HYDROCARBON PRODUCTION FROM PALAEozoic CLASTIC AND CARBONATE RESERVOIRS

INTRODUCTION

This is a compilation of public-domain information about commercial hydrocarbon reservoirs in fractured Palaeozoic formations from approximately 13 different countries.

It is a new compilation which closely relates to our fractured basements review but which looks specifically at reservoirs in Cambrian to Permian formations. As a ‘Version 1’ it is undoubtedly incomplete but we will aim to update and develop it on a regular basis. 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 In addition, some of the information, for example on production, may be out of date since it is based on historical sources.

Just as with the crystalline basements, most of the Palaeozoic formations have a pretty tight matrix and therefore sustainable production relies on the presence of secondary porosity in the form of well connected fracture systems and/or alteration effects such as weathering dissolution in carbonates.

*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.*

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Algeria

El Gassi

El Gassi is located 60 miles south west of Hassi Messaoud in central Algeria and is closely linked in with neighbouring fields El Agreb and Zotti. As found in the Rhourde el Baguel field the predominant reservoir rock of the area is Cambrian quartzite sandstone. This tends to have low permeability, be diagenetically modified and characterised by a complicated network of faults and fractures Sonatrach joined with Amerada Hess in 2000 to exploit the estimated remaining 300 million barrels of oil with the hope of reaching a production rate of 45,000 barrels of oil per day (Amerada Hess, 2000).

Hassi Messaoud

Hassi Messaoud is the largest oil producing reservoir (categorised as a Super Giant reservoir) in Algeria with total proven reserves of 6.4 billion barrels of oil. Production in 2008 had reached 400,000bbls/d, a figure which Sonatrach (field operator) is hoping to increase within the next few years (Oil and Gas Directory, Middle East, 2011). A series of Cambro-Ordovician sandstones serve as the predominant reservoir rock of the field which are commonly subdivided into four separated divisions; R3, R2, Ra and Ri (See figures, taken from Sabaou et al., 2009). “Ra” is the most productive Cambrian reservoir of Hassi Messaoud. The sandstones are deposited on top of igneous and metamorphic basement rocks and are said to be characteristic of cratonic environments which were unstable during the Cambrian due to phases of extension and compression from the Pan African Orogeny (Sabaou et al., 2009).

Faulting within the area follows a NE-SW or E-W trending pattern. Wells MD 251, MD 264, and MD 340 were based around one of these NE-SW trending faults in order to test fracture intensity. Well MD 251 was situated 0.5km south of the chosen fault and displayed a low fracture intensity which was mainly stratabound. Well MD 264 was located 0.1km south of the fault line, open fractures here were rare but porous fractures were more common with a fracture intensity of 1.5m⁻¹. Finally, well MD 340, only 0.1km north of the NE-SW fault line contained both open and porous fractures and a high fracture intensity of >5m⁻¹. The figures show the exact location of Hassi Messaoud field with respect to the rest of Algeria but also the nature and scale of the NE-SW trending faults (taken from Sabaou et al., 2009).
Lithostratigraphical column showing the four divisions of the Cambrian reservoir rock (figure taken from Sabaou et al., 2009).

Location map showing the exact location of the Hassi Messaoud Field within Algeria and showing the clarity of the NE-SW trending faults within the area (taken from Sabaou et al., 2009).
Rhourde el Baguel Field

Discovered in 1962, the Rhourde el Baguel Field is situated in the Ouargla Province in Eastern Algeria. ARCO (now part of BP) started development in the field in 1997 and by December 2000, 37 new wells had been drilled and 38 producers were active in the region. By the time the redevelopment phase had begun, Sonatrach and ARCO had produced 430 MMBO (15% of oil in place) (Robinson et al., 2000). The reservoir contains an estimated 3 billion barrels of undersaturated light oil within a 550m succession of Cambrian sandstones (occasionally interbedded with small portions of shale). With increasing depth the matrix porosity of the reservoir increases and the matrix permeability decreases. The lower 2/3 of the reservoir (zone 1) consists of “strong sandstones” with 11% porosity and an average permeability of 0.25-0.4 md, contributing to 15% of total recovered oil; whilst the upper 1/3 (top 170m) of the reservoir includes “very strong” quartz rich sandstones with 8% average porosity and 13 md permeability. The upper zones (2-6) therefore account for the most productive reservoirs, in particular zones 6A, 5B and 5A which contain the most interconnected fractures.

A noticeable divide can also be seen between the southwest and central parts of the field (containing more open fractures) and the northern part of the field (containing no open fractures). Faults as well as fractures also influence productivity within the field as they increase permeability, therefore wells that intersect these fault lines yield higher productivity than cross strike fractures (Wilkins and Belfield, 1998).

Tiguentourine Field, In Amenas

Situated in Eastern Algeria, in the southern part of the Illizi Basin, the Tiguentourine field is a gas condensate deposit in a Cambrian and Ordovician glaciogenic sandstone reservoir. Well connected natural open fractures make this reservoir viable for drilling and the area has been taken on as a joint venture between Statoil, BP and Sonatrach (EAGE Conference and Exhibition, 2007). Since the 1950’s, approximately 40 wells have been drilled by the above enterprises for “exploration, appraisal and development purposes” (North African/Mediterranean Petroleum and Geosciences Conference and Exhibitions, 2007). Production rates and total reserve values are unavailable.

Argentina

Tarija Basin

Situated in northern Argentina, the Tarija Basin has a network of natural fractures contributing to high secondary porosity and enhancing the potential reservoir volume of this mostly unexplored hydrocarbon play. Oil and gas migration and generation in this area coincide with the formation of a serious of recent (9Ma-present) anticlinal structures. The Tuyunti structure within the Tarija Basin is owned by Pan-American Energy (52%), Shell Capsa(22.5%), Repsol-YPF (22.5%), Apco (1.5%) and Northwest(1.5%) – ownership details from figures published in 2004. Palaeozoic, Silurian and Devonian quartzite sandstone units are strongly lithified, forming the fractured gas reservoirs. Further exploration of the area is due to take place (Sanders et al., 2004).
China

Junggar Basin-Karamary Oilfield
Situated in the Northwest of China, the Junggar basin covers an area of 130,000km² and has gained commercial success along the Karamary thrust belt since 1955. Exploration of the Karamary Oil field is permitted by the Karamary Oil Company (KOC) and in 1990 they estimated reserves at 200-300 million barrels. The most productive source rocks within the basin are primarily Permian lacustrine sediments; hydrocarbons migrate north-westwards out of these deep Permian source rocks and accumulate in Permian and Carboniferous reservoirs. Current production values of the area are unavailable, however in 1984, “Karamary was producing 75000 barrels a day” (Lawrence, 1990).

Tarim Basin- Manjiaer Sag
The Tarim basin is of the same origin and evolution as the Junggar Basin, only larger, 906,500km² (Lawrence, 1990). Three main source rocks of different ages (Mid-lower Cambrian, Mid-lower Ordovician and Upper Ordovician) are found within the Manjiaer Sag. Mid-lower Cambrian source rocks include both a muddy and a limey rock with thicknesses of 50-150m and 100-200m respectively, these produce high temperature pyrolysis dry gas. Mid-Lower Ordovician black siliceous rocks dominate the eastern part of the Manjiaer Sag and produce commercial amounts of oil and gas, type I and II. Upper Ordovician source rocks occur in laminated band deposits or troughs and contain types I, II and III prone oil, this source is not exploited commercially (Meng-jun et al., 2008).

With regard to possible future production within the area, PetroChina claim that recent “strategic discoveries in major exploration areas such as the Tarim Basin, lay solid foundations for the 17th Peak Growth Oil and Gas Reserves Program” (PetroChina, 2008).

Shanxi Formation – Ordos Basin
Situated in the north-west of China, the lower Permian sandstone reservoirs in the north-eastern part of the Ordos Basin are a prolific Palaeozoic hydrocarbon reserve which covers an area of 320,000 km². The main source rock comes from Upper Palaeozoic coal seams in dark mudstone found within the Upper Carboniferous and Lower Permian Strata. Although the reservoir rocks are typically ‘tight Permian sandstones’ there are three combinations of reservoir-cap rocks in which gas pools have been found: Upper Carboniferous Taiyan formation carbonate and argillaceous carbonate; Lower Permian Shanxi formation interbedded sandstone & mudstone and Lower Permian Xiashihezi formation sandstone and Upper Permian Shangshihezi formation interbedded mudstone & mudsiltstone. Combinations 2 and 3 are the most important in terms of gas reserves (Xiao et al., 2005). Exploration of this area commenced in 1907 (Zhu et al., 2008).

Czech Republic
The Liten formation in the Barrandian basin, Czech Republic, contains 2.4% total organic carbon content and is considered a potential petroleum source rock. There are three
distinguishable phases of hydrogen migration which occur within quartz and calcite veins, cross cutting dolerite dykes. These are represented by solid bitumen (oldest phase), “liquid petroleum within fluid inclusions” (second phase) and a semi solid wax blanketing the veins (youngest phase) (Suchy et al., 2010). The source of the oil is thought to originate from multiple Silurian source rocks; although the potential reservoir rock of Cambrian arkoses and sandstones has been identified, it is yet to be exploited.

Iraq

The western deserts of Iraq remain a largely under-explored area, however they are thought to hold significant hydrocarbon potential. There are two ages of Palaeozoic source rocks within the area; lower marine “hot” shales and Upper Ordovician black shales of the Khabour formation. Reservoir rocks vary in age and include Cambrian, Ordovician and Early Silurian Sandstones, reservoir quality however is a major exploration risk as some of the reservoir rocks may have been affected by quartz overgrowth (Aqrawi et al., 2012).

In Kurdistan, current exploration and appraisal drilling is proving reservoirs hosted in Triassic sequences formed by carbonates, dolomites, shales and anhydrites.

Libya

Libya is Africa’s largest distributor of oil, having produced approximately 20 billion barrels of oil to date. Although much of this has come from Mesozoic and Cenozoic reservoirs, Palaeozoic reservoirs also present an equally large potential resource for Africa.

The Murzuq Basin

The Murzuq Basin is an example of an Ordovician glaciogenic reservoir in western Libya, approximately 350,000 squared kilometres. Until the 1980’s the search for hydrocarbons within this basin was unproven. Since then, large discoveries in Upper Ordovician (Hirantian) sediments have been made, including the Elephant and El Shahara fields containing 1-1.5 billion barrels of potential reserves (Le Heron et al. 2005). These discoveries were subject to a “successful European exploration programme” 25 years ago (Le Heron, 2007).

Al Kufrah Basin

The Al Kufrah Basin is the most easterly of the great Palaeozoic sedimentary basins in North Africa. It covers a vast area of 400,000 km² which is largely yet to be exploited, however exploration of the region did commence in 2005. Holes are due to be sunk following the country’s civil unrest by Germany’s largest producer of crude oil and natural gas, Wintershall (who have been working in Libya since 1958) and Italian company ENI (Le Heron and Howard, 2011). The source and seal rocks of these Ordovician glaciogenic traps are the “hot shales” of the lower Silurian, whilst the reservoir rocks are comprised of Cambro-Ordovician sandstones. Factors making this region such a major potential reservoir include the thickness of the Hawaz Formation at the base of the succession (300m), the lack of shale;
unconformities, indicating a “well connected reservoir with few barriers prohibiting fluid flow” and significant faulting (Le Heron and Howard, 2011).

The Jebel Hadrid structure within the Kufrah basin is a circular structure measuring approximately 4.7 km in diameter. It was originally thought to have formed from endogenic processes, however recent research has led to the conclusion that it could be an impact crater. Two other craters have also been identified in Libya. This, in turn has sparked an interest for further exploration within the crater as there are many highly productive reservoirs formed from impact throughout the world. For example the Cantarell oil field within the Chicxulub crater (Mexico) produces 1.3 million barrels of oil per day, of which, 60% comes from the K-T breccia (Grajales-Nishimura et al, 2000). Two potential major plays have been identified within the Jebel Hadrid crater (Schmieder et al., 2009):

1. A Palaeozoic play with a source rock of “hot shales” from the Tanezzuft Formation and a reservoir rock of Cambro/Ordovician sandstones.
2. An Infracambrian play with source rocks of black shales and organic rich limestones and reservoir rocks of sandstones and fractured limestones.

North Africa

Exploration for petroleum from Palaeozoic reservoirs in North Africa began in the early 1950’s throughout Libya, Algeria, Tunisia and Morocco. In 1952 the first well was sunk in the Sahara Desert, Algeria and since then a further 330 hydrocarbon accumulations from Palaeozoic reservoirs have been found with an estimated recovery of 46 billion barrels of oil (Traut et al., 1998). Glaciogenic reservoirs, in particular Hirnantian deposits hold great economic significance over central North Africa with Palaeozoic, Early Silurian shales as the predominant source rock (TOC values measured 4.5% in eastern Marocco) (Le Heren et al., 2009).

Figure from Le Heren et al., 2009 – Map showing glacially related deposits of Paleozoic and Phanerozoic age.
Ghadames Basin

An intra-cratonic basin covering 350,000 km² including portions of Algeria, Libya and Tunisia. Over 700 exploratory wells have been drilled within the basin, discovering approximately 160 oil pools from Ordovician, Silurian and Devonian Palaeozoic source rocks. The basin is bounded by the Dahar Naffusah high in the north and the Qarqaf Uplift in the south.

Total oil in place within the Ghadames basin for Algeria is 5758 STOIIP whilst the total number of fields is 57. These figures for Libya and Tunisia are slightly lower: 3347 STOIIP with 61 fields and 550 STOIIP with 5 fields respectively. Production from Ordovician and Devonian reservoirs comes from the southern flank of the Ghadames basin because of the sandier facies and improved petrological features. Oil production from these reservoirs is more prolific in Algeria. For example the Ordovician quartzite sands found by AGOCO and AGIP in the Hamra High and the Devonian sandstone oil fields of Bir Rebaa, Rhourda, Messoud and Bir Berkine on the western flank of the Ghadames Basin (Echikh, 1998).

Silurian source rocks in the north-western part of the basin, in the lower Acacus provide a lucrative region of oil in Libya, including 22 oil fields and 3 gas fields. Although major new discoveries have already been made throughout this region “studies obtained by foreign companies” (Echikh, 1998) in partnership with Sonatrach have found evidence for further untapped potential in Silurian and Devonian source rocks in Algeria and the Illizi region in Libya.

Oman

Salt basins in Oman were formed from rifting during the late Precambrian and were preserved by uplift during the Hercynian. They host Precambrian, Palaeozoic and Mesozoic reservoirs which are charged by Precambrian source rocks as a result of the Hercynian uplift (Afifi, 2005). The Al Khlata Formation is a major productive hydrocarbon bearing province in Oman, with an estimated 3 bbl of oil in 1998. Palaeozoic glaciogenic reservoirs play a key role in the preservation of oil in many active basins throughout North Africa, including in the Al Khalata Formation. Hence, approximately 20 fields in the Ghaba and Nafud salt basins are accounted for by “glacial fluvial and glacial-lacustrine sandstones” (Le Heren et al., 2009).

Eastern Flank Hydrocarbon Province

Situated on the south-eastern edge of south Oman, the Eastern Flank Hydrocarbon Province defines a belt of oil zones measuring 30-70km wide and 300km long which was discovered by PDO in the 1970’s. By 1986 a total of 2x10⁹m³ of oil had been discovered and there were 6 producing oil fields found in low relief anticlines. Although primary recoveries were low (5-7%) the success rate of oil finding was high (60-70%) due to hydrocarbons migrating beneath the salt traps. Enhanced oil recovery techniques were due to take place in south Oman to improve the low recovery rates (Al-Marjeby and Nash, 1986).

Khazzan Makarem

The Kazzan Makarem field is situated in block 61 in the centre of Oman. The reservoir rock
is composed of PreCambrian and Palaeozoic clastic sedimentary formations (GeoScience Report) and covers a vast area of 2800km², containing an estimated 20-30 trillion cubic feet of natural gas. BP is the main operator of the area with 100% working interest as the company has the required technology to deal with the type of “tight gas” found in this area (BP, Upstream major projects – Middle East, 2012). Gas production from the Khazzan Makarem field is due to commence at the end of 2016, this was announced in July 2012, by Shaikh Ali Bin Thabit al Battashi, advisor to the Ministry of Oil and Gas.

Poland

Zechstein Plays
Located in the central lowlands of Poland the Zechstein Plays are composed of Permian reservoirs of sandstone or dolomite which host hydrocarbons sourced from shales formed approximately 250-270 Ma. These formations are sealed by Zechstein rock salt and contain both oil and gas. Aurelian Oil and Gas is a major producer in this region and holds a 35% interest in the Cybinka/Torzym basin, including the Meidzychod and Lubiatow fields which contain 7 billion m³ of gas and 30 million barrels of oil (discovered 2003). Aurelian also holds a 50% interest in block 249, Kalisz and a 90% interest in blocks 207, 208 and 206 in the East and North Pozan regions (AurelianOil, 2012).

Russia

Pechora Platform
Exploration of the Timan-Pechora basin has been carried out onshore throughout the past 50 years, revealing one of Russia’s most productive hydrocarbon basins. However offshore exploration in this area is still in its infancy with only five commercial discoveries of oil and gas between 1988 and 1998. The basin harbours two main source and reservoir rocks.
Firstly, the Domanik shale source rock (average thickness – 20-60m) hosted by Permo-Carboniferous reservoir rocks and secondly: Silurian-Lower Devonian source rocks, found in Lower-Mid. Devonian carbonates. Reservoir rocks vary in thickness from 9-19m. The Permo-Carboniferous reservoir rocks have enhanced porosities of up to 16-17% from dolomitization (Martirosyan et al., 1998).

90% of recoverable oil offshore from the Pechora Platform is found in Permo-Carboniferous carbonates with a further estimated 30% of undiscovered reserves expected in both the Permo-Carboniferous and the Siliurian-Devonian reservoirs. Figures published by Martirosyan et al., 1998, show the recoverable amount of offshore oil to be 111 x 10¹² BBLS and gas to be 96 x 10¹² SCF. Furthermore, operations from Gazprom are scheduled to start in the Prirazlomnoye oil field of the Pechora Basin later this year (2012). This field contains an estimated 72 million tons of oil reserves which would result in an annual production of 6.6 million tons (Gazprom, 2011).

Porosity and permeability in the Pechora Platform vary according to the reservoir rock. Sandstone reservoirs of the Lower Palaeozoic have an average porosity of 11.5% and an average permeability of 15md. Carbonate reservoirs have a low average porosity of 9% in the Lower Palaeozoic rocks and a high average porosity of 15.8% in the Lower Carboniferous reservoir rocks. The carbonate reservoirs contain a range of permeability’s from 63-930md. These significant carbonate plays were formed by tectonically controlled Upper Devonian and Lower Permian shelf edge reefs.
Within the Pechora-Barents basin, 3 types of carbonate reservoir have been identified. These are the “Upper Moscovian – Lower Sakmarian warm water carbonates, Upper Sakmarian – lower Artinskian cool water carbonates and Upper Artinskian –Kazanian cold water carbonates” (Mironcheva et al., 2007). Although these reservoirs have been identified as a future prospect for hydrocarbon exploration, the amount which they yield is yet to be confirmed.

Chuzik-Chizhapka

Chuzik-Chizhapka is a region of oil and gas accumulation within the Parabel District. Host rocks vary in age from pre-Jurassic basement rocks to limestones on the Palaeozoic-Mesozoic boundary. Potential petroleum bearing reservoir rocks from pre-Jurassic lithologies include volcanics and Late Devonian argillites. These form the Sel'Veika field and the Chaga formation, contributing to the “largest accumulation of Palaeozoic oil” in Siberia (Kontorovich, 2007). The most favourable reservoir rocks in this area include organic limestones found in regions of low uplift. Although these potential Palaeozoic reservoirs have been identified, they are yet to be exploited.

Thailand

The Khorat Basin

The Khorat Basin has a total area of 200,000km², covering major parts of northeast Thailand and western Laos. The basin includes three main areas of exploration (started by Exxon 1981) Phu Horm, Nom Pong and Dong Mun. Developed Permian carbonates of Late Wolfcampian-Early Guadalupian age account for the predominant reservoir rocks which are reputed for having low permeability, therefore the presence of any microfractures leads to good productivity (Kozar et al., 1992). Phu Horm is currently the only gas producing field in the basin; however several other potential gas fields have been discovered (Smith and Stokes, 1997).

Phu Horm

Phu Horm is a deep gas development in the north-eastern corner of Thailand above the Khorat Plateau. The field is located close to the borders of Laos and Cambodia approximately 45km north of the Nam Phong gas field and has an area of 231.6km². Exploration of the area has been carried out since 1983 when the first well Phu Horm-1 was drilled in the northern end of the Phu Horm anticline. In May 2002 drilling commenced for well Phu Horm-3 (carried out by Amerada Hess) with the target depth of 2,900m and the aim to intersect the Permian Pha Nok Khao Dolomite. The carbonate reservoir rock consists of heavily dolomitised skeletal wackestones and packstones with only a fair matrix permeability and an average porosity of 4.2%, macro and micro features increase the productivity potential of this area. Initial rates of production were calculated at 6 million cubic feet per day with the intention of raising this to 100 million cubic feet per day (PTTEP, 2006). By 2011 production from Phu Horm averaged at 85.91 million cubic feet per day of natural gas and 392.22 Bbls per day of condensate (Gulfport Energy Corporation, 2012). Estimated reserves for the Phu Horm field stand at 300-500BCF (Smith and Stokes, 1997).
United States

Alaska

Lisburne Group

The Lisburne group is situated in the north eastern corner of Alaska, next to Prudhoe Bay and was discovered in 1968, with peak developments in the mid-1980’s. The Lisburne group is the “only carbonate field developed in Alaska” (BP, 2007) and is composed of interbedded dolomite mudstones and grainstones. The fractured carbonate reservoir spans an area of 100 square miles and is Mississipian- Pennsylvanian in age. Estimated original oil in place has been calculated at 3 billion bbls with a 15% recovery factor of around 450 million barrels. There are two sets of fractures which play an imperative role in the porosity (2-18%) and permeability (1md) of the group; these are E-W fractures parallel to the fold axes which formed late during folding and N-S fractures, perpendicular to the fold axes which formed post folding. The N-S fractures tend to be much larger than the E-W fractures and have a greater possibility of interconnecting, therefore wellbores perpendicular to the N-S set strike hold the most potential for oil recovery. Stratigraphy also influences fracture density as the dolomites are more heavily fractured than the grainstones, hence the best developed reservoir is in the dolomites.

Nevada

Blackburn Oil Field

The Blackburn Oil Field in Pine Valley, Eureka Country, Nevada was discovered in 1982 by Amoco Production Company. Heavily fractured Devonian dolomite serves as the principle reservoir rock as petroleum here is found in “fractured, locally brecciated, microcrystalline to finely crystalline dolomites of the Devonian Nevada Group” (Hulen et al., 1990). Other fields within the area are hosted by fractured carbonates, for example the Grand Canyon field (produced over 6 M bbls/day, 1990). Hydrothermal fracturing of the reservoir rocks is thought to have originated from magmatic activity beneath the Blackburn Oil Field increasing the porosity (5.3%) and permeability (21 md) of the area (Hulen et al., 1990).

New Mexico

Sin Nombre Area

The Sin Nombre area in New Mexico is located north of the Permian Basin and south of the Tucumcari Basin, covering an area of approximately 7000 m². In the south east and south-central parts of the area, 100 BCF gas and 6 million barrels of oil have been produced from 17 oil pools, however the Sin Nombre is not well explored and there is significant potential for greater reserves. Permian sandstone from the Abo Formation serve as reservoir rocks hosting gas, whilst Silurian Fusselman dolostones and Pennsylvanian limestones are the predominant reservoir rocks for oil. Hydrocarbon production surrounding Sin Nombre has
been very lucrative, for example during 2000 “63.8 million bbls of oil and 553 billion ft³ (BCF) gas were produced” (Broadhead, 2003) suggesting that further exploration of this area would be beneficial.

Texas

Texas is the main petroleum producing state of the Palaeozoic dolomite reservoirs of the Permian Basin in the USA. The basin extends into the south east of New Mexico, contributing to the production of over 26 billion barrels of oil since the 1920’s. Texas contains 120 major fields of Palaeozoic reservoirs, divided into four main groups by age.

1) The San Andreas/Grayburg dolomite reservoirs, Upper – Middle Permian in age. These reservoirs include the “largest in the Permian Basin” (Saller, 2004). Production forecasts indicate that a combination of three of the reservoir fields will recover more than 1 billion barrels of oil.

2) Abo, Clear Fork and Glorietta reservoirs, Lower-Middle Permian, dolomite. These reservoirs vary in size, retrieving anything from 10-220 million barrels.

3) Siluro-Devonian reservoirs. Dolomite reservoirs with a small area and a low porosity.

4) The Ellenburg carbonate reservoir, Ordovician in age. The oldest and deepest in the Permian Basin, a well connected fractured dolomite reservoir, owing its porosity to the collapse of an intricate cave system.

Oxy is the number one oil producer in the Permian Basin of South Texas, owning 138,000 net acres and over 1000 active wells in the area (Oxy, 2012).

Barnett Total Petroleum System

Within the Barnett system, five conventional hydrocarbon plays have been identified and one unconventional play. The five conventional plays have been assessed to contain as much as “381 million barrels of oil, 103.6 million barrels of natural gas liquids, 479 billion cubic feet of associated gas and 1,029 BCF of non-associated gas” (Pollastro et al., 2003). Reservoir rocks range from Ordovician to Permian in age and compositions vary accordingly. Ordovician, Mississippian and Early Pennsylvanian ages are represented by carbonate reefs, predominantly limestone pinnacle reefs. The more productive clastic reservoirs of Middle Pennsylvanian to Lower Permian age are composed of sandstones and Band Group Conglomerates, this sequence is also thinly bedded with limestone and holds a cumulative production of 3TCFC. Cumulative production of these conventional reservoirs had reached 2 billion barrels of oil and 7 trillion cubic feet of gas by 1995. The Mississippian-Pennsylvanian Barnett Shale is the one source rock of the area and is also the one unconventional hydrocarbon play (fractured Barnett Shale). It produces high quality oil (35-50°API gravity, low sulphur) and shows the greatest promise for future exploration (Pollastro et al., 2003).
Generalized stratigraphic subsurface section of USGS Bend Arch-Fort Worth Basin Province showing stratigraphic extent of Barnett-Paleozoic Total Petroleum System, source rocks, producing oil and gas reservoir units, seal rocks, and proposed assessment units. Taken from http://www.searchanddiscovery.com/documents/pollastro/images/article.pdf [accessed 27/07/2012]
San Andreas Reservoir at Keystone Field

Keystone Field is situated in Winkler Country, Texas. The Permian San Andreas Reservoir is the predominant hydrocarbon bearing unit in the area and is part of the San Andreas platform carbonate from the Central Basin platform play. The shallow marine to tidal flat carbonate facies reservoir is heavily dolomitized inducing low permeabilities of less than 1md, despite this, productivity has been relatively high from northeast-southwest natural fractures. Anhydrite and gypsum nodules and cements are also common within the reservoir rock. Initial production rates reached 120bbls oil per day, however this decreased by 75% within 6 months. Cumulative production from the field since then has reached an estimated 2.8 million stock tank barrels (MSTB) (Major and Holtz, 1997).

Pakenham Field Area

Located in the Val Verde Basin, in south-western Texas, the Pakenham field is a recently discovered (1993) gas and condensate deposit of Pennsylvanian (Desmoinesian) age. The reservoir is composed of Strawn carbonates. Thrusting along the edge of the Ouachita front has played a key role in the preservation of these reservoirs and the rate of production often depends on the nature of fracturing. Reservoir quality is also controlled by structure: “multiple reservoirs and single reservoirs are structurally divided into multiple potential pools” (Montgomery, 1996). Discovery well 49-1ACU was drilled in 1993 by Tom Brown Inc., followed by a secondary well (49-2ACU) 0.5 miles to the east in 1994. Since then a number of major oil companies (Conoco, Chevron USA, Union Pacific Resources Corporation and Mobil Oil) and a few smaller independent companies have put drilling programs in place, looking for further exploratory prospects within the region.

The Val Verde Basin is already a well known gas rich province and includes the discovery of several giant fields, for example the Brown Bassett, Grey Ranch and Pukett fields in the fractured Ordovician Ellenburger dolomites. These occur in the hydrocarbon producing Val Verde fault zone (Montgomery, 1996).

Virginia

Eastern Devonian Shales

Eastern Devonian Shales are a highly productive reservoir rock in the west-central part of the Appalachian Basin. Current production from this region is estimated at more than 2.7 trillion cubic feet of natural gas from 9600 producing wells (Nearing and Startzman, 1988).

Trenton Limestone Reservoirs

The Trenton Limestone can be found in Lee Country, south-western Virginia. The carbonate reservoir rocks have largely been destroyed through diagenesis and are therefore mostly impermeable; however, fractures have increased the porosity and permeability of the rock.
making it a viable reservoir. Exploration of the area commenced in 1910 with the most productive years occurring between 1981-1983, during this period 35 wells produced 128,112 bbl of oil (Bartlett).

UK

London-Brabant Massif

Situated between the United Kingdom and the Netherlands, the London-Brabant Massif represents sub Permian potential reservoirs from Carboniferous sediments and Millstone Grit sandstones. Exploration of this area was led by ECL in 1984 uncovering several hydrocarbon plays through seismic data. The Barren Measures sandstone (well 53/12-3) proved to be a very promising reservoir rock with porosity values ranging from 14-28% inducing good permeability, whilst Mesozoic block faulting provides a solid structural trap. A further proven gas source could be found in the Westphalian A and B coal measures (Tubb et al., 1986).

NW Europe – The Northern Permian Basin

Exploration for potential petroleum reserves of Palaeozoic age in the Northern Permian Basin has been fairly restricted. To date, only a few fields are active offshore Scotland, one of them being the Beatrice field which produces commercial quantities of oil from Palaeozoic rocks (Devonian lacustrine shales) in the North Sea Basin (Pedersen et al., 2006). The Alum shale in the Norwegian Sea is the most promising Palaeozoic source rock in the Norwegian area, producing commercial amounts of oil offshore western Sweden. UK wells 15/19-2 and 20/10-a3 show oil prone characteristics within the offshore lower Carboniferous shales, whilst onshore Carboniferous lacustrine shales in Scotland reveal a super rich, type I oil prone source. Further exploration (well 25/10-2) off the coast of Norway exposed high petroleum potential of oil prone type II in Permian marine Kupferschiefer.

Buchan Field

Situated 55km WNW of the Forties Field and 160km ENE of Aberdeen (Mieras, 1984) the Buchan Field lies on the southern edge of the Witch Grand Graben (Edwards, 1991). The predominant reservoir rocks are found in the central horst structure of the field and are composed of Upper Devonian and Carboniferous Red Sandstones and Mudstones representing a typical alluvial sequence. The reservoir is extremely complex and fractured as it is located on an old fault line, however it holds an estimated 90MMBBL of oil within a 585m oil column. Poorer reservoir quality is found down flank due to increasing depth and mineralisation of the fractures (Edwards, 1991).

Clair Field

The Clair Field was discovered in 1977 by the exploration well 206/8-1a (BP, 2003), since then it has been declared the largest known hydrocarbon reserve on the UK continental shelf.
(Sheehan, 2011). Hydrocarbons sourced from Palaeozoic reservoirs in the Clair Field are found in fractured Devonian Carboniferous red sandstone beds, much like in the Buchan Field. The Clair field is located 75km off the west coast of the Shetlands and lies in approximately 150m of water. Thesequence of Devonian-Carboniferous sediments have an average thickness of 700m and accommodate an oil column of 568m (Coney et al., 1993). The uppermost Devonian-Carboniferous sequence includes grey argillaceous siltstones with interbedded fine-grained sandstones. Recoverable reserves from phase 1 of the Clair Development are estimated at 250 million barrels of oil. Production started in February, 2005 and the field has so far produced approximately 80 million barrels of oil (BP, 2011). Structural constraints play an important role in the nature of this important hydrocarbon reservoir and oil can be found within 9 fault bounded segments. There are two sets of faulting: NNE-SSW oblique faults, truncating the Rona Ridge and NE-SW to ENE-WSW normal fault segments (Baron et al., 2008) it is thought that the faulting occurred during the late Cretaceous period. The Clair Field contains 6 co-venturers, each with a fixed equity share holding (BP, 2011):

BP Exploration Operating Co. 27.6215%
Britoil plc (BP) 0.98%
ConocoPhillips (UK) Limited 24.0029%
Chevron North Sea Limited 19.4225%
Enterprise Oil Limited (Shell) 18.6831%
Shell Clair UK Limited (Shell) 9.2900%

The Second Phase of the Clair Development is situated to the north east of Phase One; the field has an expected recovery of 640 million barrels of oil over a 40 year period and production is due to start in 2016 (Sheehan, 2011).

Ukraine

The Rudenkovstoye Field

The Rudenkovskoye field is located in the southeast of the Poltava region in the Ukraine with a predominant reservoir rock of Devonian Sandstone and a complex fracture system. The field is operated by JKX, who claim to have a total of 21.6MMboe of reserves in the Rudenkovskoye field. Their most successful well in the area to date is well R103, drilled in December 2010 to a depth of 4641m; it exploits tight gas reservoirs within the Devonian sandstone, yielding 8.1MMcfd and 18 barrels of oil per day (JKX, 2010).
# Table of Production from Palaeozoic Reservoirs in South America, Europe and Africa:

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Reservoir Name</th>
<th>Reservoir Rock</th>
<th>Production Oil/Gas</th>
<th>Comment</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan American</td>
<td>Argentina</td>
<td>The Tuyunti structure in the Tarija</td>
<td>Palaeozoic Silurian and Devonian quartzite sandstone.</td>
<td>Gas reservoirs have been identified.</td>
<td>Still in the exploration stage of development.</td>
<td>Exploration</td>
</tr>
<tr>
<td>Energy (52%)</td>
<td></td>
<td>Basin.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shell Capsa</td>
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<td></td>
</tr>
<tr>
<td>(22.5%)</td>
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</tr>
<tr>
<td>Repsol-YPF</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(22.5%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apco</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1.5%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(1.5%)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Aurelian</td>
<td>Poland</td>
<td>The Zechstein Plays, the Cybinka/Torzym Basin.</td>
<td>Permian reservoirs of sandstone or dolomite.</td>
<td>In the Meidzychod and Lubiatow fields there is an estimated 7Bm³ of gas and 30M barrels of oil.</td>
<td>Aurelian and San Leon Energy are two key players in the European unconventional gas sector. “The combined entity will be that creates the largest foreign holder of unconventional gas concessions in Poland”. (naturalgaseurope.com – accessed 28/12/13).</td>
<td>Exploration</td>
</tr>
<tr>
<td>(35% - Now merged with San Leon Energy)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Gazprom</td>
<td>Russia</td>
<td>The Pechora Platform – Prirazlomnye oil field</td>
<td>Permo-Carboniferous Carbonate reservoir rocks.</td>
<td>Contains 72 million tons of oil reserves – an estimated 6.6 million tons of oil.</td>
<td>This development has had a lot of coverage in the press recently regarding the</td>
<td>Ready to produce but suspended due to legal reasons – the activists are still being</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
**GeoScience Limited**

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Field/Reservoir</th>
<th>Production Details</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP (Exploration Operating Co. 27.6%)</td>
<td>UK (75km offshore from the Shetland islands)</td>
<td>The Clair Field Devonian-Carboniferous grey argillaceous siltstones with interbedded fine grained sandstones.</td>
<td>From 2005-2011 the Clair Field produced 80M barrels of oil from an estimated reserve total of 250M barrels. There is a second phase of development north east of phase one, due to start in 2016. This has an expected recovery of 640M barrels of recoverable oil over a 40 year period.</td>
<td>detained in a Russian Prison (Oct. 2013). Phases one – in production. Phase two – due to start 2016.</td>
</tr>
<tr>
<td>Britoil plc (BP) (0.98%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conoco Phillips (UK) Ltd. (24%)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron North Sea Ltd. (19.4%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enterprise Oil Ltd. (Shell) (18.7%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shell Clair UK Ltd. (9.3%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JKKX The Ukraine</td>
<td>The Rudenkovstoye Field</td>
<td>Devonian sandstone</td>
<td>An estimated reserve of 21.6M barrels of oil. Well R103 produces 18bbl/d.</td>
<td>Producing</td>
</tr>
<tr>
<td>Sonatrach and Amerada Hess (Since 2000)</td>
<td>Hassi Messaoud</td>
<td>A series of Cambro-Ordovician sandstones</td>
<td>440,000bbl/d (70,000m³/d of gas)</td>
<td>Producing</td>
</tr>
<tr>
<td>Sonatrach and ARCO (now part of Algeria – The Ovargla)</td>
<td>Rhoude el Baguel Field</td>
<td>Cambrian sandstones (occasionally)</td>
<td>Out of an estimated 3Bbls,</td>
<td>Producing</td>
</tr>
<tr>
<td>Company</td>
<td>Province</td>
<td>Location</td>
<td>Rock Type</td>
<td>Reserve Type</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>----------</td>
<td>-----------</td>
<td>--------------</td>
</tr>
<tr>
<td>BP</td>
<td>Province</td>
<td>interbedded with portions of shale</td>
<td>430Mbbls (15% of oil in place has been produced since 2000).</td>
<td></td>
</tr>
<tr>
<td>Statoil, BP and Sonatrach</td>
<td>Algeria, southern part of the Illizi Basin</td>
<td>The Tiguentourine Field in Amenas</td>
<td>Cambrian and Ordovician glaciogenic sandstone</td>
<td>Gas condensate deposit</td>
</tr>
<tr>
<td>Wintershall and ENI</td>
<td>Libya</td>
<td>Al Kufrah Basin</td>
<td>Cambro-Ordovician sandstones</td>
<td>Still in exploration stage but said to be a “major potential reservoir”.</td>
</tr>
</tbody>
</table>

“wells drilled for exploration, appraisal and development purposes”.
Table of Production from Palaeozoic Reservoirs in The Middle East, South East Asia and North America:

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Reservoir name</th>
<th>Reservoir rock</th>
<th>Production Oil/Gas</th>
<th>Comment</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>Oman</td>
<td>Khazzan Makarem</td>
<td>Pre-Cambrian and Palaeozoic clastic sedimentary formations.</td>
<td>Reserve contains an estimated 20-30 Trillion cubic feet of natural gas. Production goal – 1 Billion cubic feet of gas per day. (<a href="http://www.bp.com-accessed">www.bp.com-accessed</a> 29/10/13)</td>
<td>Gas production due to commence 2017.</td>
<td>Development</td>
</tr>
<tr>
<td>Petrochina</td>
<td>China</td>
<td>Junggar Basin – Karamar Oilfield</td>
<td>Permian lacustrine sediments</td>
<td>Production rates are unavailable. The field is said to have an estimated reserve of 200-300Mbls.</td>
<td>In 1984 – the field was producing 75,000bbls/d, this was the last figure made public.</td>
<td>Producing</td>
</tr>
<tr>
<td>Hess Thailand Ltd. (operator – 35%) Apico LLC. (35%) PPTEP</td>
<td>Thailand</td>
<td>Phu Horm</td>
<td>The Permian Pha Nok Khao Dolomite – a carbonate reservoir rock of dolomitized skeletal wackestones and packstones.</td>
<td>Reserves estimated at 300-500 BCF. Figures produced in 2012 showed a production level of 93MMcf per day of natural gas and 428Bbls per day of condensate)</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Company</td>
<td>Country</td>
<td>Reservoir Description</td>
<td>Estimated Reserves</td>
<td>Peak Production</td>
<td>Status</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>--------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>Exxon Mobil Exploration (20%)</td>
<td>United States</td>
<td>Interbedded dolomite mudstones and grainstones - Mississippian/Pennsylvania in age.</td>
<td>3Bbls, 450Mbls</td>
<td>Achieved in 1986 at a rate of 45,000bls/d</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>BP Exploration (Alaska) Inc.</td>
<td>United States</td>
<td>Ordovician, Mississippian and Early Pennsylvania carbonate reefs.</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Devon Energy</td>
<td>United States</td>
<td>Mid Pennsylvanian - Lower Permian mid sands and Band Group conglomerates.</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Chesapeake Energy</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>XTO Energy</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Enervest Operating LLC.</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Quicksilver Resources</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Carrizo Oil and Gas, Inc.</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Legend Natural Gas IV</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
<tr>
<td>Premier Natural Resources II</td>
<td>United States</td>
<td>Barnett Shale</td>
<td>-</td>
<td>-</td>
<td>Producing</td>
<td></td>
</tr>
</tbody>
</table>

**Legend**
- Natural Gas IV
- Premier Natural Resources II
- Barnett Shale Operating

*figures from gulfportenergy.com/thailand – accessed 29/10/2013.*
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