Institution: Durham University

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

Title of case study: Commercialisation of Research into High Pressure Geological Reservoirs

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

Failure to predict and control geological overpressures during drilling can lead to operational delays costing millions of pounds, or to blow-outs causing serious environmental damage and costs running into billions. Using methodologies, knowledge and data analysis techniques developed at Durham, a spin-out, GeoPressure Technology (GPT; now Ikon Geopressure) (20 employees, revenues 2008-13: £10.8 million) has become a niche supplier to the global oil industry of expertise, training and software ("PressureView") that predicts and assess the causes of overpressure. GPT consultancy has had particular impacts for companies drilling in the North Sea, offshore Canada, Norway and West Africa where overpressure represents a significant technical challenge.

2. Underpinning research (indicative maximum 500 words)
[numbers] = references in Section 3

The prediction and control of geological overpressures is an essential requirement during drilling into hydrocarbon-bearing sedimentary basin sequences in the subsurface. Failure to do this can lead to operational delays or to blow-outs resulting in loss of life, destruction of facilities and/or serious environmental damage. The multi-company-funded Durham-based GeoPOP research programme investigated overpressure in sedimentary basins and was led by Richard Swarbrick (PhD Geology; Mobil Oil 1979-1989; mid-career appointment at Durham 1989-2005; Managing Director GPT 1997-present). This collaboration linked research groups at Durham, Newcastle and Heriot-Watt Universities from 1994 to 2001.

The main Durham-based research themes during GeoPOP Phase 1 (1994-1997) included: re-evaluation of overpressure generation mechanisms; establishment of relationships between overpressure and reservoir quality; and leading an integrated pressure study of the Central North Sea. The research established the predominance of compaction-/burial-related overpressure, with gas generation as the main secondary mechanism **[1]**. A new type of process - termed "Load Transfer" – was recognised relating to collapse of pores during thermally-driven chemical change (diagenesis) **[2]**. Macro-quartz dissolution/cementation was shown to be controlled by pressure, a conclusion challenging existing models of stress-independent quartz dissolution/reprecipitation. In order to build a pressure database of >850 deep Central North Sea boreholes, a research software tool was designed and used to generate single and multi-well pressure-depth plots. Maps of overpressure were created illustrating reservoir relationships – open system, hydrodynamic reservoirs above the Cretaceous Chalk, and highly compartmentalised pressures in the Jurassic/Triassic reservoir beneath **[4]**. Papers published by the Durham group **[1-4]** remain key references on overpressure mechanisms.

GeoPOP Phase 2 (1998-2001) research themes at Durham focussed on: understanding the role of fine-grained carbonates (chalk) in the development of deep overpressure; stress and rock strength analysis **[5]**; petrophysical modelling of clay compaction; and 2D basin modelling including chemical compaction processes. Papers devoted to chalk compaction as well as explaining how overpressure contributes to many aspects of the petroleum system were published in a range of journals using case study material from the North Sea, SE Asia and Gulf of Mexico basins **[3, 6].**

In 1997 GPT was founded as a University spin-out company based in Durham City, initially to commercialise the pressure database and visualisation software developed during Phase 1, now termed "PressureView". In 2001, GPT commenced a period of sustained growth. The research at Durham **[1,3,6]** underpinned new approaches to pressure prediction, a key component in the safe drilling of deep boreholes for oil, gas, water and, more recently, in the search for sequestration sites for carbon dioxide. The oil industry began to recognise that a geological approach to pressure prediction, underpinned by good science, was able to provide high quality pre-drill prediction and

complement existing approaches based on seismic and petrophysical data. In 2004, GPT completed the first basin-wide pressure study for the entire Central North Sea area. This report has been sold to more than 20 companies. From 2004 to 2011, several other regional pressure studies were completed covering high pressure areas of Europe, plus deep-water reservoirs in the Gulf of Mexico and Niger Delta. These studies are considered highly authoritative (see Section 4) and are used routinely by industry to improve safety, as well as in the exploration for new reserves.

In 2006, GPT was purchased by Ikon Science, a global technology company providing geoprediction tools to the upstream oil and gas industry. GPT was rebranded as 'Ikon GeoPressure' and the company has remained based in Durham.

A third phase industry-funded research consortium, GeoPOP3 was launched in 2012 with funding (award value £2.475M TOTAL; Durham share £1.79M) for three years from BG, BP, Chevron, ConocoPhillips, DONG Energy, E.ON, ENI, Petrobras, Petronas, Statoil and Tullow. The project involves academic researchers from Durham (**Goulty, Jones, Aplin, Hobbs**) and Newcastle universities and is run in partnership with Ikon GeoPressure (**Swarbrick**). The research builds on Phases 1 and 2 and aims to investigate pore pressure and its prediction in clastic sedimentary rocks. GeoPOP3 also maintains the strong long-term research collaboration between Ikon GeoPressure and Durham University.

3. References to the research (indicative maximum of six references)
Peer-reviewed literature - * = Durham-based PDRA; ** = Durham PhD student **[number of citations, Google Scholar]**; # = references best illustrating research quality.

[1] Osborne, M.J.* & Swarbrick, R.E., 1997**.** Mechanisms for generating overpressure in sedimentary basins: A re-evaluation. *AAPG Bulletin,* 81, 1023-1041**.** [422]#
Main published authority on the mechanisms that create high pressures in the subsurface, bringing together all previous relevant papers.

[2] Osborne, M.J.* & Swarbrick, R.E., 1999. Diagenesis in North Sea HPHT clastic reservoirs - consequences for porosity and overpressure prediction. *Marine & Petroleum Geology,* 16, 337-353. DOI: http://dx.doi.org/10.1016/S0264-8172(98)00043-9 [79]#
Controversy exists over the role of pressure in diagenesis and reservoir quality of deep, high pressure reservoirs. This paper showed, through careful petrographic examination of quartz-rich reservoirs, that overpressure controls both the magnitude and rate of precipitation of secondary quartz.

[3] Harrold, T.W.D.**, Swarbrick R.E. & Goulty, N.R., 1999, Pore pressure estimation from mudrock porosities in Tertiary basins, Southeast Asia. *AAPG Bulletin*, 83, 1057-1067. [35]
This paper presents a mean stress model (a paper by Goulty in 1998 had shown that compaction is a function of mean stress) for pressure prediction (as opposed to the more common models using only vertical stress).

(4) Swarbrick, R.E., Osborne, M.J.*, Grunberger, D., Yardley, G.S., Macleod, G., Aplin, A.C., Larter, S.R., Knight, I., & Auld, H.A., 2000. Integrated study of the Judy Field (Block 30/7a) – an overpressure Central North Sea oil/gas field. *Marine & Petroleum Geology,* 17., 993-1010. DOI: http://dx.doi.org/10.1016/S0264-8172(00)00050-7. [49]
Using data from all three GeoPOP research groups (Durham, Newcastle and Heriot-Watt) this paper is the first integrated study of a high pressure field involving reconstruction of the pressure history validated by palaeopressures determined from fluid inclusions.

(5) White, A.J.**, Traugott, M. O.** and Swarbrick, R.E., 2002. The use of leak-off tests as means of predicting minimum in-situ stress. *Petroleum Geoscience,* 8, 189-193. doi: 10.1144/petgeo.8.2.189 [25]
First paper to establish criteria for recognizing minimum stress from build-up plots and demonstrating that Leak Off and Shut-In criteria are both valid and statistically give comparable values.

(6) Swarbrick, R.E., Osborne, M.J.* & Yardley, G.S. 2002. Comparison of overpressure magnitude resulting from the main generating mechanisms. *AAPG Memoir,* 76, 1-12 [73]#
This paper is the first attempt to quantify the magnitude of overpressure from the main mechanisms established in 1997 paper (Reference 1 above). This paper remains the principal source of information to identify which mechanisms apply in different basin settings and to rank their significance.

Papers from Phase 2 GeoPOP research related to chalk compaction underpin a series of papers focussed on modelling overpressure in the North Sea. These models are used extensively by industry in planning high pressure wells for safe drilling in the High Pressure, High Temperature (HPHT) region of the Central North Sea (see Section 4).

In 1995 Durham hosted a "community research meeting" focussed on subsurface pressures, attended by an international audience, and the success of the meeting led to subsequent meetings in Paris in 1996, Pau (extended abstracts published as a book) in 1998, London in 2000 (CD published); Durham in 2008 and Galveston, Texas in 2011. Durham research staff led, or were involved in the organising committee for all these meetings. In 1995 the meeting was attended by 80 participants with 85% from academia; the Durham 2008 meeting was attended by 116 participants of which 85% were from industry.

Swarbrick has delivered numerous keynote presentations based on the Durham research, the most recent being in Singapore, 2010 (AAPG/EAGE); Durham, 2011 (TSG); Thailand, 2012 (AAPG/SPE); London, 2012 (GeolSoc); Aberdeen, 2012 (GeolSoc); Melbourne, 2013 (ASEG/PESA).

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

The accurate prediction and control of overpressures at depth is a priority during the drilling and completion of wells in the offshore oil and gas exploration industry worldwide. Since the 1970s, there have been a number of well-documented drilling and completions incidents related to overpressure of which the 2010 BP Macondo disaster is perhaps best known.

The main impacts of the Durham overpressure research were delivered through the development of the spin-out company GPT and the subsequent delivery and sales of its software tools and expertise. The company employs mainly graduate/postgraduate-level geoscientists, managers and administrative staff. The number of professionals has grown from 8 full time (FT) employees in 2008 to 18 FT geosciences staff located in Durham, Kuala Lumpur, Calgary and London. There are 8 FT and 2 P/T support staff which includes 4 trainee Geoscientists. The company has a total revenue from April 2008 to March 2013 of £10.8million **[7].** The most important tools developed by GPT based on Durham overpressure research are as follows:

a) Software: Based on Durham research using industry data, research of industry practices and writing of original source code during GeoPOP Phases 1 and 2, 'PressureView' (PV) was the first dedicated pressure database and visualisation software for use in the oil/gas industry. The first commercial sales were made in 1999 with licences subsequently sold to 140 companies worldwide, including global licences for Shell and BG. Estimated total income is over £3 million, plus annual maintenance licences (currently 20% of licence fee). During the period 2008-2013, revenue from the sales of PV amounted to £0.78M **[8].**

b) Algorithms: The fracture strength analysis in Adrian White's 2001 thesis and associated publications **[5]** led to the development of regional to local algorithms to predict fracture strength including pore pressure-stress coupling. Algorithms are now used in consultancy projects for prediction of fracture pressure in well planning. In the period 2008-2013 consultancy projects relating to this development total £1.8M. In addition, during 2019-11 GPT collaborated with 11 other organisations (including Durham University, Imperial College, Edinburgh, Herriott-Watt, BGS, Synergy and RPS) in the Energy Technology Institute-funded assessment of UK carbon dioxide

storage estimates – GPT fracture algorithms were used directly to assess hydraulic failure during injection modelling and in volume estimates based on top seal failure criteria. The value of this project to GPT to date is £0.24M, but the longer term strategic value of the project findings to the UK in planning the future deep disposal of carbon dioxide is likely to be substantial.

c) Knowledge: Chalk of Central North Sea: Since 2001, GPT has conducted specialist pressure analysis to aid drilling safely through Upper Cretaceous Chalk **[4]**, a unique challenge for pressure interpretation and safe drilling. Pressure profiles and understanding of drilling behaviour are underpinned by later research results (papers by Anthony Mallon/Swarbrick). The value to GPT of such studies varies from £15k to £40k per study, and in the period 2008-13 has generated £0.6M of income to GPT from a total of 26 projects. The importance and value to oil companies is much greater given the costs involved in drilling exploration wells (ca. $100M each).

d) Methodology: Pore pressure prediction: research on disequilibrium compaction (a common overpressure mechanism **[1,3]**) has led to a unique geological approach to predict pore pressure in shales **[6]**. The technique (known as the "Swarbrick FRD Method') is included routinely in all GPT projects and several companies (e.g. Petronas, Santos) have adopted the method and apply it to their well planning worldwide (each with a value of ~ $100M).

Worldwide, all oil wells require pre-drill pressure prediction and GPT specialises in understanding the geological context for the magnitude of these pressures, with particular emphasis on geologically complex basins, where traditional methods are unsuccessful, but still used by most of the competition for this type of business. The experiences of two oil companies in the North Sea illustrate the impact of geological overpressure research on their operational activities and budgets:

i) **BG Group** participated directly in a multi-client study led by GPT in 2009-10, the 'Central North Sea Pressure Study Phase II'. The company has operated widely in the North Sea where drilling at depth, in high-pressure, high temperature (HPHT) environments represents a significant technical challenge. The Pressure Advisor at BG Group has said: *"Research carried out initially at Durham University and then by GPT has provided a better understanding of the causes and nature of the high pressures encountered in the North Sea area"* **[9].** BG Group uses PressureView software throughout their worldwide operations (income to GPT of >£0.1M in period 2008-13), together with use of GPT technical consultants and training for their staff to mitigate risk and reduce uncertainty when planning and drilling HPHT wells.

ii) The Regional Pressure Study of the Central North Sea was used by **Valiant Petroleum** in the planning, design and drilling of its first HPHT well in the basin in 2010. The study successfully captured the changing pressure regimes related to the structure of the basin, as well as the challenges of drilling to the objective reservoir through the lithologically complex overburden. GPT, through consultancy and real-time monitoring, also helped in the safe drilling of the well. The Exploration Manager at Valiant Petroleum has stated that GPT involvement in this project during 2009-11 *"meant that we were better prepared to manage the fluid pressures encountered thereby improving the safe management of our operations"* **[10]**. With the cost of drilling North Sea HPHT wells currently running at $600K-$1Million per day, a service that can assist in predicting well conditions ahead of the drill bit and minimise costly well control operations is easily justified in economic terms. We have further testimonies from 6 other national and multinational companies confirming the impacts of Durham-based overpressure research through GPT operations worldwide **[11-13].**

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

7) ***Document****: GPT/Ikon Geopressure Ltd Company Accounts 2008-2013.*
8) ***Document:*** *Summary of PressureView* ™ *revenue 2008-13.*
9) **Testimony:** ***BG Group****, 100 Thames Valley Park, Reading, Berkshire, RG6 1PT.*
10) **Testimony:** ***Valiant Petroleum****, Victoria Gate, Chobham Road, Woking, GU21 6JD, UK.*
11) **Testimony:** ***ConocoPhillips,*** *600 North Dairy Ashford, Houston, Texas, 77079.*
12) **Testimony:** ***Tullow Oil,*** *9 Chiswick Park, 566 Chiswick High Road, London W4 5XT.*
13) **Testimony:** ***BP Exploration****, Chertsey Road, Sunbury on Thames, Middlesex, TW16 7LN, UK*