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Basement Reservoirs –
A Review of their Geological and Production Characteristics

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Introduction

This presentation describes the geological characteristics, technical issues and development challenges associated with hydrocarbon exploitation in crystalline basement formations. The term ‘basement’ here refers to crystalline formations ranging from intrusive and extrusive magmatic bodies (especially granites) to the family of low to medium grade metamorphic rocks. Hydrocarbons have been under production from these types of rocks around the world for many decades (see www.geoscience.co.uk for a review) but since around 1990 there has been growing interest and exploration in these formations where matrix porosity is neglible and storage and production are dominated by the fracture system (a Type 1 reservoir of Nelson 2001) . For example, the Arabian shield basement of Yemen and the Tertiary basement granites offshore Vietnam are two classic areas for this type of development, and significant production has been achieved. Other less publicised locations have also been investigated including prospects on the UK continental shelf.

The presentation draws on reservoir characterisation and modelling projects in basement hydrocarbon fields around the world, as well as investigations of basement rocks for deep geothermal resource exploitation (EGS) and also for sub-surface disposal of radioactive waste. The objective is to provide a synthesis and consolidation of learnings from these investigations in terms of the geological character and controls on fracture development, fluid flow and ultimately reservoir quality for hydrocarbon exploitation.

Basement Charging Mechanisms

Most basement hydrocarbons are hosted in structural highs of varying but generally moderate to large elevation (hundreds or even 1000m +). The highs are formed by fault-controlled blocks, often in rift settings, or by palaeo-hills buried below sedimentary cover. A second type of setting comprises intrusive igneous bodies (plutons) within sedimentary sequences. In all cases an overlying seal formation is found at some level. Additionally, some of the overlying, or fault-juxtaposed, sedimentary units may also be charged so that a composite hydrocarbon play is developed. For example, sandstone ‘washes’ above top granite surfaces or carbonate formations which developed on or adjacent to the fault blocks.

Most basement charging is thought to have taken place by lateral or up-dip migration from kitchen areas in nearby structural lows. The migration route is through higher permeability sedimentary units, active faults and perhaps also at the basement / cover interface, thence into the basement itself. One example, from the basement fields West of Shetland on the UK continental shelf, is shown in Figure 1. Other examples are found in the rift basins offshore Vietnam (CuuLong Basin) and onshore in Yemen (eg Sab’atayn Rift).

Up-dip and also lateral charging along fault structures is likely to occur in periods of tectonic activity when active faults are believed to be open conduits for the migration of fluids by the episodic and repeated mechanisms of ‘fault-valving’ and ‘seismic pumping’, which are intimately associated with the earthquake process (Sibson 1996, 2001). It is known that significant volumes of fluid can be mobilised in association with earthquake activity. Examples are a water release of 0.5km3 at the 1957 Hebgen Lake M7 earthquake in USA (Muir Wood 1994); and ~107 m3 at the 1965 – 67 Matsushiro earthquake swarm in Japan (Sibson 1996, 2001). A number of modelling studies have shown that active faults, even of relatively narrow aperture, are capable of allowing the passage of large volumes of hydrocarbon (eg Moretti 1998, Caillet and Batiot 2003). Mechanisms such as these may explain the presence of oil in the Carnmenellis Granite of SW England, at several hundred metres depth and tens of kilometres lateral distance from kitchen areas. It is thought that the charging took place along major deeply penetrating strike-slip faults that extend from the Jurassic kitchen areas in the Bristol Channel across the granite outcrop.

It is also possible that downward migration may take place from source rocks in the cover into underlying basement formations, which would appear to contradict the normal preference for buoyant hydrocarbons to rise. To explain this, a mechanism which relies on changes in differential stress with depth was identified during injection testing in 2 to 2.5km deep boreholes at a deep geothermal pilot scheme in the UK in the 1980's (Pine and Batchelor 1984, Batchelor and Pine 1986). Shearing due to pressure changes on fracture surfaces was, unexpectedly, found to migrate downwards rather than upwards, representing a downward 'ingestion' of the injection fluids. Figure 2 illustrates the stress condition which creates the mechanism. Although not commonly proved, this may explain some hydrocarbon occurrences such as in the Fort McMurray area of Alberta (Collins 2003), and in the Permian Basin of Texas (P'An 1982).

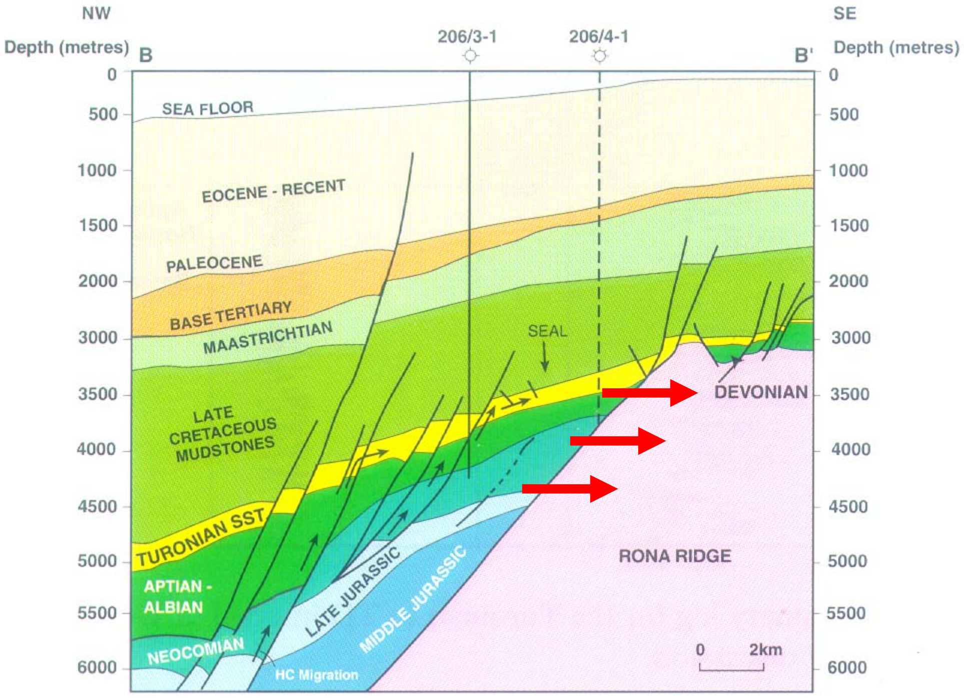

Figure 1 Probable basement migration routes at the Rona Ridge, West of Shetland, UKCS (modified from Grant el 1999).

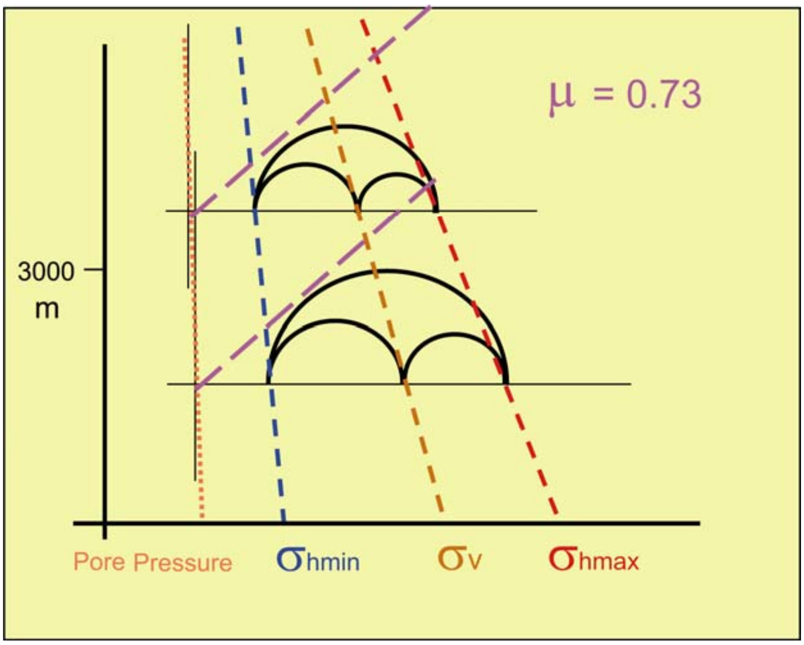

Figure 2 The stress condition (Mohr Circles at two depths) which is thought to cause downward shearing on fracture surfaces, allowing downward migration of hydrocarbons from source rocks into underlying basement. Note that failure is more likely at the lower depth than the upper, because the Mohr circle is closer to the failure line (mauve) there.

Fracture Characterisation in Basement

Mapping and characterisation of the open fracture subset in Type 1 reservoir rocks begins with meticulous analysis and integration of well data, especially core, borehole image logs, dipole sonic (Stoneley wave and fast shear direction) and dynamic data (mud losses, shows, production logs, well tests). These datasets, which ideally should be in overlapping well intervals, are used to build a conceptual model of the open fracture system at 1D scale and to help generate parameters for use in constraining static fracture models (fracture spacing, orientation, dimension, aperture etc). An additional step which is often of value in basements is to determine whether present day in-situ stress is acting to dilate apertures and hence promote fracture permeability on particular fracture orientations. This requires determination of the orientations and magnitudes of the principal stress axes (Shmin, Shmax and Sv). An example of this type of analysis is shown in Figure 3.

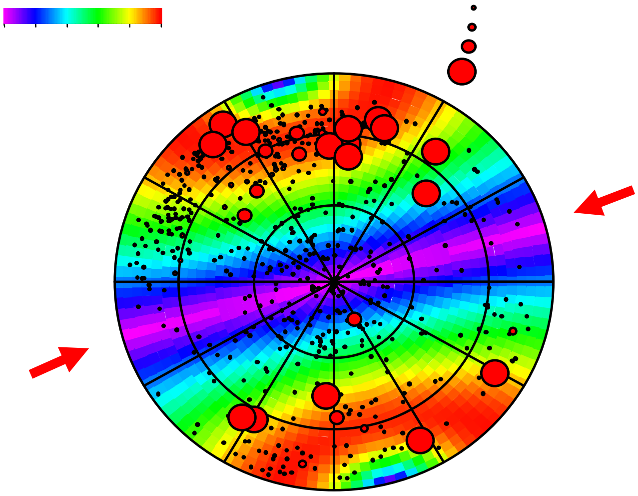

Figure 3 Critical shear diagram for an oilfield in the Yemen basement. Figure is a stereoplot with coloured background depicting the variation in critical shear potential for all possible fracture orientations, in the given stress field (Shmax oriented WSW-ENE, red arrows). Red equals high critical shear potential. Black dots are poles to fracture planes identified in borehole image logs (BHI), and red bubbles are the subset of producing fractures identified from correlation of the BHI with production logs. Their size represents the size of flow identified. Note that the producing fractures lie within the lobes of high critical shear potential to NNW and SSE.

The well-scale dynamic data is used to identify the subset of fractures which are open and dynamically active (eg Figure 4) due to the presence of porosity and connected permeability (the reservoir ‘plumbing’). Extended well tests and cross-hole interference tests are used to identify flow anisotropy and boundaries in the network at a larger, generally near-well scale.

The results of the well analysis are integrated with near-well and reservoir-scale information to build static and dynamic fracture models and to complete the process of determining fracture distributions and parameters. Owing to lack of acoustic contrasts within crystalline formations seismic techniques often meet with limitations, however faults at top basement can generally be identified and extrapolated to depth. Seismic attributes may also contribute to identifying intra-basement volumes with reservoir potential (high fracture density) and reservoir units. Finally, outcrop analog information and empirical relationships help to contribute information about fracture distribution, relationships to lithology, and scaling. This provides a basis for predictive fracture models to support simulation and well planning.

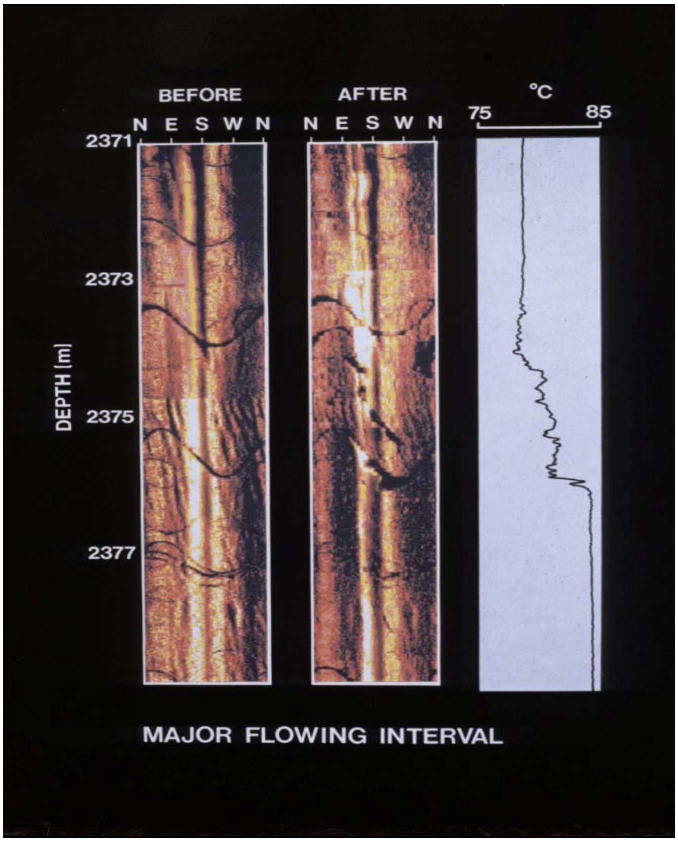

Figure 4 Example of correlation between fractures observed in a borehole image log and a flow entry identified in a temperature log. Taken from deep geothermal investigations in the UK (the 1980’s Hot Dry Rock programme).

Controls on Reservoir Quality

The main controls on reservoir quality in basements are:

- lithology: there is a tendency for fracture height and dimension to be limited in metamorphic formations by the layering, whereas in more massive or homogeneous formations such as granites the fracture network is more blocky and connected (see Yemen case history below)
- deformation history: high levels of deformation associated with fault propagation generate much higher fracture densities than seen in the background formation. Whereas cataclastic and thermo-chemical processes tend to reduce porosity and permeability on the active slip surfaces (generating faultrocks), porosity and permeability may be preserved in the adjacent damage zones (unless hydrothermal mineralisation has been active). Proximity to faults and fault zone ‘architecture’ (Caine et al 1996) are key considerations for reservoir quality

- fracture reactivation: even where mineralisation has acted to seal fractures in the geological past, subsequent stress fields may have caused reactivation of selected fracture orientations, potentially breaking previous seals. Thus it is important to understand the youngest tectonic activity as this may have controlled the open fracture subset
- secondary alteration by hydrothermal or meteoric activity: many basements have been affected by fluid migration leading to fracture sealing, however the same processes can create secondary porosity by dissolution of mineral phases in fractures and in the matrix. The impact on reservoir quality will depend on the specifics of fluid/rock interaction and the poroperm properties of the resulting mineral phases
- present-day *in-situ* stress: following from the above, high stress anisotropy at the present day is likely to cause ‘critical shear’ to take place on selected fracture orientations (Figure 3)

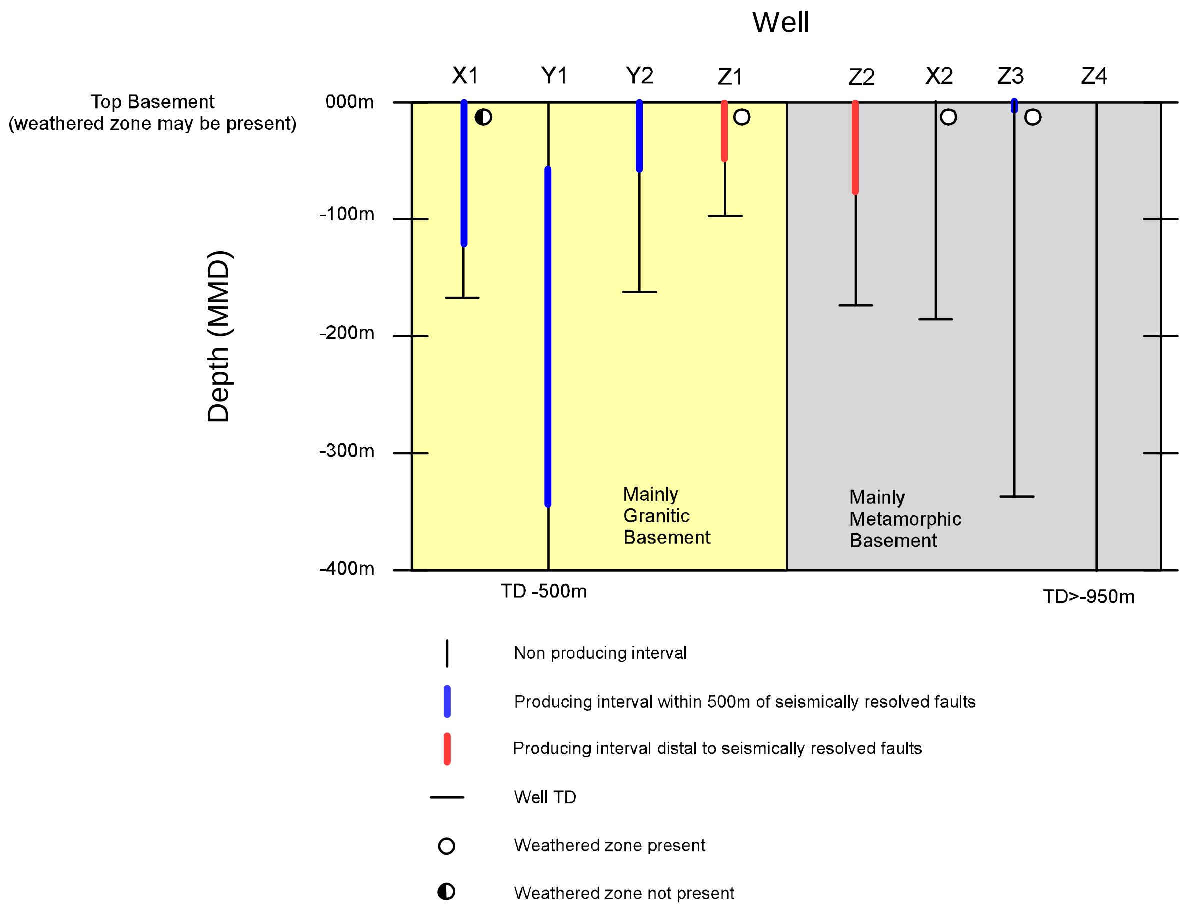

Figure 5 Distribution of producing intervals with lithology and depth below top basement, for 8 basement wells in Yemen. Note that granitic formations appear to be favoured for production compared to metamorphics.

All these factors will impact on reservoir quality, together with migration / charging history, structural height / reservoir column, and seal integrity. All require analysis under the methodology outlined above.

Case Histories

Most crystalline basement reservoirs have been affected by a long and complex interplay between the processes which either promote the creation of porosity and connectivity (generally deformation history and / or secondary alteration) or its destruction (generally by fracture sealing due to some hydrothermal or secondary alteration processes). The challenge in reservoir evaluation is firstly to discriminate which members of the fault and fracture family have the highest potential a) for storage in the geological past and b) for modern-day producibility. Secondly it is necessary to predict their distribution in volumes of rock that are resistant to many ‘standard’ investigation tools (seismic mapping, conventional petrophysics). Some examples of basement evaluations are given below.

In Yemen, the basement reservoirs underlie a major rift system which contains thick Jurassic fill overlain by Cretaceous to Tertiary post-rift sediments containing several important producing horizons. From well penetrations, the basement rocks are a complex series of metasediments and metavolcanics, with granitic intrusions, generally at a depth of some 2500 to 3000m. A number of studies suggest that the nature of the fracture network varies with lithology, especially in terms of dimension and therefore connectivity. It appears that more homogeneous lithologies of magmatic origin have better fracture properties than the layered formations of metamorphic origin (Figure 5). Depth below top basement is also a factor in reservoir quality, as is proximity to faults (but not all faults) and susceptibility to aperture dilation due to the present-day stress field. For one field, faults at seismic and sub-seismic scale were modelled, using constraints from well data, while the smaller-scale ‘background’ fracturing was included in the matrix properties. Sensitivity evaluations were run for each parameter to assess their impact on OOIP calculations, allowing uncertainties in volumetrics to be ranked. This revealed that the level of the OWC was the single biggest uncertainty, a common problem in tight, low matrix k reservoirs especially basements. Sub-seismic faults and fracture corridors were the source of the next most significant uncertainty. Fracture corridors have also been identified as an important issue in many basement reservoir projects (eg de Kok et al 2009).

At Bach Ho field offshore Vietnam a granite ‘buried hill’ produces from a ~1000m column at approximately 3000m to 4000m depth. The dominant control on reservoir quality appears to be fault proximity, with fault damage zones being associated with both storage and production. A network of open fractures in the upper part of the granite is associated with a late Oligocene thrust structure which emplaced part of the granite directly above source rock, such that active and ongoing recharge of the hydrocarbon column is possible. The presence of this fracture system is thought to be due to late and major tectonic activity which formed new fractures and also reactivated older fractures that were previously sealed due to hydrothermal circulation or secondary leaching / alteration associated with meteoric water circulation. Compared to other basement fields offshore Vietnam Bach Ho is however, considered unusual both in terms of the geological history and the degree of productivity.

Development Strategy

Hydrocarbon distribution in tight fractured reservoirs will be controlled by a combination of charging mechanisms, migration routes and timing, and susceptible formation properties which derive form the interplay of factors described above. As with conventional reservoirs, ‘sweetspots’ should exist and in the case of crystalline basement these will be dominantly formed by fracture networks with high densities and good connectivity through a volume large enough to sustain production at economic rates. This of course is not unique to basement reservoirs, other formations with tight matrix properties such as many carbonates also rely on fractures to control fluid movement. The geological record, such as the outcrop example (Figure 6) from low grade Devonian mudrocks in Cornwall (UK) is replete with evidence of the intimate relationship between stress, fracture propagation and fluid movement. The outcome is a highly heterogeneous distribution of reservoir properties.

Figure 6 Outcrop of Devonian slates (UK) showing red discolouration due to movement of iron rich fluids along fracture surfaces, and some lateral penetration into the matrix. Compass for scale.

Thus, from the arguments laid out above, a rationale for successful exploration and development would consist of the following:

- identify basement highs with adjacent kitchen areas. Gravity mapping may be a useful tool for this when basement is below significant cover rocks
- determine migration and tectonic history with particular emphasis on the youngest phase of tectonics and the fracture properties and distributions associated with it
- determine the associated mineralisation history in order to establish which fracture trends have remained unsealed
- determine present-day *in-situ* stress condition (magnitudes and orientations of the principal stress axes) and evaluate which fault and fracture trends may be most susceptible to dilation at the present day (other trends may be under closing stress)
- target exploration and development wells at the damage zones of major faults, especially those which may be in critical shear. Also target steps and jog zones along the fault structure where strain will have concentrated during deformation, leading to potentially higher fracture densities
- target fault structures in the more homogeneous lithologies, especially granitic formations
- investigate for the possibility of composite reservoir systems formed by the juxtaposition of reservoir quality formations with basement

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