Impact case study (REF3b)

Institution: University of Aberdeen

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

Title of case study: Turbidites: Deep-water hydrocarbon reservoir prediction

1. Summary of the impact

This case study describes the economic impact to sections of the hydrocarbons industry resulting from research into deep water sediment transport and depositional processes. *turbidites.org* is a multi-institutional, interdisciplinary research platform based at University of Aberdeen, which takes a multi-scale approach to understanding deep-water depositional systems and their significance as a stratigraphic record of long-term environmental change. The resulting research outputs have been applied to deep-water hydrocarbon reservoir prediction.

2. Underpinning research

Deep-water depositional systems are host to some of the world's most important hydrocarbon reservoirs (for example in the North Sea, Gulf of Mexico, Southeast Asia, Australia, and offshore West Africa and Brazil) and are sites of active exploration for new reserves. Predicting and characterising reservoir in the subsurface requires an understanding of the depositional systems that contain the reservoir, geometry, internal architecture, and porosity/permeability distribution, all of which are intimately related to processes of sediment transport and deposition.

Compared to most other depositional environments, direct observations of deep-water processes and modern depositional architecture are relatively few and difficult to obtain. Hence an understanding of deep-water systems is necessarily derived from a combination of approaches based on models, analogues, and remote sensing. This impact case study derives from a research project established by Professor Ben Kneller, Chair of Petroleum Geology at the University of Aberdeen since 2004. The project has been undertaken in two phases funded by a consortium of oil company sponsors through a Joint Industry Project, with results from the research projects published on a project website turbidites.org, an Aberdeen-based research platform initiated by and under the direction of Prof Ben Kneller. The research project is led by, and has been designed by, Professor Kneller at Aberdeen, with contributions from collaborators at Montana State University, Colorado School of Mines and the University of California Santa Barbara. , Fieldwork has been undertaken across a range of international geological sites in South America and Europe that allowed the team to investigate deep-water systems across a range of scales, from that of sediment transport and depositional processes to that of continental margins. The results have been applied to predictions of hydrocarbon reservoir architecture. Total industrial income since 2004 has been £4.54M, through a combination of single-company sponsorship and industrial consortia.

The research involves integration of multiple approaches to develop a holistic view of deep-water sedimentary systems. Experimental modelling and numerical simulation of flow processes and their resulting sediment transport and deposition has improved understanding of turbidity current processes, in particular the role of water entrainment on deposition, controlling the shape of and sand distribution within submarine levees (1); levee shape and sandstone distribution (i.e. reservoir) are largely determined by the sea-floor gradient, and scale with the width of the parent channel. Studies of the modern sea floor and comparisons with ancient depositional systems using digital field techniques (3, 4) have improved understanding of channel-fill architectures and lithology distributions on sub-seismic scales. Subsurface observations using industrial 3D seismic datasets and data from oil and gas wells, matched by seismic forward models of unique seismic-scale outcrops, have placed these observations in a larger context to better understand 3-dimensional system architectures at the reservoir scale; in the sedimentary fills of channels on the continental slope, there is a repeated pattern of architectures that can be used to constrain reservoir distribution and connectivity in subsurface channel systems. Understanding of deep-water sandstone distribution has also been substantially improved in turbidites associated with mass transport deposits; the shapes of reservoir sandstone bodies are determined by their location with respect to such deposits, and on the properties of the underlying deposits. The evolution of

continental margins (5) and sediment supply over millions of years (unpublished PhDs) has led especially to the recognition of the effects of climate on sediment supply at the scale of 10^5 to 10^6 years, and its impact on continental margin architecture development; this shows that the development of prolific slope channel reservoirs is linked to large scale climate changes such as intensification of monsoons. The work has been applied to reservoir prediction via the development of numerical inversion approaches (6), forward seismic modelling (2), neural-net recognition of lithofacies in the subsurface from wire-line logs, and the use of architectural and process analogues in the subsurface.

The group has built on concepts and research output from precursor groups set up by Kneller at Leeds University (Turbidite Research Group, 1992-2000) and University of California (turbidites.org, 2000-2004) and broadened the research approach to include modelling and subsurface interpretation.

3. References to the research

1. Birman, V.K., Meiburg, E. & **Kneller, B**., 2009. "The shape of submarine levees: exponential or power law?" Journal of Fluid Mechanics*, 619, 367–376
2. Dykstra, M., Garyfalou, K., Kertznus, V., **Kneller, B.C**., Milana, J.P., Molinaro, M., Szuman, M. & Thompson, P., 2011. "Mass-transport deposits: combining outcrop studies and seismic forward modelling to understand lithofacies distributions, deformation, and their seismic expression." In Posamentier, H., Weimer P. & Shipp, C. *SEPM Special Publication 95*. 293-310.
3. Dykstra, M. & **Kneller, B**., 2007. *"Canyon San Fernando, Mexico: A Deep-water, Channel-levee Complex Exhibiting Evolution from Submarine Canyon — Confined to Unconfined."* In Nilsen, T, Studlick, J. & Steffens G., *Atlas of Deepwater Outcrops*, Studies in Geology, 56. American Association of Petroleum Geologists, Tulsa, 226-230.
4. Gamberi, F., Dykstra, M., Kane, I., Rovere, M. & **Kneller, B**., *"Integrating modern seafloor and outcrop data in the analysis of slope channel architecture and infill."* Marine and Petroleum Geology. http://dx.doi.org/10.1016/j.marpetgeo.2012.04.002
5. Kertznus, V. & **Kneller, B.,** 2009. *"Clinoform quantification for assessing the effects of external forcing on continental margin development."* Basin Research, 21, 738-758
6. Lesshafft, L., Meiburg, E., **Kneller, B**. and Marsden, A., 2011. *"Towards inverse modelling of turbidity currents: The inverse lock-exchange problem."* Computers & Geosciences, 37, 521-529.

Grants
1. "Stratigraphic development of large-scale slope systems: Phase 2". £1.46M. Funded by oil and gas industry consortium: BP, BG, ConocoPhillips, DONG, GDF Suez, Hess, PEMEX, Petrobras, Total, StatoilHydro, RWE Dea. 2008-2011.
2. "Stratigraphic development of large-scale slope systems: Phase 1". £855K. Funded by oil and gas industry consortium: BP, BG, ConocoPhillips, DONG, GDF Suez, Hess, PEMEX, Petrobras, Total, StatoilHydro, RWE Dea. 2005-2008.
3. "Understanding marine delta-slope-basin floor systems: Phase 2" £458k. Funded by BG Group. 2007-2010.

4. Details of the impact

Application of our research results with industrial sponsors in UK, Egypt, China, India, France, Norway, Brazil, Trinidad and the USA has resulted in tangible impacts in the subsurface. We take three specific examples.

Working with BP, our research has facilitated their in-house analysis of a number of significant oil & gas fields in the Gulf of Mexico. BP has confirmed that the research "*has provided quantitative data on the geometries of sand and shale bodies in outcrop. These can be combined with our subsurface data to help estimate hydrocarbon volumes and build reservoir models. A good*

example is the relationship between bed thickness and net sand variations in levees. This data has been used in areas where we have reservoirs in levee systems".

BP have further added that "*the consortia is a prolific source of new ideas and concepts for us. This allows us to understand the range of possibilities in a system and have a more comprehensive appreciation of the uncertainties in the reservoir system. These ideas can be built, in an appropriate way, into our development plans for a field. Good examples are the range of facies and stratigraphic architecture in channel systems the team have documented; and the effect that Mass Transport Complexes can have on reservoir distribution particularly ponding and erosion*" [c2].

The recognition that turbidite sandstones may be ponded on the surface of submarine mass transport deposits has substantially influenced the understanding of reservoir geometries in, for example, offshore Sabah (Murphy Oil), and in the Nile Cone, offshore Egypt (BG).

Our work on the formation and distribution of sand within submarine levees (Birman et al., 2009) contributed to tens of millions of barrels of additional estimated hydrocarbon reserves in levees within the Krishna Godavari basin, offshore eastern India for BG, and assisted in a negative development decision in offshore Egypt (Hess) with a probable saving of hundreds of millions of dollars on the bottom line. The algorithm on which these predictions are based is being used to develop a plug-in for Schlumberger's Petrel seismic interpretation platform, in partnership with Brazilian collaborators at Universidade Federal do Rio Grande do Sul; this represents the first such tool for estimating reservoir in levees.

As well as the application offshore India, BG have used the results of funded research to examine producing fields of West Delta Deep Marine (WDDM) off the Nile Delta in Egypt. The Head of Geology for BG Group, has clarified: "*Two examples of specific impact […] occurred in Egypt activities since 2010. The first example was applied during re-evaluation of producing WDDM gas fields and re-building of reservoir models to better match production history and constrain future production forecast. Building on field observations from Slopes JIP research, Professor Kneller had developed a geological model where rugosity on the top of mass transport deposits controls distribution of subsequent turbidite sands, reservoir thickness and aquifer distribution. This model provide an explanation for the observation of perched aquifers inferred from static reservoir pressure data. The model […] was incorporated into the reservoir model re-builds with improvements in the accuracy of perched aquifer volumes. As a consequence of the appreciation of considerable volume in several perched aquifers, production strategy was updated to increase the stand-off of well completions from the aquifer. This helped sustain production from the WDDM fields and contribute to BG Group net production in Egypt in 2010 of 48.1 million barrels of oil equivalent.*" BG have gone on to confirm that research findings have also helped in decision making for placement of development wells (at a cost of $5 million each) to access additional zones in levee facies, allowing access to an additional several billion cubic feet of gas

2. Internationalisation/training impact
Apart from our contributions to understanding of deep marine processes and architecture, we have also been instrumental in the development of two multi-million pound collaborative research programmes between Aberdeen and two Brazilian universities ("Integrated Stratigraphic-Sedimentologic-Petrologic Study of the Clastic Rift Sections of Santos and Campos Basins, Eastern Brazil", at Universidade Federal do Rio Grande do Sul; and "Late Paleozoic de-glacial deposits in the Paraná Basin (Brazil) and their analogue in the Paganzo Basin (Argentina): impacts on reservoir prediction" at Universidade do Vale do Rio Sinos). These are funded by BG under the Brazilian government's 'Special Participation' scheme, based on a production levy, and were designed to inform BG's exploration strategy, specifically within the Santos and Paraná basins (offshore and onshore Brazil respectively). We were also central to the creation and development of the world's first PhD program under Brazil's Science without Borders initiative; "International Mobility Training & Research in Sedimentary Systems". Ours is also the first deep-water research group outside China (and one of the first geoscience research groups of any kind) to receive research funding from PetroChina; this will directly influence their deep-water exploration strategy

in the South China Sea and offshore Burma.

BP have taken advantage of staff training and development to learn from the results of research. BP confirm that "*the work of the Aberdeen consortia is built into our general geoscience in-house training/learning through a wide range of mechanisms. All of these approaches contribute to building our geoscience capability. Principal Investigators give talks at the UK and Houston offices every year. These talks are broadcast via net-meeting to all BP locations around the world. Prof Ben Kneller and other principal investigators regularly meet with members of the different asset teams particularly in Aberdeen, Cairo, London, and the Houston offices. During these one-on-one meetings the BP employees can share the problems they are facing in evaluating the subsurface. Prof Kneller has led core workshops in the Cairo and Aberdeen offices, and material generated from the consortia are routinely incorporated into in-house formal geoscience training courses by BP instructors*" [2].

We introduced the concept of internships for earth science PhD students to BG Group, one of our primary sponsors over the past eight years, which has resulted in a significant change in the way they recruit PhD graduates. We have been involved in coaching and training in these new approaches for many sponsor companies (field training, core workshops, short courses, in-house coaching). BG have further applied learnings from their WDDM evaluation described above, passing these to the BG team exploring and appraising fields offshore Tanzania, "*which currently (2013) stand at 8 successful wells and confirmation of around 13 trillion cubic feet of gross recoverable resources*".

The standing of our work has been recognised by a Scottish Offshore Achievement Award in 2009, and by a Scotland-China Higher Education Research Partnership award from the Chinese and Scottish governments in 2010.

5. Sources to corroborate the impact

1. Head of Geology, BG Group, Reading, UK, can corroborate the benefits of the research findings and the impact to BG Group globally.

2. A Geologist, BP Energy do Brasil Ltda., Houston, USA, can corroborate benefits to BP globally, and in the Gulf of Mexico in particular.