Fractured Basement – An Overlooked Play Type with Strong Indications of Significant Potential from a Global Seismic Database

Introduction

Fractured basement reservoirs are most commonly defined as metamorphic and igneous rocks unconformably overlain by a sedimentary sequence, where faulting has led to the creation of a natural fracture network where hydrocarbons can accumulate. Here, we also consider basement rocks to include those of sedimentary origin with little or no matrix porosity (North, 1990), such as the Cambro-Ordovician quartzitic sandstones of the Table Mountain Group in South Africa. Fractured quartzites and granites are generally considered to be the optimum reservoirs (Koning, 2013).

Basement reservoirs have been recognized for decades but are still often disregarded, with wells barely penetrating them, as many oil companies stop drilling as soon as basement rocks are intersected. Where basement has been penetrated to a sufficient depth (approximately 300 m), significant volumes of undiscovered hydrocarbons may still have been missed by a failure to intersect the fracture systems (Aguilera, 1996).

Despite inadequate exploration, fractured basement rocks are important oil and gas reservoirs around the globe (**Figure 1**). Though many were originally found by chance, the large discoveries made in Vietnam and more recently in the UK are now paving the way for an intentional and adequate exploration strategy of this unconventional highly prospective play type.

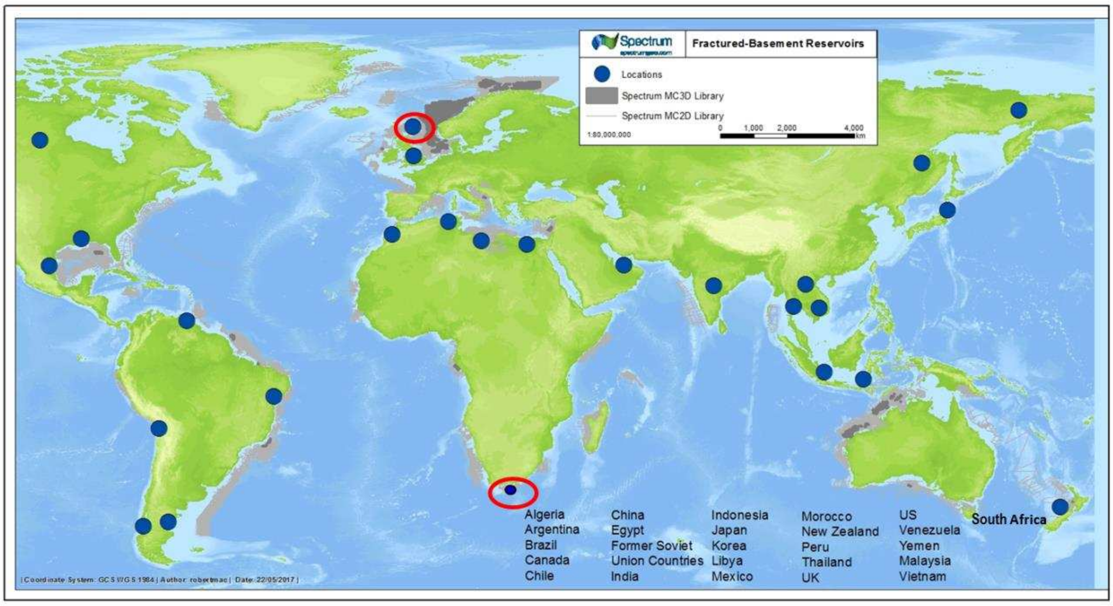

Figure 1: Fractured basement reservoirs around the globe and Spectrum seismic database. Red circle highlights seismic data example showing the fractured basement plays in this article.

Major fractured basement discoveries

The best known basement reservoir is in the Bach Ho oil field discovered in 1975 by Mobil Oil Co. in the Cuu Long Basin offshore Vietnam. The basin is a rift basin developed during the Eocene to Early Miocene (Cuong and Warren, 2009). The Bach Ho field contains major reserves accommodated within highly fractured Late Triassic to Late Cretaceous granitic and granodiorites basement rocks (Cuong and Warren, 2009). It is estimated that two billion barrels of oil (Keggin and Alaaraji , 2017), sourced from directly overlying Oligocene lacustrine shales (Hung and Le, 2004), will be produced from the fractured granitic basement.

Other significant discoveries have been made in the Yemen East Shabwa Development Area and in Argentina at the Cuyo and Neuquen Fields (Gutmanis, 2010), both producing from fractured volcanics.

More recently, Hurricane Energy have had great success on the UK Continental shelf West of Shetlands, at the Lancaster and Whirlwind fields, with best estimate recoverable volumes of 523 Mmboe (Hurricane Energy, 2017) and an upside potential of 3 billion barrels just in the Lancaster field alone. The play concept is similar to the Cuu Long Basin but with Pre-Cambrian gneiss granodiorites basement rock, formed 2.5 billion years ago and charged by the world class source rock Jurassic Kimmeridge clay in syn-rift half-grabens (**Figure 2**; Trice, 2014). The Lancaster structural closure was originally drilled by Shell (205/21-1a well) in 1974 and encountered oil and fractures in basement core. It was not until 2009 that Hurricane Energy drilled a deviated well on the same structural closure to test their fractured basement model and found oil outside the closure.

The main characteristics of the Lancaster discovery can be observed in 2006 long offset 2D seismic data (**Figure 2**). The basement structure is clearly seen on sections in both dip and strike direction. Although faulting patterns are more difficult to image, the fractured basement play fairway can be generated from the existing 2D seismic grid, identifying undrilled analogues in open acreage along the Rona Ridge.

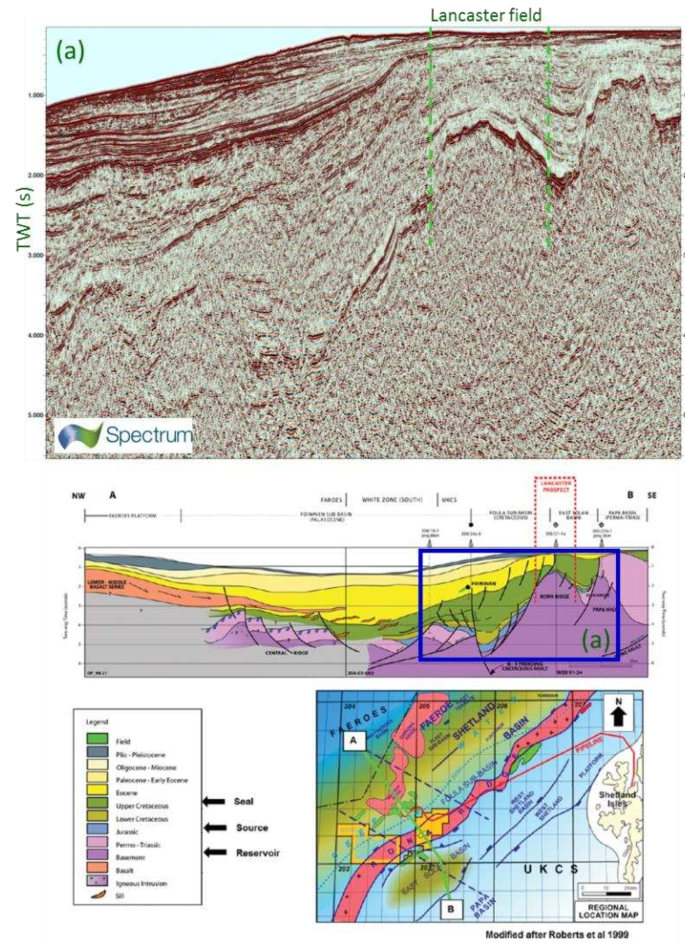

Figure 2: 2D seismic dip section demonstrates the Lancaster fractured basemen play West of Shetlands. Regional cross-section across the Rona Ridge shows the structural disposition of the Lancaster field and its relationship to the hydrocarbon kitchen of the Foula sub-basin and East Solan Basin (After Trice, 2014).

Faults and fractures with an associated damaged zone create an enhanced secondary porosity system within the basement rock (Cuong and Warren, 2009; Trice, 2014). In fractured basement reservoirs, additional hydrocarbon potential can be found outside of structural closure as oil backfills down through the highly permeable fracture network, a highly attractive characteristic proven by Hurricane Energy. A simplified schematic fracture basement reservoir modelled by Hurricane Energy showing how hydrocarbon gets charged into the basement is illustrated in **Figure 3**.

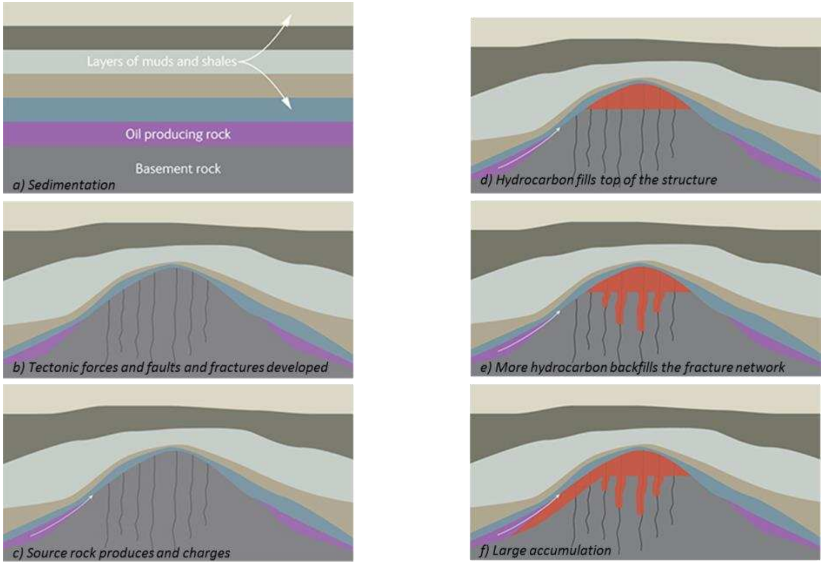

Figure 3: Hurricane's fractured basement play concept and reservoir model in the West of Shetland (Taken from Hurricane Energy website, 2017).

UK onshore analogue for Vietnam offshore granitic basement

The Bach Ho oilfield in Vietnam's Cuu Long Basin contains a 1,000m oil column in a fractured and hydrothermally altered Cretaceous granitic pluton, sourced from overlying Oligocene organic mudstones (Cuong and Warren, 2009). When Enterprise Oil was exploring for basement plays in the Cuu Long Basin, it built a model of hydrothermal porosity generation based on similar Cornubian granites emplaced in south-west England during the Hercynian Orogeny.

Despite differences in age between Cornish granites and those from offshore southern Vietnam, there existed several important similarities. Both represented composite S-Type granites formed in the core complex of an orogenic belt, and both were intruded to shallow crustal levels then rapidly uplifted and unroofed, during which they intersected the water table and underwent hydrothermal alteration and porosity creation.

Hydrothermal porosity formation within large granitic plutons is considered to commence early in the cooling history of the pluton, when super-critical acidic solutions are expelled into cooling and stress relief fractures within the solidified granitic skin. It results in sub-parallel veins separated by highly porous dissolution zones of quartz and white mica. The resultant "stratified" greisen porosity layers often follow the pluton's topography, and can be low angle where they parallel the roof zone. It is believed that such greisenisation can result in up to 5% net effective porosity within the granite.

Another important porosity production (and destruction) process is kaolinisation, a later pervasive process that begins as soon as erosional unroofing causes the granite to intersect the water table, and can last for over 100 my. The process involves enormous volumes of meteoric water and an effective porosity system through which the water can circulate. Both the Cornubian and Vietnamese granites are recognized to contain areas of both constructive and destructive kaolinisation.

Cooling, stress release, and tectonic fracturing were recognized as providing important permeability conduits within the granites at both locations, with the fractures being subsequently chemically eroded and enlarged by hydrothermal processes.

The granite basement porosity model generated from outcrops of Cornubian granite was used to build a prospect-scale porosity model for further exploration within the Cuu Long Basin. As a result, Enterprise Oil drilled and discovered oil in granite basement of the Vai Thieu prospect within Vietnam Block 17.

Similar S-Type granite core complexes emplaced during the Eo-Cambrian orogenic event have been subsequently compressionally uplifted within the late Palaeozoic Cape Thrust-Belt of South Africa. During the Jurassic and early Cretaceous, the southern offshore part of this foreland fold and thrust belt appeared to undergo extensional gravity collapse to form the various sub-basins comprising the offshore Outeniqua Basin. Many of the unroofed Eo-Cambrian granites were overlain by organically rich Neocomian marine shales, which can have acted as both source rocks and seals to potentially hydrothermally enhanced fractured granites.

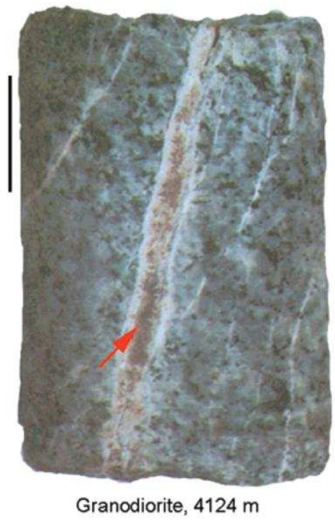

Figure 4: Residual oil staining (appears brown and is indicated by red arrow) in hydrothermally enhanced fracture porosity within Bach Ho Well 504 (After Cuong and Warren, 2009). Scale bar is 5 cm long.

Lessons from the onshore Cape Fold Belt

Onshore southern South Africa represents over a billion years of geological history that encompass a complex series of tectonic events, of which the most important are the Saldanian Orogeny (~550 Ma) and the Gondwana Orogeny (~300 Ma).

The Saldanian Orogeny was a consequence of the closure of the Adamstor Ocean between the Parana and Kalahari Cratons and resulted in the emplacement of a suite of generally S-type granites into the accretionary melange. These are collectively referred to as the Cape Granite Suite and predominantly consist of metaluminous to peraluminous granites with occasional mafic and intermediate bodies. The resulting granitoid batholiths form a series of inliers within the Phanerozoic sequence (**Figure 5**) and in outcrop, at least, are broadly located close to the present day coastline in both the southern margin and the Cape area. As is evident from potential field data, this trend is likely to extend offshore into the southern Orange Basin, although the overall geometry of the Saldanian Orogeny is poorly understood.

Figure 5: Field example of the erosional truncation of Table Mountain Group on the south coast and the onlap of subsequent stratigraphy. Also note the fracturing that is present within the TMG.

In contrast, the geometry of the onshore Gondwana Orogeny is well understood as it resulted in the Cape Fold Belt that dominates both the topography and structural configuration of southern South Africa **(Figure 7).** This orogen resulted in the compression of the passive margin that was present to the south of the present day margin and resulted in a north verging intra-continental foldbelt. Of particular importance for fractured basement is the oldest sequence of the passive margin, the Table Mountain Group (TMG), consisting predominantly of super-mature, medium to coarse grained, cross-bedded quartzitic sandstones that have undergone low-temperature and low-pressure metamorphism resulting in an indurated quartzite. As is evident from field observations, secondary porosity is present within the TMG[DP1], generated as a consequence of the Gondwanan Orogeny. This compressional event inverted the Ordovician-Silurian passive margin resulting in a series of elongated anticlinal box folds that form the topography relief along present day southern South Africa (Paton et al., 2006) as well as significant fracturing the Table Mountain (e.g. **Figure** 6).

The final stage of tectonic activity was the super-imposition of Mesozoic extension onto the Cape Fold Belt that resulted in the negative structural reactivation that is present both onshore, e.g. Oudtshoorn Basin, and the suite of offshore extensional sedimentary basins (**Figure 6**). This rift event, and subsequent passive margin subsidence, led to the deposition of various syn-rift and early post-rift source which have been proven in the offshore basins. The onshore geology, therefore leads us to speculate that given the correct juxtaposition of Mesozoic source rocks on top of the erosional top basement contact, then there is the potential for a hydrocarbon charge to migrate up dip into the fractured basement (Cape Granite or TMG) with the Hauterivian shales acting as a top seal (**Figure 6**).

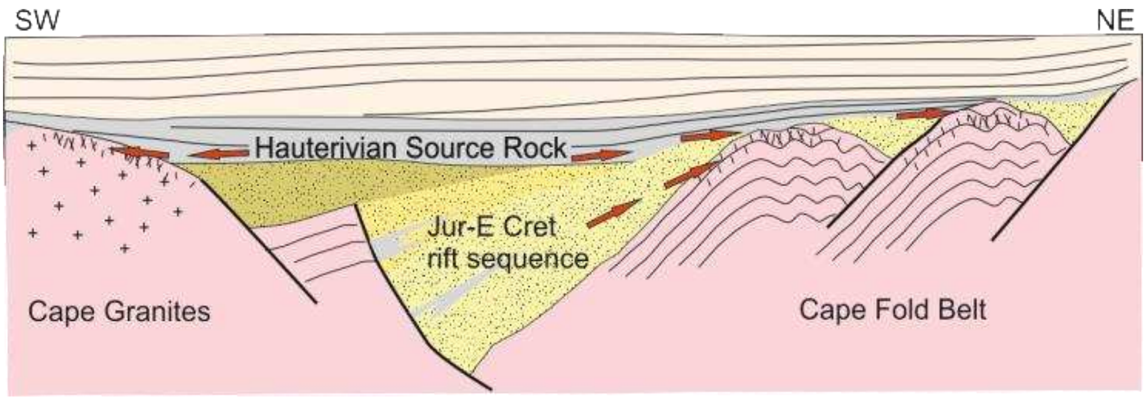

Figure 6: Play concept for fractured Cape Granites and Cape Fold Belt basement with Hauterivian and Jurassic-Early Cretaceous organic intervals source rocks providing charge.

Cape Fold Belt fractured basement offshore potential

The Ga-A-1 was the first well drilled in the Pletmos sub-basin in 1968 in the south coast of South Africa and encountered gas in fractured and sub-aerial quartzite of the Table Mountain Formation. The well was drilled vertically to test a structural closure of syn-rift draped sand and basement plays. The reservoir intervals are charged by a Jurassic lacustrine source from the Southern Pletmos sub-basin and Superior Graben (**Figure 7**). The well produced gas at rates 22 mcf/d from syn-rift shallow marine sandstone and fractured quartzite basement of Ordovician to Devonian age (TMG) (Roux and Davids, 2009). IHS has estimated 8.33 mmboe recoverable reserves within the fractured quartzite reservoir, and 77 mmboe within the syn-rift shallow marine sandstone draped over the basement high (**Figure 7 (a)**). The discovery remains un-appraised. This basement structural closure can provide an upside reserves potential, both by drilling a deviated well to intersect the fractures and by oil outside structural closure similar to Hurricane's model (**Figure 3**).

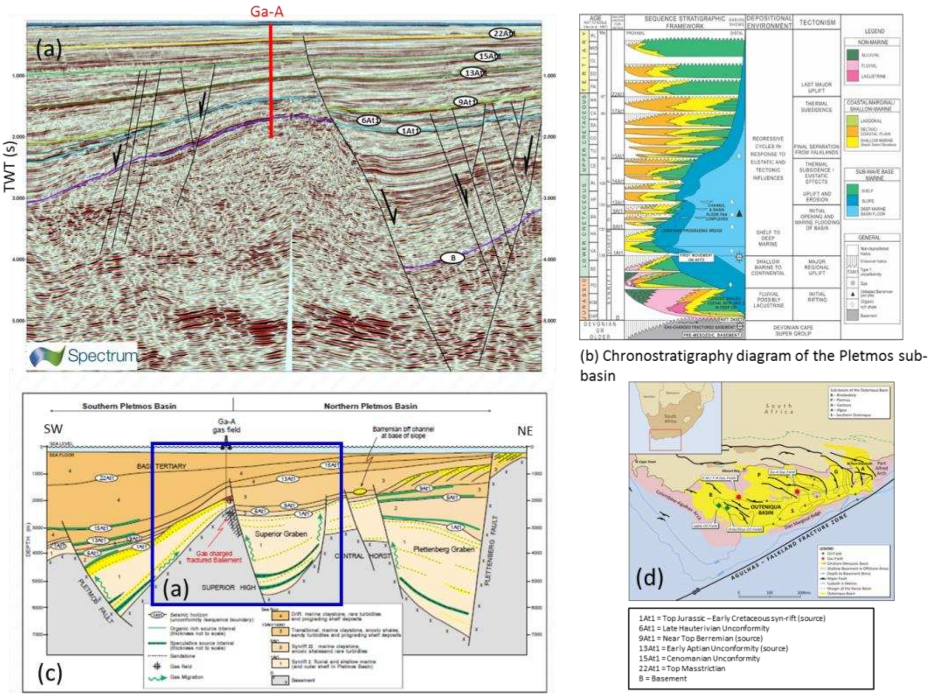

Figure 7: 2D seismic section over the Ga-A gas field in the Pletmos sub-basin, offshore South Africa. Schematic geological cross section across the Pletmos sub-basin illustrating structural style and source kitchens charging the fractured quarzitic basement of the Table Mountain Formation (Roux and Davids, 2009). Basin location and chronostratigraphic diagram of the Pletmos sub-basin is illustrated in Figure (d) and (b) (After Roux and Davids, 2009).

2D seismic reprocessed in 2016 was integrated with a gravity anomaly map, to identify similar basement highs **(Figure 8**) and to map the fractured quartzite basement play fairway in the Pletmos and other sub-basins (Bredasdorp, Gamtoo, Algoa and Soputhern Outeniqua) within the Outeniqua Basin. The Outeniqua basin is bound to the south by the northeast-southwest trending Agulhas-Falkland Fracture Zone (AFFZ) which developed during the Jurassic to Early Cretaceous South Atlantic break-up. There are three proven source rock intervals encountered within this basin; a syn-rift Late Jurassic lacustrine mudstone, a Hauterivian-Barremain restricted marine mudstone and an Early Aptian anoxic restricted marine mudstone.

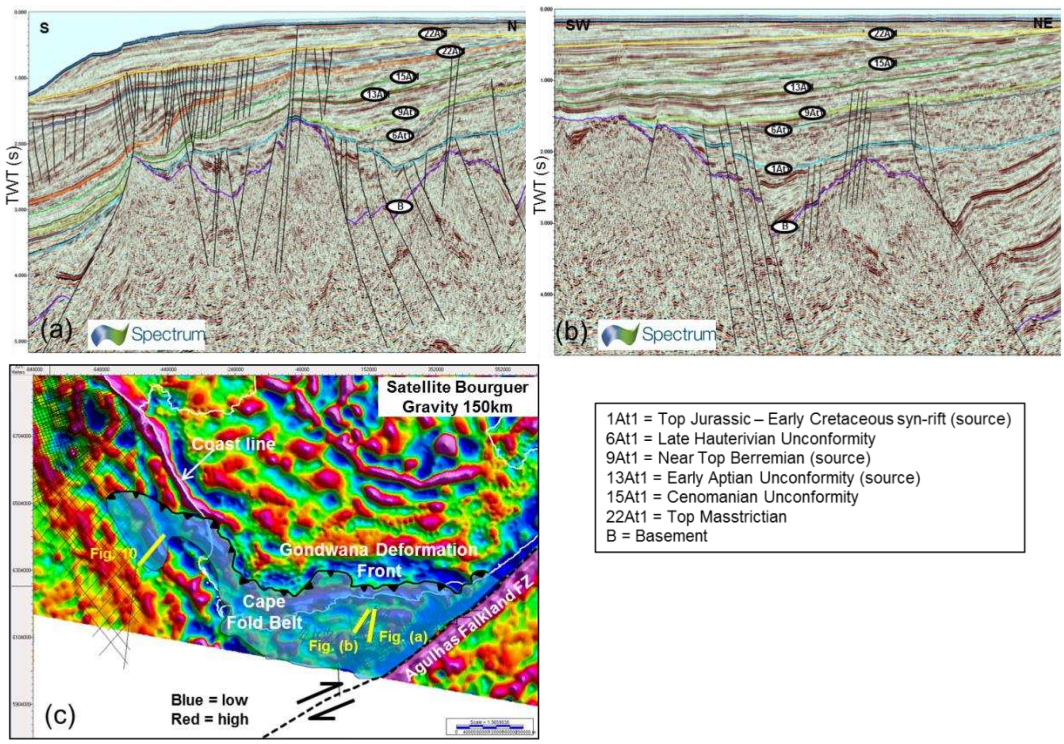

Figure 8: Undrilled basement highs identified on 2D seismic sections in the Pletmos and Southern Outeniqua sub-basins. The line location is indicated in figure (c). Interpreted basement highs within the Cape Fold Belt based on gravity anomaly.

Continuation of the Cape Fold Belt offshore

The occurrence of fractured basement potential within the CFB leads to the intriguing question of whether both the Table Mountain Formation and Pre Cape Gneiss plays are present along the entirety of the fold belt. Using the recently acquired reflection data illustrated previously, Paton et al. (2017) proposed a revised plate reconstruction for the region in which, for the first time, they identified the direct continuation of the CFB offshore into the southern portion of the Orange Basin. Using the correlation from onshore regional tectonics this reveals that the inboard portion of the Orange basin is likely to have the Table Mountain Formation sub-cropping the break-up unconformity and the folding imaged in the reflection data reflects the deformation observed in the onshore (**Figure 9)**.

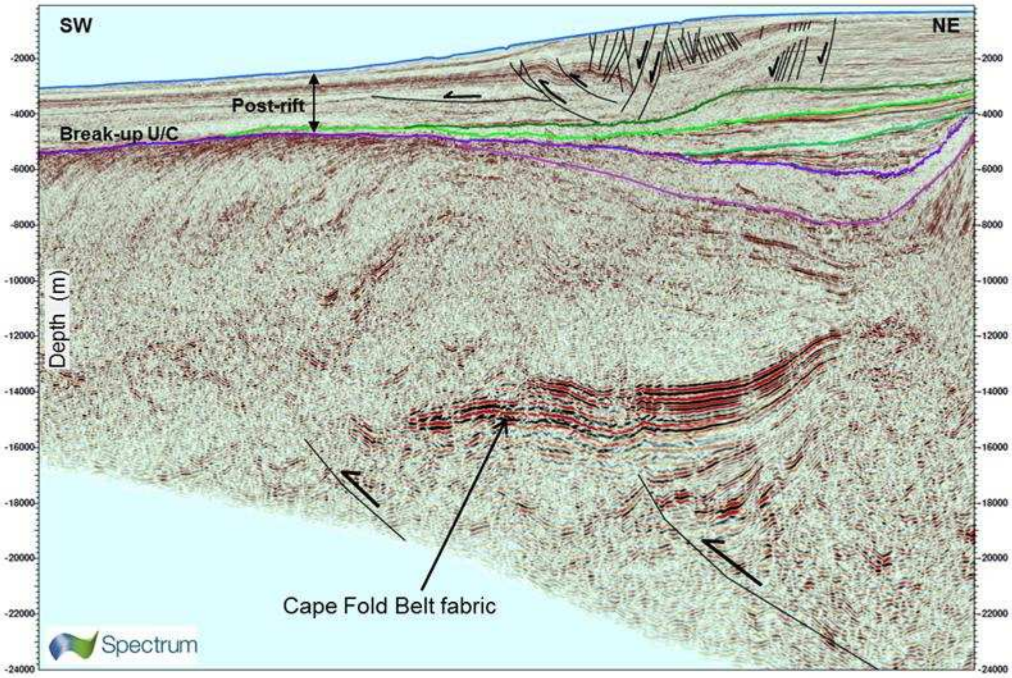

Figure 9: Cape Fold Belt fabric continues into the inboard portion of the Orange Basin in the west coast South Africa. Depth seismic line location is shown in Figure 8 (c).

The outboard portion of the base resembles the southern coast and the presence of both gravity and magnetic anomalies represent the Cape Granite Suite and therefore the sub-crop in the outer basin. The restoration presented by Paton et al. (2017) suggests the continuation of the CFB towards the west is into the Argentinian Colorado Basin. This would provide the potential for both fractured basement plays being a new play concept being feasible in the Argentinian margin (**Figure 10**).

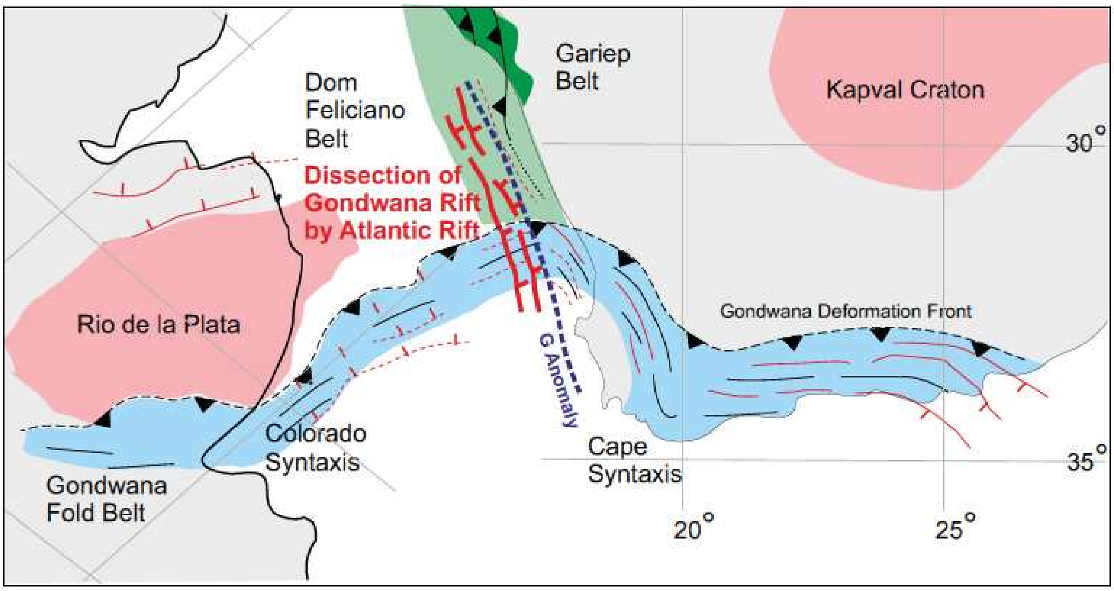

Figure 10: Reconstruction of the southern South Atlantic at 140 Ma. This reveals the continuity of the Cape Fold Belt (blue) in South African into the Colorado Basin in Argentina and predicts the potential for fractured basement plays in both the Orange and Colorado Basins (After Paton et al., 2017).

Conclusions

The fractured basement play is an overlooked play proven on a global scale. It can be associated with large reserves and significant upside potential. Basement reservoirs require hydrocarbon source rocks below, adjacent or above them. Tectonic activity plays a key role in creating and enhancing the fractures in the basements and this requires a good regional geological understanding of the region which can be gained by integrating all available data from onshore geology, information from wells, regional 2D seismic and potential field data. Such work has resulted in the identification of the continuation of the pre-Atlantic opening Cape Fold Belt deformation and the potential fractured basement play fairway in the Outeniqua Basin into the Orange Basin of South Africa and its conjugate margin the Colorado Basin of Argentina.

Regional seismic data is an essential tool for the initial identification of the potential of this highly attractive play. Long offset and reprocessed 2D seismic datasets have been successfully used in the West of Shetlands and in the Outeniqua Basin to map fractured basement play fairways. Other areas where potential fractured basement plays have been identified using seismic data include the Orange and Durban Basins offshore South Africa.

Initial identification of potential fractured basement play fairways can encourage oil companies to change their drilling practice and target, rather than avoid, basement objectives which, when drilled highly by deviated rather than vertical in order to optimally intersect the dominant fracture systems, can yield significant volumes of hydrocarbon which have been mostly overlooked.

References

Aguilera, R., 1996. Servipetrol Technical Notes on the Subject of 'Naturally Fractured Reservoirs'. Technical Note No.3 - Undiscovered Naturally Fractured Reservoirs. August.

Cuong, T.X. and Warren, J.K., 2009. Bach Ho filed, a fractured granitic basement reservoir, Cuu Long Basin, Offshore SE Vietnam: A ‘buried-hill’ play. Journal of Petroleum Geology, 32 (2), 129-156.

Gutmanis, J. and Batchelor, T., 2010. Hydrocarbon Production From Fractured Basement Formations. Compilation, GeoScience Limited Version 9 Aug 2010.

Hung, N.D. and Le, H.V., 2003. Petroleum Geology of Cuu Long Basin – Offshore Vietnam. AAPG International Conference, Barcelona, Spain, Sep. 21-24. Adapted extended abstract

Hurricane Energy website, 2017. https://www.hurricaneenergy.com/expertise/what-are-basement-reservoirs/how-does-oil-get-into-a-basement-reservoir

Keggin, J. and Alaaraji, W., 2017. Detecting basement reservoir fractures on Vietnam’s first ocean bottom seismic survey in the Cuu Long Basin. GeoExpro Vol. 14, No. 2 – 2017

Koning, T., 2013. Fractured and Weathered Basement Reservoirs: Best Practices for Exploration and Production - Examples from USA, Venezuela, and Brazil. AAPG Annual Convention, Pittsburgh, Pennsylvania, May 21. Poster paper presentation.

North, F.K., 1990. Petroleum in Basement Rocks. Bull. AAPG, 66, 1597-1543.

Paton, D.A, Mortimer, E.J., Hodgson, N., van der Spuy, D., 2017. The missing piece of the South Atlantic jigsaw: when continental break-up ignores crustal heterogeneity. Petroleum Geoscience of the West Africa Margin. Geological Society, London, Special Publications, 438, 195-228.

Roux, J., and Davids, A., 2009. Barremain Basin Floor Fan Complex: An Untested Gas Paly within the northern Pletmos Basin. AAPG International Conference, Rio de Janeiro, Brazil, November 15-18, 2009. Extended abstract and poster.

Trice, B., 2014. Basement exploration, West of Shetland: progress in opening a new play on the UKCS. Geological Society, London, Special Publications, 397, 81-105.