Enabling Geological Scale Dynamic Modelling of a Fractured Basement Reservoir using a high-Resolution Simulator - A UKCS Case Study

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Abstract

‘New Kids on the Block’ theme, using new ideas and new technology to help unlock developments

Lancaster is a substantial (207 MMboe 2C) fractured basement field West of Shetland. As a Type 1 Naturally Fractured Reservoir, hydrocarbon potential is provided entirely by the fracture network. This network is a product of initial cooling joints and subsequent tectonic events occurring throughout the 2.5 billion year history of this Precambrian rock. This has generated an exceptionally well connected fracture network, further enhanced by fluid flow, producing a potentially world class hydrocarbon reservoir.

Two reservoir facies are identified: (1) Fault Zones, seismically resolvable features with generally enhanced aperture fractures and increased porosity/permeability; and (2) Fractured Basement, pervasively fractured background host rock providing flow and interconnectivity between Fault Zones.

The strong permeability contrasts present cause Conventional Reservoir Simulators (CRS) to struggle solving and converging simulations. Fine scale gridding is also required to accurately depict the fault and fracture network. Previous Lancaster CRS simulation performance was poor, requiring coarsening to complete the runs in practical timeframes.

This paper describes the implementation of a High-Resolution Simulator (HRS) to build a dynamic model of Lancaster by matching data acquired in the highly successful 2014 Lancaster Horizontal well test using fine-scale (75-million cells) in the model. This has already proved invaluable in forecasting production, assessing the impact of uncertainties, and improving technical confidence in the dynamic reservoir properties while preserving practical runtimes of a few hours using a 16-core workstation.

This represents a step change in Hurricane’s evaluation of its basement assets, further de-risking and unlocking the fractured basement play for the UKCS.
Introduction
Resources (MMboe's) sourced from CPR dated November 2013
Reservoirs composed of crystalline rocks, such as granite, are typically associated with structural features that have developed after a long geological history. Such history includes the emplacement and subsequent cooling of the initial granite melt, post cooling deformation including fracturing and faulting. The deformation history of the reservoir is often complex involving several phases of fluid flow through the fracture network. These phases form from a combination of surface and near surface conditions (epithermal) and from fluids sourced from deeper in the crust (hydrothermal).

During epithermal phases the fractured basement is typically exposed as elevated topography forming hills or ridges. Subsequent drowning of these features during marine transgressions results in the stratigraphic trap style known as buried hills.

The above photograph is a geological analogue to the Lancaster field located on the Isle of Lewis.
The definition of fractured reservoirs is dependent on the relative contribution of matrix and fracture poroperm to fluid storage and fluid flow.

Fractures dominate Type 1 fractured reservoirs as there is little to no matrix porosity and permeability.

Lancaster is classified as a Type 1 fractured reservoir, so understanding the properties of the hydrodynamic fracture network is essential to predicting the behaviour of the reservoir under production conditions.
Basement is underexplored in the UKCS, but it has worked in many areas around the world for decades.

The above are three well-known examples of commercially productive basement reservoirs, although they have similar geological properties to Lancaster they cannot be described as directly analogous. Key learnings experienced from such examples are used by Hurricane to optimise our approach to the Lancaster field.

Vietnam and Yemen also provide good examples of how government support for basement exploration and development have lead to material increases in the country’s hydrocarbon production.
The Lancaster Field
Lancaster lies on a crestal position on the Rona Ridge which is a prominent tectonic and basement feature. The basement is the Lewisian Gneiss a complex of granitic rocks with subsidiary dolerite basalt and amphibolite.

The source rock is the Kimmeridge Clay which is juxtaposed against the basement ridge. The Kimmeridge Clay located within the Faroe-Shetland Basin has supplied enormous volumes of oil at Foinhaven, Schiehallion, Clare etc., whilst the Kimmeridge Clay in the East Solan basin has sourced the Strathmore and Solan Fields. Clearly Lancaster is located in a prolific oil generating area.

Seal is provided by thick Cretaceous mudstones.

The basement is over 2.4 billion years old and the most recent uplift of the basement at the Lancaster structure occurred in the last 50 million years, a process which generated more fractures and made the reservoir a shallow drilling target.
- Originally drilled by Shell in 1974
- Hurricane have appraised with three wells since 2009, demonstrating:
  - Oil below mapped structural closure
  - Seismically-interpreted fault network is confirmed by well penetrations
At Lancaster drilling results indicate that the bulk (80-95%) of the reservoir’s gross rock volume is composed of Tonalite, a quartz rich granite. The remaining gross rock volume (5-20%) comprises dolerite with subsidiary basalt.

Analysis of well data indicates that oil productive fractures are independent of the rock type.
Hurricanes conceptual model of Lancaster can be summarised as a two facies concept.

**Facies 1: Fault Zones**
Volumes of rock associated with faults identified from 3D seismic data and having preferential reservoir properties.

**Facies 2: Fractured Basement.**
The intervening host rock distributed between Fault Zones. Fractured Basement is highly fractured and is associated with hydrocarbon storage and flow.
Fractured Reservoirs are associated with specific challenges that need to be overcome before a numerical simulation of the reservoir can be developed. Until recently, computing power has constrained oil companies ability to effectively model many fractured reservoirs. Hurricane has overcome its modelling challenges at Lancaster through a combination of good quality subsurface data, an in-house developed work flow and the use of state of the art simulation software.
Static Modelling
Manual fault interpretation initially used to pick high confidence faults displaying clear offset/breaks in the basement seismic reflector.

Automated techniques for fault picking include FaultX (Ikon) and Ant Tracking (Schlumberger), both of which utilise coherency analysis to define faults that are not easy to resolve manually.

Hurricane has also compared the results from manual and automated fault picking on Lancaster to fault patterns seen on outcrop locations on the Isle of Lewis. Satellite imagery has been used to map Isle of Lewis faults where there is good exposure of the underlying rock. The identified fault pattern resembles that seen on Lancaster, indicating that what we are seeing with seismic techniques are geologically realistic in frequency and geometry.
Only high confidence faults were picked manually prior to drilling in 2009, to ensure a conservative case was targeted with the 205/21a-4 well. Post-drill (205/21a-4), automatically picked faults (using FaultX) have been corroborated through drilling. This well based corroboration of the seismic faults provided increased confidence, and so the fault map was improved to include these automatically picked features. RPS considered the resultant fault map to be an under-representation of the real fault network at the time of writing the CPR and consequently continued work on the manual interpretation was combined with Ant Tracking prior to drilling the 2014 horizontal well. This well penetrated all ten faults that had been mapped from the Antracking technique, giving confidence in both the Ant Tracking and manual interpretation approach. This has lead to the current Lancaster fault model that displays an extremely well connected fault network and gives confidence in Hurricane placing further wells on the Lancaster structure using the existing seismic data.
The Ant Tracking technique is based on the identification of breaks in the basement reflector and not the seismic character within the basement. Consequently faults identified by Ant Tracking are located at the Lancaster reservoirs uppermost surface.

As the Ant Tracking is extracted at the top basement surface, a correlation between the Ant Tracking response and the deeper well penetrations, which can be up to ~450m, demonstrate the near-vertical nature of the majority of the faults on Lancaster.

Note that the Ant Tracking response provides no confidence on the width of fault zones – Fault Zone width is entirely determined by well data and from comparisons with fault deformation styles seen at outcrop locations on the Isle of Lewis.

Also note that there are areas of poor Ant Tracking response that do exhibit faulting - the Ant Tracking may still be underestimating some of the faulting in the field. However, it has proved to be a very successful technique for predicting the presence of faults and will continue to be Hurricane’s preferred method, however such interpretations are always cross-checked with manual seismic interpretation to keep a sense-check on the results. Schlumberger have commented on the extremely high quality of the Ant Tracking results that Hurricane have achieved on Lancaster, which compares very favourably with results from other fields around the world.
Faults are modelled as vertical for three reasons:

1. The data indicates that the faults are vertical or near vertical (well penetrations beneath top-basement extracted Ant Tracking)
2. Any variation in fault dip within the basement is difficult to image with the quality of the seismic within the basement - much of the seismic energy is lost at the top basement surface, so the imaging is poor below ~100ms
3. There are a vast number of faults in this model (800+), which would be exceptionally difficult for software to accommodate if faults were modelled as anything other than vertical planes.

From the CPR evaluation the base case for fault zone widths is 40m, based on outcrop analogues and well data. There is a range of fault zone widths to be probabilistically applied in the model – the above image represents only the base case of 40m.

Geocellular grid has an areal extent of 10m x 10m to accurately model the fault zones. Cells are orthogonal to avoid twisted cell issues with so many faults.
There is little information in the public domain on the details of dynamically simulating fractured basement reservoirs. They represent a unique challenge compared to more conventional clastic reservoirs. Hurricane has used a number of techniques in the past which have provided reasonable results, but more recent work using a high resolution simulator has represented a significant improvement to Hurricane’s understanding of the Lancaster reservoir.
The DFN (discrete fracture network) work was carried out by Golders Associates. The approach of DFN modelling is to build a model of the fracture network based on fractures recorded from well data. Once a fracture model is constructed it is “tested” to establish if the models properties can support the pressure response measured during well testing. One of the key goals of the DFN approach is to incorporate the geometry of the hydrodynamic fracture network and evaluate the contribution of fractures and faults.

DFN modelling has demonstrated the combined importance of the Fault Zones as well as regional joint set in matching the 205/21a-4z well test.
Utilising conclusions from the DFN model a sector model was constructed in Eclipse in conjunction with RPS, following on from their 2013 CPR. The sector model was utilised to model a greater volume of the reservoir than that of the DFN, with the sector modelling results focused on a 4km x 4km surface area of the reservoir.

The sector model gave reasonable results however was constrained by long run times and a requirement to coarsen the grid thus reducing geological detail. In addition by its very nature the results of the simulation were also constrained by edge effects.
High-Resolution Simulator

- Dynamic modelling efforts provided valuable insight into properties of the field, indicating:
  - Highly connected hydrodynamic fracture network
  - Likelihood of supportive aquifer
  - Support for oil outside structural closure

- However, neither the sector or DFN model are suitable tools for full field simulation

- Therefore, a new solution was required that would allow practical simulation of the Lancaster Field

- INTERSECT, by Schlumberger, was selected for testing
Using Intersect it was possible to replicate the sector model and sector model results but in significantly reduced run times. The original sector model run using the industry standard simulating package Eclipse took 65 hours whereas Intersect produced the same results in 20 minutes. The improvement in speed meant that Intersect had the potential to run a full field simulation of the Lancaster field. This would be a first for Hurricane and if achievable a major step change in our understanding of the Lancaster reservoir.
Benefits of INTERSECT

• High resolution model
  - Fine scale to model geological complexity of fracture network
  - No need to unrealistically upscale

• Unstructured grid
  - Enables more complex fault / fracture patterns to be modelled

• Faster run times
  - Allows many more simulation cases to be run in a realistic timeframe
  - Uncertainty analysis on many factors to increase confidence in range of outcomes
  - Opportunity for full field simulation rather than limited sector model
1. Historic DFN and sector modelling yielded promising results and helped quantify static properties of the reservoir, but neither techniques are designed for, or are suitable, for forecasting full field production. One reason for this is that the hardware and industry standard simulation software (Eclipse) was not able to perform more than a sector model simulation.

2. Testing INTERSECT with Schlumberger showed a dramatic increase in performance with no detriment to results.

3. The historic modelling work was based on Hurricane’s first two wells that were drilled on the Lancaster Field, both of which suffered from various operational difficulties that compromised the well test results obtained. Drilling 205/21a-6, a 1km horizontal appraisal/development well provided a high quality dynamic data set, with excellent rates achieved.

4. The combination of a high resolution simulator and the newly acquired dynamic data has led to a step change in Hurricane’s ability to visualise and model the reservoir, achieving a first pass full field dynamic model that has allowed several major uncertainties to be modelled.

5. Future work involves further refining the full field model, extending the uncertainty analysis to explore further variables and attain a deeper understanding of the reservoir behaviour. This will provide a basis for full field development planning, which my colleague Neil Platt will be discussing this afternoon.
Now I will take a look at the high quality dynamic dataset that was acquired last year, in 2014, which has provided a new view on the Lancaster reservoir and contributed to the ability to dynamically model the full field.
205/21a-6 – 2014 horizontal well

In 2014, Hurricane drilled the first 1km horizontal well targeting fractured basement on the UKCS. This highly successful well confirmed commercial rates from the basement and provided new dynamic data for simulation modelling.

205/21a-4 provided evidence for mobile oil below the mapped 4-way dip closure of the field. The 2013 CPR by RPS defined the oil down to (ODT) depths based on the results from this well, as shown in the above figure.

The 205/21a-6 horizontal well remained approximately 140m shallower than the low case ODT, i.e. approximately 1240m TVDss.
ESP (electrical submersible pump) flow constrained primarily by the length of the flare booms with the entire well test package rated for 10,000 bopd, so this rate could not be exceeded.

The natural flow was constrained because critical flow conditions had been reached in the separator, and no more drawdown could be applied.

Hurricane was aiming for a minimum flow rate of 4,000 bopd to prove the commerciality of a 1km horizontal well (based on assumptions in the CPR), so both natural and EPS flows exceeded that minimum flow rate.
The full field model is already enabling Hurricane to better understand the behaviour of the field and to examine options for an Early Production System (EPS), which will be discussed in more detail this afternoon by my colleague Neil Platt.
A number of scenarios have been modelled, examining the potential impact of different ODT depths and aquifer strength, among other sensitivities.

The above history match to the horizontal well utilises reservoir properties in the Full Field Simulation equivalent to the CPR Base Case (2C Contingent Resource), i.e. an ODT of 1597m TVDss. The above match is excellent and provides additional confidence in Hurricane’s base case recoverable volumes.
Using the available and limited data available during the writing of the 2013 CPR it was assumed that for the base case reservoir properties a 2km horizontal well would be required to generate the above orange profile. It can be seen that the profile is characterised by an immediate decline from an initial production of 10,000 bopd.

The simulation results using the data from the horizontal well (drilled in 2014) and the CPR base case reservoir properties indicates rather the existing horizontal well will in fact plateau at 10,000 bopd for a number of years prior to declining.

It must be noted that these are only indicative first pass results - the well test match is a non-unique solution (no well test match is a unique solution) and other scenarios can match the well test, and produce different results. However, the above case has been selected as it is geologically robust and has been derived from a high quality history match.

Caveats in this first pass modelling include:

- No permeability anisotropy has been included, as currently we do not have sufficient data to quantify this property (interference testing is planned to evaluate permeability anisotropy as part of a planned Early Production System) however different anisotropy scenarios will be modelled as part of a second phase of simulation.
- No Kv:Kh ratio modelled – again we are constrained by current data availability, however scenario’s to evaluate Kv:Kh are planned for a second phase of simulation
- Hydrocarbon saturation is assumed to be 100% within the oil column in these first pass results
  - This is a reasonable assumption, as the fractures that make up the effective reservoir in this field are of such wide apertures that capillary pressure effects will not be seen, and there will be no relationship between height above free water level and water saturation. Irreducible water saturation should be theoretically zero (or close to zero).
  - Formation water was seen on previous well tests, but the source of this water is uncertain. No formation water was encountered in the horizontal well 205/21a-6.
  - Potential perched water should perhaps be dealt with as a N:G issue rather than a water saturation issue, as the water will be essentially immobile within any perched fractures.
  - The effects of variable hydrocarbon saturation and hydrocarbon distribution is an uncertainty which will be examined in more detail in a second phase of simulation however Hurricane is aware that variable oil down to distributions al though acceptable in static models are a challenge in simulation modelling.
Conclusions

- Acquiring a high quality dynamic dataset from the 2014 horizontal well has improved Hurricane’s understanding of the behaviour of the fractured basement reservoir

- Utilising an innovative high-resolution simulator (INTERSECT) has been key to modelling this challenging reservoir

- This work represents a step-change in Hurricane’s ability to continue unlocking value in this emerging play of the UKCS

- Work is ongoing to feed into Full Field development planning
  - Presentation this afternoon by Neil Platt, COO, on hub development concepts