Institution: Newcastle University

Unit of Assessment: UoA 7: Earth Systems and Environmental Sciences

Title of case study: Risk Reduction in Petroleum Systems and Pore Pressure Prediction

1. Summary of the impact

Pre-drill prediction of pore pressure and top seal integrity are fundamental aspects of petroleum exploration; incorrect predictions can result in operational difficulties, dry holes and even blow-outs which can cost the industry billions of pounds. The physical and fluid-flow properties of mud-rich sediments exert a fundamental influence on both pore pressure and top seal integrity. Research in Newcastle has quantified the geological controls on these properties and has resulted in data, practical knowledge, algorithms and software which are now used routinely by major companies (e.g. Anadarko, BG, BHPBilliton, BP, ConocoPhillips, Maersk) as part of their global drilling and prospect risking strategies.

2. Underpinning research

Fine-grained clastic sediments (mainly mudstones/shales) comprise the majority of the fill of sedimentary basins. Their low permeability and high capillary entry pressures ensure that they control the rate of fluid flow in basins, with major implications for (a) overpressure development and thus safe drilling, (b) petroleum migration, (c) the retention and leakage of petroleum from reservoirs and (d) the rate of leakage of geologically stored CO_2. Prior to the Newcastle research mudstones were largely treated as homogeneous units with very poorly defined physical and flow properties. Over 15 years, Newcastle University research has:

1. Defined the true complexity and heterogeneity of mud-rich sediments at a range of spatial scales important to the petroleum industry (e.g. [**P1**], [**P4**], [**P5**])
2. Quantified the key physical properties (e.g. compressibility, permeability, critical capillary entry pressure) of the sediments as a function of lithology (e.g. [**P2**], [**P6**])
3. Developed practical tools with which to quickly extract those properties from geophysical downhole tools (e.g. [**P3**])

The research was undertaken by *Aplin's* (*Professor of Petroleum Sciences; 1998 to 2013*) group between 1993-2013, with major contributions by his PDRAs *Yang* (*1993-2003*) and *Dewhurst* (*1997-2000*), an important collaboration with *Larter* (*1990-present*) in Newcastle and external collaborations with *Swarbrick* (*Durham, now Ikon Geoscience*) and *Cartwright* (*Cardiff, now Oxford*).

Four papers between 1995 and 1999 (e.g. [**P1**] arising from [**G1**]) quantified the way in which lithology, specifically grain size distribution or clay content, controls mudstone compressibility, permeability and pore size distributions. The permeability data reported in 1998 and 1999 were amongst the very first to be made on well characterised mudstones. The database of high quality permeability data was substantially enhanced in 2007 [**P4**] and culminated in the 2010 publication quantifying the way that mudstone permeability evolves through burial as a function of lithology (clay content) and porosity [**P6**].

The key practical aspects of the research were published in two companion papers in 2004 ([**P2**] and [**P3**] arising from [**G2**]). Previous results on mudstone compressibility were codified into

lithology-constrained porosity-effective stress relationships which can be used for pore pressure estimation [**P2**]. Practical use of these relationships depends on the rapid, log-based method we developed for assessing lithology (clay content) using Artificial Neural Networks [**P3**]. This work, plus equations in the 2010 porosity-permeability paper ([**P6**] arising from [**G3**]), is at the heart of the software ("ShaleQuant") which we have licenced to BG, BP, ExxonMobil, ConocoPhillips and Shell as part of their pore pressure and basin-scale fluid flow methodologies.

More recent research has focussed on quantifying the lithological heterogeneities of fine-grained sediments and defining effective flow properties on spatial scales which are useful in a petroleum exploration context. A geological summary of this work was published in AAPGB in 2011 (AAPGB 95, 2031-2059) and won the Best Paper award for that year's Bulletin. An example of the Newcastle work on the exploration risking of seals to petroleum reservoirs is [**P5**] (from [**G3**]). This paper, also voted Best Paper in AAPGB (2007), codified seal "bypass systems" in a petroleum exploration context, looking at situations where the seal is compromised by high permeability sub-vertical conduits.

3. References to the research

Peer-reviewed literature - * = Newcastle PDRA; **[number of citations, Scopus];** # = references best illustrating research quality

[**P1**] *Dewhurst, D.N., Aplin, A.C., Sarda, J.P. and *Yang, Y. (1998) Compaction-driven evolution of porosity and permeability in natural mudstones: an experimental study. Journal of Geophysical Research 103, No. B1, 651-661. **[67]#** doi: 10.1029/97JB02540

[**P2**] *Yang, Y. and Aplin, A.C. (2004) Definition and practical application of mudstone porosity – effective stress relationships. Petroleum Geoscience 10, 153-162. **[29]#** doi: 10.1144/1354-079302-567

[**P3**] *Yang, Y.L., Aplin, A.C. and Larter, S.R. (2004) Quantitative assessment of mudstone lithology using geophysical wireline logs and artificial neural networks. Petroleum Geoscience 10, 141-151. **[18]** doi: 10.1144/1354-079302-566

[**P4**] *Yang, Y. and Aplin, A.C. (2007) Permeability and Petrophysical Properties of 30 Natural Mudstones. J. Geophys. Res., 112, B03206. **[44]#** doi:10.1029/2005JB004243

[**P5**] Cartwright, J., Huuse, M. and Aplin, A. (2007) Seal bypass systems. AAPG Bulletin, 91, 1141-1166. Best Paper in AAPGB for 2007. **[73]** doi:10.1306/04090705181

[**P6**] *Yang, Y.L. and Aplin, A.C. (2010) A permeability – porosity relationship for mudstones. Marine and Petroleum Geology 27, 1692-1697. **[24]** doi:10.1016/j.marpetgeo.2009.07.001

Projects

The research was funded initially by the EU (G1) and then by the 10-15 sponsor consortia of major international oil companies (G2 and G3), generating a direct link between the research and its end users.

[**G1**] EU: Integrated Basin Studies and SMACCERS, 1993-2000, c. £500k.

[**G2**] GeoPOP Phases 1 and 2; 1994-2001. Sponsors: Agip, Amerada Hess, Amoco, Arco, BP, Chevron, Conoco, Elf, Enterprise, JNOC, Mobil, Norsk Hydro, Phillips, Statoil, Texaco, Total, c. £1.8 million.

[**G3**] Caprocks Phases 1-3; 2005-present. Sponsors: BG, DBIS, ExxonMobil, BHP Billiton, Shell,

Total, ConocoPhillips, Statoil, BP, Anadarko, Chevron, ENI, Petrobras, c. £2.9 million.

4. Details of the impact

The research at Newcastle has influenced the way that the global petroleum industry models and predicts exploration, production and drilling issues associated with mud-rich sediments. It is used to predict pore pressure pre- and post-drill, has been incorporated into industry-standard, basin-scale fluid flow modelling software and has reduced exploration risk by improving seal risk/column height prediction. Context and an overall assessment of how the research has influenced BP's work on exploration risk is given by a Senior Petroleum Systems Analyst at BP **[E1]**: *"The research has improved our understanding of fine grained lithologies and provided scientific breakthroughs, and software which is now used routinely by a wide range of users across the world. These mudrock concepts have been integrated into BP workflows and hence used to influence business decisions. The monetary value of research is always difficult to quantify; however, clearly the mudrock concepts have been used to reduce exploration risk and to avoid drilling dry holes and unnecessary sidetracks. Given the cost of an exploration well, which is often $100million, then the value resulting from this work is very considerable and obvious to geoscientists"*.

Below, representatives of some of the major companies who use the research state how it has impacted their business in terms of (a) Pore Pressure Estimation, (b) Seal Risk and Column Height Prediction, (c) Petroleum Systems Modelling and (d) Training.

Pore Pressure Estimation

Pore pressure prediction for well design is a critical activity within petroleum companies, firstly to ensure the safety of drilling operations and secondly for financial reasons. Maersk's Team Lead for Global Pressure Prediction Team **[E2]** points out that typical UK HPHT wells cost in excess of $100 million, so that "*accurate pressure prediction for well design and to limit non-productive time during drilling has huge cost implications".* When Maersk *"works on pressure prediction and basin modelling studies the starting point for the shale rock property models used are those developed at Newcastle University. These models underpin our assessment of pore pressure generation and retention and form an integral part of the final pressure predictions made".*

Representatives of other international petroleum companies give similar testimonies. BG Group's Technical Authority on Petroleum Systems **[E3]**: *"predicting subsurface pressures ahead of drilling is of extreme importance in the safe drilling of wells; "the research undertaken in GeoPOP made huge advances in our ability to do this".* A Geoscience Fellow and highly respected pore pressure expert at ConocoPhillips **[E4]** states*: "the basic research of GeoPoP has……improved our drilling efficiencies by avoiding pressure related problems which can run into tens of millions of dollars per event and in some cases can increase the risk of a release of high pressure fluids at the surface".*

Seal Risk and Column Height Prediction

Seal failure is one of the main reasons why petroleum accumulations are lost and expensive dry holes drilled. A Principal Geologist at BHP Billiton [**E5]** points out that *"the Caprocks consortium has helped us tremendously in understanding sealing rocks, including column height potential, and is used constantly by us to evaluate top seal risk in our multi-billion dollar oil and gas exploration programs".* Likewise, ConocoPhillips' *say that its* seal evaluation process *"has largely adopted workflows and concepts based on Caprocks research and the mud rock data base developed in the GeoPOP program. ShaleQuant is one of our standard tools for assessing mud rock properties that lead to column height prediction for our exploration risk assessment of plays and prospects*" **[E4]**. And at BP, *"much of the research has formed the foundation of our own internal research*

efforts. The technology is currently used to assess hydrocarbon column heights, helping us to make informed decisions to select prospects where our exploration wells do not fail due to column height prediction" **[E1]**.

Petroleum Systems Modelling: Pore Pressure, Charge and Retention

Many petroleum companies use sophisticated software to model fluid flow and thus to predict pore pressure and petroleum charge before drilling wells. BG's Technical Authority on Petroleum Systems states that the Newcastle research has impacted that process and points out that the methodology is widely accepted by the industry in that it has been coded into standard, basin-scale fluid flow simulation software: *"A key paper published by the Newcastle Group (P6) led to widespread awareness of the (mudstone) methodology and soon resulted in it being incorporated into high end Petroleum Systems Modelling software. Thus it became possible to predict pore pressure more accurately ahead of drilling"* **[E3]**.

BP's Team Leader in Petroleum Systems comments on how the research has helped exploration in particularly challenging geological settings: *"The use of the basic approaches inspired by Newcastle research helped us to build and populate complex 3D basin models to predict pore pressures in new areas such as beneath salt canopies in the Gulf of Mexico, and at great depths in the Caspian Sea. Without (Newcastle's) reliable lithological inputs to basin modelling we would be unable to unlock the significant resources we believe exist in these settings"* **[E1]**.

Training and Knowledge Dissemination within Companies

Both BP and ConocoPhillips have indicated that they use the Newcastle research routinely for training purposes, thus spreading the impact widely within their organisations:

BP [E1]: *"The technology is taught routinely in BP as part of the petroleum systems and PPFG courses and an overburden characterisation course."*

ConocoPhillips [E4]: *"Materials that have been generated by GeoPoP and more recently Caprocks have been an exceptional resource for developing our training courses for seal evaluation and overpressure. Publications by Caprocks and GeoPoP workers are now recommended readings for our new Geoscience employees and references for experienced employees. I would like to particularly refer to the impact that has been made by publications by Yang and Aplin on clay rock porosity and permeability (P2, P6), and seal bypass and injectites by Cartwright, Huuse and Aplin (P5). Training in seal evaluation at ConocoPhillips is based largely on concepts and materials generated by the Caprocks research which has been provided to over 200 people in our organization over the last 5 years"*.

5. Sources to corroborate the impact

[**E1**] Testimony: Senior Petroleum Systems Analyst, BP Exploration

[**E2**] Testimony: Team Lead, Maersk Oil

[**E3**] Testimony: Group Technical Authority – Petroleum Systems, BG Group

[**E4**] Testimony: Geoscience Fellow, ConocoPhillips

[**E5**] Testimony: Principal Geologist, BHPBilliton