

Impact case study (REF3b)

<p>Institution: Royal Holloway, Royal Holloway</p>
<p>Unit of Assessment: 7 - Earth Systems and Environmental Sciences</p>
<p>Title of case study: Hydrocarbon reservoirs : physical models and natural analogues</p>
<p>1. Summary of the impact</p> <p>The Fault Dynamics Research Group (FDRG) have designed and executed analogue experiments to replicate the 3D/4D geometry of oil and gas exploration targets. The main beneficiaries are the international petroleum industry. The research is “<i>pivotal to British Petroleum’s subsurface developments</i>” (R. Humphries BP 2012) in determining the number of multi-million pound wells required to access reserves. FDRG models “<i>changed the way seismic data (was) interpreted</i>” (Chief Scientist, Geoscience Australia 2012) in particular in the NW Australian frontier with “<i>BP Exploration (Alpha)....work program(s) of \$600 million</i>” (Chief Scientist, Geoscience Australia 2012).</p>
<p>2. Underpinning research</p> <p>Nature of the research</p> <p>The Fault Dynamic Research Group led by McClay (<i>employee since 1986</i>) has involved twenty post-doctoral research assistants, eight MSc and forty PhD students. The research program integrates physical and numerical modelling to improve our understanding of the 3D geometry and 4D evolution of oil and gas reservoirs using: (a) Field-based case studies (<i>e.g. western USA; Gulf of Suez-Red Sea; Turkey; Andean fold belts</i>)(<i>e.g., Munoz et al 1994</i>), (b) Remote sensing studies (<i>e.g. E African rift; Zagros fold belt, Iran</i>), (c) 2D and 3D seismic studies (<i>e.g. NW Australia; Niger delta; North Sea; west African margins; S Australian margin</i>) (<i>e.g. Francowitz & McClay 2010, DeVera et al 2010</i>) and scaled physical 3D analogue models.</p> <p>The scaled physical 3D models are created at Royal Holloway in world-leading, custom-made laboratories using powders and polymers as rock analogues. Experimental simulations of natural crustal deformational environments are performed at 1x gravity and digitally recorded using laser scanning and image correlation techniques to quantify displacements and strains (<i>McClay et al 2002</i>). Results are calibrated and integrated with outcrop analogues and industry sub-surface seismic data sets. This produces new 4D evolutionary concepts (<i>Wu et al 2009</i>) that can be applied to the exploration and exploitation of petroleum bearing structures in the UK continental shelf and worldwide (<i>e.g. Australia; Indonesia; Egypt, Nigeria</i>) (<i>e.g. Francowitz & McClay 2010</i>). 2D and 3D seismic studies are carried out using industry-standard interpretation software (<i>e.g., Landmark, Paradigm, Schlumberger and Petrel</i>) to emphasize reservoir scale structures (<i>e.g. Wu & McClay 2011</i>). 3D visualization is a key component in transfer of results to the hydrocarbon industry. Results are integrated into atlases, toolboxes and case studies that can be applied to specific exploration targets, interpretational problems and structural analyses of hydrocarbon structures by supporting companies. For example, “<i>being (a) member of FDRG has provided Nexen with access to leading edge principles of structural geology....of oil and gas fields in the North Sea, Norway, Yemen and Western Canada</i>” (<i>D. Leckie, Nexen Chief Geologist, 2012</i>). Peer-reviewed publication in international journals disseminates this knowledge internationally (<i>McClay et al 2000, 2002; Duerto & McClay 2009, Hardy et al 2009, Wu & McClay 2009, 2011, DeVera et al 2010</i>).</p> <p>Key Results</p> <ol style="list-style-type: none"> 1) New 3D models of rift systems showing fault initiation, growth and linkages for orthogonal, oblique and segmented rifts, strain and displacement distributions and 3D reconstructions (<i>e.g., McClay et al 2002, Wu et al 2009, Wu & McClay 2011</i>). 2) Models of propagation and evolution of basement faults systems and formation of extensional

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fault-propagation folds (*McClay et al 2002*).

3) New Analogue and numerical models of fault system nucleation, fault propagation and fracture systems in foreland fold and thrust belts (*Duerto & McClay 2009; Wu et al 2011*).

4) 3D models of strike-slip fault systems (*Wu et al 2009*).

5) New models for the initiation and growth of thrust faults in deepwater fold and thrust belts and for the structural styles of the Niger delta (*Wu et al 2011*).

6) New models and case studies of salt diapirism and associated fracture systems that provide analogues for North Sea diapir structures.

3. References to the research

Research quality

Hardy, S., McClay, K. & Muñoz, J. A., 2009. Deformation and fault activity in space and time in high-resolution numerical models of doubly vergent thrust wedges; *Marine and Petroleum Geology*, 26; p. 232-248.

McClay, K.R., Dooley, T., Whitehouse, P., Mills, M. & Khalil, S., 2002. 4D evolution of rift systems: Insights from scaled physical models. *Bulletin of the American Association of Petroleum Geologists*. 86, 935-960.

Wu, J.E., McClay, K., Whitehouse, P. & Dooley, T., 2009. 4D Analogue Modelling of Transtensional Pull-Apart Basins; *Marine and Petroleum Geology*. 26, 1608-1623.

Applications

De Vera, J., McClay, K.R., & Granado, P., 2010. Structural evolution of the Orange Basin gravity-driven system, offshore Namibia; *Marine and Petroleum Geology*, 27, 223 - 237.

Duerto, L. & McClay, K.R. 2009. The role of syntectonic sedimentation in the evolution of doubly vergent thrust wedges and foreland folds; *Marine and Petroleum Geology*, 26, 1051-106.

McClay, K., Dooley, T., Ferguson, A., & Poblet, J., 2000. Tectonic evolution of the Sanga Sanga block, Mahakam delta, Kalimantan, Indonesia. *Bulletin American Association of Petroleum Geologists*. 84, 6, 765-786.

Research funding for STAR (Structural Analogues for Reservoirs) consortia (Total ca. £3.55M)

STAR1 (2006-2009) 'Structural Analogues for Reservoirs'. £2.55 million – International Petroleum Company consortium: BG Group, BP, BHP Billiton, ConocoPhillips, ENI, ONGC, Nexen, PDVSA, RepsolYpf, Shell, Statoil, & Talisman.

STAR2 (2011 to date) 'Structural Analogues for Reservoirs 2'. ~£1 million – International Petroleum Company consortium: BG Group, BHP Billiton, ConocoPhillips, ENI, Marathon, Nexen, Shell, & Talisman (more companies pending).

4. Details of the impact

Since 1993 the FDRG has developed collaborative research programs with the international petroleum industry and the 'Structural Analogues for Reservoirs' consortia (2007–2014) has involved thirteen petroleum companies. Key long-standing research collaborations (e.g., BP, Shell, ConocoPhillips, Nexen, BG Group, Apache) led to new approaches to petroleum exploration and an understanding of the 4D spatial and time evolution of petroleum structures. The FDRG models provide a level of detail for hydrocarbon-bearing structures that was hitherto unavailable. Overall FDRG models directly impact on *"the cost and viability of new oil and gas prospects from exploration through to commercial development"* (bp – R. Humphries 2012).

FDRG industry-funded research has had widespread impact. *"Professor McClay's research spans many aspects of Structural Geology of interest to industry, and has a truly global focus. ... No other current industry project....has as comprehensive a suite of deliverables. Materials include: comprehensive atlases of numerical and physical model experiments; toolboxes summarizing specific structural styles (e.g., the Inversion Toolbox that comprises a comprehensive review of styles and mechanisms behind inverted basins with interpreted seismic examples from around the world, including an in-depth seismic review of the classic 'Sunda Folds' from the Natuna Sea); field-work reports (e.g., Gulf of Suez, Iran, Iraq); case histories (e.g., Australia, Niger Delta). All materials are delivered to sponsors in a timely manner via a secure web-site...FDRG (has) great impact and (is) used often and widely throughout industry. Professor McClay also provides...short courses, field trips.....and review meetings that all augment the research deliverables"*. (Hooper, Marathon Oil Company, 2012)

2008-2013 specific impact

a) **Bight Basin Australia:** Geoscience Australia *"relied heavily on [Royal Holloway] models on gravity tectonics in deltaic systems. The structural interpretation of the gravity slide system underpinned our improved understanding of the geology and structural history of the basin, including fault reactivation and the likely risks to petroleum systems. ... The acreage was awarded to BP Exploration (Alpha) Ltd in 2011, with a ...work program of \$600 million"* (Totterdell & Foster, Geoscience Australia 2012)

b) **Arafura Basin Australia:** FDRG *"work on extensional and inversion fault architectures allowed [Geoscience Australia] to understand the extremely complex geology of the Goulburn Graben. This structural framework allowed [Geoscience Australia¹ to] develop a robust sequence/seismic stratigraphic interpretation for the Goulburn Graben and Northern Platform. ...This step change in understanding underpinned the 2006 Acreage Release of exploration areas in the Arafura. ... Part of the region released in 2006 was subsequently taken up by Samson (with ConocoPhillips), with a guaranteed work program of \$7 million."* (Chief Scientist, Geoscience Australia 2012)

c) **Carnarvon Basin Australia:** FDRG predictive models provided templates for seismic interpretation and cross-section balancing/restorations (Francowitz & McClay 2010). FDRG established new concepts of tectonic evolution of this extended passive margin which underpinned new approaches to hydrocarbon exploration. Overall FDRG has *"changed the way seismic data is interpreted on rifted margins"* (Chief Scientist, Geoscience Australia 2012)

d) **Niger Delta:** *"Work in the toe thrust zone of the Niger Delta allowed ... understanding.. of faulting, which is key to understanding petroleum accumulations in the region"* (VP global New Ventures & Geoscience, CGGVeritas 2012).

e) **Collaborative industrial partnerships:** These focus on modelling of salt (Conoco Norway), salt diapirs (Shell UK), rift systems (Shell UK) and deepwater folds belts (Shell international) (De Vera et al 2010).

¹Geoscience Australia is Australia's national geological survey and in that role is involved in the discovery and development of energy resources and provides geoscientific information to industry.

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All research results are delivered to consortia partners via the internet thus maximising potential economic benefits. Earth Sciences FDRG staff have immediate use of models and field case studies as analogues of reservoir structures. Publications by the research group are widely used by the international petroleum industry (e.g. *Apache, BP for the Gulf of Suez rift system*). Animations and 3D visualizations of physical models combined with field case studies greatly aid interpreters in identifying structures as well as an understanding of how they form and change through time (*Hardy et al 2009, Wu et al 2009*) (e.g. *modelling of fold-thrust systems used in the analysis of deepwater fold belts by Shell Nigeria and Shell NW Borneo*). The compendium of structural styles developed by FDRG is widely used by the petroleum industry (e.g. *BP, BG Group, ConocoPhillips, Talisman, Nexen*) in exploration as well as in their training of geologists and geophysicists. Company geologists attend the regular training courses (both lab and field based) given by FDRG (e.g. *BHP Billiton, Shell, Nexen, ConocoPhillips*).

5. Sources to corroborate impact

Supporting letters are available from :

1. **Geoscience Australia:** Verification of the high impact the Fault Dynamics Research Group has had on economic resource exploration in Australia can be obtained from the Chief Scientist, Geoscience Australia
2. **Marathon Oil USA:** Confirmation of the overall impact of the Group's 'comprehensive suite of deliverables' on the oil industry can be provided by the Senior Technical Consultant, Upstream Technology, Marathon Oil Company
3. **Commonwealth Scientific Industrial Research Organisation (CSIRO) Australia & University of Western Australia:** The Group's impact on structural geology and industrial applications can be confirmed by the University of Western Australia
4. **Nexen:** Evidence of the impact, "applicability and usefulness to the oil industry" can be obtained from the Chief Geologist, Nexen, Canada

The following may be contacted:

5. **Shell:** The Manager Exploration Technology at Shell International in Houston can corroborate the usefulness of the analogues provided by the Fault Dynamics Research Group and the STAR project for hydrocarbon exploration in fold and thrust belts as well as in rifts and passive margins. The use of the appropriate analogues are essential particularly in regions of poor seismic data as well as also to understand the 4D evolution of hydrocarbon traps in complex terrains.