements within the FSU than all other nations combined with the consequence of greater production. For example, the Caspian district has a total of eighty fields producing from crystalline basements. Unlike the majority of drilling operations which cease as soon as basement rocks are encountered (Aguilera, 1995b), Krayushkin et al (1994) state that all of the hydrocarbon fields within the FSU producing from crystalline basements were developed intentionally.

Published articles from a working conference on oil in granite held in Kazan, Tatarstan, Russia in late 1997, (see latest reference section), refer to basement oil shows in the Chibuiuskoye, Verkhnechutinskoye and Iskosgorinskoyeoil fields, together with the Zelenetsky, Chernorechensky, Lekkemsky and Timansky oil productive areas. Production statistics from individual wells or fields were not made available.

One such example is discussed by Krayushkin et al (1994) involving an exploration project on the flanks of the Dnieper-Donets Basin. An initial geological study of the sedimentary, metamorphic and igneous rocks in the 'Northern Monoclinal Flank' of the Dnieper-Donents Basin concluded that there was no potential for hydrocarbon production. The conclusion was made because of the absence of any source rock and the presence of active, strongly circulating artesian waters.

However, the exploration and drilling programme which followed the initial study resulted in the discovery and development of 12 fields with oil reserves equal to 219 million metric tons of oil equivalent, the major part of which, according to Krayushkin et al (1994), is produced from the PreCambrian crystalline basement. However, this is difficult to demonstrate, partly because of multiple completions in basement and overlying cover (Kitchka, pers. comm., 1999).

The fields were discovered in an area covering 30-35 km by 400 km where the oil and gas bearing rocks are Carboniferous sandstones and PreCambrian granites, amphibolites and schists of the crystalline basement complex. The exploration programme also resulted in the discovery of a gas field with reserves of 100 billion cubic metres.

From a total of 61 wells drilled in a corridor 35 km wide by 400 km long, 37 produced commercial quantities of hydrocarbons (an exploration success rate of 55%). Initial flows from the productive wells varied between 40 and 350 metric tons/day of oil and 100,000-1,600,000 m^3/day of gas. Production interval depths within the PreCambrian basement varied between 3,135 m and 4,041 m. Recently we have learnt of a new discovery in PreCambrian basement called Goshinovskoye field (Kitchka, pers. comm., 2000). Near Khark another corridor 30 km wide by 100 km long is associated with 3.5 Tcf reserves (Kitchka, pers. comm., 1998)

Tatarstan

A well at Novoyelkhovskaya penetrated crystalline basement at 1845 m and significant hydrocarbon shows have been reported below 4500 m (Kitchka, pers. comm., 1998)

Georgia - Samgori Field

The Samgori field is located near Tbilisi, in the Republic of Georgia (Fig. 1, Location 10.1). Production of more than 165 M bbl of oil has come from a middle Eocene laumontite tuff which is enclosed within a thick layer of andesite-basalt tuffs and tuffites which act as a seal (Grynberg et al, 1993). Productivity is dominantly controlled by fracture porosity and permeability. The fractured tuffs are relatively isolated from the action of geostatic and geotectonic loads which would otherwise have resulted in closure of fractures and microfractures. In addition, the fluid pressure tends to maintain open fractures.

Georgia – Ninotsminda Field

Located 25 km east of Tbilisi (Fig. 1, Location 10.1), the Ninotsminda Field represents the largest remaining oil accumulation in Georgia. The field was discovered in 1979, and represents an anticlinal trap, with production mainly from the fractured Middle Eocene volcaniclastics. The reservoir is underpressured at 0.38 psi/ft, and is dominated by sub-vertical micro and macro fractures that are most concentrated in the hinge area of the fold.

In 2000, a vertical well was drilled into the oil producing formation, with production tests stabilising at a flow of 200 bo/d. After further work was carried out on the area, another appraisal well was drilled in 2003, this time with a horizontal deviation in the oil-producing strata. The oil flow using this method was 2200 bo/d.

The area is being extensively developed by the NOC (Ninotsminda Oil Company), with a 5 well prospect likely to increase production from 2000 to 4500 bo/d (Durglishvili et al., 2004).

Hydrocarbons have also been discovered in the Middle Eocene volcanic prospect at Nono PSA, Patardzeuli and South Dome fields.

Kazakstan - Oimasha (Oymasha) Field

The Oimasha oil field is located in the South Mangyshlak Trough (Fig. 1, Location 10.2), in a sub-basin sometimes referred to as the Peschanomyss-Rakushechnoe Uplift. The field was undeveloped as at 1995. However, Well 12 tested approximately 1,382 bbl/day from fractured/weathered granite at a depth of 3,720 m to 3,752 m. The granite intrudes into Early Palaeozoic metamorphics (Reisser, 1996).

Greenland

Oil was first identified in 1992 in a basalt-hosted petroleum reservoir around Marraat Killiit on Nuussuaq in West Greenland (Melville Bay region; Fig. 1, Location 11). Oil is held in vesicles and voids within the halyoclasts of thick volcanic sequences overlying petroleum source rocks. Although discovered, hydrocarbons are not being exploited from this reserve (Rogers et al., 2006).

India

An appraisal well was drilled in 1997 (Well PY-1-12) to confirm the significance of a 1980 gas discovery reported by India's Oil & Natural Gas Commission (ONGC) (see J.Pet.Tech., Sept. 2001). The discovery, named PY-1, is in the Cauvery basin about 100 miles south of Madras in the Bay of Bengal (Fig. 1, Location 12.1).

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 (see Oil & Gas J., Nov. 1995).

It was estimated that PY-1 could yield as much as 116 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 (see J.Pet.Tech., Sept. 2001).

In 1980, the 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 5,000 ft to 5,500 ft. PY-1 is within, and surrounded by, Block CY-OS/2, a 3.8 million acre tract formerly known as Block 17 (Anon, 1995).

Mangala Oil Field, northern Rajasthan

Cairn Energy (UK) completed their appraisal of Block RJ-ON-90/1 (Fig. 1, Location 12.2) in October 2004 (see E&P, Oct. 2004). Three exploration wells (Mangala-3, Mangala-5 & Mangala-6) encountered 125 m of net pay in the high quality oil bearing Fatehgarh Sands, followed by a 30 m oil column hosted by the underlying fractured basement.

Production tests on a 34/64 in. choke indicated a possible 2000 bo/d from the Fatehgarh Sands, and 1084 bo/d from the underlying basement (with an associated 1490 b/d of water). Production tests also established an API of 41.5°, confirming the basement rock as a viable exploration target in the heavily faulted areas of the basin.

Raageshwan, 75 km south of Mangala

Exploration wells drilled by Cairn Energy in 2004 encountered modest volumes of gas from basement rocks (Fig. 1, Location 12.3), along with minor oil shows (untested). Gas was also found in fractured volcanics at a depth of 3000 m, with production tests revealing a gas output of 1 MMcf/d (Cairn Energy press-release, 24/03/05).

Bombay High Field

The Bombay High Field was first discovered in 1974, 150km off the west coast of India (Fig. 1, Location 12.4). The field contains both a limestone reservoir and a basement reservoir composed of basaltic and granitic gneiss. The basement hydrocarbons are located at a depth of 1900m, note that the granitic basement contains a higher fracture density and is therefore more lucrative than the basaltic gneiss reservoir rock. By 1993, wells BH-36, BH-19 and II-7 had been drilled and were successfully extracting oil from the basement at rates exceeding 1000 barrels per day (Akbar et al., 1993).

Indonesia

Sumatra – Beruk Northeast

The Beruk Northeast oil field of Central Sumatra (Fig. 1, Location 13.1) 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 have been reported as producing from Pre-Tertiary basement in Indonesia. Koning & Darmono (1984) state that oil production from Pre-Tertiary rocks is exceptional in Southeast Asia.

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 1,634 ft into the basement. An openhole test of the basement flowed at 1,680 bbl/day. A thin Telisa sand located approximately 100 ft above the basement was tested and flowed at 480 bbl/day.

By 1984, Beruk Northeast Well No. 1 had produced in excess of 1,100,000 barrels of oil, 640,000 barrels of water and 42 MMCF of associated gas. All production from the well has been obtained through the naturally occurring fracture system in the Pre-Tertiary basement metaquartzites (negligible matrix porosity exists from core studies). Subsequent development wells have been less productive, possibly due to the poor characteristics of the weathered argillite and granite reservoirs (Koning & Darmono, 1984).

In the Sei Teras field, South Sumatra, 15,000 barrels of oil and 1 BCF of gas has been produced since 1977 from two wells in basement limestone and quartzite. Approximately 21 million barrels of oil and 14 BCF of gas has been produced from Pre-Tertiary rocks in the Tanjung field, South Kalimantan (Koning & Darmono, 1984, after Tiwar & Taruno, 1979). The basement rocks in this field consist of porphyritic extrusives (lava) and volcanics as well as metamorphosed sandstones, shales and claystones. In both the Sei Teras and Tanjung fields, the basement is locally deeply weathered and fractured (Koning & Darmono, 1984).

Sumatra - Suban gas field

The Suban field gas discovery (Fig. 1, Location 13.2) occurred in 1999, when 3 wells were drilled by Gulf Indonesia into fractured pre-Tertiary granites. The Durian Mabok 2 Well collected gas at a rate of 26 million cubic feet per day, leaving a remaining 5 trillion cubic feet; equivalent of 500 million barrels of oil (Koning, 2003). As of 2005, interest holders of the Suban gas field included ConocoPhillips 54%, Talisman Energy Inc. 36% and PT Pertamina 10% (Oil and Gas Journal, 2007).

Sumatra - Tanjung field

Situated in the Barito basin, South Kalimantan (Fig. 1, Location 13.3), the Tanjung field is one of 7 productive fields within the Talang Akar sandstone formation (Hassan and Soebandrio, 1988). Oil is produced from pre-Tertiary rocks of metamorphosed sandstones, pyroclastics and volcanics, as well as clays and shales. Since its discovery in 1938, the Tanjung field has produced over 21 million barrels of oil (Koning, 2003). The discovery well, Tanjung labon – 1 was not drilled until 1982, when it was inserted by Asamera (South Sumatra) Ltd.

Sumatra - Gunung Kemala Field

The Gunung Kemala field (Fig. 1, Location 13.4) was discovered in 1938 when BPM drilled a folded structure in the South Palembang Sub-basin (see PEG.GB, March 2005). Hydrocarbons were contained within the sedimentary Talang Akar Formation, with production from this unit peaking in 1953 at 6610 bo/d.

In 2003 Pertamina drilled to 3500 m at a location around 3.5 km east of the previously producing Gunung Kemala field. The well's primary target was the pre-Tertiary basement, with drilling extending 600 m deeper than any previous wells. A 50 m interval of net pay was encountered in the basement, with a tested flow of 500 b/d of 50° API crude and 9 MMcfg/d of gas.

Gas was also discovered in the fractured basement of the Suban-Karan Ringin sub-block of South Sumatra. The well was drilled to a depth of 2697m, and targeted the Batu Raja Formation clastics, the Talang Akar Formation clastics and the fractured basement. 260 m of net gas pay was discovered, although no details of the proportion of gas existing in the basement are available.

Java - Jatibarang Field

The Jatibarang field is located in Northwest Java (Fig. 1, Location 13.5), approximately 200 km to the east of Jakarta. The field produces from eight shallow sedimentary zones, but major production zones are in naturally fractured volcanic formations (Soewono & Setyoko, 1987). The Jatibarang volcanic formation consists of lava flows (andesite/dacite/basalt), tuff and agglomerate/volcanic breccia. Oil was first discovered in the volcanic reservoir in November 1969 with the drilling of Well JTB-44, at a depth of 2,011 m (Sembodo, 1973) and has been developed since 1973. Initial production from 20 wells was approximately 40,000 bbls/day. Since then, many wells have been drilled, the production of which varies from 250 bbls/day to 3,000 bbls/day. The depth of wells varied between 2,000 m and 2,300 m, with hydrocarbons found between 1,900 m and 2,200 m (Sembodo, 1973). By April 1987, the cumulative recovery of the Jatibarang volcanic reservoir was 83.9 M bbls of net oil from 136 wells (Soewono & Setyoko, 1987).

Kalan et al (1994) present the results of a geological investigation of the Jatibarang Field performed in 1991/1992 by Elf Aquitaine Indonesia. The investigation was part of a feasibility study into the utilisation of horizontal drilling to improve production from the Jatibarang volcanics. The feasibility study concluded that the drilling of horizontal wells would provide increased recovery from the volcanic reservoir (actual production figures were not provided).

Fracturing in the volcanics is believed to be the most intensive in the tight folds of the Central and Western Blocks which accounts for the good production (previously discussed above).

Kalan et al (1994) proposed the use of a horizontal well in the Eastern Block of the Jatibarang Field where the volcanic reservoir has produced less than expected due to lower intensity of folding and fracturing.

Japan

Throughout Japan approximately 100 oil and gas fields had been discovered by 1991, producing 1755 kilolitres of oil per day and 5.5 million cubic metres of gas per day (Kikuchi et al., 1991). Many of Japans commercially productive reservoirs are deep seated volcaniclastic reservoirs (otherwise known as “green tuff”) found in the backarc basins of island arc settings (Fig. 1, Location 14). Volcanic reservoirs were first discovered in the Mitsuke field in 1958, important fields at present include: Katakai, Kumoide, Sekihara, Fujikawa, Kashiwazaki (operated by Teikoku Oil Co.,) and Yoshii (operated by Japan Petroleum Exploration Co., Ltd). Volcanic reservoirs are found in two forms in Japan: Pillow-brecciated and high porosity lava facies such as the Minami Nagaoka-Katakai gas fields in the Niigata region; or basalts, for example the Yurihara oil and gas field in the Akita area (see Map 16; Kikuchi et al., 1991).

In western Japan gas is produced from granite at a depth of about 4300 m. The best well is said to produce about 800 bbl of condensate per day (Russell and Warren Hunt, pers. comm., 2000) and an unspecified, but large, gas flow. In the Nagaoka and Niigata fields 5400 bopd oil and 14 bcf gas is produced from green tuff and volcanic formations (Kitchka, pers. comm., 2000).

Yufutsu

Yufutsu is a naturally fractured gas condensate reservoir, situated in Hokkaiddo, Japan (Fig. 1, Location 14.1). The reservoirs basement rocks consist of Cretaceous granite overlain by an alluvial/fluvial conglomerate of Eocene age. The field was discovered in 1989 and production commenced in 1996, since then 12 wells have been drilled, operated by Japan Petroleum Exploration Co., LTD. (Japex). Yufutsu covers an area of 4km x 8km, starting at a depth of 3800 metres (Ghorayeb et al., 2000).

Kenya

The Turkana Depression

Hydrocarbon exploration in the East African Rift Valley started during the 1970’s. Investigation into the Turkana Depression (Fig. 1, Location 15) by Amoco Kenya Petroleum Company and project PROBE revealed several N-S trending grabens with positive reservoir quality and source rock potential. Clastic volcanic rocks, thought to have originated from the Samburu Basalts Formation form part of the Auwerwer/Lomerimong reservoir section (Tiercelin, 2004).

Korea

Oil has been recovered from fractured granite.

Libya

Nafoora-Augila Field

PreCambrian granite is the host for one of the primary oil producing reservoirs in the Nafoora-Augila field (Fig. 1, Location 16) which is one of the main giant fields in the Sirte Basin (Belgasem, 1991). The Nafoora-Augila field is located in the northeast of Libya (southeast of the Amal field) and is at the top of the Rakb High. The Nafoora-Augila area was originally a concession of Oasis Oil Co., the owner of the Amal field. The company drilled two wells near the top of the High but then abandoned the concession as the wells proved to be dry. The concession was then obtained by Occidental Petroleum (UK) Ltd in 1966. The first successful well of Occidental was Dl, which had an initial production of 14,800 bbl/day. Production came from porous fossiliferous limestone perforated throughout the interval from 8,530 ft to 8,563 ft (2,600 m to 2,610 m). This reservoir rock was lower Rakb carbonate and was not a basement reservoir (P'An, 1982). The fractured and weathered basement (a late PreCambrian or early Paleozoic granite) is one of three producing horizons. Some of the oil wells started production from the basement reservoir only while others produced from the basement and/or sedimentary reservoirs. The basement rocks are gradations of granophyre, granophyric granite, granite and rhyolite (Belgasem et al, 1990). The basement reservoir contains a large accumulation of oil in fractures and weathered zones. However, due to the heterogeneous nature of the reservoir, the porosity distribution is not well known.

The first basement reservoir encountered was Well D2 drilled on possibly the highest point of the High. Well D2 produced at a rate of 7,627 bbl/day from devitrified rhyolite and highly weathered and fractured granophyre. Well D9 also produced from the basement only with an initial production of 1,500 bbl/day. The reservoir rock was weathered granite. Wells D3, D4, D5 and D6 were all step out tests that became oil wells, the most productive being D5 which produced at a stabilised rate of 14,140 bbl/day from two perforated intervals consisting of 59 ft (18 m) of carbonate rock and 39 ft (12 m) of granite. Well D6 produced from the basement reservoir with an initial flow of 1,200 bbl/day. D8 was an openhole basement completion, testing at 18,000 bbl/day from basement rocks and 36 ft (11 m) of perforated carbonate rocks (P'An, 1982).

Malta Offshore and Surrounding Regions

Basalt dikes, sills and flows, and marine and subaerial tuffs with variable ages ranging from Ordovician to Miocene occur in many wells, including those at the lsis oilfield and the Miskar gasfield (Fig. 1, Location 17).

Mesozoic volcanics with a thickness up to 100m are present in Libya. Additionally, Jurassic volcanics occur in the GeZa and Ragusa fields in Sicily (Schramm and Livraga, 1984). Several hundred meters of Lower and Middle Jurassic and thinner Upper Cretaceous volcanics were penetrated in wells of the Malta plateau. The Aqualta well encountered Upper Cretaceous weathered basalts, with abundant augite and olivine interbedded with red clay in three zones 60-80,m thick, probably subaerial flows (Bishop and Debono, 1996).

Mexico

Many thousands of oil seepages in Mexico are associated with various forms of ferromagnesian igneous intrusions. Most of them occur in the Tampico embayment (Fig. 1, Location 18). The Furbero oil field produces from a laccolith of gabbro and from the overlying shales. The Fubero oil field is located in the canton of Papantla, State of Vera Cruz. A thick sill of gabbro has been intruded into Tertiary shales. The sill is folded and follows bedding. Metamorphism of the overlying shales has occured. Well No. 27 at 30 ft into the gabbro came in with an initial production of 893 barrels and had produced over 200,000 barrels at a rate of 1000 barrels a day. Similarly, Well No. 28 initially produced oil from 157 ft into the intrusion (DeGolyer, 1932).

Namibia

Kudu Field

Located 130km offshore Namibia (Fig. 1, Location 19), the Kudu field holds 1.3 trillion cubic feet of gas reserves and an estimated 9 trillion cubic feet of possible reserves. Reservoir rocks include Lower Cretaceous Aeolian sandstone interbedded with Etendeka, volcanic rock (Rocha Mello et al., 2011) and are located at burial depths of 4400m. The estimated production life span of the field is 25 years making it a hugely important potential resource for Namibia. The drilling of the “wild cat” well Kudu 9A-1 block 2814A, led to the discovery of the Kuku field in 1974 by Chevron Texaco (Offshore technology, 2012). Since then the field has had many different owners; at present Tullow Oil is the operator with production being a joint venture between Namcor and one other (to be announced later this year, 2012).

Morocco

Landes et al (1960) state that there are at least eight oil fields in northwestern Morocco which produce from fractures in basement rocks (Fig. 1, Location 20). Lardenois et al (1956) refer to nine named fields in basement. In a couple of the fields, the reservoir rock consists of fractured, pink PreCambrian granite. In seven fields, the reservoir is a fractured chloritic quartzite and shale or slate of Palaeozoic age which is also basement rock. The basement rock accumulations are in upfaulted blocks that are marginal to a Mesozoic sedimentary basin. It is assumed that the fractures in the PreCambrian granite and in the Palaeozoic meta-sediments were filled with oil by lateral migration from the adjacent deeper Mesozoic sediments. Although the source of oil in the basement rock is probably the sediments in the adjacent Mesozoic basin, more oil has been produced from the basement rocks than from the sediments. By the end of 1957, the basement reservoirs had produced more than 3.75 million barrels of oil since discovery in 1947 (P'An, 1982)

New ZealandKora Oil Field

Located approximately 30 km north of New Plymouth and 30 km west of Awakino in the northern Taranki Basin (Fig. 1, Location 21), New Zealand, the Kora oil field is a 10 km to 12 km diameter, 1 km thick, subsurface, volcanic/plutonic complex (Russell, 1997; Bergman et al, 1992). The basement rocks range from Mesozoic granitoids, most abundant in the southern part of the basin, to Paleozoic forearc basin deposits.

Four wells were drilled at the Kora oil field. The Kora-1 wildcat exploration well was drilled between 1987 and 1988 to a depth of 3,450 m with the primary reservoir target in the

Eocene/Oligocene Tangaroa Sandstone. Residual hydrocarbons were encountered in the Tangaroa and produceable crude oil was found between 1,790 m and 1830 m in the Upper Miocene volcanic interval. A further 3 wells (Kora-2, -3 and –4) were drilled to constrain the hydrocarbon distribution at Kora and encountered only residual hydrocarbons in the upper most volcanic rock intervals in Kora-2 and -3 (Bergman et al, 1992).

Bergman et al (1992) state that volcanic reservoirs are viable targets for hydrocarbon reservoirs in the northern Taranaki Basin. Based on observations at Kora, the most prospective volcanic reservoirs are those complexes more deeply buried in the axis of the Taranaki Basin where the development of a suitable seal and the existence of thermally mature Pakawau source rocks are most likely.

Pannonian Basin, Europe

The Pannonian Basin, bordered by the mountain ranges of the Alps, Carpathians, and Dinarides, is an inter-mountain basin which occupies the northern part of Yugoslavia, the southeastern part of Austria, most of Hungary and a small part of western Romania and north-eastern Croatia (Fig. 1, Location 22). The Pannonian basin is developed on the Hercynian folded basement rocks.

Yugoslavia

Oil in the Yugoslavian part of the Pannonian Basin is mainly produced from Upper Tertiary reservoirs with a small part produced from fractures in basement rock (Filjak, 1969). The basement is composed mainly of schists, granites, and gneisses of PreCambrian, early Paleozoic, and late Paleozoic age. The main reservoir rocks of this field are the Miocene and the basement crystalline schists. In many places in the Yugoslavian part of the Pannonian Basin (especially the Banat depression), the Tertiary oil generating and oil bearing formations directly overlie metamorphic basement rocks and are the most favourable areas for finding basement reservoirs. The reason little oil has been produced in the past from the basement is that it has not been an exploration target (P'An, 1982).

Romania

The Banat depression of northeastern Yugoslavia extends northeastward into western Romania. In the Banat depression in Romania, some small basement oil and gas reservoirs have been found. Oil is stored in the weathered zone of crystalline basement rocks (P'An, 1982).

Hungary

Exploration for hydrocarbon reservoirs within fractured and weathered zones of crystalline basements is of great importance in Hungary (Kiss & Tóth, 1985). The majority of hydrocarbon reserves found in recent years have come from basement metamorphic reservoirs. These metamorphic hydrocarbon-bearing formations are generally characterised by complex lithology, low porosity and a heterogeneous distribution of pore sizes and fractures (Kiss & Tóth, 1985).

Except for a small part northeast of Budapest, almost all of Hungary is in the Pannonian Basin. On the southeastern part of the Great Hungarian plain, there are 4 oil fields (Battonya, Pusztafoldvar, Algyo, and Asotthalom) in which the major part of the oil is produced from

Tertiary rocks. Also in the Pannonian Basin, there are several examples of oil fields producing from fractured metamorphic rocks (P'An, 1982). An example of which is the Sarkadkeresztur field at the Hungarian/Romanian border (Matyas, 1996). There is also a reservoir hosted in gneiss at Szeghalom (Nelson, 2001).

Croatia

The Sava Depression, located on the southern margin of the Pannonian Basin, contains a few small oil and gas fields in basement (Baric et al., 2000). The basement lithologies consist of weathered Palaeozoic metamorphic and magmatic rocks: granites, quartz-mica schists, and gneisses. The present low production is associated with a mature stage of production and water flooding.

Other

The Zdanive-Krystalinkum field in the Bruno-Vistulicum area of the Czech Republic is said to produce minor hydrocarbon from PreCambrian basement (Nelson, 2001). The basement lithologies consist of Neoproterozoic igneous rocks overlain be Vandian greenschist-facies metamorphic rocks. The area lies within the Moravian zone of the Carpathian Foredeep, however there is a lack of published information on the area.

Russia

Petroleum ages in Russia extend over a 1000 million year time period with source rocks ranging from late pre-Cambrian to Miocene (Tull, 1997). Examples from the Pechora Platform, the Riphean reservoirs and the Tatarsan Arch demonstrate how source rocks of Permo-Carboniferious and Silurian-Lower Devonian are more petroliferous in Russia than the more recent Jurrasic-Quaternary source rocks.

Shaim Field

Located on the western side of the West Siberia basin on the Shaim uplift, the Shaim oil field is situated on the eastern slope of the Ural Mountains (Fig. 1, Location 23.1). Oil was first found in a basement fracture in 1959 (from Well 2). Well 7, on the west flank of the uplift, produced 25 bbl/day in April 1960 from basement fractures. Well 11, also on the west flank, produced 28 bbl/day from fractured basement rock. The basement rock consists of Paleozoic metamorphic and igneous rocks mainly composed of sericitic/siliceous schists intercalated with fine sandstone, fine conglomerate, marble, granite and gneiss (P'An, 1982). Well 6 on the east flank flowed at 2,380 bbl/day in June 1960 from the Vogulkin sandstone (Upper Jurassic).

Oil from the very productive wells in the Shaim oil field does not come from basement rock. The basement rock (producing from wells 7 and 11) yields only several tons of oil per day (about 25 bbl/day).

Kola Peninsula

Hydrocarbons have been reported in the Nepheline-Syenite dykes of the Kola Alkaline Province. These dykes were intruded into carboniferous schist, which is the likely source rock for the methane-dominated inclusion.

The Tatarsan Arch

The South Tatarsan Arch is situated in the eastern third of the East European Craton in the Volga-Ural region of Russia (Fig. 1, Location 23.2). This area hosts the large oil fields of Romashkino and Tatarstan which are currently exploiting oil pools found within the Palaeozoic (Devonian and Carboniferous) sedimentary strata overlying pre-Cambrian basement rocks (Plotnikova, 2006). As part of the Deep Drilling Program, wells Novoelkhovo-20009, (bottom hole depth 5881m) and Minnibaevo-20000 (bottom hole depth 5099m) were sunk into the South Arch crystalline basement in order to assess the potential reservoir quality of the rocks (Plotnikova, 2009).

Fractured and fractured-brecciated reservoirs formed from geodynamic deformation since the early Late Proterozoic were found between 5 and 7 km depth. These zones were created by two phases of deformation. A compressional phase, creating catalastic and mylonitised zones, followed by a decompressional phase allowed the fractures to open up and permit the circulation of hydrothermal fluids. Friable rocks which are unable to be cemented because of continued vertical geodynamic movements are common in these crystalline basement rocks and provide excellent potential hydrocarbon reservoirs (Sitdikova and Izotov, 2006). The sedimentary rocks of the Tatarsan Arch have proved to be highly productive with production reaching 2.7 B t (2006), however the crystalline basement rocks of the area are yet to be exploited but are deemed equally promising.

Thailand

Sirikit Oil Field

The Sirikit field lies in the Phitsanulok Basin (Fig. 1, Location 24). It's one of a series of Tertiary rift-related structures in central and northern Thailand. The tectonic history of the area is complex: the original, extensional, half graben was deformed during deposition of the upper reservoir sequence by left-lateral strike-slip faulting (Knox & Wakefield, 1983). During the Mesozoic, most of central and western Thailand was affected by large, left lateral wrench faults and compressional tectonics. More recently, most of the Thai region was rotated clockwise developing large extensional (growth) faults and minor divergent wrench movement. These extensional tectonics lasted throughout the Tertiary and caused the formation of the many relatively small sedimentary basins in central and southwest Thailand. The pre-Tertiary structures in the Sirikit field consist of block faulted and tilted basement rock in an upthrown position. Basement in this field consists mainly of metamorphic clastic red beds

The Field has produced about 1.17 M bls of oil from basement so far (November 1998). About 14 wells had been drilled into the pre-Tertiary basement (to 1995) many of which had oil shows and two have been placed under production. Using the seismic data of the area, a model was created of the Central Sirikit High. This part of the field has the only producing well. 3 wells were drilled in this area, one has been in production since 1991, one was shut in after it rapidly watered out and one only produced water. This proved the assumption that hydrocarbon distribution was directly related to the fracture pattern.

A fracture simulation model using software packages (Frame and Poly3D) has come up with a prediction of the fracture pattern of this field (Smitt, 1998).

United Kingdom

Clair Field and West of Shetland

Discovered in 1977, Clair oil field lies 75 km west of the Shetlands, offshore UK (UKCS), in waters of up to 150 m in Block 206 (Fig. 1, Location 25). Clair comprises an elongate NE-SW trending ridge of Lewisian basement (the Rona or Clair Ridge) and an associated roll-over (or terrace) containing a thick sequence of mainly Devonian continental red beds with lacustrine and fluvial deposits (Coney et al, 1993). The first well (206/8-1A in 1977) 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 further wells drilled between 1977 and 1985 indicated OIP of 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 later 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 (Coney et al, 1993). 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 basement which were believed to act as preferential drainage paths for the hydrocarbons situated in the overlying and adjacent red beds source rock (Falt et al, 1992).

In late 2001, BP and its partners decided to go ahead with development and since around 2005 there has been ongoing production, mainly with development wells in the Devonian although it is likely that connectivity to the basement is present. A recent summary of the field geology is in Barr et al (2007), though dealing primarily with the Devonian.

As of 2011 the Clair field extends over an area of 54,300 acres and is primarily operated by BP (28.6%) with co-venturers Shell (28%), ConocoPhillips (24%) and Chevron (19.4%). Although exploration in this area has been ongoing since the 1970’s, recent government permission (2011) has been granted for production to start in 2016 on Clair Ridge (ConocoPhillips, 2012). The total investment required for this venture including 40 years production has been calculated at £4.5 billion, with estimated reserves of 640 million barrels and peak production at 120,000 barrels of oil per day. BP Exploration will be the operating company for Clair Ridge with 27.6215%, along with co-venturers ConocoPhilips (U.K) Limited (24.0025%), Chevron North Sea Limited (19.4225%), Enterprise Oil Limited (Shell) (18.6831%), Shell Clair UK Limited (Shell) (9.2900%) and Britoil plc (BP) (0.98%) (BP, 2011).

In 2009 Hurricane Exploration drilled the Lancaster well in Block 205/ 21a West of Shetlands, announcing it as a light oil discovery in fractured basement which also sits on the Rona Ridge. A contingent resource range of 62-456 million barrels of oil equivalent (MMboe) are estimated (Trice, 2014). In 2010 the well Whirlwind, located at 12km north of Lancaster along the Rona Ridge, was drilled. It has similar reservoir properties to Lancaster and might be associated with light oil or gas condensate.

Other

The literature concerning hydrocarbons in the UK contains occasional references to trace hydrocarbons found in the Cornubian granites of SW England. These Hercynian granites are intruded into rocks of Devonian and Carboniferous age and minor traces of a 'mineral' pitch are found on some fracture surfaces within the granite. No significant accumulations of hydrocarbon have been found in any of the extensive mining activities (as deep as 1000 m) in the region nor in boreholes as deep as 2800 m near the centre of the Carnmenellis granite. All the mines in the region are now closed (the last one, South Crofty, was shut down in March 1998) and the few samples that are accessible are at the Camborne School of Mines.

Massonat et al (1993) have described the geological and reservoir approaches to optimising the oil recovery from a field in the United Kingdom (the authors did not name the field, then owned by Elf). The reservoir consists of several hundred metres of sandstones, conglomerates, siltstones, and shales with poor reservoir characteristics. The well productivity is generally low. However, a vertical well has shown higher productivity coming from both the sandstones and the underlying fractured granite basement. The authors expect that a horizontal well within the basement and intersecting the major fracture orientations could possibly produce hydrocarbons from the overlying and adjacent accumulation with good productivity.

United States, California

Production has ceased in most fields, however Wilmington field (see below) in South California is still active (Fig. 1, Location 26). There are approximately 300 million barrels remaining from the original estimated reserves of 3 billion barrels, making it the 3rd largest oil field in the whole of the USA.

Landes et al (1960) and Hubbert & Willis (1955) state that oil has been produced from fractured basement metamorphic rocks in five fields of the Pacific Coast province, California. These are Edison and Mountain View in the San Joaquin Valley, and Wilmington, El Segundo, and Playa del Rey in the Los Angeles Basin. Few wells produce oil from the basement rocks alone. Most are multiple completions in the basement schist and the overlying schist conglomerate.

McNaughton (1953) states that the first commercial oil production from basement metamorphic rocks in California was probably in Placerita Canyon near Newhall. According to Brown & Kew (1932, after McNaughton, 1953), small quantities of light-gravity oil were produced from 5 wells drilled between 1899 and 1901. The basement complex in the vicinity of the wells consisted mainly of schists.

The next discovery of oil in the basement complex was made in the Playa del Rey field at Venice in 1929. Available descriptions of the Playa del Rey field have been limited. Production was from a fractured schist reservoir with relatively low rates, approximately 400 bbl/day (Eggleston, 1948).

An important basement discovery was made in El Segundo field in 1937. It was accidental in that the objective of the test well was the schist conglomerate capping the basement. Examination of cores revealed that the well stopped in fractured schist containing oil. The well was highly productive and the discovery was followed by intensive development of the basement reservoir in the field.

Another basement pool was discovered in 1942 in the Santa Maria Valley field. The discovery was also accidental, a fortunate consequence of ignorance concerning the exact depth of the basement in the central part of the field (McNaughton, 1953). Similar exploration in the Edison field southeast of Bakersfield disclosed oil in fractured metamorphic rocks in 1945. Intensive development of the basement reservoir followed this discovery with 103 wells being drilled into the basement and all but 6 were completed as commercial producers. Oil production from these wells in the first 18 months after discovery amounted to 4,500,000 barrels. In 1947, the estimated reserve in the basement pool was 25 million barrels (McNaughton, 1953).

Another basement oil reservoir that was discovered accidentally was in the Wilmington field in 1945. Apart from the Santa Maria field (in which the oil is produced from sandstone), oil from basement rocks was produced from fractures in schists (Aguilera & van Poollen, 1979). Most of the oil-producing schists are in a relatively high position. They have usually undergone weathering and erosion that has increased porosity.

Edison Field

Located in the southeastern San Joaquin Valley 18 km east of Bakersfield, Kern County, California, the Edison Field was discovered in 1931. From 1931 to 1945 production from the field was exclusively from two separate sands in the Tertiary sediments (Hubbert & Willis 1955). In June 1945, one well was drilled through the entire sedimentary section, penetrating 100 ft (30 m) into the schist and encountered the basement reservoir complex. Slight traces of oil were found in the sediments but more promising showings were observed in the fractures of cores from the basement. A test was made and the well was completed in the metamorphic rocks of the basement complex with the well initially flowing oil at 528 bbl/day.

Rapid development of the basement followed. Initial daily production in other wells varied greatly. A few wells produced more than 2,000 bbl/day, most produced about 1,000 bbl/day. The height of the oil column in the schist gradually increased from the southwest to the northeast, the maximum being 1,000 ft (305 m). Wells with daily production of more than 1,000 barrels of oil were concentrated in the north-central part of the Edison field. By the end of 1955, the cumulative oil production from the fractured schist was more than 20 million barrels (Eggleston, 1948; P'An, 1992). The estimated ultimate production was around 50 million barrels (Hubbert & Willis 1955).

El Segundo Field

El Segundo oil field, which was discovered in 1935, is located along the coast of Santa Monica Bay, southwest of Los Angeles County. The field is divided into two areas by a northwest trending zone of faulting. The eastern part produces from a basal conglomerate made up of schist pebbles with the western part producing directly from fractures in the schist itself.

The first well was drilled to the east of the faulted fracture zone. The daily production of oil from the basal conglomerate was about 600 barrels. The western part of the field began producing in 1937 from the fractured schist reservoir. The production rate was 4,563 bbl/day at a depth of 7,253 ft (2,210 m). This discovery was accidental as the well was exploring for the schist conglomerate. 66 wells were drilled in the development of the El Segundo field with a wide variation in production from adjacent wells (Eggleston, 1948; Landes et al, 1960; P'An, 1982).

Wilmington Field

The Wilmington oil field is located in the city of Wilmington and includes the harbour area of Long Beach (the Los Angeles basin). The discovery well was completed in January 1932 with oil production from the Union Pacific E-47 well during May 1945. The schist reservoir was encountered at a depth of 5,787 ft (1,764 m). Production from well E-47 was initially 387 bbl/day. However, in 1946 rates of 1,200 bbl/day to 2,000 bbl/day were established from wells producing from the schist reservoir. Wilmington has produced more than 22 million barrels of oil from the basement reservoir (Cabeen & Sullwood, 1946; Landes et al, 1960; P'An, 1982).

Eight productive zones are present in the Wilmington field. Of these, seven are in Pliocene and Miocene sediments with the eighth in the fractured basement schist, known as 237 Basement (Robertson et al, 1987). The productive zone in the schist does not extend below 6,200 ft (1,890 m). The Wilmington field is the third largest oil field in the USA in terms of cumulative production, at 2.8 billion barrels (Gibson, 1997).

United States, Central Kansas Uplift

There are more than 10 small basement oil fields producing from some 50 wells which lie on the Central Kansas uplift (Hubbert & Willis, 1955; P'An, 1982; Aguilera, 1995ac; Fig. 1, Location 27). Oil is stored in the fissures of the PreCambrian quartzite and granite which constitute the buried hills (or buried topography) of the uplift (Landes et al, 1960). By the end of 1952, the cumulative production from the 10 oil fields was more than 1.5 million barrels (Hubbert & Willis, 1955). The PreCambrian basement rocks consist mainly of quartzite, schist, gneiss and granite which are overlain by about 500 ft of Cambro-Ordovician sediments.

Orth Field, Central Kansas (Rice County)

Discovered in 1933, the Orth field lies in northwestern Rice County. The oil was produced from fractured PreCambrian quartzite on the summits of the buried hills. Each well produced an average of 120 bbl/day of oil with a maximum production of 939 bbl/day. About 1,243,000 barrels of oil had been produced from quartzite in 16 wells in the Orth field by the beginning of January 1952 (Walters, 1953; P'An, 1982).

Ringwald Field, Central Kansas (Rice County)

The Ringwald field, which lies approximately 2.4 km southwest of the Orth field, was discovered in 1949. The structure and stratigraphy are similar to the Orth field. There is a PreCambrian quartzite hill with Lansing-Kansas City limestones abutting and draped over it in an anticlinal fold. The field contains 6 wells which are producing (or have produced) from fractured PreCambrian quartzite. Daily production per well is low. After treatment by hydrofracturing, the daily production reached 190 bbl/day.

The Silica field, which lies south of Ringwald, is another low producing reservoir in Rice County. An average of 100 bbl/day were produced from irregularly distributed fractures in the PreCambrian quartzite at a depth of 3,270 ft to 3,284 ft (997-1,001 m) (Walters, 1953; P'An, 1982).

Kraft-Prusa Field, Central Kansas (Barton County)

The Kraft-Prusa field, discovered in 1937, lies northwest of the Orth field and extends across parts of three townships in the northeastern corner of Barton County. The field, which is 10 miles long and 3½ miles wide, has a producing area of 15,000 acres (Walters, 1946; Walters & Price, 1948). The Kraft-Prusa field, one of the major oil fields of the Central Kansas uplift, is typical of that area in its stratigraphic and structural relationships but is exceptional because of its high ratio of dry holes to producing wells (Walters & Price, 1948; Landes, 1959b). The hydrocarbons occur in the Pennsylvanian Lansing-Kansas City limestone, 'unconformity sand', Arbuckle dolomite and fractured PreCambrian quartzite. There is no doubt that the oil in the PreCambrian quartzite belongs to a basement reservoir. The fractures in the quartzite from which oil is produced probably originated as a system of joints resulting from prolonged subariel weathering. It is estimated that less than 5% of the wells drilled into quartzite have encountered fracture porosity. Characteristic of these reservoirs (like other basement reservoirs) is the irregular distribution of porosity and permeability. It is believed that the oil migrated from the overlying Pennsylvanian rocks into fractures in the quartzite.

In 1945, the PreCambrian rocks at Kraft-Prusa were known to produce oil from only one well, Oeser 'B' No.2 well. Wells drilled into the PreCambrian quartzite reached depths ranging from 3,180 ft (969 m), producing 65 bbl/day, to 3,337 ft (1,017 m) which produced 108 bbl/day.

By the middle of 1952, about 11 PreCambrian basement reservoirs had been discovered in the Central Kansas uplift. Most of the wells were drilled initially to prospect shallow oil reservoirs but often oil was found in the basement rocks (Walters, 1953).

The Beaver, Bloomer, Trapp, Eveleigh, Silica and Heinz oil fields are all similar to the Kraft-Prusa field in that there is some production from fractured PreCambrian quartzite occurring in the buried hills in Barton County (Aguilera & van Poollen, 1979). Production from the fields varies from 55 bbl/day, at a depth of 3,300 ft (1,006 m) to 434 bbl/day at a depth of 3,332 ft (1,016 m).

The Hall-Gurney and Gorham fields of Russell County (Central Kansas) are similar to each other, each has several wells which produced from a fresh, pink, biotite-granite (355 bbl/day at 3,244 ft and 306 bbl/day at 3,330 ft respectively). Drilling indicated that there was an erratic distribution of oil in the granite. One well encountered significant porosity and oil 70 ft below the top of the granite while many others failed to find any trace of hydrocarbons (Walters, 1953; P'An, 1982).

United States, Arizona

The Dineh-Bi-Keyah oil field, Apache County, represents a stratigraphic accumulation of hydrocarbon at the northwestern end of the Toadlena anticline (Fig. 1, Location 28), discovered in the early 1960’s. The field produces from a sub-aerially fractured Tertiary (Oligocene) syenite sill, with the hydrocarbon sourcing from the surrounding bioclastic limestones (McKenny, J.W. & Masters, J.A., 1968). Production peaked in 1967 at 3300 bo/d, and in 2006 had a cumulative production of 18.3 million barrels of oil and 4.7 billion cubic feet of gas. This reservoir has a potential CO_2 sequestration capacity of 9 million metric tons (McPherson, 2006).

United States, Nevada

The Eagle Springs oil field (Fig. 1, Location 29), discovered by Shell in the 1950's, produced fractured volcanics of Oligocene age. To date, 1.8 million barrels of oil have been produced from these volcanics with an OOIP estimated at 40 million barrels (Snow, 2001). Oil is being produced from the Miocene aged Humbolt Basalt at the Blackburn oil field (Nelson, 2001). The Trap Spring oil field, in Sheep Pass (Great Basin), produced 11 to 15 million barrels from fractured volcanic rocks (Schutter, 2003).

United States, Oklahoma

The Ames impact structure in Oklahoma (Fig. 1, Location 30) produces from fractured granite in the central uplift (Rajmon 2005 Pers.Comm and Johnson and Campbell 1997).

United States, Pennsylvania

Hydrocarbons are produced from the fractured Silurian Tuscarora Formation quartzites. The accumulation is present in a folded structural trap at the Devil's Elbow field (Nelson, 2001; Fig. 1, Location 24).

United States, Utah

Tertiary basalt hosts hydrocarbons at the West Rozel field, Utah. Connectivity within the crystalline reservoir is due to the presence of faulting and columnar joint sets (Nelson, 2001).

United States, Coastal Plains, Texas

The Thrall oil field in Williamson County (Fig. 1, Location 32), Texas was discovered in 1915. Oil is produced in commercial quantities from pyroclastic rocks and serpentine within Cretaceous formations. Since the first field, 7 additional fields have been discovered through the Gulf Coastal Plain of Texas and these include Chapman, Hillbig Pool, Yoast, Lytton Springs, Dale, Buchanan, Lytton- Springs townsite and Schimmel-Batts. The rock containing the oil was originally of basaltic character but has been altered to chlorite or serpentine. It is probably extrusive in origin but may be in small part intrusive. Production from the combined fields was over 13 million barrels of oil by 1931 (Shellard, 1931).

Oil is currently being produced at Fort Worth, Texas (Nelson, 2001), with the Burnett Oil Company tapping a granite wash reservoir (Akota Formation). Production testing revealed a flow of 1400bbl of oil from an untreated interval between 2008 and 2011 m.

Venezuela

Reports from Le Vela (June, 1999) say that Phillips have tested both the Cauderalito Limestone and the fractured basement in well LVC-29 at a depth of 2826 m. Three Drill Stem Tests were completed between 2363-2444 m producing a combined flow of 15.5 MM cf/day of gas and 83 b/day condensate. A second sidetrack was underway. No details of the flows from the basement were easily available.

<u>La Paz Oil Field</u>

Discovered in 1922, the La Paz oil field lies approximately 40 km west of Maracaibo City (Fig. 1, Location 33). Oil was first produced from Guasare (Paleocene) sandstone, limestone and Eocene sandstone. Initial production averaged about 500 bbl/day. As a result of deeper drilling, higher production was obtained from Cretaceous limestone (Cogollo Group) from which initial production averaged 5,000 bbl/day (Aguilera & van Poollen, 1979). The reservoir rock was more than 1,650 ft (500 m) thick, the oil mainly stored in secondary voids, cracks, and fissures (Smith, 1956; Landes et al, 1960).

Since oil was stored in Cretaceous limestone fissures, it was felt that if the underlying strongly folded and faulted basement rocks were similarly fissured, they might also contain oil. The granitic basement unit is part of a large inversion structure that was partially uplifted during the Late Eocene (Nelson et al., 2000). The fractures within the basement unit are associated Miocene-Pliocene inversion, with a secondary microporosity related to Eocene upift. The first two wells purposely drilled into the basement were unsuccessful. The third well (Well P-86) was completed in April 1953 to a total depth of 8,889 ft (2,709 m) which was 1,089 ft (332 m) below the top of the basement complex. Since then, at least 12 wells have been drilled into the basement with an average penetration of 1,650 ft (503 m), the maximum being 3,087 ft (941m). Average initial production, purely from the basement, was 3,600 bbl/day but one well had an initial yield of 11,500 bbl/day (Landes et al, 1960).

La Paz produces from granite in the cores of anticlines and the total reserve has been calculated at 905 MM bbls (P'An, 1982).

Mara Oil Field

Considered as the 'champion' of basement producers (Landes, 1959), the Mara field lies northeast of the La Paz field (Fig. 1, Location 33). The complex basement is composed of metamorphic and igneous rocks. The metamorphic rocks are in the main slightly metamorphosed sediments with hydrocarbon storage exclusively in fractures (Landes, 1959). Their age is uncertain, possibly Silurian-Devonian. The igneous rocks are granitic and are believed to be Hercynian in age. Cores of the basement show intense vertical fracturing and core recovery is often poor. By 1956, the Mara field was producing from 29 wells in the basement reservoir at an average depth of 1,190 ft (363 m). Initial production was about 2,700 bbl/day but one well produced 17,000 bbl/day from the basement (Landes et al, 1960).

Although the oil in both the Cretaceous and basement is practically identical, bottomhole pressure measurements in the Mara field indicate separate reservoirs. It is possible that the well cemented basal sandstone or a 90 ft thick (27 m) marl and shale horizon, which occurs about 76 m above the basement, may have acted as a partial seal.

In July 1955, the Mara and La Paz basement reservoirs together were producing 77,000 bbl/day. The cumulative production for both the La Paz and Mara field by the end of July 1955 was over 31 million barrels.

La Vela Offshore Field

The La Vela Offshore Field is on the Northeast coast of the Paraguana Peninsula in Falcon State. A total of 28 wells were drilled between 1972 and 1994, proving reservoirs in fractured basement and overlying Tertiaries at depths up to 10,000 ft.

Vietnam

Cuu Long Basin

Exploration initiated in the 1970's resulted in the discovery of several oil and gas fields (Dmitriyevskiy et al, 1993; Areshev et al, 1992) including White Tiger (Bach Ho), Dragon

(Rong) and Rang Dong fields (Fig. 1, Location. 34). White Tiger has been a major producer and is the subject of a recent paper by Cuong and Warren (2009) which covers the geology and production characteristics. As of 2005 the basin represented 95% of total hydrocarbon production in Vietnam, with 85% being produced from the fractured basement.

Vietsovpetro started producing oil from offshore S Vietnam 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 cores recovered from 26 wells (mostly from White Tiger). By the mid-1990's, the company was producing 180,000 bbl/day with 8,000 bbl/day from Dragon field basement (George, 1995).

Recent production rates for White Tiger are listed at 202,000 bbl/d in 2004 (PESGB, Jan. 2005) but declining to 140,000 bbl/d in 2009 (Cuong and Warren 2009), with a 25,000 bbl/d decline between 2007 and 2008. The volume in place has been calculated at 1.59 billion barrels of oil, with around 95% of this amount contained within the fractured basement.

In 1988, while testing in White Tiger (Well MSP-1-1), an oil flow of 1,500 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 (Areshev et al, 1992).

Granites constitute the basement in the central part of White Tiger and predominate in the basement of the Dragon field. They also occur 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 5,000 m, of which 4,000 m is fractured basement granite with a pay zone interval of 1,000 m (Russell, 1997).

Well 17-VT-1XR (Vau Thieu), located in Block 17 offshore Vietnam (southwest of the White Tiger and Dragon oil fields), was originally drilled as an exploration well. The well was the fourth exploration well to be drilled by Enterprise Oil in Block 17 (Anon, 1996a). The first 3 wells proved to be disappointing, especially when considering their proximity to the White Tiger and Dragon oilfields (Anon, 1996a).

Well 17-VT-1XR was drilled to a TD of 2,389 m and was tested at 750 bbl/day of oil. The well penetrated 430 m into the basement granite in the Cuu Long Basin (Enterprise Oil, 1996; Anon, 1996b) and was abandoned as an oil discovery (Tang, 1996).

SOCO International achieved success in the SE Vietnam continental shelf, with Blocks 9-2 and 16-1 proving to be extremely fruitful. The Ca Ngu Vang discovery well was drilled in 2002 and encountered an oil column over 1000 m in height, mainly within a granitic basement unit between 3696 m and 4567 m in depth. Testing in the discovery well recorded a flow of 3100 b/d of oil and 7.9 MMcf/d of gas. The subsequent appraisal well (spudded on 29th January 2005) was drilled to 6000 m, with an 80° deviation to intersect the various fracture orientations that exist in the basement (SOCO press-release, 23/07/03). A barefoot production test carried out in this well had disappointing results, with the testing results of the discovery well unable to be matched. No natural flow was recorded.

The Voi Trang vertical exploration well in Block 16-1 flowed 3500 b/d of 42° API crude from the Oligocene and basement between 2086 and 2490 m. 250 b/d were produced from the basement (SOCO press-release, 24/03/03)

Blocks 9-2 and 16-1 have provided several successful basement oil plays. Discoveries in the Cuu Long basin include the Su Tu Den (Black Lion) field, with an estimated 200 MBBl of oil in a granite reservoir, currently (2005) producing 10,000 bbl/d of 36° API crude from seven production wells. The Su Tu Vang (Golden Lion) field also lies within the Cuu Long Basin, with an estimated reserve of 100-400 MBBl of oil within the basement and Lower Miocene sandstones (ConocoPhillips press-release, 18/11/03. In-depth analyses have discovered the oil within the basement and the oil within the overlying sandstones to be virtually identical. Migration models suggest that hydrocarbons migrate updip through faults into basement horst blocks (Nielsen, L. & Abatzis, I., 2003).

Further major fields within the Cuu Long Basin include: the Sunrise field, NE of White Tiger, also composed of fractured basement reservoirs, producing 60,000 bopd; The Black Lion Field, a mixture of fractured basement reservoirs and Oligocene/Miocene sandstones with approximate reserves estimated at 1730 million barrels of oil and 85 million cubic metres of gas and the Ruby Field, dominantly Miocene sandstones and Oligocene volcanics, producing 20,000 bpod. Production in the Black Lion field is carried out by PetroVietnam Exploration Production (50%), ConocoPhillips (23.25%), SK Corporation (9%) and Geopetrol (3.5%).

Nam Con Son Basin

The Nam Con Son Basin, which lays directly SSE of the Cuu Long Basin and contains similar plays, was estimated to contain 4.5 Bboe, equivalent to 20% of the country's total hydrocarbon reserves. It includes the Dai Hung Field (Big Bear), discovered in 1988 in Block 5-1A and which contains significant accumulations of oil and gas in a fractured granitic basement (up to 100 million tonnes of oil), sourced from lacustrine shales. It was producing around 25,000 bbl/d in the mid-1990's but had declined to 5400 bbl/d by the early 2000's (Cuong and Warren 2009). In the mid-90's it had been forecast to produce 250,000 bbl/d.

Other producing fields in the Nam Con Son Basin include the Lan Tay and Lan Do gas fields. Combined estimated output from these fields is 95 billion cf/year, with an expected life span of 20 years. The Hai Thach and Moc Tinh Fields also produce gas from the Cainozoic granite basement (Petrovietnam press-release, 04/10/02)

Song Hong Basin

A largely unexplored basin with only a few wells, situated N-E of the Phu Khanh Basin. Hydrocarbon reserves here are being exploited by Gazprom. The basin mainly produces type III kerogen and is widely regarded as gas prone.

Gazprom are exploiting hydrocarbon reserves in the north of the Vietnamese continental shelf. The Song Hong Basin formed in the Late Cretaceous to Early Tertiary is thought to contain 10% of the country's total hydrocarbon resources, with an estimated 2.5 Bboe in place. The area represents a north-west/south-east trending rift zone, with dominant hydrocarbon reservoirs likely to be buried basement hills and overlying sandstone formations.

20 Tcf of gas is thought to be contained within Block 112, with fields including Bach Chi (White Lion), Zebra, Sky Lark, Seagull, Hangbird and White Elephant (Nielsen & Abatzis, 2003).

Phu Khanh Basin

The Phu Khanh Basin is the least explored Vietnamese hydrocarbon resource or potential resource. It is situated offshore southern Central Vietnam in the narrowest part of the South China Sea, south of the Song Hong basin and north of Cuu Long. There is currently no production being carried out within the Phu Khanh Basin. However, evidence from oil seeps in the nearby Dam Thi Nai lagoon (separated by a 700m wide fractured granite horst) indicates an active petroleum system within the Phu Khanh Basin. Fyhn et al., 2009 suggest that this basin could be a promising hydrocarbon play with both mature and post mature potential source rocks within the area, from Miocene carbonates and sand deposited facies in the east and fractured basement highs in the west.

Yemen

Yemen has attracted much interest from the oil community in recent years, with hydrocarbons being discovered in both conventional and unconventional reservoirs (Fig. 1, num. 35). The geology of Yemen is closely linked to the break-up of Gondwana during the Mesozoic (Harris *et al*., 2003). Major rift basins, orientated north-northwest, south-southeast, developed during the Late Jurassic and Early Cretaceous. Thick accumulations of sediments were deposited in the basin areas, overlying the igneous and high-grade metamorphic basement.

Exploratory drilling in Yemen began in 1961, with the first commercial oil discovery being made in 1984 by Hunt Oil Co. in the Marib Al Jawf Basin, western Yemen (Harris *et al*., 2003). Production is mainly from the Cretaceous Quishn Sandstone unit, however another dominant play is focussed on the fractured basement.

Kharir field

SOCO have been developing Kharir Field in the East Shabwa Block 10/10A, with four deviated appraisal wells drilled since August 2004. The primary drilling target was the fractured basement, with secondary targets lying in the overlying sedimentary sequence. As of 2005 production from the East Shabwa Development Area was 27,800 bo/d, with some 30% of this figure being produced from the basement (SOCO International press-release, 18/02/05 and 07/04/05).

Well KHA-401 was spudded on the 17th August, 2004 and drilled to a total depth of 3873 m. Oil shows were encountered in two thin Cretaceous zones, and in 340 m of basement. Testing revealed an uneconomic flow, and the well was plugged and abandoned in October 2004 (SOCO press-releases, 18/02/05 and 07/04/05).

Well KHA-402 was spudded on the 17th October 2004 and drilled to a total depth of 3441 m. Following casing and long-term testing, flow stabilised at a rate of 710 bbl/d (SOCO press-releases, 18/02/05 and 07/04/05).

Well KHA-403 was spudded on the 6th December 2004, with the purpose of delineating the basement reservoir and evaluating possible reservoir development in the western extremes of the structure (previously undrilled). The well was drilled to a total depth of 3383 m, and produced a flow of 6500 bbl/d. The well is now connected to Kharir's main production facility (SOCO press-releases, 18/02/05 and 07/04/05)

Well KHA-404 was spudded on the 1st February 2005, and drilled to a total depth of 3539 m. Production tests carried out on the basement flowed 5500 bbl/d, with the well being subsequently joined to Kharir's main production facility.

DNO have also had significant successes in Block 43. The Nabrajah wells have targeted both the Qishn Formation sandstone and the Kohlan Formation dolomite; however significant hydrocarbons have also been discovered in the basement. Production tests carried out in the basement lithology flowed 5800 b/d of 38.6 API crude and 4162 Mscf/g of gas using an ESP. Following a pressure build-up test, flow was 2812 b/d of 41.9 API crude and 3054 Mscf/d of gas with no pumping. Oil is also being produced from the basement in the neighbouring Blocks 10 and 14 operated by Total and Nexen respectively (DNO press-release, 13/04/05)

Many other basement exploration and development projects are underway as of 2012, including OMV in Block S2 (de Kok et al 2009), Oil Search in Blocks 3 and 7 and Janah Hunt in Block 5.

Habban Field

Situated in west-central Yemen, the Habban Field lies in the Arabian-Nubian Shield (670-540Ma). Fracturing of the high grade gneiss or low-grade island arc basement rocks, allows hydrocarbons to laterally migrate, creating a potential hydrocarbon reservoir in the crystalline basement (Veeningen et al., 2012).

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