Institution: University of Bristol

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Reservoirs Under Stress: Improved productivity through geomechanics and microseismicity in petroleum systems

1. Summary of the impact

Bristol researchers have been working with the oil and gas industry to develop new methods for monitoring and modelling deformation in oil and gas reservoirs. Industry and NERC funded research has led to the development of (i) novel techniques that better utilise microseismicity monitoring of petroleum reservoirs, and (ii) new software which couples geomechanical deformation and fluid flow with geophysical observations. The research has led directly to development and improvement of commercial software to enhance exploration efforts and minimise costs. Bristol software is now used by several multinational companies worldwide and its development has led to a successful start-up company.

2. Underpinning research

Since 2005, the Bristol Seismology Group has received £2.4 million for largely industry-funded research to investigate the microseismicity, fluid-flow and geomechanics of oil and gas reservoirs **[1-12]**. This research has been conducted under the umbrella of two large Joint Industry Projects (JIPs): (i) the Integrated Petroleum Engineering, Geophysics and Geomechanics (IPEGG) project, which aims to better integrate the disciplines of petroleum engineering, geology, geophysics, and geomechanics in order to achieve maximum value from reservoirs **[13-15,10]**, and (ii) the Bristol University Microseismicity Projects (BUMPS), which investigates natural and induced microearthquakes in petroleum reservoirs in a variety of settings **[3,16-18]**.

Geomechanics has, in recent years, emerged as an important area for the oil and gas industry because of the need to extract petroleum from challenging environments such as deep water, high temperature-high pressure, or structurally complex fields. Many reservoirs experience significant compaction during petroleum extraction, which can lead to problems such as sea floor subsidence and seismicity, which can dramatically alter reservoir permeability and redistribute reservoir stresses. These geomechanical-related problems are not easily addressed by conventional software tools used by petroleum engineers. IPEGG (2005-2009) has brought together expertise in reservoir deformation and fluid flow at the University of Leeds, the University of Bristol, and Rockfield Software Ltd – a Swansea-based company that specialises in advanced numerical analysis for geomechanical applications. *"The project was led by Quentin Fisher at Leeds, with Bristol coordinating the geophysics component. The University of Bristol played a significant role in the project, helping in part to build production simulation and geomechanical models, developing methods to populate the geomechanical models with mechanical properties based on down-hole tool and field seismic data… Bristol led the component that built seismic models to investigate the use of 4D and passive seismic for detective fault compartmentalized reservoirs"* **[a]**. IPEGG has made key developments in linking deformation and fluid flow within reservoirs to geophysical observations, such as microseismicity **[13-18]**. IPEGG developed numerical techniques and workflows to couple Rockfield's finite element model (ELFEN^{TM}) to industry standard production simulation models (e.g. Tempest^{TM}, Eclipse^{TM}, VIP^{TM}), which predict reservoir behaviour.

Reservoir stimulation is one of the fastest growing sectors in the petroleum industry and is used extensively in unconventional reservoirs such as shale gas, shale oil and tight gas sandstones. Monitoring the geomechanical response through induced seismicity is the primary means of assessing the efficacy of stimulation, but is also important for regulating the industry. Kendall has established one of the world's leading consortia in microseismicity (BUMPS; 2009-present), the first to develop downhole and surface seismic monitoring techniques for fracture characterisation and stress field evaluation, extending the utility of microseismic data far beyond simply locating microearthquakes **[b,16-18]**. The project has developed novel migration methods for automatically locating events in near real time using surface arrays of sensors. It was the first to use shear-wave splitting measurements to quantify fracture induced anisotropy, most recently extending this work to estimate fracture size and compliance, invaluable information for assessing the efficacy of hydraulic stimulation. The considerable synergies between IPEGG and BUMPS have been used, for example, to compare the geomechanical and microseismic response in the world's largest CO_2 sequestration projects **[15,17]**.

3. References to the research

Grants:

[1] Kendall (2012-2015). *FRACGAS: Improved hydraulic fracture stimulation of tight gas reservoirs using FE modelling and microseismic monitoring*. Industry Technology Facilitator (EBN, Shell, Chevron, Marathon, Nexen, Total, ExxonMobil, Noble). £160,000 to Bristol (a further £780,000 to PI Rance, Rockfield; Fisher, Leeds).

[2] Kendall (2011-2014). *Still or sparkling: Microseismic monitoring of CO_2 injection at In Salah*. NERC Partnership Grant with BP. £281,000.

[3] Kendall (2010-2016). *Bristol University Microseismity ProjectS (BUMPS).* Joint Industry Project (funding from 8 companies; ExxonMobil, Pinnacle, Microseismic Inc., Maersk, Chevron, Schlumberger, Rio Tinto, BP). £940,000.

[4] Kendall (2009-2012). *Enhanced integrated geomechanics-seismic model of improvement of lifecycle performance of tight gas sand reservoirs (GESER).* Industry Technology Facilitator (Shell, Chevron, ConocoPhilipps, DECC). £195,000 to Bristol (a further £465,000 awarded to co-PI Dutko, Rockfield; Fisher, Leeds).

[5] Kendall (2008-2010). *Passive seismic emission tomography: the dynamics of a reservoir*. NERC Partnership Grant with BP. £218,619.

[6] Kendall (2008-2012). *Passive seismic monitoring of CO_2 injection: Weyburn Phase I and II*. Petroleum Research Technology Council (Canada). £75,000 and £110,000.

[7] Kendall (2006-2009). *Microseismic monitoring and geomechanical modelling of CO_2 storage in subsurface reservoirs*. U.K. Energy Research Centre. £60,000.

[8] Kendall (2006-2010). *Microseismicity in the Ekofisk Field: Faulting and fracturing in a compacting chalk reservoir*. NERC CASE studentship with Schlumberger Cambridge Research. £60,000.

[9] Awarded to Imperial College University of London and 15 other institutions (including Kendall at Bristol) (2005-2008). *UK Carbon Capture and Storage Consortium.* NERC Consortium Grant. £2,000,000 (£50,000 to Bristol).

[10] Kendall (2005-2008). *Integrated Petroleum Engineering, Geomechanics and Geophysics (IPEGG)*. Industry Technology Facilitator (Statoil, BP, BG, ENI). £580,000 (£192,000 to Bristol) (co-PI Fisher, Leeds; Crook, Rockfield).

[11] Kendall (2005-2006). *Analysis of passive seismicity using life of field survey data*. BP Norge. £40,000.

[12] Kendall (2005-2008). *Development of robust tools for focal mechanism and shear-wave splitting analysis of microseismic data*. Shell (UK). £51,000.

References

[13] Angus, D.A., **Kendall, J.M.**, Fisher, Q., Segura, J.M., Skachkov, S., Crook, A. and Dutko, M. (2010), Modelling microseismicity of a producing reservoir from coupled fluid–flow and geomechanical simulation. *Geophysical Prospecting* 58: 901-914. DOI: 10.1111/j.1365-2478.2010.00913.x.*

[14] Angus, D.A., **Verdon, J.P.**, Fisher, Q.J., **Kendall, J.M.**, Segura, J.M., Kristiansen, T.G., Crook, A.J.L., Skachkov, S., Yu, J. and Dutko, M. (2011), Integrated fluid-flow, geomechanics and seismic modeling for reservoir characterization. *Canadian Society Exploration Geophysics - Recorder*, 26-35, May. Can be supplied upon request.

[15] Verdon, J.P., **Kendall, J.M.**, **Stork, A.L.**, Chadwick, R.A., White, D.J. and Bissell, R.C. (2013), Comparison of geomechanical deformation induced by megatonne-scale CO_2 storage at Sleipner, Weyburn, and In Salah. *Proceedings of the National Academy of Sciences USA* 110 (30): E2762-71. DOI: 10.1073/pnas.

[16] Chambers, K., **Kendall, J.M.**, Brabdsberg-Dahl, S. and Rueda, J. (2010), Testing the ability of surface arrays to monitor microseismic activity. *Geophysical Prospecting* 58: 821-830. DOI: 10.1111/j.1365-2478.2010.00893.x.

[17] Verdon, J.P., **Kendall, J.M.**, White, D.J. And **Angus, D.A.** (2011), Linking microseismic event observations with geomechanical models to minimise the risks of storing CO_2 in geological formations. *Earth and Planetary Science Letters* 305: 143-152. DOI: 10.1016/j.epsl.2011.02.048.*

[18] Baird, W.A.F., **Kendall, J.M.**, **Verdon, J.P.**, **Wuestefeld, A.**, Noble, T.E., Yongyi, Li., Dutko, M. and Fisher, Q.J. (2013), Monitoring increases in fracture connectivity during hydraulic stimulations from temporal variations in shear wave splitting polarization. *Geophysical Journal International*: 1030-1038. DOI: 10.1093/gji/ggt274.*

4. Details of the impact

Research from the Bristol seismology group has led to a broad range of software that has been incorporated into commercial code used for geomechanical modelling, measuring shear-wave splitting, characterising fractures, and assessing induced seismicity. Consequently, the end users (and thus beneficiaries) of this research are oil and gas companies looking to decrease their risk, improve oil and gas exploratory efforts and minimise exploration costs. For example, commercial impact is broad in that many (> 50 worldwide) multinational companies are now using Rockfield's coupled software to study the geomechanical behaviour and seismic properties of producing reservoirs and understanding fracturing and permeability effects; *"the output from the IPEGG project has been used regularly to address major challenges facing the petroleum industry"* **[a]**. Consequently, the IPEGG project has been viewed as highly successful by both Rockfield Software and the project sponsors (BG, BP, ENI, Statoil), with the resulting software being applied to various projects, such as *"predicting stress changes and subsidence due to the production from major chalk fields in the North Sea; assessing optimum position to place an oil platform in the North Sea; assessing the optimal mud-weights to use when drilling deviated wells in the North Sea and Gulf of Mexico. In addition, we are currently using the software to conduct a major (£950,000) project to optimize hydraulic fracturing within shale gas reservoirs"* **[a]**.

Rockfield has witnessed impressive software sales leading directly to an expansion in their oil and gas business. This increase in Rockfield's capabilities has driven international business to a medium-sized UK based company; "*Since the completion of IPEGG we have witnessed significant impact both in terms of sales of the software resulting from the project and consultancy projects that we have undertaken using the software/workflows. In particular, ELFEN™ and the module to couple to production simulation models was purchased by BP and ENI of the IPEGG sponsors at a cost of £40,000 per license per year over the past three years. Additional licenses, which total £80,000/year have been sold to other companies. In addition, Rockfield Software have conducted around £400,000 of consultancy work for the petroleum industry using the software developed"* **[a]**. There is then benefit for the operators who are hiring Rockfield, in that the improved reservoir models will enable them to maximise production while minimising the environmental and operational cost of geomechanical issues like subsidence (damage to be paid for), well-bore failure (cost of workovers and/or drilling replacement wells) and caprock fracturing (loss of hydrocarbon into overburden formations).

A novel aspect of the IPEGG project has been the development linking geomechanical modelling with fluid flow **[14]**. For instance, Roxar has led to the development of a very efficient memory-passing interface (MPI) by coupling their software Tempest™ with ELFEN™, which *"At a time when operators are looking to optimise production from increasingly marginal assets and make effective decisions over the allocation of capital and resources, the models and analytical processes that define modern reservoir simulation have never been more important"* **[c]**. More recently, this software has been utilised to assess potential leakage from CO_2 storage sites and to assess the use of seismic tools for monitoring CO_2 movement in the subsurface **[15,17]**. This research conducted at Bristol has *"influenced BP operations and future directions in a number of ways, specifically with application to the Valhall oil field…The success of the project was influential in BP's decision to use ELFEN for geomechanical modelling in our North Sea reservoirs. Notably, we are applying the software extensively to better manage the giant Valhall oilfield which is the 5th*

largest field in Norwegian waters" **[d]**. This has led to two further JIPs, the GESER and FRACGAS project **[a,1,4]**. Consequently, IPEGG and its underpinning research is viewed as a major success by the Industry Technology Facilitator (ITF); *"One of the things that ITF has tried to encourage is the formation of consortia with world class expertise to tackle fundamental industry issues. This project is a good example of how well this approach can work – it has brought together people that not only have an excellent track record of rapidly applying research findings to meet the needs of industry but also have experience bringing software packages to the market place"* **[e]**.

At the inception of the BUMPS project *"there was significant scepticism in large parts of industry regarding the viability of the use of surface seismic arrays for the monitoring of hydraulic fracturing"* **[f]**. However, the BUMPS project has demonstrated that surface seismic monitoring was feasible and has helped to provide confidence to the industry that surface monitoring was viable **[f]**. Indeed, Bristol's research into ocean bottom sensors to monitor passive seismic events in oil fields has influenced the establishment of the Life of Field Seismic array at Valhall in 2003 at a cost of over $46 million **[d]**. This research has led to the formation of a small spin-out company, which in 2012, was bought by Halliburton Energy Services and can be viewed as a measure of the success of the project **[d]**; "*The BUMPS research on surface-microseismic imaging spawned a new company that was ripe for acquisition given the dramatic rise in shale play activity worldwide. Kit Chambers left Bristol and formed Reservoir RockTalk [sic in 2010], a microseismic imaging start-up, which was subsequently bought out by Halliburton Energy Services*" [sic in 2012] **[b]**.

The BUMPS consortium has grown from having 4 sponsors to 10 in a short amount of time and is widely recognised as an industry-leading project with Kendall providing advice on research quality and directions for international companies such as Schlumberger. As such, *"Schlumberger views the work of Professor Kendall's consortium as being of both a high scientific quality and highly relevant to real world problems, setting it apart from many other academic consortia"* **[f]**. Research conducted at Bristol has also been *"key to defining the standard magnitude measures used in the mitigation of risks due to induced seismicity during hydraulic fracturing"* and to *"reduce location uncertainties of microseismic events"* **[f]**. It can be concluded that *"BUMPS is an important industry consortium providing independent fundamental research into new capabilities and applications of microseismic and other passive seismic monitoring under the advice of industry service providers and operators. Such research fills a critical need in the industry due to limited research investments in the private sector…and allows for quicker advancement and adoption of new technology across industry improving commercial results and addressing public interests"* **[b]**.

To summarise, *"the work done at Bristol over the past decade in microseismic research has made a significant contribution to the development of microseismic technology through innovative research, publication of ideas and case studies, and the training of young geophysicists who currently work in this business. The research carried out at Bristol has had significant commercial impact in helping drive the growth of this business"* **[g]**. In addition, both the IPEGG and BUMPS projects have trained numerous PhD students, many of whom have gone on to successful careers in the oil industry as a direct result of the training, reputation of research excellence, and academic-industry collaborations of the UoA.

5. Sources to corroborate the impact

[a] Rockfield Software Limited. Factual Statement.

[b] Microseismic. Factual Statement.

[c] Atomation.com Products Review. Available from: http://www.automation.com/product-showcase/emerson-enhances-roxar-tempest-reservoir-simulation-software

[d] BP Norge. Factual Statement.

[e] ITF Report. Available from: www.oil-itf.com/index/cms-filesystem.../ipegg-technical-article.pdf

[f] Schlumberger Gould Research. Factual Statement.

[g] Pinnacle Halliburton Energy Services. Factual Statement.