Institution:

University of Leeds

Unit of Assessment:

7, Earth Systems and Environmental Sciences

Title of case study:

Case study 5: Predicting the impact of faults on fluid flow in hydrocarbon reservoirs

1. Summary of the impact (indicative maximum 100 words)

Research on faults and fluid flow led by the University of Leeds has dramatically increased the ability of the petroleum industry to predict the impact of faults on fluid flow in petroleum reservoirs. The work has allowed the industry to reduce the risks associated with the exploration of fault-bounded reservoirs, and to identify areas of un-drained reserves in producing reservoirs. The research has won a series of important industrial and academic awards, and has provided a platform for the growth of Rock Deformation Research, a successful consultancy spin-out company whose turnover rose from £1.93 million in the period 2008-2010 to £4.0 million today.

2. Underpinning research (indicative maximum 500 words)

Faults within petroleum reservoirs can act as significant barriers to fluid flow and therefore knowledge of their flow properties is essential so that production strategies can be planned to maximize recovery and increase profit. Despite their importance, prior to the mid-1990s there was little understanding of and virtually no quantitative data available on the flow processes and permeability of faults in petroleum reservoirs. Consequently, petroleum engineers were forced to guess the values of fault rock permeability when modelling fluid flow in petroleum reservoirs.

Between 1994 and 2005, **Rob Knipe** and **Quentin Fisher** led a series of frontline Joint Industry Projects (JIPs) and NERC grants (e.g. GR3/5765, GR3/4612) at the University of Leeds to remove this knowledge gap. These JIPs were integrated/multidisciplinary studies of faulting mechanisms and fluid flow behaviour; and the generation of a robust database on the structure and petro-physical properties of faults within petroleum reservoirs. Three of the JIPs built up the most extensive database of the permeability and capillary entry pressure of fault rocks ever generated.

Rock Deformation Research (RDR), an applied research Fault Foundation programme, was established in 1997 as a University of Leeds spin-out company to assess faulting processes and flow behaviour. With 15 company sponsors in 2012, RDR represents one of the largest active global structural geology consortia. This project built up the data and knowledge on sub-seismic structure of faults based on extensive outcrop studies. Some results from the studies of faults in petroleum systems were published **[1,2,3,4]**, although most remain confidential.

University of Leeds research has pioneered the determination and prediction of flow properties in faulted reservoirs. In the early 2000s, **Knipe**, **Fisher** and their team became the first scientists to recognise and provide evidence for the potential importance of incorporating the multiphase flow properties of faults into production simulation models **[3,5,6]**. The research showed that it was important to understand the multiphase flow properties of the fault rocks to predict whether or not other reservoir compartments need to be drilled. Unfortunately, no data were available on the multiphase flow properties of fault rocks.

The University of Leeds responded by investing nearly £2 million in building a state-of-the-art multiphase flow laboratory (www.see.leeds.ac.uk/wolfson). This provided an important platform for the School of Earth and Environment's petroleum research programmes, and for the initiation of a large JIP involving 9 major oil companies to make the first ever measurements of the relative permeability of fault rocks **[6]**. The Wolfson laboratory has now received over £2 million of sponsorship from industry (BG, BP, Chevron, ExxonMobil, EBN, Perenco, Petrobras, Shell, Statoil, Total, and Wintershall).

The University of Leeds continues to host a thriving group of more than 10 academics, post-docs

and PhD students conducting frontline research on the impact of reservoir deformation on fluid flow. Results of the multiphase flow properties on fault rocks have recently been published in the journal *Geology* **[5]**, which has led to Leeds being commissioned to undertake a study on the potential impact of faults on CO_2 injection on one of the only few sites currently being appraised for offshore storage of CO_2 in the UK.

Key researchers:

Quentin Fisher, Researcher, University of Leeds spin-out company RDR (1992-2008); Principal Researcher (2003-2007) and Professor of Petroleum Geoengineering (2008-present) in the School of Earth and Environment, University of Leeds.

Rob Knipe, Professor of Structural Geology (1995-present, now Emeritus) in the School of Earth and Environment, University of Leeds; Director, Chairman and Technical Lead of Consulting Group (1992-present), Rock Deformation Research.

3. References to the research (indicative maximum of six references)

1. Knipe, R.J. (1997) Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs, *American Association of Petroleum Geologists Bulletin*, **81**, 187-195.
2. **Fisher**, Q.J. and Knipe, R.J. (1998) Fault sealing processes in siliciclastic sediments, *Faulting and Fault Sealing in Hydrocarbon Reservoirs*, Geological Society, London, Special Publication, **147**, 117-134.
3. **Fisher**, Q.J. and Knipe, R.J. (2001) The permeability of faults within siliciclastic petroleum reservoirs of the North Sea and Norwegian Continental Shelf, *Marine and Petroleum Geology*, **18**, 1063-1081.
4. Freeman, S.R., Harris, S.D. and Knipe, R.J. (2008) Fault seal mapping incorporating geometric and property uncertainty, *Geological Society, London, Special Publications*, **309**, 5-38.
5. Tückmantel, C., **Fisher**, Q.J., Manzocchi, T., Skachkov, S., and Grattoni C.A. (2012) Two-phase fluid flow properties of cataclastic fault rocks: Implications for CO_2 storage in saline aquifer, *Geology*, 40, 39-42.
6. Zijlstra, E., Reemst, P., and **Fisher**, Q.J. (2007) Incorporation of the two-phase flow properties of fault rocks into production simulation models of the Roliegend reservoirs, *Structurally Complex Reservoirs*. Geological Society, London, Special Publication, **292**, 295-308.

4. Details of the impact (indicative maximum 750 words)

During the REF period, the research of **Knipe** and **Fisher** has continued to have a major impact on predicting the flow behaviour of faults within the petroleum industry, in part through their association with RDR. This impact is evidenced by the growth of RDR business, and through growth of fault research, consultancy, and training within the School of Earth and Environment.

Between 2008 and 2010, RDR had an average annual turnover over of £1.9 million, and the estimated annual turnover today is £4.0 million **[A]**. Since 2008, RDR has conducted consultancy for 90 oil companies on a total of 200 petroleum reservoirs throughout the world **[A, B]**. In 2008, the company released a database of fault rock properties that has been purchased by 9 companies (BG Group, Wintershall, Bayergas, BHPbilliton, ConocoPhilips, DetNorsk, Maersk, Nexen and Statoil). Most importantly, in 2008, RDR entered into an exclusive agreement with Schlumberger Ltd, in which RDR have created a plug-in software module for the most popular geological modelling software (Petrel™) used by the petroleum industry (see www.rdr.leeds.ac.uk/petrel-software.html) **[C,D,E]**. This module has sold over 500 licenses and allows geoscientists to model all of the major uncertainties associated with fault-related fluid flow in petroleum reservoirs so as to reduce the risks associated with drilling new exploration and production wells **[B].** This work incorporated results from both laboratory studies of fault rock petrophysics as well as structural interpretations conducted during the numerous JIPs in Leeds. In recognition of the high quality of this plug-in, RDR were presented with the 2010 SIS Global Forum Innovation Award at the 2010 Global Schlumberger Information Solutions forum **[F]**. In addition to software production and consultancy, RDR have conducted around 30 short courses on fault-related fluid flow for the petroleum industry that have been attended by up to 700 people **[B]**.

Research, consultancy and training on fault-related fluid flow have also continued in the University of Leeds separately from RDR. **Fisher** has established two JIPs to continue research in this area. The first (sponsored by ADMA, BHP, ConocoPhilips, Shell, Statoil and Wintershall) is a £450,000 project developing a database on the relative permeability of fault rocks. The second (sponsored by Chevron, ConocoPhillips, DECC and Shell) is a £590,000 project which has investigated the impact of faults and fractures on gas production from tight gas sandstone reservoirs. **Fisher** has also given over 40 presentations and 4 short courses to industry, and continued to conduct consultancy work on fault- and fracture- related fluid flow on 9 petroleum reservoirs, a CO_2 storage site (Middle East) and a project on shale-hosted radioactive waste repositories (NAGRA – Switzerland).

The non-uniqueness in the interpretation of subsurface data and the extreme confidentiality of many projects means that it is difficult to assign an accurate monetary value to the impact of this research, consultancy and training. Although software sales, training courses and consultancy projects offers one indication of impact, other examples such as:-

- Failure to predict fault-related reservoir compartmentalisation often leads to dramatic downgrades in reserves (e.g. 100 million barrels – from a single Gulf of Mexico reservoir).
- Failure to predict the sealing capacity of wells often leads to dry wells being drilled at costs in excess of £50 million per well.
- Demonstration that sandstones are not connected across faults allows companies to claim small fields tax allowances in excess of £75 million.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. RDR accounts available as PDF files from 2008 to 2012.

B. Further corroboration can be obtained from the Commercial Operations Officer, RDR.

C. Press release from Schlumberger on the Petrel plug-in "*This is the first Ocean* partner plug-in to be released as a module with Petrel. The RDR plug-in, combined with the wealth of prospect assessment and uncertainty analysis capabilities in Petrel, provides unmatched power to reduce risks associated with exploration*" (http://www.slb.com/news/press_releases/2009/21203.aspx).

D. E-mail (dated 20/09/2013) from Shell Upstream Americas, Shell Canada Energy, which states: *".. the Leeds-based research, has in the last few years, led to methods that enable us to incorporate the single-phase and two-phase fluid flow characteristics of faults into our reservoir models and flow simulators. This allows us to model and predict the trapping potential and flow characteristics of faults and thus identify, select and optimize our exploration and/or field development*".

E. E-mail (dated 23/09/2013) from ConocoPhillips, which concludes: ".. we have supported your research from its inception and have applied your research results in significant ways through the years."

F. Press release from Schlumberger on the 2010 SIS Global Forum Innovation Award at the 2010 Global Schlumberger Information Solutions Forum, London (http://www.rdr.leeds.ac.uk/news-award.html).