Institution: University of Manchester
Unit of Assessment: UoA 7 Earth Systems and Environmental Sciences
Title of case study: **Development of predictive models for the distribution of hydrocarbon reservoir rocks in rift basins**

1. Summary of the impact

Our research has had a global impact on understanding the tectonic development and fill of rift basins, providing a predictable spatial and temporal template for the distribution of hydrocarbon reservoir rocks. The models are embedded in exploration workflows of global oil companies and have influenced recent exploration success (North and East Africa, Atlantic conjugate margins). Translational research on 3-D rift basin outcrop data capture and resulting software licencing has improved reservoir modelling, optimising positioning of $100m wells. Field-based training for several hundred oil industry staff since 2005 has ensured in-depth knowledge transfer.

2. Underpinning research

The integrated research was undertaken in Manchester from 1993 and is on-going within the expanded group.

The key researchers have been:

Prof Robert Gawthorpe (1993-2010)

Dr David Hodgetts (Senior Lecturer, 2005 to present)

Prof Jonathan Redfern (2003 to present)

Dr Cathy Hollis (Senior Lecturer, 2007 to present)

Prof Stephen Flint (2012 to present)

Rift basin research at Manchester led the way in developing process-response models for the effect of extensional fault systems on 3-D accommodation, by applying concepts from structural geology to stratigraphic analysis for the first time [1, 2]. This work was fundamental in turning sequence stratigraphy from a 2-D treatment of simple passive margins into a rigorous 3-D analysis of the structural template across which accommodation varies in 3-D over time, as function of the basic mechanics of crustal stretching [1, 2]. The work has shown the importance of relay zones in delivery of sediment into rifts, at points of low accommodation (fault tips) and was pivotal in the appreciation that depositional dip at the end of a relay can be multidirectional. The Group went on to convolve 3-D subsidence uplift patterns with eustatic sea level changes and ideas on sediment supply to produce the first holistic tectono—sequence stratigraphic models for rift basins [3, 4, 5]. This work provided a deeper understanding of how stratal geometries and reservoir rocks are distributed with a rift basin and therefore a better prediction of lithologies directly from seismic reflection data.

The work programme was extended to carbonates following appointment of Hollis, which has included the linking of fault-related fluid movement to dolomitisation, which has predictive power in porosity/permeability generation during diagenesis. Extensive studies of basins across North Africa by Redfern (North Africa Research Group) have applied and critically tested the concepts [5] and have influenced exploration activities across the region. The importance of inherited rift fabric on post-rift intrabasinal shelf morphology is being documented by Flint.

The development of new 'digital outcrop' research techniques to collect quantitative sedimentological and structural data for reservoir modelling has served as a translational way of harnessing the more fundamental results into databases on sand body geometries and architecture for reservoir modelling [3, 6]. The development of software *(Virtual Reality Geological Studio, VRGS)* by Hodgetts allows integration and interpretation of terrestrial laser scanning, satellite data, digital imagery and geological datasets in a series of outcrop analogue studies funded by the oil industry, to refine subsurface reservoir models. The software has been licenced to oil companies and Universities.

3. References to the research

All of these papers are in international journals and show the evolution and translation of the research. References 1 and 2 are highly cited and regarded globally as foundation papers in rift basin geology. All have been the subject of invited international presentations.

Key Publications

[1] **Gawthorpe, R.L.,** Fraser, A. and Collier, R. 1994. Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills. Marine and Petroleum Geology, 11, 642-658 (89 WoS citations). DoI 10.1016/0264-8172(94)90021-3

[2] **Gawthorpe, R.L**. and Leeder, M.R. 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research, 12, 195-218 (123 WoS citations). DOI: 10.1111/j.1365-2117.2000.00121.x

[3] Wilson, P., **Hodgetts, D**., Rarity, F., **Gawthorpe, R. L**. and Sharp, I. R. 2009. Structural geology and 4D evolution of a half-graben: New digital outcrop modelling techniques applied to the Nukhul half-graben, Suez rift, Egypt. Journal of Structural Geology 31, 328-345 (8 WoS citations). DOI 10.1016/j.jsg.2008.11.013

Other Relevant Publications

[4] Finch, E., Hardy, S and **Gawthorpe, R**. 2004. Discrete-element modelling of extensional fault propogation folding above rigid basement fault blocks. Basin Research, 16, 489-506 (40 WoS citations). DOI: 10.1111/j.1365-2117.2004.00241.x

[5] Fabuel-Perez, I., **Redfern, J. and Hodgetts, D**. 2009. Sedimentology of an intra-montane rift-controlled fluvial dominated succession: The Upper Triassic Oukaimeden Sandstone Formation, Central High Atlas, Morocco, Sedimentary Geology, 218, 103-140 (6 WoS citations). DOI 10.1016/j.sedgeo.2009.04.006

[6] Fabuel-Perez, I., **Hodgetts, D. and Redfern, J**. 2009. A new approach for outcrop characterization and geostatistical analysis of a low-sinuosity fluvial-dominated succession using digital outcrop models; Upper Triassic Oukaimeden Sandstone Formation, central High Atlas, Morocco. AAPG Bulletin, 93, 795-827 (13 WoS citations). DOI 10.1306/02230908102

4. Details of the impact

Prior to the work referred to in this case study, no linked process-response model for sedimentation in rift basins existed and hence no consistent way of predicting the distribution of

hydrocarbon reservoir rocks in time and space. Specifically the models provide better prediction of lithologies directly from seismic reflection data, which are the only data commonly available in hydrocarbon exploration. Global use of the models have steered exploration in rift basins worldwide.

The combination of concept-driven prediction of reservoir rock positioning and timing of deposition with quantitative measurements of geometries and architecture has had the threefold impact of (a) success in exploration in rift settings, including the South Atlantic conjugate margins, North and East Africa, (b) harnessing of additional reserves in 'near field exploration' that required the linked structural-stratigraphic understandings and (c) optimal siting of wells based on the quantitative reservoir models made possible through the geometrical databases developed from VRGS, thus reducing the number of $50M-$100M wells needed per development.

Pathways to Impact

I. Research on normal fault growth and syn-rift sedimentation was undertaken as part of the Rifts Analogues Project (TRAP) headed by Gawthorpe and Hodgetts and funded by Statoil, BP and ConocoPhillips. Outcrop observations and measurements from modern and ancient rift settings were distilled into tectono-stratigraphic models. This new knowledge was embedded into sponsor company workflows through professional training workshops in classroom and field and supported by the development of numerical modelling procedures. The pathway has been consolidated by several generations of project PhDs joining the oil industry.

II. The Virtual Reality Geological Studio (VRGS) software has being commercialised by UMIP (who manage Manchester University's IP portfolio). VRGS provides a new innovative tool for reservoir analogue studies to generate new sedimentological and structural data and interpretations, centered around LiDAR scanning of outcrops. This allows the quick and accurate capture of data on reservoir body geometries and spatial architecture, which has been used to feed reservoir modelling software used by the industry. This has resulted in more realistic reservoir models. VRGS has been licenced to Chevron, ConocoPhillips and Fugro Robertson for in-house reservoir characterisation and modelling projects [A], [B],[C}.

Reach and Significance of the Impact

1. The results of the research are embedded in the global exploration models of Statoil, for example."*Innovative new exploration concepts have resulted from the research that has led to exploration successes*" [D] In addition, the results of this research "*are very much in use in defining new exploration plays and concepts, and are recently used for the new concession round application in the North Sea and were also used for the 27th Concession Round application on the UK Continental Shelf*" [D]. The concepts have also directly influenced exploration for the last 15 years in BP, who state "*the technical impact of this research has been substantial, particularly in relation to understanding of depositional processes in rift systems"* [E]. The models have been used by the industry in frontier exploration along the South Atlantic conjugate margin, with successful new discoveries in completely new areas (e.g. French Guyana, Ghana). The new exploration models have improved business performance across the exploration sector.

2. The new concepts for hydrocarbon reservoir prediction have been embedded into the professional workforce of many oil companies including Statoil and BP by a series of bespoke knowledge transfer training courses in Norway, Egypt and Greece. Statoil "estimate *"that at least 200 Statoil geoscientists have attended these workshops"* [D]. BP state that *'the incorporation of integrated structural-stratigraphic rift models in BP's in-house training programs has been achieved through knowledge transfer from Manchester via field courses for BP over the last 15*

years [2]. We regard the production of a highly trained doctoral workforce for the industry as an impact as well as a pathway to impact because it has led to changes in practices and improvements in processes. This argument is supported by the UK Government Oil and Gas Industrial Strategy and the plans for a NERC Centre for Doctoral Training in oil and gas, both of which are responses to an identified skills shortage in engineering and geoscience.

3. The impact of VRGS has been an improved ability to develop models of subsurface reservoirs by constraining in outcrop analogues: a) the geometry of key stratal surfaces defining the boundaries of reservoir zones, and b) the geostatistics of sedimentary bodies that occur within the reservoir zones. This has reduced the time taken to capture analogue data and has allowed statistically more sophisticated conditioning to be developed. The impact is in enabling better and more constrained understanding and characterisation of uncertainty in subsurface reservoir descriptions, allowing the creation of alternate scenarios. A direct application is in refined well placement, where the saving of a single well can save $50m - $100m from a development project of commonly 5-50 wells.

As explained by BP [E], it is not possible to fully quantify the global savings from the increased geological understandings because other factors also influence well positioning but the saving of one well per field across the industry in which several hundred wells have been completed in rift basin prospects over the last 5 years is considerable. When this work started, over 200 billion barrels of recoverable hydrocarbons was known to be hosted in rift basins and one of the most significant new plays is the syn-rift pre-salt succession of the South Atlantic basin, currently thought to contain 38 Billion barrels of oil equivalent. With an oil price of $100+ per barrel, this is a multi billion dollar industry.

The research has involved training company personnel in data collection and interpretation, placing members of the research team within the sponsors' offices for work periods and the employment of the highly skilled researchers by the global industry.

5. Sources to corroborate the impact

These research projects have all been funded directly by industry, and the research has involved close liaison with the companies, for dissemination of the results and training of company staff. Rather than supply letters from every company who has been impacted by the research (20+ companies) we will supply detailed supporting letters from two companies with global portfolios who have worked with Manchester for the last 20 years.

[A] License agreement for VRGS corroborating permission for Chevron to use our software package.

[B] License agreement for VRGS corroborating permission for ConocoPhillips to use our software package.

[C] License agreement for VRGS corroborating permission for Fugro Robertson to use our software package.

[D] Statoil supporting letter corroborating the strong research collaboration previously developed between the Manchester group with Norsk Hydro and the ongoing and lasting relationship that has persisted since the merger between Statoil and Norsk Hydro.

[E] BP supporting letter corroborating the use that BP have made of the conceptual framework developed in Manchester in their global exploration activities.