

## Impact case study (REF3)

<b>Institution:</b> Durham University		
<b>Unit of Assessment:</b> 7 Earth Systems and Environmental Sciences		
<b>Title of case study:</b> Opening-up Fractured Basement Petroleum Reservoirs		
<b>Period when the underpinning research was undertaken:</b> Since 1 January 2000		
<b>Details of staff conducting the underpinning research from the submitting unit:</b>		
<b>Name(s):</b>  Professor Robert E Holdsworth, Professor Ken JW McCaffrey	<b>Role(s) (e.g. job title):</b>  Both Professors of Structural Geology	<b>Period(s) employed by submitting HEI:</b>  Since 1989 and 1994 respectively
<b>Period when the claimed impact occurred:</b> Between 1 August 2013 and 31 July 2020		
<b>Is this case study continued from a case study submitted in 2014? Y</b>		
<b>1. Summary of the impact</b>		
<p>New data and understanding of fractured basement reservoirs developed at Durham in partnership with the hydrocarbon industry has materially underpinned the appraisal and drilling of the UK's first basement-hosted oilfields (Clair, Lancaster and associated prospects) west of Shetland. With &gt; 25 billion barrels of oil in place, the investments required and value of the potential hydrocarbon resources run into billions of US dollars and are of major strategic importance to the UK. Durham research has enabled other companies to explore UK basement assets and in 2020, directly influenced the chosen location of the forthcoming BP Clair Ridge basement well.</p>		
<b>2. Underpinning research</b>		
<p>Holdsworth &amp; McCaffrey led a NERC Ocean Margins LINK (OML) project co-sponsored by BP, Statoil and CogNIT (2001-2005) investigating basement influences on fault and fracture development during North Atlantic rifting. New methodologies were developed to integrate fracture attribute datasets (e.g. geology, orientation, length, intensity, aperture, connectivity) collected at differing scales onshore with those interpreted using 3D seismic and well data from offshore areas. In 2004, a spin-out company, Geospatial Research Ltd (GRL) was set up (in part) to commercialise this methodology using NERC funding (Follow-on Fund), University seedcorn support and venture capital from the Regional Development Agency, OneNE.</p> <p>Two key research findings from this project were:</p> <ol style="list-style-type: none"> <li>Proof that the onshore-offshore methodology can address scaling issues between surface and subsurface datasets, improving understanding of the geometry, kinematics and fluid transport/storage potential of large-scale structures seen in cores and imaged on seismic reflection profiles <b>[R1]</b>. Attribute data extracted from the small-scale analogues (Virtual Outcrops) can be used directly to condition deterministic discrete fracture network (DFN) models <b>[R2]</b>.</li> <li>A demonstration that when pre-existing basement structures are oblique to far-field tectonic stresses, this leads to distinctive non-Andersonian, polymodal faulting patterns <b>[R1]</b>.</li> </ol> <p>In partnership with GRL, Holdsworth and McCaffrey further developed the knowledge and IP generated during the OML project. This included:</p> <ol style="list-style-type: none"> <li>Fractured Reservoirs 3D Digital Atlas (2006-8), a Shell/BG, DTI-funded consortium using digital methods to construct deterministic 3-D fracture models in a range of tectonic and sedimentological environments <b>[R2]</b>.</li> <li>Four projects (including 3 PhDs) funded by the Clair Joint Venture Group (BP, Shell, ConocoPhillips, Chevron) and two projects with Hurricane Exploration (2006-present). These studied onshore analogues in Scotland (Lewisian Complex <b>[R5, R6]</b>, Orcadian</li> </ol>		

Basin [R4]) for fractured basement and cover reservoirs of the Rona Ridge, together with offshore core materials from the Clair, Lancaster, Halifax, Whirlwind and Lincoln basement fields. Durham onshore fracture characterisation work was integrated with structural interpretations made in the subsurface using offshore 3D seismic data, subsurface core logs and extensive thin sections from both cores and outcrops.

- 3) Three Statoil (Equinor)-funded onshore-offshore studies of faulting patterns and processes in the Faroe/Shetland Basin, including a PhD and PDRA [R3].

Research highlights derived from these projects demonstrating the fluid transport potential of fractured basement include:

- a) The first detailed understanding of fault zone development and permeability evolution in upper crustal crystalline rocks [R3].
- b) The first combined use of microstructural analysis and geochronology (Re-Os sulphide, U-Pb calcite) to determine the timing of fracture formation, mineralization and hydrocarbon filling in both an onshore analogue for the Clair Field [R4] and in offshore basement cores of the Rona Ridge [R5].
- c) A new geological model for fractured basement plays where hydrocarbon influx is intimately associated with sediment ingress and low-temperature (50-150°C) hydrothermal mineralization along open near surface (<2 km depth) seismogenic fissure systems [R5]. The fills act as natural proppants that hold fracture systems open over tens of millions of years. This allows the ingress and accumulation of oil in very large volumes (billions of barrels)
- d) Demonstration that basement-hosted fracture systems are highly connected over at least 5 orders of magnitude length scale based on an analysis of the largest ever basement fracture attribute dataset collected anywhere in the world [R6].

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

\* = Holdsworth/McCaffrey research students; [number of citations, Web of Knowledge]

[R1] 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, <http://doi.org/10.1029/2005TC001895> [34]

[R2] 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, <https://doi.org/10.1016/j.cageo.2007.09.007> [90]

[R3] Walker, R.J.\*, **Holdsworth, R.E.**, Armitage, P.J. & Faulkner, D.R. 2013. Fault zone permeability structure evolution in basalts. *GEOLOGY*, 41, 59-62, <https://doi.org/10.1130/G33508.1> [27]

[R4] Dichiarante, A.M.\*, **Holdsworth, R.E.**, Dempsey, E., Selby, D., **McCaffrey, K.J.W.**, Michie, U. McL., Morgan, G. & Bonniface, J. 2016. New structural and Re–Os geochronological evidence constraining the age of faulting and associated mineralization in the Devonian Orcadian Basin, Scotland. *Journal of the Geological Society*, <http://doi.org/10.1144/jgs2015-118> [11]

[R5] **Holdsworth, R.E.**, **McCaffrey, K.J.W.**, Dempsey, E., Roberts, N.M.W., **Hardman, K.**, Morton, A., Feely, M., Hunt, J., Conway, A. & Robertson, A. 2019. Natural fracture propping and earthquake-induced oil migration in fractured basement reservoirs. *Geology*, 47, 700-704, <http://doi.org/10.1130/G46280.1> [11]

[R6] **McCaffrey, K.J.W.**, **Holdsworth, R.E.**, Pless, J.\*, Franklin, B.S.G.\* and **Hardman, K.\*** 2020. Basement reservoir plumbing: fracture aperture, length and topology analysis of the Lewisian Complex, NW Scotland. *Journal of the Geological Society*, <https://doi.org/10.1144/jgs2019-143> [4]

Paper [R1] was entered as research output for RAE 2008. 97.3% of the Durham UoA 17 Research outputs were rated ≥ 2\*, with 71.2% rated ≥ 3\*.

Papers [R2] and [R3] are highly cited. Paper [R3] was entered as a research output for REF 2014. 100% of the Durham UoA 7 Research outputs were rated ≥ 2\*, with 88% rated ≥ 3\*.

Papers [R4-6] are all related to the research that underpins the impact related to the Rona Ridge hydrocarbon fields. Paper [R5] is an output submitted for REF 2021.

A similar ICS was a finalist and runner up in the **NERC Impact Awards 2018 competition [E9]**.

Grants (awarded to Holdsworth & McCaffrey unless indicated otherwise; linked to **[Research]**):

NERC OML project: 'Quantifying fault zone evolution and basement reactivation in passive margins.' (NER/T/S/2000/01018)	GBP237,000	2002-5 <b>[R1, R2, R5, R6]</b>
NERC Follow-on Fund: 'The commercialisation of GAVA - Geospatial Acquisition, Visualisation and Analysis: a new tool for field-based scientists. (NE/C506964/1) [Led to creation of GRL]	GBP87,000	2004-6 <b>[R2]</b>
Royal Society Industrial Fellowship to McCaffrey	GBP91,000	2005-9
BP postdoc to Wilson	GBP100,000	2006-7 <b>[R1]</b>
NERC CASE studentships (Watts, Moy, Ashby)	ca GBP200,000	1998-2010
Statoil PhD student, Faroes fracture systems To Holdsworth & Imber	GBP100,000	2006-9 <b>[R3]</b>
ITF JIP 'FRE3DA' (Shell, BG, DTI) postdoc (Wightman)	GBP120,000	2006-8 <b>[R2]</b>
Statoil postdoc (Walker): fractures in basalts	GBP250,000	2009-10 <b>[R3]</b>
NStar Proof of Concept Funding (to GRL)	GBP60,000	Loan repaid
NERC KE Fellowship to Holdsworth: 'Development of opportunities for co-financed research with industry, and Knowledge Networks/Clubs within area of hazard and Risk, and Energy.' 1 Oct 2010 - 30 Sep 2012.	GBP145,000	2009-12
Clair JVG PhDs (Pless, Franklin, Dichiarante)	GBP330,000	2007-2015 <b>[R4-6]</b>
Clair JVG Re-Os dating study (Selby & Holdsworth)	GBP220,000	2013-2015 <b>[R4]</b>
BP/Clair JVG Clair Ridge study	GBP83,060	2014-2016 <b>[R5-6]</b>
Hurricane Exploration: Fractured basement of the southern Rona Ridge	GBP47,862	2018-2020 <b>[R5]</b>

Since 2000, Holdsworth (h index 44), McCaffrey (h index 30) have published over 200 papers on fault reactivation and fractured basement reservoirs studying examples from UK, Europe, S America, N America, Greenland, Japan and the Philippines. Awards for research by Holdsworth include a Geological Society of America Fellowship (2004) and the Lyell Fund (2000), Aberconway Medal (2006) and Coke Medal (2018) from the Geological Society, London (GSL). The Aberconway Medal is awarded for "distinction in the practice of geology, with special reference to work in industry." Other awards for research include the GSL Murchison Fund (to McCaffrey 2005); the Clough Medal (to Holdsworth 2018) and Clough Memorial Award (to former staff member Imber 2003) by the Edinburgh Geological Society; 2 Royal Society Industry Fellowships (McCaffrey 2006, Imber 2012) and a NERC Knowledge Exchange Fellowship (Holdsworth 2009).

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

Fractured basement reservoirs are a globally underexploited hydrocarbon resource, with only 126 commercially producing fields spread across 26 countries **[R5]**. The crystalline nature of the low porosity basement means that almost all the hydrocarbon is held in fracture systems. These plays are poorly understood by industry and are difficult to explore due to problems with geophysical imaging in basement rocks and a paucity of core samples core **[E1-6]**.

Holdsworth & McCaffrey's research findings and expertise have had impacts for the appraisal and development of the UK's first ever basement-hosted oil fields along the Rona Ridge, west of Shetland (see below). The investments required and value of the potential hydrocarbon resources run into billions of US dollars and are of major strategic importance to the UK [E1-3, E6]. They include:

- i) The giant Clair oilfield is operated by BP for the *Clair Joint Venture Group* (CJVG; a consortium of BP, Shell, ConocoPhillips [now Chrysaor] and Chevron). The field is the largest hydrocarbon resource in the UK Continental Shelf with an estimated 7 billion barrels of Stock Tank oil initially in place (STOIP) [E1, E2]. The Phase I area came on stream in 2005, whilst the Clair Ridge (Phase II) began production in 2019. The reservoir target is Devonian sandstones that rest directly on Lewisian-like metamorphic basement. Both rock units host oil and are highly faulted, with fracture description and water flood performance considered to be the two main risks in field development. A dedicated basement well in the Clair Ridge is also due to be drilled in 2021 [E2].
- ii) In 2009 *Hurricane Exploration Ltd* drilled and tested the UK's first exploration well targeted specifically at fractured basement. Two further appraisal wells and two horizontal development wells were then drilled and led to the UK Oil and Gas Authority (OGA) assigning field status to Lancaster in 2015. The Lancaster field (2.3 billion barrels STOIP) produced its first oil in June 2019 from two wells at a rate of 20,000 barrels of oil per day. Hurricane has also undertaken further basement exploration making additional discoveries at its Whirlwind, Lincoln and Halifax prospects (estimated 15.8 billion barrels) all of which lie along the Rona Ridge [E3, E6].
- iii) In 2018, *Spark Petroleum* acquired the licence to develop the Bader prospect located in the region separating Clair from the Hurricane fields.

The Durham research that has that has impacted on the developments outlined above stems from analysis of the fault and fracture systems in the sub-surface Rona Ridge (using core samples, well data and geophysical images) and from surface analogues of the equivalent fractured basement (Lewisian Complex) and cover sequences (Orcaian Basin) in NW Scotland [E1-3, E7-8].

For the CJVG, the Clair Reservoir Development Manager [E1] stated in 2018 that the Durham research set out in our final report [E7] has “*significantly improved the industry understanding of the basement rock hydrocarbon prospectivity and potential*” and that it “*gave sufficient confidence to the JV to allow advance planning of a dedicated basement well which will be produced through the Clair Phase I facility (cost GBP22 million)*”. They also highlighted that this work helped demonstrate the CJVG commitment to developing basement resources and that Durham “*helped the basement licence retention negotiation with OGA*” during 2018. In 2020, the Clair Area Reservoir Development Manager [E2] explained that, in the planning of the dedicated basement well (costing GBP20-25 million), the views of the Durham team were “*instrumental in convincing the Clair JV that a crestal well location is a better option, with a higher flow-rate potential than the previous well location. The revised well location is a shorter well, implying a cost saving in the range of GBP1-5 million.*”

For Hurricane, the CEO has written that two reports on fractured basement commissioned from Durham in 2007 [E8] (precursors to [R5-6]) were “*a big influence on our decision to explore and ultimately develop fields in the southern part of the Rona Ridge west of Shetland*” [E3]. He has also stated that since 2013, “*Durham onshore data and expertise on fractured basement rocks has been used by Hurricane in reducing uncertainties by constraining its subsurface models which are utilised for determining drilling locations and quantifying the likely economic returns in terms of hydrocarbon production and resource of the Lancaster field*”. Since each development well costs upwards of GBP20 million and the decision to finally sanction the entire development programme is significant in both financial and economic terms [E1-3, E5, E6]. In summing up, the CEO states that research at Durham was: “*pivotal in allowing us to develop Lancaster as the first fractured basement reservoir ever established in the UKCS region.*”

Since 2013, Holdsworth has additionally led annual field workshops with CJVG geoscientists (42 individuals to date) to view fractured analogues in N Scotland. This has helped the industry subsurface teams to better conceptualise the structural framework in the fractured basement and associated Devonian cover sequences and to design improved alternative fracture models [E1-3,

**E5].** A similar field workshop was run for Hurricane in 2012 and influenced their conceptual models for the Lancaster and other fields in the period 2014-present **[E3]**.

A similar Case Study was a finalist and runner up in the NERC Impact Awards 2018 competition in the Economic Impact category **[E9]**. Award money from this success was used to host a stakeholder workshop on “*The Geology of Fractured Basement Reservoirs*” held in the Outer Hebrides in September 2019 and attended by representatives from 13 companies and the UK Oil & Gas Authority (OGA). A day of presentations and discussion was followed by 2 days in the field visiting onshore analogues of fractured basement rocks. Impacts derived from that event are presently on hold due to effects of the COVID pandemic.

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

**E1** - Testimony from Clair Subsurface Manager, BP (letter 28<sup>th</sup> March 2018)

**E2** – Testimony from Clair Area Reservoir Development Manager, BP (letter May 2020)

**E3** – Testimony from CEO Hurricane (letter 6<sup>th</sup> February 2020)

**E4** – Testimony from Global Chief Scientist, Energy & Geoscience Institute at the University of Utah [formerly VP, Statoil/Equinor] (letter 23<sup>rd</sup> February 2020)

**E5** – Testimony from Andy Conway, OGA [formerly Conocophillips] (letter 16<sup>th</sup> February 2020)

**E6** – RPS Competent Person's Reports for Lancaster Field (2017) and for 'West of Shetland Assets' (Lincoln, Whirlwind, Halifax, Strathmore) (2017).

**E7** – CONFIDENTIAL: Holdsworth R.E. & McCaffrey, K.J.W. 2016. *Understanding the Clair field basement and its associated fracture systems: implications for reservoir appraisal. Final report for the Clair JVG, 315pp.*

**E8** – CONFIDENTIAL: Consultancy reports commissioned by Hurricane Exploration plc. i) Holdsworth, R.E. et al. 2007. *Outcrop Data as an Analogue to HEX Lewisian Basement Acreage: Characterisation of Lewisian Fracturing in Scotland & the Møre-Trøndelag Fault Zone in Norway. Consultancy Report commissioned by Hurricane Exploration plc.* ii) Jones, R. et al. 2007. *Outcrop Data as an Analogue to HEX Lewisian Basement Acreage: Analysis of Fracturing on Lewis & Harris, Outer Hebrides.*

**E9** – Documents related to 2018 NERC Impact Award (Economic category), including certificate and NERC press releases & movie.