Institution: Durham University

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

Title of case study: New geology tools and knowledge used to improve the exploration and development of structurally complex hydrocarbon reservoirs

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

Enhanced structural geology models of complex fractured reservoirs, utilising new virtual- and field-based techniques developed at Durham, have been applied by industry in the Faroe-Shetland region, N Britain and helped sanction development of the 8 billion barrel Clair Ridge project, a £4.5 billion investment by the Clair Joint Venture Group (BP, Shell, ConocoPhillips, Chevron). Geospatial Research Ltd (a spin-out launched in 2004) has additionally used Durham structural geology research methodologies and expertise to provide > £1.3 million of consultancy services to the global hydrocarbon industry creating, since 2008, 12 new highly skilled jobs.

2. Underpinning research (indicative maximum 500 words)

[numbers] = references listed in Section 3

Initial Durham-based research by Holdsworth and students into the nature and causes of basement fault reactivation **[1]** (1994-2001) led to a NERC Ocean Margins LINK (OML) project co-sponsored by BP, Statoil and CogNIT (with McCaffrey, Jones, Imber [PDRA] and PhD students; 2001-2005). This investigated the basement influences on fault development during rifting in the N Atlantic passive margins. It required the development of a new methodology to integrate structural datasets collected at differing scales from rocks exposed onshore with those interpreted using 3D seismic data from offshore areas. The resulting workflow **[2, 4, 5]** ('**GAVA**' - **G**eospatial **A**cquisition **V**isualisation & **A**nalysis) uses field observations, GPS surveying and terrestrial laser scanning techniques to create virtual fracture models from which geospatially referenced attribute data (e.g. orientation, density, interconnectivity) may be extracted.

Three key Durham research findings from this project were:

a) Proof that the GAVA-methodology addresses the scale issue between surface and subsurface structural datasets, improving understanding of the geometry, kinematics and sealing potential of large-scale structures imaged on seismic **[2, 4]**. Attribute data extracted from the small-scale analogues (Virtual Outcrops) can be used directly to condition deterministic discrete fracture network (DFN) models **[5]**.

b) A demonstration that when pre-existing basement structures are oblique to far-field tectonic stresses, this leads to transtension and signature patterns of non-Andersonian, polymodal faulting **[4].**

c) The development of a new microcrack interaction model based on the three-dimensional Eshelby solution (formulated with Healy, at Durham 2006-7) to explain the development of such polymodal faults **[3].**

In 2004, a spin-out company, **Geospatial Research Ltd** (GRL), with MD Jones, was set up to commercialise GAVA using NERC funding (Follow-on Fund), University seedcorn support and venture capital from the RDA, OneNE.

In partnership with GRL, the SGRG has further developed the knowledge and IP generated during the OML project. This includes:

1) FR3DA (Fractured Reservoirs 3D Digital Atlas) (2006-8), a Shell/BG, DTI-funded consortium using GAVA methods to construct deterministic 3-D fracture models in a range of tectonic and sedimentological environments.

2) Four projects (including 3 PhDs) funded by the Clair Joint Venture Group (BP, Shell,

ConocoPhillips, Chevron) have studied onshore analogues in Scotland (Lewisian Complex, Orcadian Basin) for the fractured basement and reservoir in the giant offshore Clair Field (2006-15). The onshore fracture characterisation work was integrated (using the GAVA methodology) with structural interpretations made in the subsurface using offshore 3D seismic data and subsurface core logs. The onshore work included the creation of virtual outcrop fracture models using terrestrial laser scan data and the analysis of fracture attributes from those models.

3) Three Statoil-funded onshore-offshore studies of faulting patterns and processes in the Faeroe/Shetland basin, including PhD and PDRA to Walker (2006-12).

Research highlights derived from these projects include:

d) New geological and predictive statistical insights into the controls and scaling relationships of basement-hosted fracture systems in the Lewisian Complex as an analogue for the Clair basement (see Section 4).

e) The first detailed understanding of fault zone development and permeability evolution in upper crustal basaltic rocks [6].

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

Peer-reviewed literature - * = SGRG research students; [number of citations, Web of Knowledge]; # = references best illustrating research quality.

[1] Holdsworth, R.E, Butler, C.A* & Roberts, A.M. 1997. The recognition of reactivation during continental deformation. Journal of the Geological Society, London, 154: 73-78; doi:10.1144/gsjgs.154.1.0073. [98]

[2] McCaffrey, K.J.W, Jones, R.R, Holdsworth, R.E, Wilson, R.W*, Clegg, P*, Imber, J, Holliman, N & Trinks, I*. 2005. Unlocking the spatial dimension: digital technologies and the future of geoscience fieldwork. Journal of the Geological Society, London, 162: 927-938, doi: 10.1144/0016-764905-017. [78]#

[3] Healy, D., Jones, R.R. & Holdsworth, R.E. 2006. Three-dimensional brittle shear fracturing by tensile crack interaction. Nature 439 (7072), 64-67, doi:10.1038/nature04346. [32]#

[4] Wilson R.W.*, McCaffrey, K.J.W., Holdsworth R.E., Imber, J., Jones R.R., Welbon, A. & Roberts, D. 2006. Complex fault patterns, transtension and structural segmentation of the Lofoten Ridge, Norwegian margin: Using digital mapping to link onshore and offshore geology. Tectonics, 25, TC4018, doi:10.1029/2005TC001895. [16]

[5] Jones, R.R., McCaffrey, K.J.W., Clegg, P*. Wilson, R.W.*, Holliman, N.S., Holdsworth, R.E., Imber, J., Waggott, S. 2009. Integration of regional to outcrop digital data: 3D visualisation of multi-scale geological models. Computers & Geosciences, 39, 4-18, doi:10.1016/j.cageo.2007.09.007. [27]

[6] Walker, R.J.*, Holdsworth, R.E., Armitage, P.J. & Faulkner, D.R. 2013. Fault zone permeability structure evolution in basalts. Geology, 41, 59-62, doi:10.1130/G33508.1. [1]#

Quality of Research:
Paper [1] is highly cited and underpinned the setting-up of the SGRG in its former guise as the Reactivation Research Group. Since 1994, Holdsworth and students have published over 50 papers on the nature and causes of fault reactivation studying examples from UK, Europe, S America, N America, Greenland and Japan. This work has been recognised by his peers by awards from the Geological Society of America (*Fellowship* 2004) and the Geological Society, London (GSL) (*Lyell Fund* in 2000; *Aberconway Medal* 2006). Note that the latter is awarded based on “distinction in the practice of geology, with special reference to work in industry.” Other

awards for research by members of the SGRG include: the GSL *Murchison Fund* (to McCaffrey 2005); the *Clough Memorial Award* by the Edinburgh Geological Society (to Imber 2003); 2 Royal Society Industry Fellowships (McCaffrey 2006, Imber 2012) and a NERC Knowledge Exchange Fellowship (Holdsworth 2009).

Papers [2-4] were entered by Holdsworth or McCaffrey as research outputs for RAE 2008. 97.3% of the Durham UoA 17 Research outputs were rated ≥ 2*, with 71.2% rated ≥ 3*.

Papers [2 and 5] describe the Durham research underpinning a 5 day Geological Society of America **Penrose Conference** hosted by the SGRG in Durham in 2006 *"Unlocking the Spatial Dimension in 3D Earth Systems"*. This event was predicated on our global leadership in this field and was attended by 50 delegates drawn from academia and industry across the world. http://www.geosociety.org/penrose/reports/06pcrpt4.htm

Paper [6] has been submitted by Holdsworth as an output for REF 2013. A related paper by Walker, et al. (2011), titled 'Onshore evidence for progressive changes in rifting directions during continental break-up in the NE Atlantic' and published in the Journal of the Geological Society, London (v 168, 27-48) was awarded the ***Ramsay Medal*** for 2012 by the UK Tectonic Studies Group for 'best international paper published by a research student'. This was the 4th such award made to a SGRG PhD student in 6 years (other awards in 2005, 2009, 2010, 2011).

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

[numbers] = research outputs listed in Section 3 or corroboration sources listed in Section 5.

a) *Business and jobs:* Since 2008, Geospatial Research Ltd (GRL) has created 12 new highly skilled jobs for graduate and post PhD-level geoscientists. The company has a total income to date in excess of £1.3 million and has provided consultancy services based on SGRG research **[1, 2, 5, 7]** to the global hydrocarbon sector, including BP, TOTAL, ExxonMobil, Hess, Neftex, Maersk, Marathon, Petronas, Shell, Tullow and others.

b) *Commercial advantage to end-users:* Clair Joint Venture Group
SGRG research findings and expertise have had impacts for the development of the Clair Ridge Project by the Clair Joint Venture Group **[8-10]** (CJVG; a consortium of BP, Shell, ConocoPhillips and Chevron). The Clair field is the largest hydrocarbon resource in the UKCS with an estimated 8 billion barrels of Stock Tank oil initially in place (STOIIP) **[11]**. The Phase I area came on stream in 2005, whilst the Clair Ridge (Phase II) is due to begin production in 2016. The reservoir target is Devonian sandstones that rest directly on Lewisian-like metamorphic basement. Both rock units are highly faulted and fracture description and water flood performance are considered to be the two main risks in field development. This risk is exacerbated by a lack of industry experience in working with metamorphic basement rocks **[8-10]**.

The Durham research that has so far contributed directly towards addressing these risks stems from the analysis of the fault and fracture systems developed in the Lewisian Complex of NW Scotland as an onshore analogue for the fractured basement in the Clair Field **[9, 10].** The Durham research results were acquired using the GAVA methodology. Quantitative data concerning the geometry, density, aperture and nature of infills were incorporated into the structural model for the Phase II Clair Ridge by the CJVG **[9, 10]**. The basement fracture framework is known to be directly connected to the overlying reservoir impacting subsequent fluid flow movement across and through the oilfield. The structural model is used to derive a detailed reservoir simulation on which an economic assessment is made, with up to 36 new development wells for the Ridge planned. In 2013, BP announced a further two year appraisal Programme to develop a third Phase involving the drilling of up to 12 more wells in the Greater Clair area **[11]**. Each development well costs upwards of £20M and the decision to sanction the entire development programme is significant in both financial and economic terms **[8-10, 12-14]**.

Since 2008, the SGRG have additionally led annual field workshops with CJVG geoscientists (42

individuals to date) to view the complex nature of the fractured basement in NW Scotland. This has helped the industry subsurface teams to better conceptualise the structural framework in the basement and to design improved alternative fracture models **[9, 10]**. Fracture networks within the reservoir are known to boost the average permeability by orders of magnitude and allow economic oil production rates in otherwise unpromising metamorphic rocks. The CJVG Basement Sub-surface Team Leader (ConocoPhillips) **[9]** has stated that:

"*The basement fracture models used in our reservoir simulator to estimate recovery are substantially based on the Durham onshore data and are additionally informed by knowledge gained during the field workshops. Populating the fractures into a Discrete Fracture Network (DFN) model requires a complete understanding of the interaction between all scales of fractures observed from large seismic scale faults to small sub-seismic scale joints. The model has been built and run, showing an economically robust project. This ultimately led (in 2012) to the sanctioning of the Clair Ridge for development – an investment of around £4.5 billion"* **[11]**

c) *Commercial advantage to end-users:* Statoil/Jardfeingi, Faroe-Shetland Basin

The Faeroe-Shetland Basin is one of the most important exploration targets in the UKCS region **[13].** It is geologically challenging as it is strongly faulted and associated with substantial volumes of Tertiary volcanics. The SGRG research into basalt-hosted faulting in the Faroes (Walker, Holdsworth, Imber) is considered by both Statoil and Jardfeingi (a Faroes-run consortium of companies) to be the definitive study. The Leading Geoscientist in this area (Statoil) **[14]** writes*: "The findings have been of great benefit in the search for oil beneath the basalts and, by changing our understanding of the nature and significance of NW-SE 'transfer zones', have definitely influenced our exploration strategies in the Faroe-Shetland Basin."* It is difficult here to precisely quantify the value of the Durham contribution, but in a frontier area of this kind, improved predictions in the subsurface lead to commercial advantages with values typically running into tens of millions of pounds or more **[13-14]**.

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

Note that in general it is difficult to provide copies of internal technical reports from oil companies who consider such documents to be highly confidential and commercially sensitive. We therefore present testimony from industry end-users and information from publically available web documents (with web links given).

7] **Document***: Abbreviated Company Accounts for* ***GRL*** *2008-13*.

8] **Testimony:** *Director Basin Analysis, Exploration Renewal,* ***BP Exploration****, Building H, 2nd Floor, Chertsey Road, Sunbury on Thames, Middlesex, TW16 7LN, UK.*

9] **Testimony:** ***ConocoPhillips*** *(U.K.) Limited, Rubislaw House, Anderson Drive, Aberdeen, AB15 6FZ, UK.*

10] **Testimony:** *Clair Subsurface Manager, North Sea Region,* ***BP Exploration****, 1 Wellheads Ave, Dyce, Aberdeen, AB21 7PB, UK.*

11] **Press release:** *"Greater Clair Appraisal Programme Approved"* BP Press Release 28th March 2013, *http://www.bp.com/genericarticle.do?categoryId=2012968&contentId=7085428*

12] **RCUK Report:** "*NERC IMPACT REPORT 2012: Environmental science for UK economic growth and wellbeing", p 8* *http://www.nerc.ac.uk/about/perform/documents/impactreport2012.pdf*

13] **Web article:** Mary Guevara & Joanna Lumley (PGS) *"New Era Of Understanding For Faroe Shetland Basin"* E&P *http://www.epmag.com/Exploration/New-Era-Understanding-Faroe-Shetland-Basin_103966*

14] **Testimony:** *Leading Geoscientist, EXP INT EA Europe,* ***Statoil*** *(U.K.) Limited, 1 Kingdom Street, London W2 6BD, UK.*