Institution: University of Oxford

Unit of Assessment: UoA7 (Earth Systems and Environmental Sciences)

Title of case study: UoA7-1: Understanding major events in earth history enables petroleum industry to improve exploration strategy and reduce costs

1. Summary of the impact

The Oceanic Anoxic Event (OAE) model, developed in the UoA, has been widely used by oil companies to improve prediction tools for the presence of hydrocarbon source rocks. The model and predictive tools are used to improve exploration strategy, increase the discovery of hydrocarbon resources, and reduce costs of exploration. When exploring new territory, knowledge about which strata are oil-prone, improved by use of the OAE model, is key to 'derisking' when deciding where to drill. Wells can therefore be sited in areas of higher probability of a find than previously possible. At a cost of ≈£200M per well, increased success rates of drilling are of significant benefit to this large global industry.

2. Underpinning research

Research carried out in the UoA has demonstrated the global reach of major environmental events and explains how the planet behaves during such periods, in particular at times of exceptional warmth. This work has identified periods of earth history – OAEs – during which high biological productivity and low oxygen levels in the deep ocean lead to preservation of very organic-rich sediments. These OAE sediments represent significant hydrocarbon source rocks.

The changes in oceanic redox conditions are due to rapid rises in global temperature, probably forced by the addition of huge quantities of volcanically derived carbon dioxide to the atmosphere. Global temperature rise accelerates the hydrological cycle, increasing nutrient supply to oceans and lakes, hence enhancing productivity and the delivery of planktonic organic matter to sediment: such organic matter is the original source for all hydrocarbons.

Careful stratigraphic research in the last two decades has demonstrated that these events are global – occurring synchronously and impacting many marine and lacustrine settings. Chemostratigraphic work has indicated that the events are encoded in the trace-element and isotope composition of sedimentary rocks, enabling strata deposited during OAEs to be identified even in the absence of high organic content at the specific location being studied, and enabling correlation of the event both locally and globally.

The OAE model was first proposed before the REF period in the late 1970s, with a pioneering paper in 1976 by Schlanger and Jenkyns based on observations in the North Pacific. This model, which was not without its detractors when first advanced, but has been refined and developed by work in the period 1993 to present to demonstrate its resilience. Jenkyns, as the co-originator of the OAE model, has continued to be a world-leading expert on the subject and to pursue extensive research on OAEs throughout the 1993-2013 period. His, and other UoA research on the OAE model, has led to a significant shift in the way that petroleum companies think about potential hydrocarbon source-rock distribution.

Jenkyns' research is complemented by that of others at Oxford, principally Hesselbo (Oxford Professor 1986-2013) and Morgans-Bell (Oxford PDRA, 1998 – 2002). The research conducted in the 1993-2013 period and leading to impact includes:

1. Documentation of the global nature of OAEs, and of the widespread deposition of organic-rich shales during these events, including in open-ocean settings [1-3]
2. Discovery that isotopic signatures (e.g. $\delta^{13}C$, $^{87}Sr/^{86}Sr$) of sedimentary rocks could be used to identify and correlate OAEs, constrain their relationship to perturbations of the global carbon cycle, and provide evidence of the global and local environmental conditions that led to organic-rich deposition in sedimentary basin settings [2-6]

Because the cost of drilling oil/gas wells is so high, industry requires evidence-based models to inform drilling decisions. A fundamental necessity for successful oil/gas exploration is the

occurrence of a hydrocarbon-prone source rock within the target sedimentary basin – usually in the form of an organic-rich shale. The OAE model has become a fundamental aspect of hydrocarbon resource exploration. In addition, chemostratigraphy [2-6] enables the dating and correlation of sedimentary sequences by geochemical means in the absence of biostratigraphically useful fossils. One particular chemostratigraphic tool - carbon-isotope stratigraphy - also offers insight into the fraction of carbon deposited as organic carbon through time, providing an additional pointer to the likely presence of potential petroleum source rocks in any basin under investigation.

3. References to the research

The three asterisked outputs best indicate the quality of the underpinning research.

*1. Jenkyns, H.C. 2010. Geochemistry of oceanic anoxic events. *Geochemistry Geophysics Geosystems*, 11, doi:10.1029/2009GC002788, 30pp. (102 citations in Scopus)
This paper provides a state-of-the art summary of proposed causes and effects of OAEs and syntheses much Oxford research from the period 1993-2010. Although this is a review paper, it is succinct way of citing a large number of relevant original Oxford contributions from the 1993-2010 period.

*2. Jenkyns, H. C.; Jones, C. E.; Gröcke, D. R.; Hesselbo, S. P.; Parkinson, D. N. 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *Journal of Geological Society, London*, 159, 351–378, DOI: 10.1144/0016-764901-130. (218 citations in Scopus)
Documentation of the application of chemostratigraphy to a specific period of geological time during which many petroleum source rocks were formed.

*3. Hesselbo, S.P., Gröcke, D.R., Jenkyns, H.C., Bjerrum, C.J., Farrimond, P.L., Morgans-Bell, H.S. & Green, O. 2000. Massive dissociation of gas hydrates during a Jurassic Oceanic Anoxic Event. *Nature*, 406, 392–395, DOI: 10.1038/35019044. (373 citations in Scopus)
First chemostratigraphic demonstration of the global reach of a key OAE, and identification of likely forcing functions and driving processes.

4. Jenkyns, H. C., Paull, C. K., Cummins, D. I., Fullagar, P. D. 1995. Strontium-isotope stratigraphy of Lower Cretaceous atoll carbonates in the Mid-Pacific Mountains. In: Winterer, E. L., Sager, W. W., Firth, J. V., Sinton, J. M. (eds.) Proceedings of the Ocean Drilling Program, Scientific results, Volume 143: College Station, Texas, Ocean Drilling Program, 89–97. http://www-odp.tamu.edu/publications/143_IR/VOLUME/CHAPTERS/sr143_05.pdf

5. Jenkyns, H. C.; Wilson, P. A. 1999. Stratigraphy, paleocanography, and evolution of Cretaceous Pacific guyots: Relics from a greenhouse Earth. *American Journal of Science*, 299, 341–392. http://www.ajsonline.org/content/299/5/341.full.pdf+html (115 citations in Scopus)

6. Jones, C. E.; Jenkyns, H. C. 2001. Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous. *American Journal of Science*, 301, 112–149. http://www.ajsonline.org/content/301/2/112.full.pdf+html. (192 citations in Scopus)

4. Details of the impact

The impact described here has occurred in the period 2008–2013, and is based on research published in open scientific literature and widely available. The key chemostratigraphic data accessed by the oil companies was generated at Oxford University. All research was that of Jenkyns, Hesselbo, and associated Oxford researchers.

The beneficiaries of this research have been the exploration departments of many international energy companies, with evidence provided in particular from BP, Shell and Petrobras, and wider use exemplified by the service company Neftex. The impact of this research is described in the context of each of the companies that have provided corroborating evidence, but similar impact extends to many other petroleum companies.

British Petroleum, Libya Exploration team.

The Libya Exploration Manager at BP (quoted below) describes using Jenkyns' OAE model and its consequences for source-rock distribution / prediction as a key 'metric' when deciding whether to access new acreage / countries to explore for hydrocarbons. This methodology enables BP to have a higher degree of certainty that an exploration well will be successful, thereby reducing the cost of siting wells.

- "*We use your work as an analogue for our area, informing the risking of prospects that we will drill with wells in 2014 at costs >$200m each.*"

The BP Libyan team use Jenkyns' research on source-rock distribution to develop models for the prediction of source-rock presence.

- "*A specific example would be the Libya team between 2008 and 2012 directly using your (Jenkyns') work on Tethyan source rock distribution, particularly at the C/T boundary, in order to help build models to predict for source-rock presence offshore Libya.*"

BP also train their exploration geologists in the OAE model and its implications for hydrocarbon distribution. Jenkyns helps with this training by running annual field courses illustrating the OAE model and the use of chemostratraphic tools. Staff are taught, for example, about Tethyan source-rock distribution and shallow-water carbonate-platform evolution; highly relevant subjects for exploration activity.

- "*By leading the BP field trip to the Italian Alps you educate ~25 BP geologists per annum with respect to Tethyan source rock distribution and shallow-water carbonate platform evolution. The outcrops that you guide us through are direct analogues for what we expect to encounter in Libya.*" [7]

Petrobras

The Brazilian company, Petrobras used the UoA's research on palaeoenvironments to help reformulate their exploration strategy for the giant offshore oilfields of the western South Atlantic. Papers 1-4 above were used directly by Petrobras (quote from the Head of the Chemostratigraphy Group, Petrobras):

- "*works were used to get reference curves and understand palaeoenvironments of pre-salt rocks. They also were used to understand the oceanic anoxic events and their implications*" [8]

Shell

Shell's Vice-President Emerging Technologies and Chief Scientist Geology Projects and Technology says that Dr Jenkyns' work:

- "*has been a significant contributor to the company's exploration success*"

Oxford University work on OAEs has led to a fundamental change in the way Shell views source rocks. The work was used to develop their exploration strategy and has been used to understand how economically viable spots can be identified in exploration areas. It led to the development of the "15 focus basin strategy" formulated in 2003, which guided Shell's exploration policy until 2010, before being replaced by the "source rocks can be reservoirs" strategy which continues to rely on Dr. Jenkyn's work to the present day to understand the location and formation of source rocks.

- "*Dr Jenkyns' work on OAEs triggered a fundamental shift in the way oil companies view source rocks in terms of the importance of singular events versus uniformitarian models. This paradigm shift led, within Shell, to us focusing the search for hydrocarbons on particular periods of geological time and geographies. It was used within Shell as part of our '15 focus basin strategy' allowing us to concentrate resources on a particular set of target sedimentary basins rather than spread them world-wide.*"
- "*Dr Jenkyns' recent work with colleagues highlighting, in some cases with forensic detail, the distinctiveness of different source rocks and unravelling their origins from stratigraphic and*

geochemical clues is, we believe, fundamental to the understanding of how economic sweetspots will be identified within these plays." [9]

Neftex

Neftex is an earth-science research company and leading provider of geoscience products and services to earth-resource exploration industries. The company comprises experts in the worldwide search, discovery and analysis of geoscience information. Their integrated global geological database – the Neftex Earth Model – delivers insight to help clients reduce geological risk in exploration and investment activities. It has been extensively used across the oil and gas industry during the period 2008-2013. Head of Innovation at *Neftex* Petroleum Consultants Ltd states:

- "*Without research published by Oxford, the Neftex Earth model could not have been generated…*

  …The impacts for Neftex are as follows:

- *The painstaking work of generating high resolution, well biostratigraphically calibrated chemostratigraphic records has been invaluable in allowing and improving the precision of our global correlations.*
- *The fact that we have a good understanding of the spatial extent of organic-enriched facies during the Mesozoic/Cenozoic OAE's helps us to make inferences beyond data control as to the likely occurrence of potential source rocks for undiscovered hydrocarbons.*
- *High-resolution, biostratigraphically well-calibrated chemostratigraphic records are also instrumental in allowing the driving mechanisms behind the Neftex eustatic model to be evaluated.*
- *The detailed sequence stratigraphic work (carried out on the Jurassic, Cretaceous and Paleogene) using chronostratigraphically well-calibrated sections has provided a fundamental basis from which to compare additional sections to allow us to generate a global sequence stratigraphic model.*" [10]

The Neftex bibliographic database contains 90 papers published by Jenkyns and/or Hesselbo from 1993 onwards, with the majority of these indexed and used in their work.

5. Sources to corroborate the impact

Documentation held on file at Oxford include emails from the four sources quoted above, including the extracted quotes:

7. Libya Exploration Manager, BP
8. Biostratigraphy and Paleoecology Manager, Research and Development Center, Petrobras. Leonardo Tedeschi, Chemical Stratigraphy Division, Petrobras.
9. VP Emerging Technologies and Chief Scientist Geology Projects and Technology, Innovation Research and Development, Shell Global Solutions International.
10. Head of Innovation at *Neftex* Petroleum Consultants Ltd.