Best Practices for Exploring and Producing Oil and Gas from Fractured and Weathered Basement: Examples from Asia*

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Search and Discovery Article #20181 (2012)**
Posted November 26, 2012

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012, see similar article Search and Discovery Article #20281 (2014)
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Abstract

Basement rocks are important oil and gas reservoirs in various basins in the world, including Indonesia, China, Vietnam, the West Siberian Basin, Middle East (Yemen), North Africa (Libya, Algeria and Egypt), South America (Venezuela) and the USA (California, Texas, and Kansas). The reservoirs include fractured and weathered granites, quartzites, and metamorphics. The author has followed this subject very closely for 30 years and herein shares his knowledge and experience. This article is mainly focused on oil and gas fields in the basement in Asia. Also included are slides that represent background and/or context, outcrop occurrences of fractured basement, and Vietnamese seismic features related to basement characterization.

Review of Select Basement Oil and Gas Fields

Most of Vietnam’s oil production is from fractured granite basement in the Cuu Long Basin with six major oil fields producing primarily from basement. Overlying and adjacent Oligocene lacustrine shales generated the oil which migrated into the fractured basement. The Bach Ho (White Tiger) (Pages 22-24) is a giant field with recoverable reserves of 1.0 to 1.4 billion barrels of oil. Other fields include Rong, Rang Dong, Ruby and Su Tu Den with oil reserves ranging from 100 to 400 million barrels (Hung and Le, 2004). Locations of the fields are shown in Page 27. The Ca Ngu Vang (CNV) Field (Pages 23-29, 31-37), discovered in 2002, is the deepest oil-bearing structure in the basin, where the top of basement is at a depth of 3700 meters. Indeed, the SOCO-operated CNV-3X well was the longest measured depth well drilled in Vietnam (6123 meters) with over 2000 meters of basement penetrated in a near-horizontal well emplacement and was tested at 13,040 BOEPD (Page 35).

The Dongshenpu Field, onshore central China (Pages 41-44), is presented as an example of a Chinese “buried hill” basement oil field. This field was discovered in 1983, and the reservoir consists of Precambrian granites, granulites, diabases and hornblenidc metamorphics (Guang
The rocks have no primary porosity, but the porous reservoirs are due to weathering and fracturing. The discovery well tested at 1570 BOPD, and subsequent development drilling has proven the oil column to be 400 meters thick.

To date in Indonesia, oil production from basement rocks has been minimal, but major gas discoveries in South Sumatra, including the giant Suban Gas Field (Pages 58-60), have been discovered in pre-Tertiary basement reservoirs. Gas reserves in basement are estimated in the range of 5 TCF (trillion cubic feet) according to Hennings et al. (2012). This has led to further exploration for gas in basement due to the need for more gas as the Indonesian economy continues to grow. The largest basement oil pool in Indonesia is the Tanjung Oil Field in Kalimantan (Pages 45-50). This field has produced over 70 million barrels of oil from overlying Eocene sandstones and conglomerates, but it has also produced over 20 million barrels of oil from pre-Tertiary basement rocks, including weathered volcanic, pyroclastics, and metasediments. Although this presentation reviews “success stories” with basement reservoirs, there are also failures since these reservoirs can be exceedingly complicated. Accordingly, the Beruk Northeast Oil Field in Central Sumatra (Pages 45, 51-57) is presented as a small basement oil pool (approximately 2 million barrels cumulative production) which appeared promising based on initial flow rates but where subsequent development drilling and production proved the field to be barely commercial (Figure 3).

**Best Practices for Discovering and Producing Oil and Gas from Basement Reservoirs**

1. 1) Production wells should be drilled near-perpendicular to the dominant fracture system. Exploration wells should also be drilled highly deviated, rather than vertical, in order to intersect the dominant fracture systems.
2) Highly focused 3D seismic such as CBM (Controlled Beam Migration) is needed to define the fracture systems in basement.
3) Although coring in fractured basement is difficult to map, nonetheless extensive core coverage is needed to provide critically important information on the rock types and reservoir parameters.
4) Development wells must be sufficiently deep to fully drain the reservoir. Wells should not just “tag” into the top of basement; for example, wells in the La Paz Field of Venezuela (Page 61) were typically drilled 500 meters into the basement. In China’s Dongshenpu “buried hill” basement field, the oil column is 400 meters thick, thus necessitating the drilling of development wells deeply into the reservoir.
5) There are a number of cases worldwide, such as the La Paz Field (Page 61), where the basement oil field was discovered much later (30 years) in the life of the field, with attention initially focused on producing oil from the shallow sedimentary reservoirs. Accordingly, in the case where an operator is producing oil or gas from reservoirs in sediments lying relatively close to basement, a “second look” at basement may be warranted, especially using today’s high-resolution seismic.
6) In a general sense, fractured granites and quartzites are the optimum reservoirs. Weathered “rotten” granites can also be excellent reservoirs, as can be observed in outcrop in tropical areas. Rocks such as schists and gneisses are less attractive because they are ductile and tend to “smear” and not fracture when subjected to tectonic stress. The high mafic content of schists also negates the creation of secondary porosity by weathering. Likewise, granites and quartzites are more likely to provide attractive, highly porous “granite wash” sands, whereas eroded schists do not produce such good reservoirs.
Basement-Focused Explorers

While oil and gas fields in crystalline basement are still discovered mostly by accident, there are a few companies which have been especially successful in their focused exploration effort for hydrocarbons in basement, such as SOCO International in Vietnam and Yemen. Very noteworthy also has been Hurricane Exploration’s successful exploration resulting in the Lancaster and Whirlwind basement oil field discoveries in the North Sea (West of Shetlands) (Pages 62-69). To present, the North Sea has had no oil or gas produced from basement, thus Hurricane’s success can be viewed as a possible “basin revival play” for the North Sea.

Conclusions

The conventional way of thinking, certainly in the past, has been that the top of basement underlying the sediments is most likely tight and in oil-patch lore was generally regarded as “tombstone”. Even the sands near the top of basement were often described tongue-in-cheek as “the suitcase sands” as that signified the well was near to total depth and likely a dry hole, and so it was time for the geologist to pack up his suitcase and depart from the wellsite.

However, the author believes that significant oil and gas fields in basement rocks remain to be discovered worldwide. Unconventional geological thinking and risk-taking has led to many of the world’s major oil and gas discoveries, and such strategies will reward the explorers searching for oil and gas in basement.

Acknowledgement

The author would especially like to acknowledge Roger T. Eubank, Caltex chief geologist, an inspirational geologist and team leader in Sumatra in the early 1980’s, who encouraged his team members to present papers at conferences and to help disseminate information about the petroleum geology of Sumatra.

Selected References


Koning, T., 2000, Oil and gas production from basement reservoirs – Examples from Indonesia, USA and Venezuela: Proceedings of the 16th annual World Petroleum Congress, Calgary.


Best Practices for Exploring and Producing Oil & Gas from Fractured and Weathered Basement: Examples from Asia

Presentation to the AAPG 2012 International Conference & Exhibition
Singapore, September 16 – 19, 2012

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Presentation is entirely based on public domain non-confidential information:

- Technical journals from the AAPG, SEG, SPE
- Upstream magazine, World Oil, Oil & Gas Journal, etc
- Websites (SOCO International, others); ConocoPhillips AAPG paper on Suban Gas Field
- T. Koning papers published in Indonesia Petroleum Association & Geological Society of London
Don’t forget basement!!!
Requirements for Oil or Gas in Basement

- **Reservoir** – need fractured or weathered basement
- **Source** – need hydrocarbon source rocks below, adjacent to, or above the basement reservoir
- **Closure** – need structural closure
- **Cap** – need cap rock above the basement reservoir
Tako’s Preference Scale for Reservoir Rocks for Oil & Gas in Basement – Need *Brittle* Rocks

- Fractured quartzites *Most preferred*
- Fractured granites
- Fractured carbonates
- Weathered granites
- Fractured gneisses
- Weathered gneisses
- Fractured schists
- Weathered schists *Least preferred*
Potential of Gneisses & Schists as Basement Reservoirs

• **Gneisses**: a foliated metamorphic rocks corresponding in composition to granite or feldspathic plutonic rocks

  Problem: can be massive or dense or slabby with open fractures parallel to the direction of foliation; fracturing is too planar

• **Schist**: a fissile metamorphic rock with closely foliated structure consisting of parallel planes

  Problem: are generally too micaceous, thinly bedded, fissile and ductile to be prone to mega-scale fracturing
Asian Oil & Gas Fields to be Reviewed

- Bach Ho oil Field, Viet Nam
- Ca Ngu Vang (CNV) oil pool, Viet Nam
- Chinese “buried hill” oil pools – Dangshanpu & Yaerxia
- Tanjung Oil Field, Kalimantan, Indonesia
- Beruk NE oil pool, Sumatra, Indonesia
- Other Examples - Worldwide
Best Practices – Lessons Learned!!!

• Look for “profound” basement structures like Bach Ho (Viet Nam), Tanjung (Indonesia), La Paz (Venezuela), Lancaster (UK North Sea).

• Look for oil in basement beneath existing oil and gas fields – “the best place to find oil is where oil has been already found”.

• Drill 200 meters into basement, don’t just “tag” into it.

• Drill perpendicular to the fractures, don’t drill parallel to the fractures.
Fractured Precambrian granite – interior of Angola
Fractured Precambrian granite – interior of Angola
Fractured Precambrian granite – interior of Angola – example of a fracture corridor
Fracture corridor – granite - interior of Angola
Fractured Precambrian granite – interior of Angola

Granite rock on the way to Huambo (E. Holtar)
Fractured Gneisses – Eastern Margin of Kwanza Basin, Central Angola
Diagrams Color Coding

PURPLE = basement
BLUE = limestone/dolomite
BROWN = shale
YELLOW = sandstones/conglomerates
GREEN = oil
Bach Ho-White Tiger Fractured Precambrian Basement Oil Field, Viet Nam (paper by Hung & Lee, Search and Discovery #10062 (2004))
Bach Ho-White Tiger Fractured Precambrian Basement Oil Field, Viet Nam

- Giant oil field with estimated reserves 1.0 – 1.4 billion barrels recoverable
- Approx 1975 - discovered by Mobil, oil found was in Oligocene sediments
- 1988 Vietsovpetro found oil in fractured granite basement
- Oil production peaked at approx 280,000 BOPD in 2005
- 2009 production down to 125,000 BOPD and declining 20,000 BOPD between 2009 & 2014
- Oil is 90% from basement and 10% from Oligocene sediments
Bach Ho-White Tiger Fractured Precambrian Basement Oil Field, Viet Nam

Seismic line across two fields and prospect in Cuu Long basin.
Two-dimensional model of the play concept for the Cuu Long basin.
Bach Ho-White: Lessons Learned for Exploration in Asia & Elsewhere

• Most fractures inside basement are high dip angles (40- 75 degrees)
• Matrix porosity in the granite is negligible
• Oil stored in macrofractures, microfractures and vuggy pores in fractures
• Porosity in fractures is only 2 – 3% but permeabilities are good to excellent at ten to thousands MD

• **Flow rates of up to 14,000 BOPD**
• **Giant reserves due to up to 1500 meters of oil column**
VIETNAM – FROM SOCO WEBSITE 2005 & 2006

- 13,040 BOEPD discovery on CNV-3X in Block 9-2
- Shallow Oligocene potential in CNV-4X
- 9,432 BOEPD discovery on TGT-1X on Block 16-1
Fractures in basement outcrop in LongHai
CNV Seismic Based Fracture Orientation

Good Fractures Areas

Optimum drilling azimuth to intersect most Tension Fractures
CNV Appraisal Well Locations

- New improved seismic processing allowed for detailed mapping of the internal structure of the Basement
- Mapped fractures and fracture lineaments allow interactive well bore target planning to maximise success
CNV-3X Actual Well Trajectory

Metres TVDSS

ROP (m/hr) in Basement Section

CGG PSDM 2004 – Seismic Depth shifted up 60m to tie actual Top Basement at CNV-3X
CNV-3X Actual Well Trajectory

Metres TVDSS

ROP (m/hr) in Basement Section

CGG PSDM 2004 – Seismic Depth shifted up 60m to tie actual Top Basement at CNV-3X
CNV-3X Actual Well Trajectory

CGG PSDM 2004 – Seismic Depth shifted up 60m to tie actual Top Basement at CNV-3X
CNV-3X Well Results

- **Evaluation Success**
  - Each target fracture zone within Basement came in within 2-6 metres of prognosis demonstrating value of enhanced seismic reprocessing and analysis approach.
  - Rate of Penetration (ROP) shown to be excellent indicator of fractures

- **Operational Success**
  - Longest measured depth well drilled in Vietnam (6,123 metres) with over 2,000 metres in Granitic Basement
  - Mudcap drilling was used successfully to drill majority of Basement with total losses – some 150,000 bbls drilling fluid/seawater estimated to be lost for well control

- **Testing Success**
  - DST #1 Basement (barefoot 4,116–6,123 metres) clean-up still underway.
VIETNAM – BLOCK 9-2

...year to date

- 13,040 BOEPD discovery on CNV-3X in Block 9-2...
Commitment to the Very Core

Kirchhoff PSDM section.

Controlled Beam PSDM section.

CHALLENGE
- To image the oil-bearing fracture zones in a complex granite basement reservoir offshore Vietnam where conventional methods fail to produce convincing results.

SOLUTION
- The data was reprocessed using the CGGVeritas Controlled Beam Migration algorithm for the velocity model building and the final migration.

RESULTS
- Based on the new CBM images, the operator was able to confidently carry out a successful drilling campaign to develop the reservoir.
CGGVeritas Seismic Processing – Controlled Beam Migration in Fractured Granite Reservoirs, Viet Nam
CGGVeritas Seismic Processing – Controlled Beam Migration in Fractured Granite Reservoirs, Viet Nam

Kirchhoff PSDM depth slice through the top of a fractured basement reservoir. The basement is heavily faulted and has a complex topography. Fracture and solution porosity are associated with major faults. Kirchhoff PSDM struggles to resolve these faults.

Controlled Beam PSDM has been applied during re-processing of the data. The combination of multi-arrival imaging, improved signal-to-noise and enhanced steep dips results in well-defined basement contacts and internal faults.
Chinese “Buried Hill” Basement Oilfields

Map of North China basin (Gung and Zuan, 1991).
Lithological characteristics of the Dongshenpu buried hill. This field was discovered in 1983 with Sheng-3, which tested at 1,570 BOPD and 0.5 MMCFGPD from Archean metamorphics. The buried hill consists of biotite-plagioclase granulite and granitic migmatite. The metamorphic rocks do not have original porosity but have secondary porosity and fracture porosity. The oil column is about 400 meters. (Guang and Zuan, 1991.)
Chinese “Buried Hill” Oil Fields  (information in AAPG paper by Guang & Zuan, 1991)

- Dangshenpu buried hill oil field found in 1983
- Discovery well tested at 1570 BOPD and 0.5 MMCFG/D
- Reservoir rock are Precambrian in age and are mainly migmatic granite, granulite, diabase, hornblende
- Rocks have no primary porosity but have secondary weathering and fracture porosity
- **Oil column is 400 meters thick**
- Estimated reserves of 190 MMbils oil
Other Chinese “Buried Hill” Oil Fields

- YAERXIA Oil Field, first basement reservoir discovered in China in 1959; produces from Paleozoic phyllites, slates and meta-sandstone
- Wells are moderately productive with 12 wells producing <70 BOPD, 3 wells at 200 BOPD and 2 wells at 875 BOPD – the problem is that basement lithology is mainly phyllites and slates
- Little published information on this and other Chinese buried hill oil fields
Locations of Tanjung Field, Kalimantan & Beruk NE Pool, Sumatra

Locations of Indonesian oil fields producing from pre-Tertiary basement rocks.
Tanjung Field, Kalimantan, Indonesia

Structural cross-section through the Tanjung area, Barito basin, Kalimantan, Indonesia (Koning, 2000). In the Tanjung Oil Field, approximately 21 million barrels have been produced from pre-Tertiary basement rocks. Fractured and locally weathered volcanic rocks, pyroclastics and metasediments are the dominant basement lithologies. Approximately 74 million barrels of oil has been produced from the overlying Eocene sandstones and conglomerates.
Tanjung Oil Field, Kalimantan, Indonesia

<table>
<thead>
<tr>
<th>Age</th>
<th>Thickness</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligocene</td>
<td>Beral</td>
<td>Limestone, interbedded with marl, sandstone, reeval in part.</td>
<td></td>
</tr>
<tr>
<td>Eocene</td>
<td>Tanjung</td>
<td>Sandstone and shale, interbedded thin coal layers.</td>
<td></td>
</tr>
<tr>
<td>Pre-Tertiary</td>
<td>Basement</td>
<td>Sandstone, red-brown, fine to medium grained, also red coloured clays, basal conglomerate.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>Extrusive and volcanic rocks, calcite veinlets, zeolites, fractured pyroclastics, metasandstones, dark shales, locally weathered.</td>
<td></td>
</tr>
</tbody>
</table>

General stratigraphy of Tanjung Field, Kalimantan (Koning, 2000).
Structure on top of basement, Tanjung Field, Kalimantan (Koning, 2000).
Locations of Tanjung Field, Kalimantan & Beruk NE Pool, Sumatra

Locations of Indonesian oil fields producing from pre-Tertiary basement rocks.
Locations of Tanjung Field, Kalimantan & Beruk NE Pool, Sumatra

Major tectonic elements
(modified from Eubank and Makki, 1981, and Lee, 1982).
Beruk NE Basement Oil Pool, Sumatra
Beruk NE Basement Oil Field, Sumatra

- Field discovered by Caltex (Chevron-Texaco) in 1976 by Beruk NE-1, 1680 BOPD from fractured quartzite
- 2 subsequent development wells drilled into argillite and hornsfelsic basement (poor reservoirs) produced 200 BOPD
- 1 development well drilled in same fractured quartzite as Beruk NE-1, tested at 2252 BOPD but flowed 100% water after 3 months
- Field went on production in 1981 and experienced rapid water influx and cumulative production of only 2 million barrels & lost money
- Lesson learned – basement reservoirs in some cases can be exceedingly complicated; fracturing can also result in unexpected rapid water influx
- Detailed geological and engineering work is required to accurately determine the commerciality of any basement oil discoveries
Beruk NE Basement Oil Field, Sumatra

SW-NE seismic profile over the Beruk Northeast Field (Koning and Darmono, 1984).
Figure 3: NW-SE seismic profile over the Beruk Northeast Field. Note thinning of sediments over the basement high. Seismic shows basement is highly faulted. Early and rapid water influx resulted in the field depleting much sooner than predicted. (Koning and Darmono, 1984.)
Beruk NE Pool –
Very Complex Basement Lithologies!

<table>
<thead>
<tr>
<th>Well</th>
<th>Rock Type</th>
<th>Age (K/Ar)</th>
<th>Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Quartzite</td>
<td>Permian</td>
<td>1680 BOPD</td>
</tr>
<tr>
<td>2</td>
<td>Granite</td>
<td>Jurassic</td>
<td>No flow-tight</td>
</tr>
<tr>
<td>3</td>
<td>Argillite</td>
<td>Cretaceous</td>
<td>200 BOPD</td>
</tr>
<tr>
<td>4</td>
<td>Granite</td>
<td>Triassic</td>
<td>200 BOPD</td>
</tr>
<tr>
<td></td>
<td>Argillite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Quartzite</td>
<td>No age date</td>
<td>2252 BOPD</td>
</tr>
</tbody>
</table>
Beruk NE Basement Oil Pool, Sumatra

Structural cross-section, Beruk Northeast Field.
Composite log, Beruk NE. No. 4, Beruk Northeast Oil Field, central Sumatra, Indonesia, a small complicated oil field with reserves of approximately 3 MMBO. Radiometric (K/Ar) ages of basement cores include Permian, Triassic, Jurassic, and Cretaceous, indicating a long complicated tectonic history. Basement reservoirs consist of fractured quartzites, weathered granite, and weathered argillite. The field has multiple oil-water contacts. Two wells watered out rapidly. Koning and Darmono (1984) highlight the difficulties that can be encountered with some basement oil fields.
Suban Gas Field, South Sumatra

Tectonic setting, regional and local structural configurations, and simplified stratigraphic units of Suban Gas Field. The location of regional seismic section-AA’ is shown on the inset map.
Suban Gas Field, South Sumatra

Note approx 300 meters (1,000 feet) basement penetrated

From: Hennings & ConocoPhillips team, AAPG Bulletin, April 2012
Suban Gas Field, South Sumatra
Suban Gas Field, South Sumatra

Suban-11 well path into basement fractures. Well had AOF of 1.0 BCFG/day.
From: Hennings & ConocoPhillips team, AAPG Bulletin, April 2012
Suban Gas Field, South Sumatra
La Paz Oil Field, Venezuela

Vertical section through the La Paz field, onshore Venezuela. Approx 830 MMbbls oil produced from low porosity Cretaceous limestones and 325 MMbbls produced from fractured granite basement. Maximum IP of basement wells was 11,500 BOPD average IP of 3,600 BOPD. Average penetration into basement is 500 meters (1,700 feet). Source rock is the La Luna Shale which is also the cap rock for the limestone reservoir.
Hurricane Exploration PLC – Lancaster Basement Oil Discovery – West of Shetlands, UK North Sea
Hurricane Exploration PLC – Lancaster Basement Oil Discovery West of Shetlands, UK North Sea

• A ground-breaking oil discovery in fractured basement in the UK North Sea
• First time basement was a primary target in UKCS
• Well drilled on 100% basis by Hurricane Exploration
• 225 meters of basement penetrated
• Well flowed good quality oil (34 – 39 API) but bad weather well prevented obtaining flow rates
• P50 reserves of 147 MMbbls oil – one of the largest oil finds in the UK in recent years
Hurricane Exploration PLC – Lancaster Basement Oil Discovery West of Shetlands, UK North Sea

Information from farm-out brochure of ENVOI Energy Venture Opportunities International – Mike Lakin
Hurricane Exploration PLC – Lancaster Basement Oil Discovery – West of Shetlands, UK North Sea
Hurricane Exploration PLC – Lancaster Basement Oil Discovery – West of Shetlands, UK North Sea

NW-SE section across the Lancaster closure showing potential basement charge.
Hurricane Exploration PLC – Lancaster Basement Oil Discovery – West of Shetlands, UK North Sea

Schematic orthogonal cross-section of the Rona Ridge fracture porosity.
Hurricane Exploration PLC – Lancaster Basement Oil Discovery – West of Shetlands, UK North Sea
Lancaster Basement Structure (left) vis-a-vis Bach Ho (White Tiger) Basement Structure (right)
CONCLUSIONS: BEST PRACTICES FOR EXPLORING FOR OIL AND GAS

• Focus on optimum basement reservoir rocks such as fractured granites
• Look for ‘significant’ basement structures (‘profound structures’)
• Carry out specialized 3D seismic surveys
• Drill at high angles perpendicular to the fractures
• Plan minimum 200 meters penetration into basement
• Obtain core control to get a better “insight” into the reservoir
• Recognize these reservoirs are more complicated that sedimentary reservoirs so it takes a special “mind set” to deal with basement reservoirs
THANK YOU FOR YOUR ATTENTION!!!

&

DON’T FORGET BASEMENT IN YOUR OIL & GAS EXPLORATION PROGRAMS!!!