Institution: Newcastle University

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

Title of case study: Improved production from biodegraded heavy oil reservoirs

1. Summary of the impact

Newcastle University research on biodegraded petroleum systems has had a number of broad reaching impacts on the oil industry (ExxonMobil, Statoil, Woodside, and Shell), related companies (Permedia) and regulators (Alberta Energy Regulator). A new approach to oil viscosity determination was developed, which directs well-placement in biodegraded oilfields to lower viscosity areas, resulting in improved production of heavy oil. Software tools developed to model oil composition have been incorporated into proprietary in-house, oil company reservoir simulations. A spin-out company was founded, Gushor Inc., which provides services to the heavy oil sector and was recently acquired by Schlumberger. Collectively the research from Newcastle University has saved oil companies hundreds of millions of pounds by avoiding poorly producing viscous zones in biodegraded reservoirs.

2. Underpinning research

The majority of the world's petroleum deposits comprise heavy oil, which is difficult and costly to produce and refine and is therefore generally a less valuable resource than light oil. Heavy oil is formed by biodegradation of crude oil *in situ* in petroleum reservoirs over geological timescales but the factors that lead to in-reservoir biodegradation were poorly understood prior to this Newcastle University led research. Our research was aimed at understanding the controls on the occurrence of biodegraded crude oil, initially in the context of exploration to avoid targeting biodegraded reservoirs, but subsequently to understand the effects of biodegradation on petroleum fluid properties and production strategies.

The research by Newcastle University overturned decades of conventional wisdom in the oil industry which suggested that in-reservoir biodegradation was driven by oxygen delivered in meteoric waters, when it is actually an anaerobic process driven by water-hydrocarbon reactions at an *oil-water contact* (OWC) zone [**P1**-**P3**]. The key anaerobic process driving in-reservoir oil biodegradation is, in many cases, methanogenic crude oil degradation and our research showed that patterns of methanogenic oil degradation in laboratory incubations are similar to oils from degraded oil fields that have developed over geological timescales [**P3**]. Biodegradation of oil at the OWC at a rate greater than diffusion from the oil column leads to gradients in the oil composition and its related fluid properties (e.g. oil viscosity) in biodegraded petroleum reservoirs [**P1**, **P4**]. Furthermore, oil compositional gradients and viscosity are dictated by the interplay between reservoir filling and biodegradation over geological timescales [**P4**]. Understanding the detailed chemical changes in oil composition during degradation has allowed the development of geochemical means of assessing oil viscosity enabling reliable viscosity measurements in heavy oilfields, obviating the need for expensive coring and facilitating the avoidance of poorly producing viscous zones [**P4**, **P6**].

We identified reservoir temperature history as a primary control on degradation flux, showing that in-reservoir crude oil biodegradation is prevented if a reservoir has been exposed to temperatures in the region of 80 to 90ºC. This concept that we formulated, is now known as Palaeopasteurization [**P5**]. Reservoir geometry, oil water contact area, oil volume and oil mixing are other important factors affecting oil biodegradation in reservoirs, and the resulting large fluid property gradients produced have a major impact on oil recovery processes [**P6**]. Knowledge of these compositional gradients can be used to target regions of biodegraded oil fields where the flow properties and hence production of the oil are most favourable. The same principles also allowed barriers in reservoirs to be identified permitting the source of production for individual wells to be determined.

The underpinning research came from a project funded in 3 phases by an oil company consortium (Bacchus; http://www.ucalgary.ca/prg/bacchus). Phase I and II were based in Newcastle and Phase III was a joint enterprise between Newcastle and the University of Calgary (UoC) when one

of the PIs (*Larter; Professor of Geology – 1989-present, 2006 joint appointment with UoC*) took up a joint appointment. The research has generated 54 publications (including 4 nature papers) which collectively have been cited 1396 times. Other Newcastle researchers include *Head* (*lecturer, 1992-2000, Reader, 2000-2005, Professor of Environmental Microbiology, 2005-present*), *Jones* (*Analytical Manager, 1989-2007, Lecturer, 2007-2011, Senior Lecturer 2011-present*) and *Gray* (*RCUK Fellow, 2007-2009 , Reader, 2009-present*). Eleven Postdoctoral researchers and 6 PhD students also researched this area over the lifetime of the Bacchus project.

3. References to the research Literature citation data from Scopus 24 September 2013.

[**P1**] *****Head, I.M., Jones, D.M., Larter, S.R. (2003). Biological activity in the deep subsurface and the origin of heavy oil. *Nature* 426, 344-352. ***(269 citations)*** doi:10.1038/nature02134

[**P2**] Aitken, C.M., Jones, D.M., Larter, S.R. (2004). Anaerobic hydrocarbon biodegradation in deep subsurface oil reservoirs. *Nature* 431, 291-294. ***(128 citations)*** doi:10.1038/nature02922

[**P3**] *****Jones, D. M., Head I. M., Gray, N.D., Adams, J.J. , Rowan, A.K., Aitken, C.M., Bennett, B., Huang, H., Brown, A., Bowler, B.F.J., Oldenburg, T. Erdmann, M., Larter, S.R. (2008). Crude-oil biodegradation via methanogenesis in subsurface petroleum reservoirs. *Nature* 451, 176–180. ***(140 citations; Geochemical Society Best Paper Award, 2009)*** doi:10.1038/nature06484

[**P4**] *****Larter, S., Wilhelms, A., Head, I., Koopmans, M., Aplin, A., Di Primio, R., Zwach, Z., Erdmann, M., Telnaes, N. (2003). The controls on the composition of biodegraded oils in the deep subsurface - part 1: biodegradation rates in petroleum reservoirs. *Organic Geochemistry* 34, 601-613. ***(109 citations)*** doi:10.1016/S0146-6380(02)00240-1

[**P5**] Wilhelms, A., Larter, S.R., Head, I., Farrimond, P., Di-Primio, R., Zwach, C. (2001). Biodegradation of oil in uplifted basins prevented by deep-burial sterilization. *Nature* 411, 1034-1037 ***(112 citations)*** doi:10.1038/35082535

[**P6**] Larter, S., Adams, J., Gates, I.D., Bennett, B., Huang, H. (2008). The origin, prediction and impact of oil viscosity heterogeneity on the production characteristics of tar sand and heavy oil reservoirs. Journal of Canadian Petroleum Technology, 47 (1), pp. 52-61. ***(42 citations)*** doi:10.2118/08-01-52

Grants:

S.R. Larter, I.M. Head. Petroleum Biodegradation: From exploration towards production (Bacchus projects I, II and III). Period of grants: 01/03/00 – 31/05/04, 01/06/04 – 31/05/07, 02/07/08 – 30/09/11. Value of grants: £600K, £780K, £578K. Sponsors: Exxon, Norsk Hydro, Petrobras, Shell, Total-Fina- Elf, Phillips Petroleum, Chevron-Texaco, Japan National Oil Corporation, BP, Conoco, Statoil, Armco, ENI S.P.A, Woodside, Anadarko.

4. Details of the impact

Newcastle research on methanogenic oil biodegradation has had widespread impacts, not only in academia but on the oil industry (e.g. Statoil, Woodside, Shell [**E1**-**E4**]), related companies (Permedia, [**E5**]) and oil industry regulators (Alberta Energy Regulator, [**E8**]). The research principles and concepts have "*…fundamentally revised understanding of the subsurface process of the biodegradation of petroleum, which once and for all finished off old obsolete and wrong process models*" (Leader of Petroleum Systems Analysis in Exploration Research, Statoil [**E2**]), and "delivered a step-change in our understanding of biodegradation in hydrocarbon reservoirs" (Principal Technical Expert for Production Geochemistry, Shell [**E4**]). Importantly, take up of the research by industry has been rapid "*In more than twenty years of working in petroleum industry in Europe and Canada I have never seen industry grasping, and so rapidly applying, concepts developed by academia as it is case with findings from research projects led by Drs. Larter and Head*" [**E1**].

The impacts of our research on in-reservoir biodegradation and heavy oil have been numerous:
1. Improved production strategies for heavy oil reservoirs
2. New methods for fluid property (viscosity) determination
3. A biodegradation module for basin modelling software
4. A successful spin out company, Gushor Inc., providing services to the heavy oil sector

5. Provision of concepts used by the regulatory authority for oil sands development in Alberta
6. Impact on popular culture

1. Improved production strategies for heavy oil reservoirs

The identification and explanation of biodegradation-induced oil viscosity gradients in heavy oilfields has impacted substantially on production technology. "*Vertical compositional gradients of biodegradation susceptible compounds, another product of biodegradation identified by the Newcastle/Calgary researchers, have also very rapidly been utilized by industry for predicting behaviour (rate) of steam growth in thermal recovery processes*" [**E1**]. Evaluation of viscosity gradients in heavy oil reservoirs now forms an important part of production process design in the oil industry with several major oil companies (e.g. Statoil, Woodside, Shell) with a global footprint incorporating these insights into their heavy oil businesses [**E1-E4**]. One project sponsor specifically highlights how the science developed in the Bacchus project has had a direct influence on the value of a specific field, "*understanding of the reasons for fluid property variability influenced the decision to sell the field to another company and also added significant value (probably in the $10's of millions) to the asset*" [**E3**]. Well placement to avoid highly viscous oil in poorly producing zones is informed by knowledge of oil property gradients. It allows detection of barriers in reservoirs and allocation of the source of production in complex compartmentalised reservoirs [**E1-E3,** and **E8]**. These are now important components of cold and thermal heavy oil recovery in many parts of the world (e.g. Canada, Oman, Cameroon, Mauritania; **E1-E3, E8**). Improved recovery efficiencies with existing heavy oil recovery processes have resulted from avoiding difficult to recover hydrocarbons and well placements that could not have worked, improving cost-benefit ratios and project net present value (NPV) - "*the improved picture of the reservoir fluid state saved the drilling of at least one well at the cost of ~ $US 50 Million*" [**E3**] and "*Considering the number of projects and tens of billions of dollars of investment in oil sands, the impact of their new findings can be estimated to be measured in hundreds of million and perhaps even billions of dollars in the long term*" [**E1**]. Moreover principles developed from our research are "*routinely used as (i) a screening criterion for caprock integrity for thermal recovery processes (i.e. presence of gas indicates good caprock under reservoir conditions) (ii) a tool for evaluating the geometry and size of these zones and their volumetrics. This is a critical development risk (water and gas are 'thieves' for injected steam in reservoir and significantly impact the economics of thermal operations*" [**E1**] and "*Numerous projects that have suffered in the near past would have been a success stories if these principles had been applied!*" [**E1**].

2. New methods for fluid property (viscosity) determination

Design of optimum production processes requires high quality data on oil heterogeneity across a reservoir. Understanding the detailed chemical changes in oil composition during degradation has allowed the development of geochemical methods for assessing oil viscosity, enabling reliable viscosity logging from drill cuttings in heavy oilfields "*The temperature-viscosity relationships elucidated in the Bacchus project helped us predict that traps flanking the anticlinal structures and hence at slightly higher temperature could contain producible oil*" [**E3**]. This technology is now routinely deployed around the world [**E1-E3**], and is being used to reduce costs by providing a low cost alternative to expensive well testing procedures that rely on obtaining cored reservoir material that is costly and technically challenging.

3. A biodegradation module for basin modelling software

The fundamental principles developed from our research and specific models developed have been incorporated into practical software tools developed in-house by oil company sponsors [**E2-E4**], for example, "*A predictive framework resulted from the synthesis of data from laboratory simulations and field studies, and this provides a basis for our in-house development of improved basin modeling tools*" [**E4**]. Permedia, a company that develops and markets basin modelling software [**E5**] worked closely with Bacchus researchers to couple Permedia's high resolution modelling software with the science base from our oil biodegradation research. The product is a 3D fluid property prediction tool that integrates the dynamics of active oil charging with biological degradation of oil in reservoirs across individual accumulations or for whole basins. This substantial technical challenge has been met and a tool ("BaccPath") within Permedia's MPath software platform can effectively predict oil density and viscosity for accumulations through time and space. An interrogation tool ("Gnawd") developed within our research spin-out company, Gushor Inc. [**E6**], models individual reservoir segments and estimates vertical compositional

gradients related to biodegradation [**E6**]. Permedia has recently been acquired by Halliburton and BaccPath has been incorporated into Halliburton's proprietary software [**E5**].

4. A successful spin out company providing services to the heavy oil sector

In 2006, the research led to the formation of a successful spin out company, Gushor Inc., [**E6**] which provides services to the heavy oil industry. Gushor develops reservoir characterisation technologies for heavy oil reservoirs and specialises in applying understanding of in-reservoir petroleum biodegradation and its impact on petroleum fluid properties to design and monitor heavy oil production systems. Gushor quickly dominated the Canadian heavy oil fluid property characterisation market and won both technical and commercial accolades including an Alberta government ASTech award for commercial success in 2009 [**E6**]. One of the services Gushor provides, ProxVisc^{TM}, provides high resolution oil viscosity data based on geochemical measurements conducted on drill cuttings and a range of geochemical analysis services for the heavy oil sector. It also provides the biodegradation modelling software, Gnawd, and bespoke viscosity reduction technology (BRUTUS^{TM}). In 2012-2013 Gushor Inc. employed 19 staff and had a turnover of C$3.4 million (£2.08 million). It has provided services to the heavy oil operations of many major oil companies in China, the North Sea, Columbia, Brazil, Oman, the Gulf of Mexico, California and Canada [**E6**]. This not only underlines the success of Gushor Inc. itself, but provides evidence of the global application of knowledge and technology that has been developed as part of our research on biodegraded petroleum reservoirs and heavy oil. In June 2013, Gushor Inc. was sold to the world's leading oilfield services provider, Schlumberger, for an undisclosed sum [**E7**].

5. Provision of concepts used by the regulatory authority for oil sands development in Alberta

In addition to the industry impacts detailed above Newcastle research on heavy oil has meant that we have advised regulators such as the Alberta Energy Regulator (AER) on best practice in energy production from heavy oil and bitumen reservoirs [**E8**]. The AER have used our research to "*teach Applications staff the basic principles of oil-sands geology and technology*" and specifically contribute to "*understanding bitumen viscosity variations, and determining recovery factors of bitumen and heavy oil in oil sands reservoirs to give realistic estimates of reserves numbers that go into the Province of Alberta budgets*" [**E8**].

6. Impact on popular culture

Our research has provided the basis for a science fiction novel, "Petroplague" by Amy Rogers [**E9**] with our research (Jones, et al. Nature 451, 176–180; Section 3, Reference 3, above) one of the sources cited in the technical annex (p. 322).

5. Sources to corroborate the impact

E1. Testimonial: Research Geologist in Heavy Oil Technology Centre, Statoil Canada Ltd.

E2. Testimonial: Leader of Petroleum Systems Analysis in Exploration Research, Statoil ASA.

E3. Testimonial: Petroleum Systems Advisor in Sub-Surface Technology, Shell/Woodside Energy
E4. Testimonial: Principal Technical Expert for Production Geochemistry, Shell International.

E5. Webpages of the Permedia Research Group (owned by Halliburton since 2010) describing the incorporation of the Bacchus project biodegradation module into Permedia MPath basin modelling software. (http://www.permedia.ca/news_july04.html; http://www.permedia.ca/news_jun09.html)

E6. Webpages that show the existence of Gushor Inc. and that the spin-out company won the ASTECH Award for outstanding commercial achievement in Alberta science and technology in 2009. (http://gushor.com/20091111/gushor_wins_2009_astech_award/search; http://www.youtube.com/watch?v=YkScl9oDtho)

E7. Press releases from the Wall Street Journal, Calgary Herald and Schlumberger media relations showing that Gushor was sold to Schlumberger in June 2013. (http://tinyurl.com/q8y28l2; http://tinyurl.com/ns5fa7c)

E8. Testimonial: Chief Geologist, Alberta Energy Regulator.

E9. Webpage showing the existence of "Petroplague". http://www.sciencethrillers.com/petroplague/; http://www.amazon.com/Petroplague-Amy-Rogers/dp/1467038261