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Abstract

- 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.

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. 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.

- **Hurricane** is an independent oil company, focussed on the development of the under-explored fractured basement play within the UKCS. This largely untapped resource has been overlooked in the past within the UK, and through specialisation and innovative technical work, Hurricane is opening up this play in the West of Shetland region and appraising the significance of fractured basement for the oil industry of the UK as a whole.

- **Dan Bonté** has been working closely with Schlumberger and other industry leaders to develop a robust methodology for maintaining geological scale and complexity within the dynamic simulation model of Hurricane’s Lancaster Field. The use of new software enables a single user (with additional training) to perform the duties of geologist and reservoir engineer, and so carry the modelling work through from the static to dynamic, capturing a wide range of uncertainties in the characterisation of this unusual reservoir.

Abstract submitted to the SPE, along with information on Hurricane and the author.

Available on SPE web site and email communications promoting the event.
Hurricane worked closely with the Schlumberger team in constructing the initial model and comparing the performance of Eclipse and Intersect.

Schlumberger provided training for Hurricane staff in the use of the Intersect software, enabling the modelling to be performed in-house by Hurricane with support – rather than being modelled offsite by a third party. This working approach was very valuable.
Background
Fractured basement is a proven resource around the world, but underexplored in the UK – Hurricane are pioneering the exploration of this play within the UK continental shelf.

Historically, Hurricane has focussed exploration within proven petroleum provinces such as this area adjacent to the highly productive Faroe-Shetland basin and the supportive West Shetland back basin. These basins have supplied oil for the large Foinaven and Schiehallion fields, the Clair Field (a close analogue for Lancaster) and the under-development Solan Discovery, among others. Oil shows along the Rona Ridge above the basement highs provided confidence of oil presence and migration within these structures. Drilling into the Lancaster and Whirlwind basement structures proved this concept to be successful, discovering potentially large accumulations of oil in place.

The Rona Ridge itself is significantly uplifted, which brings structures like Lancaster into an easy-to-drill window. The tectonic history of the ridge that has led to this uplift contributes greatly to enhancing the reservoir potential of the fractured basement.
Basement is the igneous or metamorphic rock underlying or intruding into the sedimentary cover – in the Rona Ridge area, it is granitic (primarily tonalite with some dolerite present). The basement here has been dated to ~2.5 billion years old.

As the rock is crystalline, there is little to no matrix porosity and permeability. However, the presence of natural fracture systems can make this type of rock into a high-quality reservoir. This makes fractured basement a Type 1 Naturally Fractured Reservoir - fluid storage and mobility is entirely dependent on the fracture network.

The extremely long and complicated geological history of this rock has created an enhanced hydrodynamic fracture network, capable of storing large quantities of oil and delivering high flow rates.

The fractured nature of the rock requires special consideration when modelling, compared to more familiar clastic reservoirs.
Dolerite doesn’t impact the fracture network, meaning that it is ignored for the purposes of geocellular modelling.

Fault Zones and Fractured Basement are the two facies that are included in the model, as the tectonic activity that defines the Fault Zones has caused enhancement to the fracture network within the damage zone surrounding the fault plane – thereby increasing the reservoir properties. However, the Fractured Basement is also heavily faulted and does contribute to the storage and flow of hydrocarbons.

Based on well data and the combination of seismic interpretation with average fault zone widths, the GRV split is close to 50:50 between Fault Zones and Fractured Basement.
Analogue work on the Isle of Lewis is used to understand the fracture characteristics of the basement rock. This is a good analogue, on the same trend and comprising of similar age and lithology rock but uplifted and exposed at surface so it can be studied.

Water flowing out of exposed rock faces shows the percolation that can be achieved through the fracture networks of these otherwise tight rocks,

Log analysis, particularly FMI and UBI, is used to characterise the fractures within the basement, penetrated by wells. This is combined with mud logs, geochemistry analysis, and Production Logging Tool (PLT) during well tests to establish which fractures are contributing to or dominating the flow into the wellbore.

It is important to ensure there is corroboration between different datasets.
Challenges to Consider when Modelling Fractured Basement

- Confident identification of the fractures that are contributing to fluid flow
- Accurate characterisation of the fracture network
- Fine gridding to capture heterogeneity of the fracture network
- Practical methodology to accommodate high contrasts in poroperm and allow for anisotropy within a continuum model
- Computer and software power to simulate a full field reservoir model which needs to accommodate over 450 faults as permeability “high ways”

These are five of the key challenges when modelling fractured basement in geocellular grids

Fractures are identified through image log analysis, and a combination of gas chromatography and PLT data gives confidence in which fractures are the most productive. PLT data from 205/21a-4Z shows a continuous increase in contribution throughout the interval, indicating the majority of identified fractures are contributing to the flow.

Intersect allows fine gridding of the static model to be maintained in the dynamic model – conventionally, simulation models are upscaled from static models so the resolution is reduced (e.g. 10x10m cells become 100x100m or 200x200m). The fine gridding is not going to be down to a well log or individual fracture scale, but the fine gridding selected for the static modelling enables a good representation of repeatable elements of the fracture network, and also enables a good representation of the interpreted Fault Zones.
Photo taken onboard rig Sedco 712 during 205/21a-6 well operations, 2014
Lancaster is a large basement structure within the P1368 Central Licence Block, wholly owned and operated 100% by Hurricane.

The crest of the field is approximately 1,000m TVDSS

At the crest, a four-way dip structural closure exists to create a conventional trapping mechanism down to the 1,380m TVDSS contour. Oil has been discovered and produced from within this four-way dip closure (known as the Phase 1 accumulation in the RPS Competent Persons Report, 2013). All four wells on the field have discovered oil within the structural closure.

Below this structural closure, Hurricane’s initial exploration well (205/21a-4) encountered evidence of oil throughout the interval to it’s TD at 1,781m TVDSS, which creates the maximum Oil Down To depth applied in the CPR to the Contingent Resource calculation.
Sector modelling was performed in Eclipse by RPS, after the initial draft of the CPR was complete. A 4km x 4km area was the largest model that could be realistically modelled in Eclipse in a reasonable timeframe - this is not ideal, as this means that boundary edge effects are observed that impact forecast production profiles. However, running single well profile comparisons against the decline curve inputs to the CPR provided some confidence in the CPR profiles and allowed additional sensitivities to be investigated. RPS concluded that it was more likely that a supportive aquifer was present, based on the results of this simulation modelling.

The long run times an inability to perform a full field simulation meant that Eclipse was not deemed appropriate for future full development planning. Hurricane also required further dynamic data to use as input to any simulation model - the Eclipse sector model was based on data from wells 205/21a-4 and 205/21a-4Z only.

Therefore, the results gathered from the single well profile comparisons was found to be useful but an alternative solution and more data was required to further advance the dynamic evaluation of the Lancaster Field.
Drilling the horizontal well in 2014 provided an extremely high quality dataset that could be used as further input to the simulation modelling.

The total testing period of seven days included main flowing periods both using an ESP, for drawdown control, and a natural flowing period. Both of these main flowing rates were constrained by the surface equipment on the rig - the ESP flow was constrained as the total testing package was rated for 10,000 bopd, and the flare booms would not safely allow flow exceeding this rate. The natural flow was constrained because critical flow conditions were reached in the separator, meaning that with different testing equipment both of these rates could have been exceeded.

The reservoir delivered high rates with very low drawdowns, and the pressure response during shut-in was extremely quick, indicating a highly productive and well connected fracture network.

All water that was seen during the well test was tested and confirmed as returning drilling brine that had been lost into the formation during drilling. No formation water was produced.
Hurricane use Axis Well Technology as consultants to interpret well test data, providing a professional third party opinion on the results of the well. They have examined all of Hurricane’s well results to date.

The Productivity Index (PI) of the well gives an indication of how the reservoir delivers the rates observed - a high PI number indicates a highly productive reservoir that can deliver high rates at low drawdowns. A PI of 160 STB/d/psi is world class, meaning that this horizontal well is among the most productive wells in the world.

Hurricane intended to improve the hole cleaning strategy used in 205/21a-4Z for the horizontal well - this was successful in reducing the skin from over 200 to an average of around 15. This skin value was decreasing throughout the test, as matched by Axis in their well test modelling. This indicates the well was cleaning up and would continue to do so with further production - it is reasonable to assume zero skin for production wells going forwards.

A large minimum connected volume means that the fracture network is extensive and well connected. No barriers were observed. This provides valuable input to simulation modelling.
Axis interpreted the pressure derivative as a conventional dual porosity response - this is consistent with Hurricane’s observations of both static and dynamic data acquired to date.

This does not mean that the fractured basement is not a Type 1 fractured reservoir, as the dual porosity response is provided by different scale of fracturing rather than by intergranular porosity.

Alternative explanations for the upturn during the late time of the derivative are not fully consistent with all other static and dynamic observations (e.g. interpreting as a barrier) - the dual porosity interpretation is considered by Axis and Hurricane as the most reasonable interpretation, which is consistent with other data.
The interpretation of the 2014 horizontal well test data provided the new dynamic data required to advance the simulation modelling beyond the post-CPR Eclipse modelling. However, a new solution was also required in order to enable this data to be used effectively in performing a full field simulation. Schlumberger approached Hurricane to review their new high resolution simulator, Intersect, and see if it would work better for simulating the Lancaster Field.

Working closely with Schlumberger, Hurricane initially compared the performance of Intersect against Eclipse - on an equivalent dual core computer, Intersect ran the sector model in 3 hours vs. 65 hours in Eclipse. Intersect also enables much better scaling of performance with additional processor cores - meaning that with a 16 core workstation, the same sector model could be simulated in 20 minutes. This dramatic increase in speed of running the sector model was incredibly encouraging, as long as the result was unchanged. Hurricane and Schlumberger confirmed that running the sector model in 20 minutes using Intersect produced exactly the same result as the 65 hour Eclipse run time.

This meant that Hurricane was more than confident to proceed with simulation of the entire full field model, which would run in a reasonable timeframe despite containing over 75 million cells. This enabled Hurricane to maintain the geological resolution of the model when simulating, without the requirement to upscale.
Hurricane’s Intersect Lancaster Simulation Model
Static geological data and dynamic well test interpretation must be combined effectively to create a robust simulation model.

The conceptual model of the Lancaster Field can be refined with the addition of the observations from the well test analysis. The bimodal facies model of Fault Zones and Fractured Basement remains, but the dual porosity observations mean that two basic categories of fractures must be considered - highly productive Discrete Fractures, and supportive Non-discrete Fractures that provide the matrix-like response interpreted by Axis. Both types of fracture exist in each facies, and it is the behaviour and interaction of these fracture types within the two facies that must be understood and modelled.
Faults are important to detect as they include preferentially higher poroperm properties and so are higher quality reservoir targets

Seismic data is used to manually interpret breaks in the Top Basement surface

Automated techniques have been used to enhance the interpretation – but are always cross-checked with the manual interpretation

Several automated techniques have been used by Hurricane, and most recently Ant Tracking has proved the most useful. This technique uses a variance cube to detect discrete features on the Top Basement surface. Corroboration with the manual interpretation has provided confidence in the fault interpretation
The composite fault map results from a combination of manual fault interpretation and automated techniques. Additional work is required to finalise the fault map to the east of the field, but to date the focus has been on accurately representing the fault network surrounding the area to be developed. This is important for well planning and modelling the well test responses.

Ant tracking results are compared to Fault Zone interpretation in the wellbores. The faults identified at the Top Basement surface are a good match for the interpretation from the wells that penetrate those faults at depth. This indicates that the Fault Zones are generally vertical, or near vertical.
As the comparison with well log-derived Fault Zones indicates that the faults are generally near vertical, the faults in the model are constructed as vertical. This is only a slight simplification from the seismic interpretation, and makes the model much easier to deal with - as over 450 faults are included in the model, including inclined fault planes is challenging as it causes many geometrical issues when gridding.

Gridding the model to construct a property that measures how far each cell is from a fault plane enables different scenarios to be modelled with varying Fault Zone widths. Maintaining the geological resolution of 10m x 10m enables the low case Fault Zone widths of 20m to be accurately modelled, as well as the high case of 80m. The base case Fault Zone width is 40m (as measured on well logs)
As the fractured basement reservoir is not the same as a conventional clastic reservoir, the only way to effectively distribute reservoir properties away from well control is to determine if the cell is within a Fault Zone or not. Those cells within a Fault Zone will tend to have higher poroperm properties than those in Fractured Basement.
Modelling the effective behaviour of the cells within the model involves estimating the effect of the combination of fractures within the fracture network. A repeatable volume of 10m x 10m x 10m appears representative of the reservoir. A number of different fractures are identified within this REV - these are all different types of discrete fractures. Additionally, the pervasive non-discrete fractures exist between these larger fractures.

This enables an estimation of porosity and permeability within 10m x 10m x 10m cells within Fault Zones and within Fractured Basement - upscaling the log interpretation to a scale feasible for modelling in the geocellular grid.
Total porosity has been interpreted using a number of techniques - the bateman-konen method is used as the base case. This log-derived porosity cannot distinguish between discrete and non-discrete fractures - it is the total porosity and so the dual porosity model must be estimated. As can be seen, the average Fault Zone porosity is higher than the average Fractured Basement porosity.

The average porosity for the basement reservoir is 4.4% calculated from the horizontal well - this is comparable to the average porosity in the CPR.
Fluid distribution data is provided by Hurricane’s deep inclined well, 205/21a-4.

In the CPR, a model of varying fluid distribution was applied to take into account the downside possibility of perched water being encountered in this well. Re-interpretation of this data indicates that the water encountered could have in fact been coned from deeper down, rather than being perched water. Additionally, comparison with the extremely high productivity of the horizontal well and observations of a highly connected fracture network make the model of perched water within the reservoir far less likely. Therefore, a Free Water Level has been modelled in the simulator rather than a complicated perched water model - this is useful as there is no way to distribute perched water effectively, and the simulator is unsupportive of running such a model as initialisation of the model enforces equilibrium and drops the water to the base of the structure.

Uncertainty remains over the Oil Down To and fluid distribution, but the modelling of a FWL is reasonable. Two FWL scenarios were considered - one with oil in structural closure only, and one with oil down to the 2C depth used in the CPR (which corresponds to mobile oil brought into the 205/21a-4 wellbore during a drilling swab)
Uncertainty Analysis
Uncertainty Analysis

- The simulation model has been used to match the well test history of the 2014 test of the 205/21a-6 horizontal well

- The history match is a non-unique solution, so uncertainty remains in the forecasting of production profiles
  - History match and other well data does limit the number of realistic scenarios

- A small selection of the uncertainty scenarios are presented here, with their impacts on the forecast production from a single horizontal well (notionally limited to 10,000 bopd)
Porosity
‘High Conductivity’ is an alternative name for the Discrete Fractures. ‘Dynamically Compressible’ is an alternative name for the Non-discrete Fractures.

The history match to the well test data is reasonable, with variation of only 1-2 psi on the build-ups. Some more refinement can be applied to improve this match still further, but this was considered by both Hurricane and Schlumberger to be a successful match using a simulation model that is upscaled significantly from the well log or fracture scale (10m being far larger than the largest fractures).

It was found that varying the porosity, by quite large amounts, had no discernible effect on the well test match. The variations imposed were arbitrarily constructed, not based on actual observed uncertainty from the log interpretation. They were applied simply to investigate the potential uncertainty in the history match modelling.
Though there was little effect on the history match, a variation in porosity has a substantial effect on forecast production. The increased STOIIP associated with higher porosity means that more oil can be removed from the system before a substantial decrease is seen in the bottomhole pressure, meaning that the plateau gets longer with higher porosity values. This variation in STOIIP has little effect in the few days that the well test was performed.
Aquifer support
During the Eclipse sector modelling work, RPS concluded that it was most likely that there was some form of supportive aquifer beneath the Lancaster Field.

A test was performed using oil within structural closure only to try and match the well test data - porosity below structural closure was reduced to zero, so there was no pressure support whatsoever. The top graph shows the result of this test, which is a very poor match for the well test data. This indicates that there must be significant pressure support from below structural closure to match the test - this can be in the form of an extensive oil column, a supportive aquifer, or both. This is unsurprising, as it is clear from the 205/21a-4 well that open fractures exist at a similar scale and frequency all the way to TD of that well, However, using the dynamic data to demonstrate this provides additional confidence in the behaviour of the reservoir away from well control. The precise size and strength of any supportive aquifer cannot be determined from this analysis, but it does indicate that there is significant pressure support beneath structural closure.
As the precise size and strength of the aquifer is not yet determined, a number of scenarios have been run to investigate the effect of varying the aquifer strength. These different strength aquifers do not have a substantial effect on the pressure during the well test, but greatly affect the forecast production plateau.
Permeability Anisotropy
The vertical vs. horizontal permeability ratio is an important factor, and may impact production effects such as water coning. Currently, Hurricane has no data to determine if there is permeability anisotropy in the fracture network, either vertically or in a specific lateral direction. To investigate the effect of any Kv:Kh variation, Hurricane included one case with the vertical permeability three times larger than the horizontal permeability, and another case where the horizontal permeability was three times larger. This was performed as a quicklook investigation, and so to be more accurate would require the total average permeability to be maintained at the original average of 265 mD - in this case, the average permeability was allowed to increase. As a quicklook investigation into the effects of varying Kv:Kh ratio, this was considered an acceptable compromise to find out how much difference it makes and assess whether it should be further investigated.

In terms of single well production profiles, this variation in Kv:Kh ratio makes very little difference. Though no data is available, Hurricane does not expect that either vertical or horizontal permeability is likely to be more than three times larger than the other - indeed, the incredibly well connected fracture network may mean that a completely isotropic system is realistic.
Though it makes little difference to the production profiles, varying the Kv:Kh ratio does impact the movement of fluids in the model. One benefit of constructing a detailed geocellular grid for simulation is being able to interrogate the movement of fluid within the model over time. These pictures illustrate the difference in water coning between the high vertical and high horizontal permeability cases. The high vertical permeability case cones water vertically quicker. However, in this single well case, neither permeability scenario causes water to cone into the wellbore before the production comes off plateau - at that point, the water begins to recede back down towards it’s initial position because the drawdown being applied by the well reduces significantly.

Further work will focus on trying to understand the true anisotropy in the field, and performing scenarios using multiple wells to investigate the risk of water coning on the field development.
Hurricane intends to continue gathering data with future well operations, and the incorporation of this data into the simulation model will enable refinement of forecast production profiles.
Hurricane is one of the few companies to be drilling new wells in the UKCS during 2016. Both wells are in an advanced stage of planning, and the data gathered will be easily incorporated into the simulation model.
The EPS has been discussed in other open forums, e.g. AGM, Devex etc.

EPS follows the same principle as Phase 1 development detailed in the CPR, with reduced CAPEX, to lead on to a full field development of the field. It is designed to be economically viable as a standalone case. Additionally, it is a data gathering exercise that will inform future development decisions and enable the optimal development of the full Lancaster Field.
As well as helping in the development of the full Lancaster Field, the data gathered during the EPS will enable Hurricane to move on to its other basement assets and also develop them optimally. Ultimately, the success case will lead to a large hub development that could have a substantial positive effect on the West of Shetland region and the UK oil industry as a whole.

In addition to this, the UK government has identified a number of promising areas for basement exploration within the UKCS, as shown on this PILOT scheme map. If Hurricane is successful with opening the basement play West of Shetland, this methodology could be applied to these other areas of interest and significantly increase the petroleum potential of the UKCS.