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Global Overview of Fractured Basement Plays

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Abstract

The 'fractured basement play' remains to be one of the most 'extensive underexplored' targets for hydrocarbon exploration. Naturally fractured basement reservoirs are a global phenomenon and are often serendipitous discoveries. Despite this, these plays have proven their significance to the global geoscience community with the discovery of major hydrocarbon basement accumulations in Vietnam, China, the U.K. and Yemen. Commercial production of hydrocarbons from fractured basement is proven in 25 countries but little is known about the global variability of producing fractured basement fields. This paper synthesizes attributes of this play type semi-quantitively based on the systematic analysis of relevant data in the IHS Markit (IHSM) International E&P Database and the IHSM US Enerdeq Browser. The analysis shows that hydrocarbon in basement reservoir discoveries exist in just 29 countries. Globally over 640 fields have been discovered, most (260 fields) are in the Far East with China hosting the majority (>160 fields). Current volumetric estimates suggest that 0.001% or 15,000 million (MM) barrels of oil equivalent (boe) of the total global estimated ultimate recovery (EUR) (approx. 1,177,500 billion boe) are stored in fractured basement. The bulk of hydrocarbon recoverable resources are currently located in Southeast Asia (approx. 4,500 MMboe), the majority of which are situated in Vietnam.

Components of the basement petroleum system resemble conventional plays. Source and top seal are typically the same lithology, mostly organic rich shale, claystone, or marl, onlapping and draping the reservoir. Because there is no source underneath the reservoir, lateral or downward charge is invoked. Structures are commonly fault blocks or buried hills. The reservoir is mostly provided by brittle magmatic intrusive rocks and the most commonly encountered lithology is granite, with porosity and permeability associated with fractures. These can be solution enlarged. Other common reservoir types include effusive magmatic (basalt, tuff) or metamorphic rocks such as gneiss, quartzite or marble; less common are pelitic metamorphic rocks. More than three thousand wells have targeted the basement so far. Most are drilled in Russia and China. Reported well rates vary between 10 bo/d to 30,000 bo/d and this range most likely reflects fracture intensity and connectivity. The synthesis presented here suggests that the play has significant potential and therefore warrants dedicated exploration and revisiting producing assets to unlock its full capacity.

Keywords: *Fractured basement; Global review; Review per country.*

1. Introduction

Fractured basement plays are defined here as elevated structures composed of rocks with little or no matrix porosity inspired by the definition of North [1] for buried hills. Porosity and permeability is provided by fractures only. These might be enlarged by surface or basin fluids [2]. Charge and migration are a differentiating factor of fractured basement plays compared to

conventional hydrocarbon accumulations [3]. There is usually no source rock below the reservoir (Figure 1) as organic matter in basement sequences is over mature. The source rock is developed adjacent to or above the reservoir, often onlapping and/or draping the basement above an unconformity. Charge thus occurs due to lateral (juxtaposition) migration or downward migration. Source and top seal are usually the same formation and consists predominantly of shale or marl. Intercalated in these shales or marls might be streaks of evaporite, siltstone and sandstone.

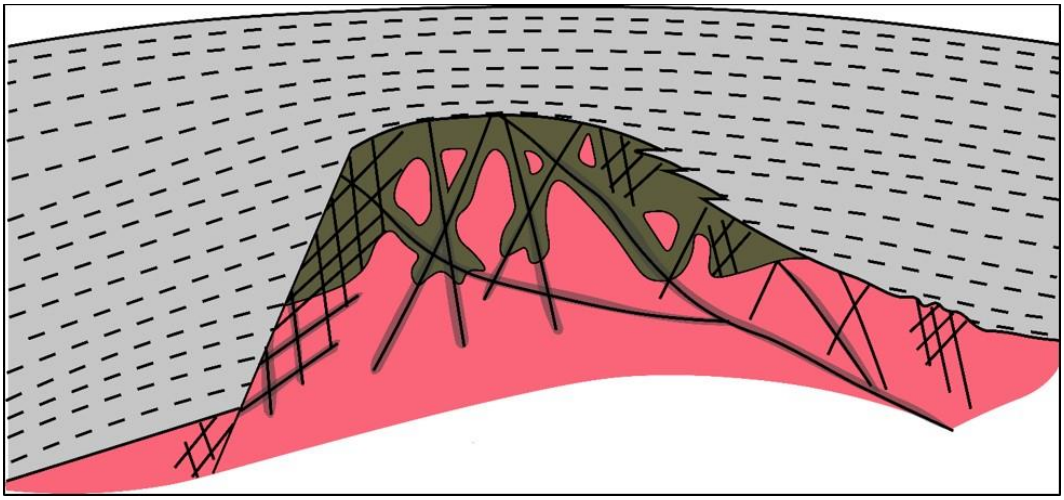

Figure 1 Schematic cross section of a faulted and fractured (black lines) granite horst (red) draped by organic rich shale (grey). Elements of the petroleum system of fractured basement plays (modified from [3])

The reservoir is a tight, brittle, magmatic or metamorphic rock penetrated by a fracture network. Fractures might be enhanced by leaching that increase porosity by up to 10%. In carbonates, solution-enlarged fractures, vugs, and cavities might further elevate reservoir quality.

The oil and gas industry typically concludes exploration activities at the 'economic basement', meaning fractured basement plays are under-explored and often discovered by chance from drilling too deep [5]. However, since the mid-'90s, the broader geoscience community took notice of the major basement discoveries in Vietnam and Yemen following successful commercial production [6]. So, what are the critical factors for this sub-set of naturally fractured reservoirs? This review provides a semi-quantitative summary of some common elements of fractured basement plays based on data from IHSM's International E&P Database and US Enerdeq Browser.

The authors would like to caution that despite our best efforts all numbers have associated uncertainties. Estimated Ultimate Recoverable figures (EUR, 2P/2C) are heavily estimated and well numbers/flow rates are approximated. The list of the biggest/significant fields is subjective due to difficulties to separate dynamically connected sub-unit(s) and/or associated EUR reserves/resources. Our best estimate suggests that of the total global EUR – roughly 1,177,500 billion boe (figure estimated from global remaining reserves (BP, 2016) and total global production to date [7]), approximately 0.001% of this is stored in basement plays (roughly 15,000 MMboe [7]).

Following is a global review of exploration and development of existing basement plays by region and where possible at country level. Due to the varied nature of oil and gas reporting by location, information is limited in places and maybe resolved at field level as opposed to basement reservoir level.

Southeast Asia is one of the regions where significant discoveries of this play type have been made, i.e. China, and Vietnam [5]. These discoveries (as well as the recent advancements in the U.K.) highlight the potential of the play and thus calls for a systematic compilation of the current knowledge to focus on future opportunities.

(Information extracted at time of writing, for exact figures and current data, please refer to IHSM's International E&P Database and US Enerdeq Browser [8].)

2. Previous studies of fractured basement play

The fractured basement play refers to paleotopographic highs that are covered by younger sediments [9]. Oil and gas fields associated with fractured basement are termed fractured basement fields. The Healdton oil field in Oklahoma, discovered in 1916, was the earliest recognized buried-hill field which belongs to fractured basement plays. With subsequent discoveries of such fields in the mid-continent United States in the 1920s [10], fractured basement fields have been discovered in other parts of the world. Landes *et al.* [11] made a review of petroleum resources in basement rocks, which consist of crystalline metamorphic and igneous rocks, in Venezuela, California, Kansas, and Morocco. Later, P'an [12] expanded the topic of petroleum in basement rocks in two aspects. First, he broadened basement rocks to include not only metamorphic and igneous rocks but also unmetamorphosed but tight lower Palaeozoic sedimentary rocks (Figure 2). Second, he added more examples of basement reservoirs in areas such as Brazil, Libya, Algeria, Egypt, and Russia, which were not covered by Landes *et al.* [11]. Fractured basement reservoirs were further documented in Petford and McCaffery [13]. Using the definition of basement rocks of Landes *et al.* [11], GeoScience Limited [14] compiled an updated database of fractured basement reservoirs throughout the world. The Cuu Long Basin in Vietnam is the best-known basin with production primarily from fractured basement granite [15-16]. It appears that the term basement reservoir became more widely used since the work of Landes *et al.* [11]. However, it should be noted that the basement reservoirs exclude the sedimentary rocks in these publications except P'an [12]. As a result, some important fractured basement fields were not included because the reservoirs contain sedimentary rocks.

Figure 2 Intensely fractured tight Carboniferous limestone in NW Malaysia. Similar fractured basement rocks produce hydrocarbons in SE Asia.

3. Database

The IHSM International E&P Database is a detailed database (Figure 3) capturing past and present worldwide E&P activities [7]. With over 13,000 E&P data attributes, International Exploration and Production Database (IRIS21) is the most comprehensive and reliable dataset available to oil and gas industry professionals today. IHSM Enerdeq Browser provides a single point of access to critical IHSM North American content [8]. Using a set of mapping, reporting, and analysis tools, Enerdeq Browser allows users to download, query and process over 5 million Well completions and over 2 million Production entities, Interpreted Formation Tops, Rig Activity and Permits, 2D/3D Seismic, Land and Lease, Pipeline and Facilities, and Spatial information.

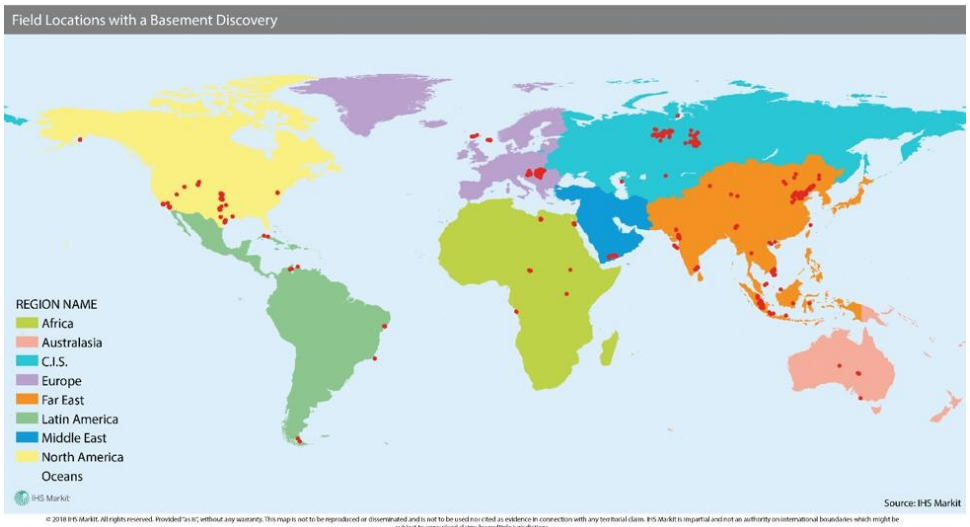

Figure 3. Image showing the global distribution of fractured basement discoveries (extracted from the IHS Markit databases)

3. AFRICA

The fractured basement plays in Africa are developed locally and have never been considered as exploration targets. They were mostly discovered "accidentally" when drilling below the main objectives, especially in rift basins, which rest unconformably above basement or above a very thin pre-rift section. Some basement reservoirs are contiguous with overlying sedimentary-rock reservoirs; in a few cases they share a common oil-water contact.

Basement reservoirs consist of fractured and weathered granitic rocks. They are sealed and sourced from the overlying pre-rift and syn-rift sequences. The fractured basement plays have been identified in 27 discoveries (Figure 4) in Egypt (13), Chad (5), Libya (4), Uganda (2), Angola (2) and South Sudan (1); with the bulk of resources (73%) located in Libya. Production from basement reservoirs is established in Egypt, Libya and Chad.

Figure 4 Image showing geological basins in Africa that host fractured basement discoveries (circles locate at basin centroid)

However, production figures are not differentiated by reservoir but at field level. Flow rates between less than 500 and 20,000 b/d of oil per well have been recorded in Libya and Egypt.

Despite small reserves, basement reservoirs have been recently considered as important targets in countries such as Chad and Sudan. Therefore, in the future more exploration activity could be expected in the Cretaceous rift basins of Chad and Sudan, and Tertiary rift basins of Uganda and Kenya that are part of the East African Rift System (EARS).

Egypt

In Egypt, the basement play is present in 13 fields/discoveries, which are located onshore and offshore in the southern Gulf of Suez Basin, where they form an important reservoir. Sidki was the first discovery in this play in early 1976, while the last one, Rabeh East, was discovered in 1997.

Recoverable reserves discovered to date in this play are currently estimated at 167 MMbbl of oil and 145 Bcf of gas. Zeit Bay is the largest field, accounting for 45% of the basement total reserves in Egypt. The field was discovered in 1981 and since then, the Precambrian basement has been considered as a secondary reservoir target in the southern Gulf of Suez Basin.

The basement is granitic, highly weathered and intensively fractured in response to tectonic activity in the area. Reservoir net-pay thicknesses vary between 10 and 300 m, and porosities are usually low (2-15%), but the fracture system is often highly permeable and productive. Some block crests were exposed to erosion during the first phases of rifting, facilitating weathering and fracturing of the basement. In almost all cases, the basement reservoir is adjoining the Pre-Miocene or Miocene reservoirs and shares a common oil-water contact with the overlying units. The best reservoir potential is in the uppermost section, corresponding to the enlargement of the fractures and vertical communications, and the intensive effect of diagenetic processes. The main directions of fractures are NW-SE, NE-SW, and ENE-WSW [17].

Basement reservoirs are producing in ten fields: Ashrafi, Ashrafi Southwest, Esh El Mellaha, Esh Melala East Marine, Geisum, Hilal (GH 404), Rabeh Est, Shoab Ali, Sidki and Zeit Bay. First production goes back to late 1970s when the Sidki and the Shoab Ali fields were brought onstream together with overlying reservoirs. Zeit Bay started producing in 1983, and the flow rates/well for the rest of the decade were in the range of 700-9,000 bo/d. Until 1988, about 60% of development wells in the field were drilled down to basement [18]. During the plateau phase in 1986, the Zeit Bay field produced around 30,000 b/d of oil from the basement as part of a total field production of 80,000 b/d. In the 1990s, the Zeit Bay and Ashrafi fields were producing up to 25,000 bo/d from basement reservoirs [19]. Production figures at reservoir level are not available.

Libya

The fractured basement rocks constitute a major play in Libya, where they form one of the main reservoirs in two giant fields, Amal (12-B/E/N/R) and Augila-Nafoora (102-D/51-A/G) discovered in 1959 and 1965 respectively. Fields Rakb (12-D) in 1962 and Rakb (12-JJ) in 1965 added some modest reserves to the play. The four fields are in the Rakb High of the eastern Sirte Basin.

Total recoverable reserves are currently estimated to be in the region of 715 MMbbl of oil and 355 Bcf of gas, of which about 95% correspond to the two giant discoveries.

The reservoirs are fractured and weathered granites, which are in direct contact with the overlying Paleozoic-Mesozoic and Lower Tertiary reservoirs. They are sealed and sourced by shales and evaporites of the Upper Cretaceous Rakb Group.

Basement reservoirs were developed and produced jointly with the other reservoirs of the fields. Oil production started in 1966 from the Amal (12-B/E/N/R) and Augila-Nafoora (102-D/51-A/G) fields, which followed the construction of the pipeline connecting them with the terminal and refinery at Ras Lanuf on the coast. The Rakb group of fields were brought onstream in 1968. There are no production figures at reservoir level.

Chad

The fractured basement play in Chad was first discovered in 2013 in the Northern Slope of the Bongor Trough. This play is developed directly below the Lower Cretaceous syn-rift play, where the lacustrine shales of the latter form the seal and source rocks for the basement reservoirs. More than 80 wells have reached the basement in the Bongor Trough, of which only five flowed commercial rates. They include the Baobab, Mimosa, Raphia South, Kubla-Phoenix and Lanea [20].

The fractured basement in the Bongor Trough is composed of granites and granodiorites arranged on rotated horst blocks and a series of faulted hills. The extensive fracturing of the basement was formed by deformation, weathering and hydrothermal alteration. Three types of basement lithology have been distinguished, depending on the intensity of the fracturing: unweathered (no fractured), leached (fault breccias and altered fractures), and fractured un-leached (regularly and intensely fractured). Fractures are arranged in two sets of ENE-WSW and WNW-ESE direction, respectively [20-21].

Effective porosity values are in the range of 4-12%, rarely reaching 30%. Reservoir properties are better in the Raphia South field than in Lanea East, and the latter shows more extensive fracturing. Raphia South shows better weathering and leaching conditions and therefore, the lithologies are more suitable for hydrocarbon accumulations [21].

Given the early stage of exploration, small amounts of resources have been discovered, totalling approximately 90 MMbbl of oil and 14 Bcf of gas. There are no production figures for the basement reservoirs. Flow well-rates of 1,500 b/d of light oil have however, been recorded. Please refer to Figure 5 for basin locations.

South Sudan

Interest in exploration of the basement play in South Sudan has been growing since the late 2000s. This play was first tested in 2008 by the Gandool Southeast 1 well, located in the northeastern part of the Melut Basin, but recovered only water. In the same year, Gandool North-Northwest 1 encountered tight basement rocks, apparently not fractured.

The Ruman North discovery in 2009 is the only example of a proven basement play in the country. The field is located in the central part of the Melut Basin. The Ruman North 2 wildcat well tested about 400 bo/d from the fractured basement at a depth of roughly 860-915 m. The well appears to have only two major contributing open-fracture zones [37]. The source rock is juxtaposed to the basement structure which means a direct charging of the hydrocarbon through the fractures and faults. In the same year, Ruman 1A, Ruman Northeast 1 and Ruman North-Northeast 1 encountered oil shows in the basement.

In 2010, the Ruman North 3A well targeted the basement reservoir, which was the primary objective. The well was located 1.5 km to the southeast of Ruman North 2 and recovered in the region of 25 bbl of heavy oil. In the same year, Ruman Central 1 encountered tight basement rocks. In 2011, the Ruman B 1 exploratory well targeted the basement as its primary objective. The well was designed to penetrate 724 m of basement to evaluate the fracture continuity and hydrocarbon distribution in the center of the Ruman basement structure. The well drilled approximately 2,500 m but the results were not released.

The Ruman North discovery found minor amounts of oil and as such, its contribution to field production is insignificant.

Uganda

In Uganda, this play is associated with few wells drilled in the basement, immediately below the rift section in the Albertine Graben of the EARS, Western Branch.

The presence of hydrocarbons in fractured granitic basement was deduced from well-logs and limited tests in the Mputa 1 and Nzizi 2 wells. Mputa 1, drilled in 2006, recovered only minor amounts of oil during a Drill Stem Test (DST) in the granitic basement, likely due to a restricted and tight fracture system. In 2007, a simple test was performed in the Nzizi 2 well at 950 m, but it did not flow oil to the surface.

Figure 5 Image showing the location of fractured basement discoveries in Africa, Middle and Australasia (red circles). The turquoise circles indicate significant basement finds.

Only very small quantities of oil have been discovered in the basement play, and no production has been established yet in the whole EARS, Western Branch in Uganda.

Angola

The fractured basement play in Angola is of minor importance. It is present in two discoveries, 37-1 and 61-1, in the Lower Congo Basin, onshore Cabinda, where they form a single-well oil pool. The 61-1 well produced 600,000 bbl of oil on an extended test from fractured basement in the early 1970s. The well was surrounded by dry holes. The 37-1 well was located on the Zila Ridge and tested 60 b/d and 24 b/d of oil [22].

4. MIDDLE EAST

Yemen

Yemen is one of the better-known countries with respect to basement exploration and development; it hosts 24 discoveries, eight of which were placed on production. Here the basement is predominantly a complex series of metasediments and metavolcanics, with granitic intrusions [5] occurring at depths below 2,400 m. Only one of the eight producing basement finds is located in the Marib-Al Jawf-Hajar Basin, the remainder of the productive fields are located in the Sayun-Masila Basin. Please refer to Figure 6 for basin locations.

Basement reservoirs provide 50% of Yemen's production [23], with an average oil density of 35° API.

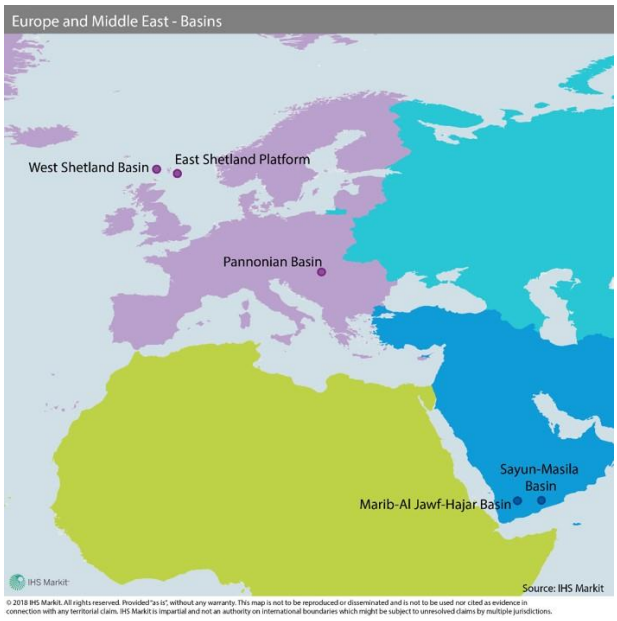

Figure 6. Image highlighting basins where fractured basement discoveries exist in the Middle East and Europe

Marib-Al Jawf-Hajar Basin

Yemen's first basement discovery was in 1988 and is situated in the Marib-Al Jawf-Hajar Basin. The Cambrian granites are trapped on structural highs and were discovered by well, Ayad East 4, drilled by Soviet Petroleum Exploration & Expedition (SPEE). This small structure is un-developed at basement level however there was a further discovery at the neighbouring structure, Ayad West (1988) which flowed approximately 20 bo/d from a 90 m basement interval. Ayad Central 2, discovered in 1989 was also reported as a non-commercial basement oil find by SPEE.

Perhaps the most well documented basement field in Yemen is Habban, situated in the Shabwa Sub-basin of the Marib-Al Jawf-Hajar and discovered in 2005 by OMV. The Habban fractured basement reservoir is extremely heterogeneous and comprised of fractured metamorphic and granitic rocks. The fractures in the basement have been characterised into two distinct groups: pervasive background fractures with a very low effective permeability, up to 0.001 mD and fracture corridors associated with faults with effective permeability from 0.01 mD up to 10 mD [24]. In Yemen, the basement reservoir is often in communication with overlying pre-rift clastics of the Kuhlan Formation. The Kuhlan has been shown to be laterally limited and displays regional variations in reservoir quality.

In 2005, OMV suspended the Habban 1 wildcat well as a fractured basement oil discovery after drilling approximately 750 m into the basement. The well was reported to have flowed in the region of 2,500 bo/d with 1.0 MMcfg/d from at least two basement tests. OMV re-entered an associated Habban well in the same year, deepening it into the fractured basement where a 430 m oil column was encountered. Subsequent tests resulted in a sustained flow of 1,800 b/d of 38° API oil from the basement and 200 bo/d from the Kuhlan Formation. Production commenced in 2006, with basement production levels reaching approximately 10,000 bo/d in 2009. The field was active in terms of basement development until end-2014. The estimated resource for the Habban basement is approximately 75 MMbo, including the contribution from the overlying Kuhlan sub-unit.

Further finds in the Marib-Al Jawf-Hajar Basin include: Al Meashar 1 discovered in 2009 by Oil Search and partners; and Tubb'a 1, a gas and condensate discovery by Total and partners also in 2009.

Sayun-Masila Basin

The majority (17) of the fractured basement finds in Yemen are located in the Sayun-Maslia Basin. A significant basement exploration programme was carried out during the early 1990's in Hadhramaut province (Sayun-Masila Basin). Well Sunah 4, drilled in 1992 by Canadian Oxy Group, was the first oil discovery made in the basement complex in the Masila Sub-basin and in 2005, it was reported that the Sunah 4 well had produced over 30 MMbo.

Kharir was discovered by Total and partners in 1992. Production commenced in late-1997 at an initial rate of approximately 17,000 bo/d from four wells, and by end-2002, flow rates averaged 22,000 bo/d. Basement estimated ultimate recovery at the Kharir field amounts to 200 MMbo (including the contribution from the Kuhlan Formation), making it the largest basement find in Yemen with respect to recovery size. Further productive discoveries in this area include: Wadi Taribah (1995) and Jathma (2006).

In 2004, DNO discovered Nabrajah. This field is made up of two Cretaceous clastic reservoirs with a deeper oil pool in the basement and overlying Jurassic and Lower Cretaceous carbonate formations, the Shuqra and Nayfa. The Nabrajah deep pool contributes to production through only one well. The Nabrajah 2 well discovered hydrocarbons in the fractured basement and overlying carbonates in late 2004 however, the well was never put on production. As of mid-2014, the Nabrajah field had only one well producing from the basement.

Bashir Al Kharir K was discovered in 2006. The structure was drilled as part of a comprehensive block-wide exploration and appraisal programme by Canadian Nexen. Production from the field is assumed to have commenced in the discovery year.

Dove Energy Group and partners discovered oil in the basement with well Bayoot Southwest 2 in 2006. Production from the discovery well commenced in late 2006 and in 2013, Dove reported that the Bayoot field was producing primarily from this basement reservoir at rates in excess of 1,000 bo/d. The estimated ultimate recovery in the basement section of the Bayoot field amounts to some 11 MMbo.

Sayun Sub-basin and South Hadhramaut Uplift (Sayun-Masila Basin)

The Qarn Qaymah 1 gas, condensate and light oil discovery was made by British Gas in 1994. However, the well was considered to be uncommercial at the time. After taking over as

operator, Calvalley drilled two further appraisal wells between 2007 and 2011 which successfully tested gas, condensate and light oil from the Kuhlan and underlying basement. Unfortunately, wellbore production problems and lack of equipment restricted further appraisal work.

Henin 1, drilled in 2008 by Sinopec and partners was suspended as a granitic basement long term test after recovering 150 bbl of light oil. Following this, Judayaah 1 was confirmed as a basement oil discovery after having been logged and tested in 2010.

DNO and partners drilled Yaalen 1 in 2008 and tested gas and condensate from an open hole interval in the basement which was a secondary target. Additionally, some liquid hydrocarbons were recovered from the Kuhlan Formation by wireline testing. There has been no further appraisal of the basement at this field.

Due to the security situation in the country, further development has been suspended. The majority of Yemen's producing fields were shut-in during mid-March 2015.

5. COMMENWALTH OF INDEPENDENT STATES (CIS)

Russia

The majority of the fractured basement reservoirs discovered in Russia are situated in the West Siberian Basin. According to the IHSM definition, this basin accounts for six sub-basins or provinces (Figure 7), which correspond from north to south, to the South Kara-Yamal, Nadym Taz, Ural-Frolov, Middle Ob, Kaymys-Vasyugan and Southern West Siberia provinces. The first basement play proven in the basin was discovered in the Ural-Frolov Province in 1961, at the Mortymya-Teterevskoye field. The well Mortyminskaya 0028, operated by Khanty-Mansiysk Neftegazgeologia, encountered oil in the weathered Paleozoic basement at approximately 1,600 m measured depth (MD).

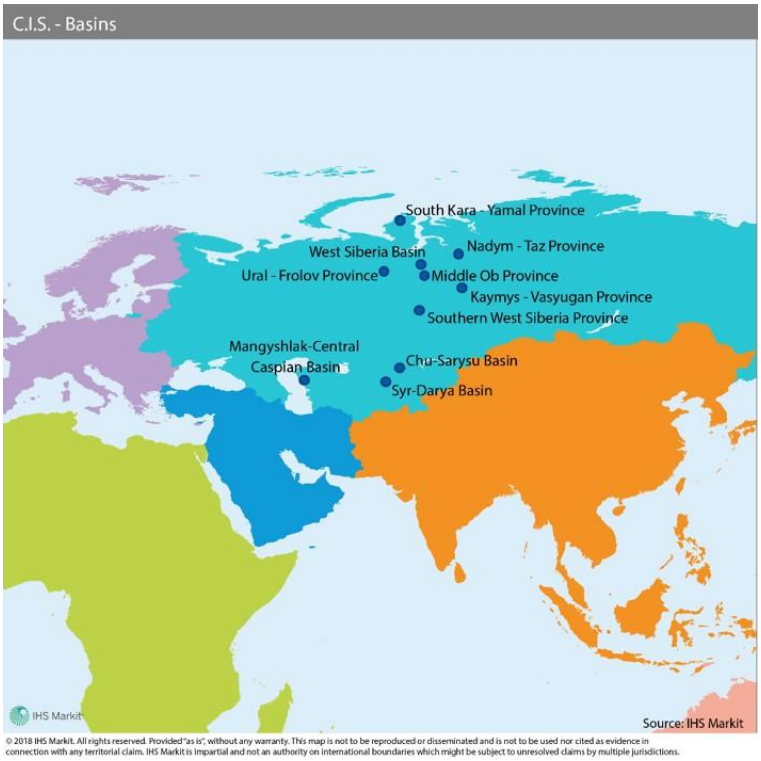

Figure 7. Image indicating basins (and sub-basins) that host fractured basement plays in the C.I.S.

By 2016, 108 oil prone basement reservoirs had been discovered in the West Siberian Basin; the majority being in the Ural-Frolov (57) and in the Kaymys-Vasyugan (49) provinces. The Paleozoic play has also been proven in the Middle Ob, Nadym-Taz and South Kara-Yamal provinces, but in only one reservoir. Please refer to Figure 8.

Figure 8. Image depicting fractured basement discoveries (red circles) and significant finds (turquoise circles) in the C.I.S. Ural-Frolov Province

In the Ural-Frolov Province, basement reservoirs are constituted of weathered granites, brecciated metamorphic rocks, or locally by Paleozoic sediments preserved from the Upper Paleozoic-Lower Jurassic erosion phase. The average areal extent of these reservoirs is 10 km2 on average and top depths range from approximately 1,490 to 3,150 m (MD). Reservoir properties are heterogeneous mainly due to differences in alteration, erosion and cementation processes. Net reservoir thickness ranges from 2 to 110 m. Effective porosity of the net pay from 10 to 25%. The top seal is provided by the lowermost shale of the Tyumen Formation or its stratigraphic equivalents of Lower to Middle Jurassic age., These unconformably onlap the oil bearing intervals. Traps usually correspond to buried-hill type structures inherited from the basement paleo-topography associated with the Paleozoic/Jurassic unconformity and faults. The majority of the basement reservoirs in the province have been sourced by the Togur Beds of Early Toarician age.

Recoverable resources of most fields in the Ural-Frolov region are estimated to be lower than 50 MMbbl. Only four of them have volumes greater than 75 MMbbl and are found at the Krasnoleninskoye, Srednenazymskoye, Danilovskoye (Khanty-Mansiysk) and Danilovskoye Severnoye fields. By 2016, 20 of the 57 reservoirs discovered in the province were producing. Sixteen reservoirs were awaiting development approval, 16 were considered as discoveries and three were being appraised. The latest reported activity targeting these basement reservoirs in the province was conducted by Rosneftegaz. In 2016, the operator spudded two new field wildcats in the Yamal-Nenets Autonomous Okrug, (Kharvutinskaya and Tyyaktarskaya licenses) in order to explore for basement reservoirs. To date, results have not been disclosed publicly.

Kaymys-Vasyugan Province

In the Kaymys-Vasyugan Province, the first basement reservoir was discovered in 1971 at the Festivalnoye field. The well Aykagalskaya 252 tested oil from the Paleozoic section between approximately 3,050 and 3,070 m depth (MD), flowing at roughly 155 b/d. By 2016, 49 basement reservoirs had been discovered in the western half of Kaymys-Vasyugan province. The majority of them corresponds to oil prone intervals in the Unit M, the uppermost

section of the Paleozoic basement. This unit consists of weathered granite showing a vertical extent of a few tens of meters and practically extending across the entire the province. Locally, basement reservoirs are also present in the overlying Kalinovaya Formation. This formation is comprised of elements from Unit M eroded during the Upper Paleozoic-Lower Jurassic erosion phase and preserved at the feet of Paleozoic highs.

In the Kaymys-Vasyugan Province, reservoirs have an areal extent averaging 7 km^2. Net thickness varies between 1 and 55 m and porosity between 3 and 30%. Net pay intervals are found in the region of 2,350 to 3,600 m depth (MD) and are sealed by the overlying Lower-Middle Jurassic formations. Traps correspond to buried-hill type structures associated with the Paleozoic/Jurassic unconformity and faulting. Most of the basement reservoirs in the province are interpreted to have been sourced by the Togur Beds (Lower Toarician).

Recoverable reserves/resources estimated in the Kaymys-Vasyugan reservoirs average 22 MMbbl. The three largest reservoirs are found at Kalinovoye (124 MMbbl), Archinskoye (134 MMbbl) and Urmanskoye fields (180 MMbbl). In 2016, ten of the 49 reservoirs discovered in the Ural-Frolov Province were producing, 15 were being appraised, 13 were considered as a discovery, nine were awaiting development approval, and two were being developed.

Middle OB Province

By 2016, the basement plays had been proven by a single discovery made in 1963 at the Sovetskoye field (Khanty-Mansiysk Autonomous Okrug). Tomskneft discovered oil in the basement reservoir at 2,680 m depth (MD) and commenced commercial production in 1983. This reservoir is small with estimated reserves of around 2.5 MMbbl. In 2015, Lukoil spudded the well Ust-Kotukhtinskaya 105 in the Ust-Kotukhtinskaya license (Khanty-Mansiysk Autonomous Okrug), with the purpose of exploring the basement play. In early-2016, the operator tested the well without disclosing results.

Nadym-Taz Province

In the Nadym-Taz Province, the basement play was proven for the first time in 1986, at Varyeganskoye Severnoye field (Khanty-Mansiysk Autonomous Okrug). The reservoir, which was discovered at an approximate depth of 3,300 m flowed non-associated gas and condensate. It has estimated resources of some 1 Bcf gas and 130 MMbbl condensate.

South Kara-Yamal Province

In the South Kara-Yamal Province, the only basement reservoir found to-date belongs to Novoportovskoye field, in the southern Yamal peninsula. In this area, weathering processes during the Upper Paleozoic-Lower Jurassic erosional phase have created karstic intervals along NE-SW trending basement faults. The reservoir, which was discovered in 1982 contains non-associated gas and condensate (resources of 1.5 Bcf gas and 18 MMbbl condensate, respectively). In 2016, Gazprom Neft Yamal was awaiting Government approval to develop the reservoir.

Kazakhstan

Chu-Sarysu Basin

In the Chu-Sarysu Basin, a basement play is known in one field only, Ortalyk, discovered in 1976 by Aktyubneftegazgeologiya. Weathered fractured schists are sealed by Lower Carboniferous argillaceous siltstones. No development has been reported.

Mangyshlak-Central Caspian Basin

There is one basement reservoir discovery (1981) in the Mangyshlak-Central Caspian Basin. The Oymasha field's Paleozoic reservoir is associated with a weathered and fractured granite batholith overlain by Triassic shales. The field is located in the Peschanomys-Rakushech High in the west of the basin's onshore part. The trap is a buried hill-type structure. On testing, the

well flowed 20 b/d of oil from this Upper Paleozoic reservoir, and is currently producing. Productive zones of these granites extend 300 m below the basement surface. Oil flow rates in discovery well 12 achieved rates in the region of 1,500 b/d.

6. FAR EAST

India

India is host to a total of 24 basement discoveries within the Assam, Barmer, Bombay, Cambay and Cauvery Basins (see Figure 9). It is assumed from available information, that nine of the fields were put on production (one of which has since been shut-in). Basement plays remain fairly under-developed with operators concentrating on overlying sedimentary formations. Again, it is important to note, reserves/resources are estimated and the production status of basement reservoirs is often unclear.

In March 1970, Oil and Natural Gas Corporation Ltd. (ONGC) made the first basement discovery in India with the Borollah 04 well at the onshore Borholla-Changpang field in the Assam Shelf. The well was drilled to explore the Pre-Cambrian metamorphic/igneous basement after three previous wells were dry. It flowed at 730 bo/d during testing and the pool was declared commercial, changing schools of thought about basement prospectivity. Approximately 20 MMbo was estimated to be recoverable from the basement with production beginning in 1981. Fracture analysis from core samples and detailed seismic surveying has helped build a complex geological model of the field, revealing intricate fault block geometries. The most intensely fractured reservoir sections were found on the flanks of the domal structure and wells drilled here had the highest production rates with low initial GORs. Peak production from the basement occurred between 1988-89 at an average rate of roughly 1,170 bo/d; following which, a rapid increase in water cut was observed. Production has continued to present but is in decline.

Figure 9. Image showing geological basins in the Far East with fractured basement fields

In the late-1980s, the Pre-Cambrian metamorphic basement and the directly overlying Cretaceous Deccan Traps basalts at the offshore Mumbai High field in the Bombay Basin, were explored by ONGC. BH-36 was drilled in 1987 and it tested 460 bo/d (stabilized flow) from the basement. Further drilling with the wells BH-19, SY-5 and 11-7 all confirmed oil and each initially produced over 1,000 bo/d. The basement fractures were associated with major NNW-SSE trending fault zones cut by minor E-W trending faults. Approximately 160 MMbo is estimated to be recoverable from the basement and although there was initial success with wells drilled to basement, development concentrated on the prolific overlying L-III and L-II carbonate reservoirs. However, in 2011, a pilot study was initiated in which 30 wells were to be drilled into the basement with the aim of augmenting production by roughly 20,000 bo/d. If successful, the operation could see expansion under the current Phase-III re-development of the Mumbai High with a potential upside of 50,000 bo/d from the basement.

More recently, ONGC discovered oil from basement rocks in the onshore Cauvery Basin with the Madanam 3 and Pandanallur 8 exploratory wells were drilled in 2012 and 2013 respectively. The two fields lie in close proximity to one another on a NE-SW striking basement high associated with a horst and graben structure formed during rifting in the Late Jurassic/Early Cretaceous. Drilling in the Madanam area discovered the first hydrocarbons in the basin in 1969, but it wasn't until the Madanam 3 wildcat, that the first significant oil volume was encountered from the basement. The well tested more than 725 bo/d and less than 1 MMcfg/d. In 2015, ONGC approved a Field Development Plan for the Madanam field, which included drilling of 15 development wells in addition to three existing wells, envisaging cumulative production of approximately 8 MMbo and 95 Bcf. The Pandanallur 8 well tested around 190 bo/d and 0.6 MMcfg/d with the discovery currently undergoing further appraisal work. Initial estimates indicated that as much as 45 MMbo and 34 Bcf gas are present within its basement reservoir.

China

Oil and gas reserves accumulated in fractured basement plays in China are mainly distributed in its eastern rifting basins, with the majority of the largest fields discovered in the Bohai Gulf Basin. Basement fractured basement plays have been discovered in other onshore/offshore basins in China however, there are no large-scale discoveries such as Renqiu (please refer to Figure 10).

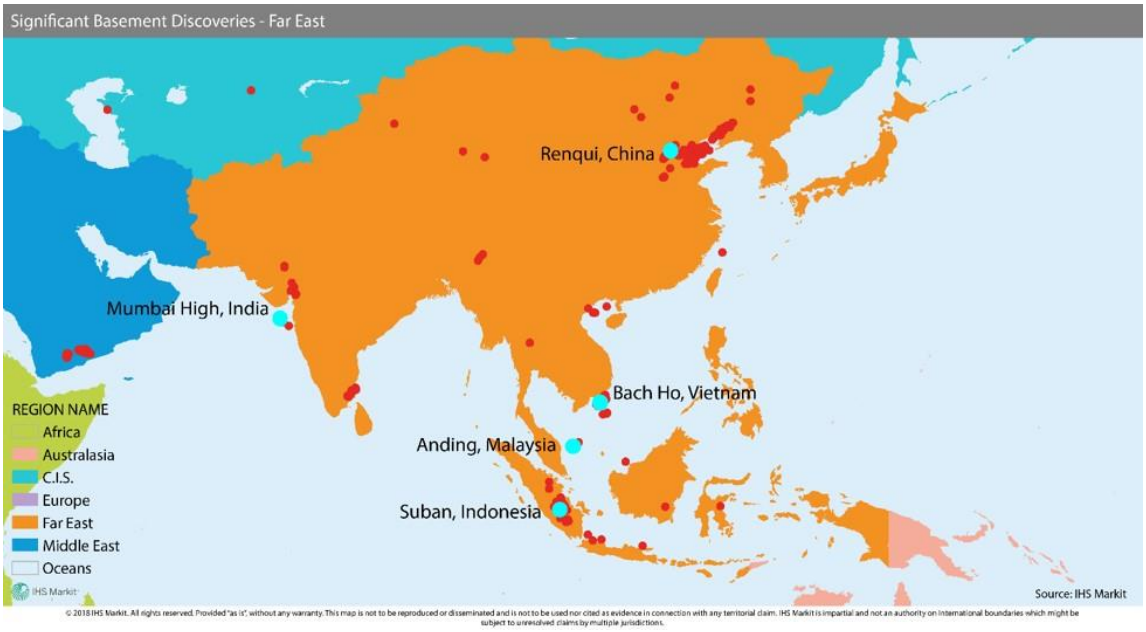

Figure 10. Fractured basement discoveries in the Far East (red dots) and significant finds (turquoise dots)

The first buried hill play was discovered in 1959 at the Yaerxia oil field located in the Jiuquan Basin, in northwestern China. Production rates were in the order of 1,000 bo/d from fractured metamorphic reservoirs of the Upper Silurian Quannaogou Formation [25].

Bohai Gulf Basin

Between 1975 and 1978, significant volumes were discovered in the basement at the Renqiu oil field in the Bohai Gulf Basin (the field was discovered in 1975). The basement is estimated to contain over 70 MMbo of recoverable reserves (2P). The Renqiu field (including non-basement reservoirs) reached its peak production at approximately 95 MMbbl of oil in 1979, amounting to roughly 10% of China's total production of that year [26].

Following this success, more than 50 basement fields were discovered in the Bohai Gulf Basin from 1975 to 1985; from 1986 to 1995, only small-scale discoveries with fractured basement reservoirs were made [27].

Since 2006 with improved seismic acquisition and processing technology, fracture identification and prediction technology, and new well completion and drilling techniques - some deep and small scale fractured basement reservoirs were discovered in the Bohai Gulf Basin, e.g., the Xinglongtai, Damintun and Niudong 1 discoveries.

Fractured basement reservoirs in the Bohai Gulf Basin are below the Cenozoic units and represent paleo-highs formed by Proterozoic and Paleozoic carbonates, Paleozoic and Mesozoic clastics, and Archean metamorphic rocks. These are mainly distributed in the Jizhong, Lower Liaohe, Jiyang, Huanghua and Bozhong depressions [28].

To date (August 2018), there are more than 120 fractured basement discoveries in the Bohai Gulf Basin, with reservoirs in Archean metamorphic to Paleozoic carbonates.

Southeast Asia

Basement plays represent key targets in some of the mature and transitional basins in Southeast Asia. Success in this play dates to 1913 when the Kluang 1 wildcat in the onshore South Sumatra Basin was drilled along an anticline in the western half of the Corridor block, originally targeting the Air Benakat Formation. The well encountered oil and gas by chance in the Cretaceous granite reservoir, 460 m below the crest of the structure with estimated recoverable reserves of less than 1.5 MMboe.

Aside from the South Sumatra Basin, the fractured granites in the offshore Cuu Long Basin produced some of the big fields in the region. More than 4.5 billion bbl of recoverable oil equivalent have been discovered in the basement plays, with the Cuu Long and South Sumatra basins accounting for 94% of these resources. Around 73 discoveries have been generated from the basement plays and these are in South Sumatra (28), Cuu Long (26), Song Hong (4), Nam Con Son (3), West Java (3), Malay (2), Central Sumatra (2), Phitsanulok (1), Tatau (1), East Java (1), Banggai (1) and Barito (1). Most of these basins are in a back-arc setting.

Almost 4 Bboe, dominated by oil, have been produced from the basement reservoirs in the region.

Around 80% of the basement plays are either in a 'structural-unconformity' and 'stratigraphic-structural-unconformity' trap setting. These combination traps contributed to around 95% of the total basement recoverable resources.

Vietnam

Cuu Long Basin

The largest basement field in the region, Bach Ho, was discovered by chance in 1988 while exploring the Oligocene section of the Cuu Long Basin. The fractured granite reservoir is estimated to contain more than 4,000 MMbbl oil in place. The recoverable reserves are estimated 1.7 billion bo). Continuous appraisal and exploration drilling is being conducted in the Bach Ho as well as adjacent fields such as Tho Trang, to evaluate near-field potential within the basin. As of November 2016, at least 25 wells successfully appraised the discovery.

Following the Bach Ho success, a series of large discoveries replicated this success namely the Rang Dong (1994), Ca Ngu Vang (2002) and Nam Rong (2004) basement reservoirs. The single production test of the Pre-Cenozoic Basement in Rang Dong 1X had one of the highest flow rates in South East Asia.

The longest well in Vietnam with an along hole length of > 6,100 m was drilled in Ca Ngu Vang field with over 2,000 m in granitic basement. The appraisal well had "tested water-free" at a maximum combined rate of approximately 13,000 boe/d.

Song Hong Basin

High H_2S readings were recorded in the Yen Tu 1X basement discovery of 2004, leading to severe operational difficulties. No further information has been reported regarding its development.

In 2008, the northwest-southeast trending carbonate fractured basement in the Ham Rong field was discovered. The well flowed approximately 5,000 bo/d from fractured and karstified carbonate basement section. The discovery well was sidetracked several times due to mechanical problems in the main borehole and the development plan was on as of mid-2016 due to the low oil price at that time.

Nam Con Son Basin

To date, only a few discoveries represent the play in this basin and there is no reported basement production. The development of the 2007 Gau Chua 1X discovery was on hold pending further exploration activity. The best quality reservoirs are found to be the weathered and fractured granitoid rocks in the upper part of the basement rocks.

Indonesia

South Sumatra Basin

In South Sumatra, large discoveries were encountered in Dayung and Sumpal basement reservoirs (following the initial Kluang 1 success of 1913). The 1994, Sumpal 1 discovery well primarily targeted sandstones of the Talang Akar and Lemat formations. Operations were ongoing in 1994 before the operator decided to terminate the well at around 2,000 m in basement. The appraisal well Sumpal 2 proved hydrocarbons deeper than previously tested on the structure and indicated a gas column of at least 750 m. The Sumpal and Dayung gas discoveries later became the focus of the Corridor Block Gas Gathering Project, the gas being earmarked for supply to Caltex's Duri Steam-flood Project in the Rokan PSC, Central Sumatra.

The giant gas reservoir in the basement of Suban field was discovered in 1998 from an outpost well, which flowed at 43.5 MMcfg/d and 365 bc/d. Hydrocarbons are in fractures subunconformably and paleotopography trapped. The Upper Cretaceous metamorphic/granite basement reservoirs are generally associated with Plio-Pleistocene rejuvenated faulting, which enhanced the fracture porosity and permeability. ConocoPhillips is currently planning Phase 3 development to boost production at Suban.

Barito Basin

Basement is considered a secondary target in this basin. The Tanjung field encountered oil in the basement in 1938. Resources in this play account for 14% of the total field volume.

Central Sumatra Basin

The Beruk Northeast (Beruk High) and Pulai Utara (northern end of Lirik Trend) fields have produced oil from fractured basement. Beruk produces from fractured Early Permian metaquartzite, Early Cretaceous weathered argillites and altered granite (Late Triassic-Early Jurassic). Fracture porosity generally averages 20% but the altered granite is a poor reservoir [29]. The structure is a fractured basement composed of basement and onlapped and sealed by shales of the Telisa Formation. The Pulai Utara structure is assumed to be similar but with a seal of the Tualang Formation.

Beruk Northeast (discovered in 1976) came on stream in 1981 at an initial average rate of 2,200 bo/d from one well. The field reached its optimum daily production rate in 1997 from four wells. The subsequent development wells have been less productive due to rapid water influx, separating fluid contacts and poorly developed fracture systems in the granite.

Banggai Basin

An ophiolite basement play was reported in the Dongkala 1 discovery of 1986. The well was drilled to test a presumed Miocene reef below a Pleistocene unconformity but encountered ophiolites which yielded gas at a rate of approximately 1 MMcfg/d. Its estimated recoverable resources amount to 50 Bcf gas, representing 18% of the total volumes discovered in the basin.

West Java Basin

The main reservoir is the Mesozoic basement which is made up of predominantly metamorphosed rocks. Trapping style is typically an unconformity associated with a faulted anticline controlled by igneous intrusive deposit facies. Minor oil was discovered in 1983 in the Bima Zu basement high at Asri Sub-basin. All three basement discoveries in this basin have not been developed due to non-commercial reserves.

East Java Basin

A low rate of dry gas flowed from the KE 29 1 basement reservoir, discovered in 2013. The well originally targeted the younger Eocene Ngimbang Group which is one of the major reservoirs in the basin.

Malaysia

Malay Basin

The basement in the Malay Basin exists in two fields and is composed of metasediments of Permian-Cretaceous age and crystalline granitic plutons of Permo-Triassic age. In the eastern flank of the Tenggol Arch the basement highs are draped over and abutted by Lower Tertiary sediments most likely the Group L, which provides both the source and seal for the uppermost fractured and weathered basement reservoirs.

Basement rock in the Malay Basin can be divided into a southwestern and a northwestern province [30]. In the northwest, the basement consists of Mesozoic to Carboniferous carbonates and Mesozoic granites [31].

The first basement discovery was encountered in well Anding Utara 1 in 2004, in the southwestern part of the basin. This discovery was followed by Ledang Tengah Deep 1 in 2010 wherein minor basement gas was encountered.

Tatau Province

The first and only oil discovery in the fractured basement reservoir in East Malaysia (Sarawak) was encountered in well Nuang 1 in 2015. Oil shows were observed in over 100 m of metasediments with quartzite and phyllite. Oil was proven from wireline sampling.

Thailand

Phitsanulok Basin

The only basement find in Thailand was discovered in 1991 at the Sirikit field. The basement play here comprises fractured and weathered pre-Cenozoic meta-sediments and indurated sediment reservoirs, drape sealed and sourced by the Cenozoic lacustrine shales. Further appraisal by deepening existing wells was not successful and existing seismic data was not sufficient to resolve at depths below 3,000 m

7. AUSTRALASIA

Australia

There are five proven basement discoveries in Australia (Figure 8), only one of which has produced commercially (Sturt). The first discovery, Kalangadoo 1, was in 1965; however, it is the most recent discovery of 2014 (Mount Kitty 1) that is potentially of the most interest in the region. Figure 11 highlights basin locations.

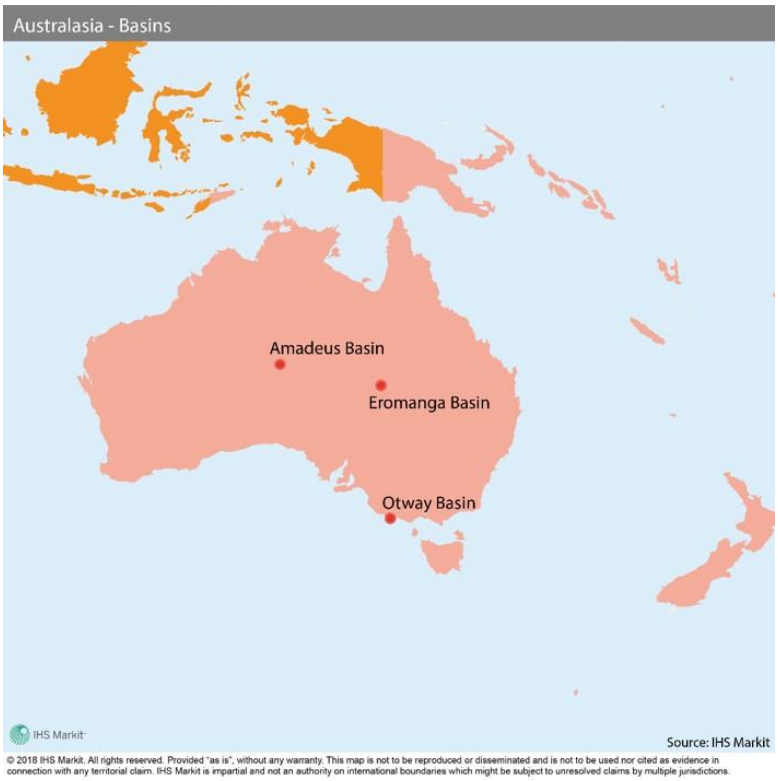

Figure 11. Image showing the location of basins in the Australasia region that contain fractured basement discoveries

Amadeus Basin

The Proterozoic basement structural play was discovered by Mount Kitty 1 in 2014. The well primarily targeted gas, condensate and helium within the Heavitree Formation. Sidewall cores confirmed that the Heavitree Quartzite was absent and that gas flows were actually from fractured granitic basement. Image logs indicated the extensive nature of fractures, which is typical of many structures in the Amadeus Basin.

The discovery itself is not on commercial production but flow rates from the well from granitic basement at a depth of approximately 2,150 m reached a maximum of 530 Mcfg/d of gas. At the time of writing, the Mount Kitty 1 discovery is under appraisal.

Helium generated via radiogenic decay within basement forms an important element of the play (9% at Mount Kitty 1), potentially enhancing the economics of discovered accumulations.

Two structural 'plays' have been described by Ambrose & Heugh [32] that are fractured basement structural play. The first occurs where Gillen Formation source rocks onlap a basement palaeohigh ('Fractured basement Play') while the second occurs where hydrocarbons are trapped within imbricate thrust sheets ('Thrust Belt Play') which was represented in the Mount Kitty 1 discovery. The source and seal for both plays are the same, the only difference being the structural configuration and potential migration pathways.

Cooper Eromanga

A discovery of note is the Sturt oil discovery. In 1988, Sturt 6 discovered, within a fault block, significant oil in fractured Mooracoochie Volcanics of Early Cambrian age. Net oil pay of approximately 6 m was mapped in the felsic tuffs (upper basement). The discovery was commercially productive with cumulative production from 1990 to 2002 from the Patchawarra/ Mooracoochie Volcanics interval totaling 72,860 bo.

The 1990 gas discovery, Lycosa 1 flowed gas from several tests in the fractured metasediments (anticlinal structure) within the Cambrian Dullingari Group.

The Warburton – Cooper – Eromanga Basin contains a further basement associated play, the Basement Unconformity Play. This play has one gas discovery associated with it in the basin, the Farina Field. The weathered basement zone (weathered porosity) was discovered by well Farina 1 in 1992. It encountered just over a 1 m of net gas pay. It tested around 0.4 MMcfg, with minor amounts of heavy oil also being recovered.

Otway Basin

The basement play in the Otway basement was discovered by well Kalangadoo 1 in 1965. It encountered significant gas shows over an approximate 115 m interval within a tilted basement fault block. During testing, the well flowed predominantly CO_2 gas at a maximum rate of 2.8 MMcfg/d from steeply dipping arenaceous sediments of Paleozoic age.

8. NORTH AMERICA

USA

There are a small number of relatively minor fields producing from basement rocks in the US. The most noteworthy are along the Central Kansas Uplift in Kansas. Scattered production exists from volcanics in Colorado, Arizona and Nevada but they are local anomalies with little further success to date. Figure 12 shows the location of basins with fractured basement accumulations.

Figure 12. Locations of basins in North America that host fractured basement discoveries

Alaska

The McArthur River field is located in the Cook Inlet Basin, Alaska and is thought to have produced (on test) 180,000 bo from Jurassic metamorphosed marine volcaniclastics and tuffites of the Talkeetna Formation (discovered in 1990). This volume represents less than 1% of the total oil produced from the McArthur field up to the end of 2013 [33] and the discovery has yet to be appraised [34].

California

There are five fields in California producing from fractured basement rocks (Figure 13). The Edison, Playa del Rey, El Segundo and Wilmington fields produce from fractured Jurassic schists within the California Continental Borderland Basin and the Great Valley Basin. In the Salinas Basin, hydrocarbons are produced from a fractured sandstone basement within the Santa Maria Valley field.

At the El Segundo field, in the east, production is from a basal schist conglomerate; and in the west from a Jurassic fractured schist. Oil has been tested to up to 4,500 bo/d with 27° API crude [15]. The Wilmington field is the third largest oil field in America in terms of cumulative production (2.8 Bbbl) and 22 MMbbl is from fractured basement [14]. Oil production from the Edison field basement reservoir is reported to be in the region of 20 MMbbl [14].

Kansas

Oil is produced from fractured quartzites. Within the Central Kansas Uplift there are more than 10 small basement oil fields. The oil is predominantly found in fractures within the Pre-Cambrian quartzite and granite. Specific fields include: Orth (first drilled in 1926 and has three actively producing wells), Ringwald (1948) and Silica (1915) situated in Rice County; Kraft-Prusa (discovered in 1900, 21 wells targeted the Pre-Cambrian but only two are currently active), Beaver (1934), Bloomer (1900), Trapp (1900) (one well producing), Eveleigh (1944) and Heinz (1938) all situated in Barton County. Additionally, Hall-Gurney (1930) and Gorham (1924) of Russell County have previously produced hydrocarbons from a biotite rich granite. Each of these fields are small oil pools containing approximately 150,000 bo/well.

Nevada

Within the Eastern Great Basin Province, the Eagle Spring field produces from crystalline rocks –four wells have produced from Oligocene fractured volcanics and currently, two are active.

Oklahoma

Five wells exist within the Hardeman-Hollis Basin, the Amarillo Uplift, and the Anadarko Basin which have historically produced from granite in Oklahoma. The wells are located within five different fields namely: Altus, Altus East, Lake Creek, Liberty and Willow Northeast. The first producing field was the Altus Field (initially drilled in 1935) however these wells are currently inactive.

Pennsylvania

Within the Appalachian Foreland Basin two wells targeted the fractured Silurian Tuscarora quartzite. Both of these wells are located within the Devils Elbow Field but only one is active. The wells have cumulatively produced approximately 2,900 bbl of oil and over 4.5 MMcf of gas. Hydrocarbons were first produced from this formation in 1980.

Texas

It is reported within the Gulf Coast Basin, the Ouachita Thrust Belt and the Bend Arch-Fort Worth Province that oil is produced from basalts, chlorites and serpentinites within the following fields: Thrall (three wells), Chapman, Yoast (21 wells, two of which are active), Dale (at

least one well) and Lytton-Springs (31 wells - 16 currently active). The Thrall oil field was discovered in 1914 and identified oil within serpentinite rocks.

Figure 13. Locations of fractured basement discoveries in North and Latin America (red circles). The turquoise tots indicate significant finds

Utah

In the Utah Great Basin Province there are four wells that have historically produced hydrocarbons from tertiary basalts but at the Rozel Point field they are all inactive. Oil from the basalts was first produced in 1967.

Wyoming

There are 11 wells in Wyoming that have produced from Pre-Cambrian basement rocks. The wells are distributed over three basins, the Green River and Big Horn Basins and the Central Wyoming Overthrust. A total of eight wells are currently active all within the Green River Basin (Lost Soldier and Wertz fields). The Lost Soldier field first produced from the Pre-Cambrian in 1983 and is currently producing minor amounts and has low future potential. Cumulative production from the eight wells is approximately 605,500 bbl.

9. LATIN AMERICA

Brazil

In the Sergipe-Alagoas Basin (Figure 14), the basement play is reported in seven fields, including the Aruari field (discovered 1986), the Carmopolis field (discovered 1963) and the Riachuelo field (discovered 1961). Reservoirs are in highly fractured metamorphic rocks located in horst-type features.

In the Campos Basin, the Badejo (1976), Linguado (1978) and Trilha (1983) fields have Neocomian fractured volcanic basement - the Lower Cretaceous basalts of the Cabiunas Formation is oil producing. These igneous rocks have usually negligible permeability, but where affected by fractures, they may have developed brecciated zones with interconnected porosity [35]. In December 1982, three wells were producing from the Cabiunas Formation at the Badejo field, where combined rates of 5,160 bo/d were reported. Additionally, one well produced at a rate of 2,200 bo/d.

Figure 14. Locations of basins that host fractured basement discoveries in Latin America

Chile

In Chile, the fractured basement play is only observed at the Punta Baja field, which was discovered in 1952 and the Lago Mercedes fields, discovered in 1992. Both fields are situated in the Austral Sub-Basin of the Magallanes Basin. The reservoir consists of Permo-Triassic fractured granites in an overthrust structure. Combined resources/reserves for the two fields amounts to approximately 15 Bcf of gas and 50 Mbo. This basement reservoir is assumed to be productive at Punta Baja and appraisal is ongoing at Lago Mercedes.

Cuba

In Cuba there are oil discoveries in fractured serpentinite. These include the Bacuranao-Cruz Verde field (1955), the Camarioca field (discovered 1971), the Cantel field (discovered 1982), the Guanabo field (discovered 1968), the Jarahueca field (discovered 1943), the Motembo field (developed 1930-45), the Penas Altas field (discovered 1956) and the Santa Maria del Mar field (discovered 1955); all are located in the North Cuban Province.

Venezuela

There are six fractured basement finds in Venezuela. Four are located in the Maracaibo Basin. One of which, the Totumo field, was abandoned in 1947. Two fields are non-developed discoveries in the Falcon Basin. Production from the Pre-Cretaceous basement section is considerable, particularly in the La Paz-Mara area of the Maracaibo Basin [14].

The Caribbean Petroleum Company was the first to discover oil in the Venezuelan basement with the Totumo discovery in 1915. After the completion of two wells and work on a third, the company suspended its activities in 1915. The field was reactivated in 1928 by the Rio Palmar Oil Fields Corporation who completed ten wells in the basement between 1928 - 1929. The whole field was finally abandoned in 1947 having produced approximately 150,000 barrels of 22° API oil.

In Venezuela, basement production is entirely from the Maracaibo Basin; at La Concepcion field (discovered in 1925) approximately 7 MMbo is thought to be recoverable from the basement reservoir. By 1959, at the near-by Mara field (discovered in in 1945) 46 wells had been drilled to the Paleozoic granitic basement reservoir. Reserves in this field are estimated at roughly 110 MMbo. The La Paz Basement which was discovered in 1953, has approximately 350 MMbo reservoired in its Pre-Cretaceous Structural basement play.

10. EUROPE

Norway

As of 2018, basement on the Norwegian Continental Shelf (NCS) has largely been under-explored. Despite the fact that numerous indications of hydrocarbons have been reported in wells dating as far back to the 1960s the play received little attention. The very first well drilled on the NCS in 1966 (8/3-1) was drilled 50 m into basement but it wasn't until recently that this play was proven here. Work surrounding fractured basement plays on the NCS has been focused on the Utsira High. The first indication of the basement potential in this area was proven by exploration well 16/1-4, drilled in 1993. The well encountered gas/condensate in the upper part of the Pre-Devonian basement section at a depth of approximately 1,865 m.

Almost two decades later in 2007, exploration well 16/2-3 was drilled on the Ragnarrock prospect to check the presence of hydrocarbons in the basement and to test its permeability and productivity. The well was drilled 9 m into basement rock to a total depth (TD) of around 1,900 m but only encountered dead oil stains in the upper 7 m. Appraisal well 16/2-4 followed later in the same year encountering oil and gas in basement rocks however, a series of small scale tests showed limited flow properties.

Work to delineate this new play continued in 2009 with exploration well 16/1-12, drilled to target the Luno South prospect. The well proved oil in weathered and faulted/fractured granitic basement beneath a thin, 20 - 30 cm, early Cretaceous conglomerate. The weathered and fractured basement showed moderate reservoir characteristics with an average porosity of 9% and an average permeability of 1 mD.

Drilling continued in 2011 with exploration well 16/1-15 proving a 45 m oil column in weathered and porous /fractured basement. Top of basement was encountered at 1,920 m. The well was subsequently tested and flowed oil at a rate of 650 bo/d. Following the test, the Norwegian Petroleum Directorate confirmed that it was the first successful full-scale production test of a fractured basement reservoir on the NCS. In other words, a new play model had been defined. The basement pay is now part of the Edvard Grieg field, which commenced production in 2015.

A second production test was performed in basement rocks in 2015 when 16/1-25 was drilled to appraise the 2009 Luno South discovery. The well encountered a 30 m gross oil column in porous granitic basement and flowed oil at a rate of 265 b/d.

The basement play on the Utsira High is now proven by the Edvard Grieg in the East Shetland Basin (Figure 15), Edvard Grieg South, Ragnarrock, Cliffhanger North, Rolvsnes and 16/1-4 discoveries. This play may be found in other sub-basins of the Horda Platform but as yet it is unproven.

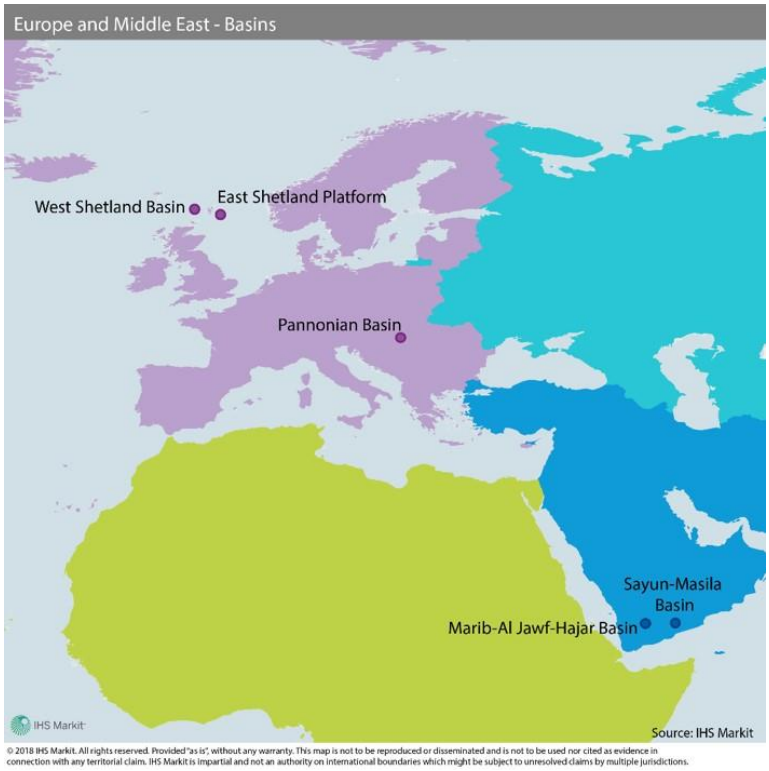

Figure 15. Image showing location of basins with fractured basement discoveries in Europe (pink region)

UK

The Lewisian Basement play in the UK Continental Shelf (UKCS), has until recently, been relatively under explored despite its potential. The Basement play in the West of Shetland was first encountered in 1974 when the Lancaster structure was originally drilled. Well 205/21-1A targeted the Mesozoic sediments overlying the Basement but actually encountered traces of oil over a 75 m section in the Pre-Cambrian Basement. At the time, the potential of this as a reservoir was dismissed. Further drilling in 1977 resulted in the discovery of the giant shallow Paleozoic Clair field (Figure 16). The field's main reservoir is of Devonian/Carboniferous age. However, well 206/7-1 also penetrated a 200 m oil column in the fractured Lewisian Basement. Oil density was 23° API and flowed approximately 965 b/d. This was followed by an appraisal well which tested the basement via a 530 m horizontal section. After acidification, production rates from the basement were reported at 2,110 bo/d from an interval with five fracture zones. Production from the Clair field commenced in February 2005 and up to 2016 has produced over 100 MMbo from the Clair Group - Lewisian Complex reservoir.

Following on from these two successes a series of basement discoveries were made in the West of Shetlands. Typhoon proved the presence of hydrocarbons in 1981 and Whirlwind (operated by Hurricane) in 1999. The company is now focusing mainly on developing the basement play in this area, and in October 2016 it completed testing the Lancaster discovery. Results from a horizontal sidetrack proved that with an electric submersible pump (ESP) flow rates of 14,500 bo/d were achievable. The well was suspended as a future producer with first production expected in 2019. Hurricane had further success in December 2016 when it discovered Lincoln. The company believes Lincoln to be an analogue of Lancaster, with the two structures separated by a sealing fault. Lincoln could contain in excess of 550 MMbo. As of August 2018, alongside developing Lancaster, Hurricane is focusing on the Warwick prospect which is expected to be an extension of the Lincoln discovery.

The East Shetland Platform also has hydrocarbons in a basement play. In 1990 the Cairngorm prospect was found to be hydrocarbon bearing by Marathon. Exploration well 16/3a-11Z encountered oil in a fractured granite reservoir and upon testing, the well flowed 40° API oil

at an approximate rate of 2,000 b/d. Appraisal drilling took place in 2008 and 2013, the results of which concluded that a great deal of uncertainty remained on recovery potential and more information was required on the fault/fracture distribution.

Hungary, Croatia, Serbia

Pannonian Basin

The Pannonian Basin is built-up from microplates enclosed by the Carpathians, the Alps and the Dinarides. It covers Hungary, the north-eastern part of Croatia, the north-western part of Romania, the north of Serbia and some small areas in Austria, Slovakia and Bosnia Herzegovina. The highly fragmented basement, composed mainly of metamorphic rocks, has developed through a series of complex tectonic events throughout the Jurassic and Cretaceous.

The arrival of significant volumes of sediment in the Neogene triggered faster subsidence, resulting in the formation of basement uplifted highs separated by deep trenches. The deepest are the Mako Trench and the Bekes Basin. Fractured basement plays an important role in the petroleum system of the basin. It serves as a pathway for the hydrocarbons from deep trenches, where they are generated and overpressured. This explains one characteristic of the basin: most fields lie above Palaeozoic highs with Pannonian reservoirs usually forming curved arches over them.

Exploration and testing of the fractured basement in the Hungarian Pannonian Basin began in the late fifties. In 1959, the exploration well Nagykoros Del 1 tested up to 28 MMcf/d of gas from granite. The gas was of poor quality and the well was abandoned. Between 1959 and 1963, tests were conducted in the quartzite and granite of the Battonya field in 16 wells. Flows up to roughly 4 MMcfg/d with minor condensate or up to 300 bc/d with minor gas were measured. The field is still producing.

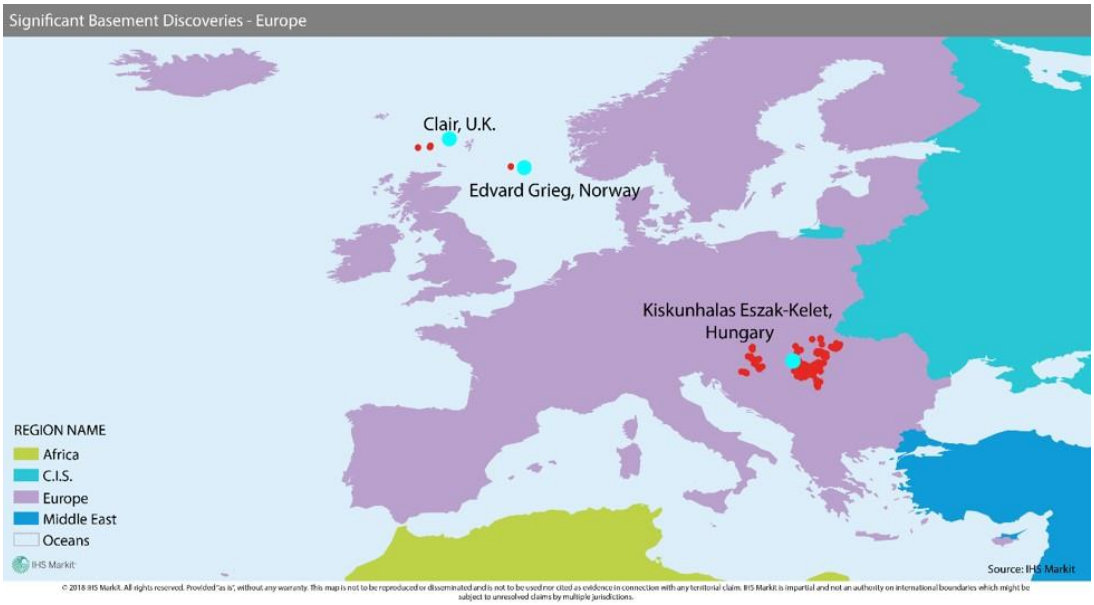

Figure 16. Image showing the location of fractured basement fields in Europe (red circles), turquoise dots indicate significant finds

In total, more than 300 wells had tests in the fractured basement, most of them before 2000. The biggest gas flows were measured in the Sarkadkeresztur field in 1982 with up to 85 MMcfg/d and 300 bc/d coming from the metamorphic rocks. In 1980, the Szeghalom field tested 50 MMcfg/d and over 300 bc/d from the metamorphic basement. The biggest oil flows were measured in the Kiskunhalas Eszak-Kelet field in 1974 with almost 1,400 bo/d streaming from gneiss. The Kiskundorozsma field recorded 1,100 bo/d in 1992 from the mica schist basement.

According to studies carried out in Hungary, the quality of basement rocks as reservoirs is highly variable and depends mainly on the rock type which influences preferred fracture orientation, the extent of the fractures and the fracture connectivity.

Many basement discoveries also exist in Croatia (e.g., Sumecani discovered in 1948, currently shut-in), Romania including the Nadlac field, which was discovered in 1979 and the Zimandu Nou field discovered in 1990 and Serbia (e.g., the Kikinda field).

11. Synthesis

11.1. Discoveries

This analysis shows that hydrocarbon in basement reservoir discoveries exist in just 29 countries (Figure 17). Globally, there are more than 640 discoveries. Africa is a frontier area with only 27 discoveries; the same applies to the Middle East with only 24, all of which are situated in Yemen. The centre of development for fractured basement plays is the Far East (50%), over 260 fields are located in the region with China hosting most (> 160). This is followed by Europe (19%), the C.I.S. (dominated by Russia, 15%), North America (4%), Latin America (3%), Africa (3%) and the Middle East (3%) solely represented by Yemen, and finally Australasia (< 1%) (rounding errors).

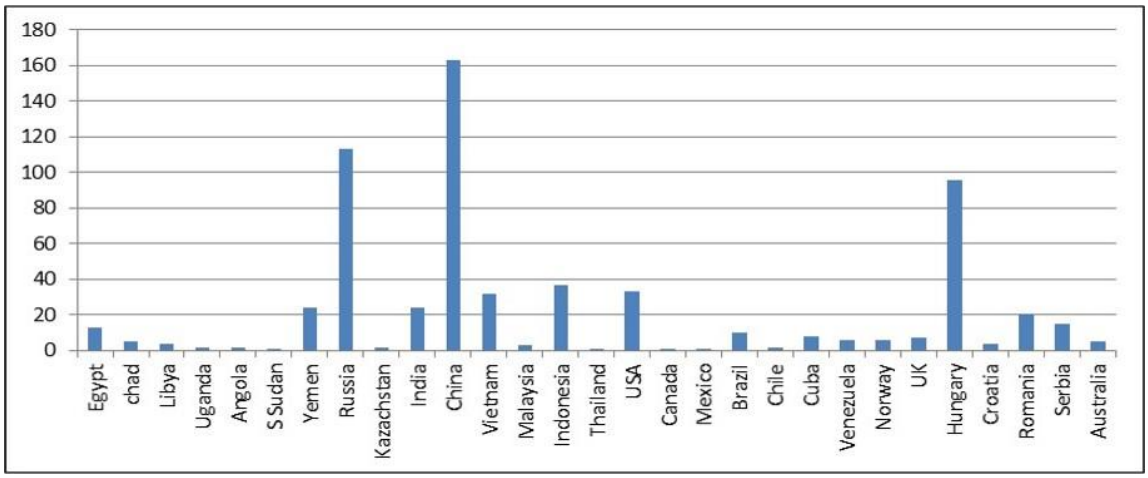

Figure 17. Approximate number of basement finds per country with number producing

11.2. Estimated ultimate recovery

The EUR (2P/2C) associated with these discoveries are at best rough estimates. The total discovered recoverable volume amounts to roughly 15,000 MMboe or ca. 0.001 % of global EUR (BP (2016) and IHSM (2016)).

Most of these volumes (Figure 18) are located in the Far East (56%), followed by Europe (19%), the C.I.S. (9%), Africa (7%), Latin America (5%), Middle East (3%), North America (1%) and Australasia (< 1%). The discoveries are clearly dominated by single large fields. The bulk of reserves are currently located in the Far East; the largest volumes are found in Vietnam and China.

11.2.1. Largest fields

The average field contains some 22 MMboe (average of volumes / fields) of recoverable oil and gas. However, volumes across the globe show a large range and a dominance of a few large fields (Figures 5, 8, 10, 13 and 16).

11.2.2. Number of productive fields

Approximately 220 fields (Figure 21) have produced from the basement. The majority (86 fields) are located in the Far East (39%). This is followed by Europe (21%), CIS (14%), North

America (11%), Africa (7%), Latin America (4%) and the Middle East with 8 previously productive fields (4%). Australasia has no production at present (last production from 1 field in 2002). Please refer to Figure 17.

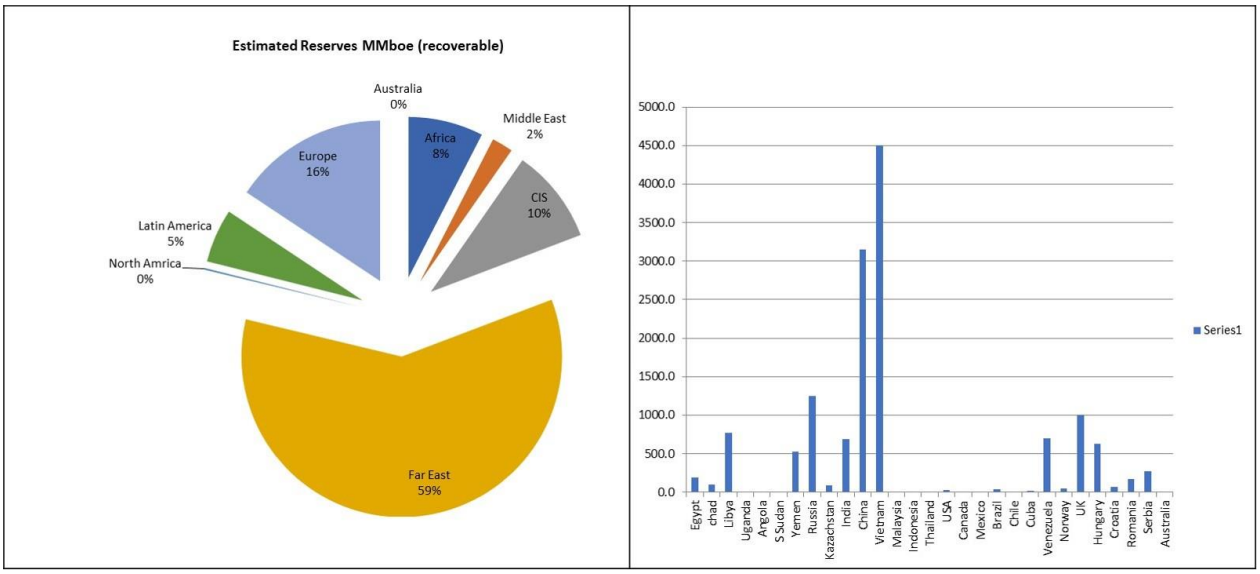

Figure 18. Pie chart showing estimated recoverable reserves (EUR) per region and country (MMboe) (bar chart)

11.2.3. Maximum production rates

Maximum production is highly variable (Figure 19). The architecture and properties of the fracture network are significant controls on well deliverability. Reported well rates vary between 10 bo/d to 30,000 bo/d. This range likely reflects fracture intensity and connectivity. This synthesis suggests that the play has significant exploration potential and warrants a relook at producing assets to unlock its full capacity. Please note that there are gaps due to unreported data.

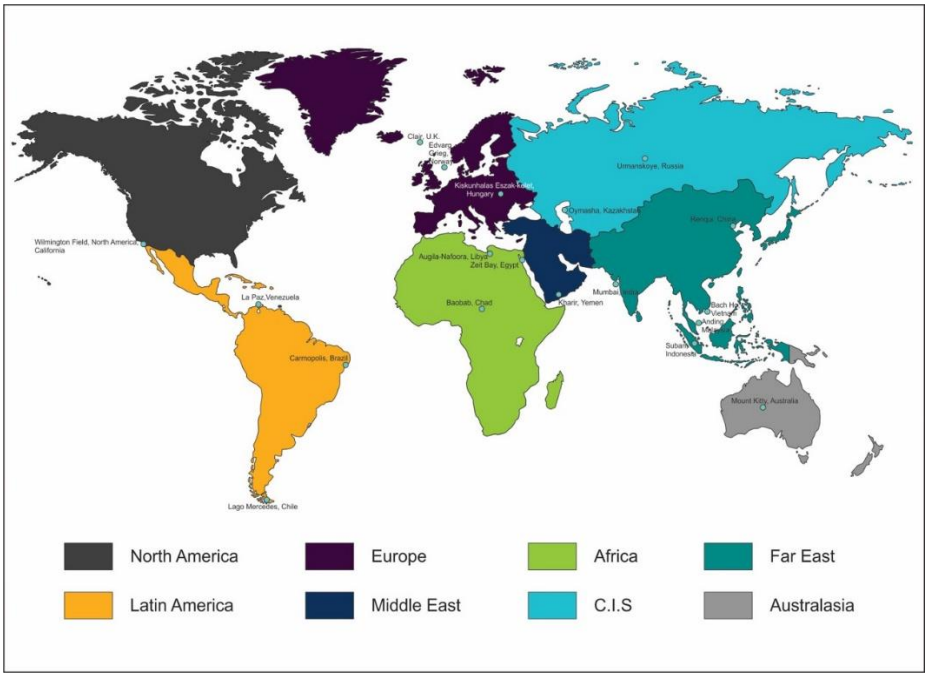

Figure 19. Maximum individual well rates for selected countries

12. Petroleum system

Components of the basement petroleum system resemble conventional plays (Figure 20).

12.1 Seal and source

Source and top seal are typically the same lithology, mostly organic rich claystone or marl onlapping and draping the reservoir. Because there is no source underneath the reservoir, lateral or downward charge or invoked (Figure 20).

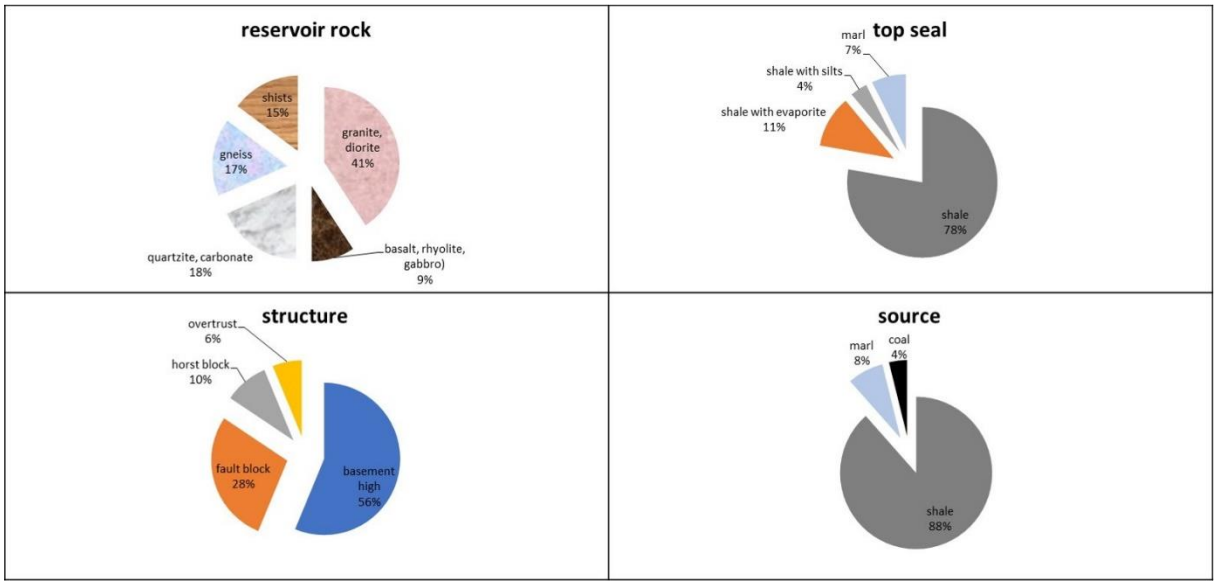

Figure 20. Common lithologies of reservoir, source and seal and nature of structure for fractured basement plays from selected global examples

12.2. Reservoir

The reservoir is mostly provided by brittle magmatic intrusiva. The most commonly encountered lithology is granite, with porosity and permeability associated with fractures that can be solution enlarged. Other common reservoir types included effusive magmatic (basalt, thuff) or metamorphic rocks such as gneiss, quartzite or marble. Less common are pelitic metamorphic rocks.

12.3. Structure

Hydrocarbons are stored in structural highs, most commonly fault blocks or buried hills.

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