Impact case study template (REF3b)

Title of case study: Evolution of sedimentary basins and deep-water continental margins

1. Summary of the impact (indicative maximum 100 words)

Prof. White's research, and the associated computer algorithms he has developed, **have played a key role in decision-making in the petroleum industry, particularly as the search for new resources has moved into increasingly hostile and remote regions on deep-water continental margins, where the uncertainty of exploration involves multi-million pound risks.** The key to reducing the geological element of that risk is a detailed understanding of the structure and evolution of the thinned crust and lithosphere that underlie these margins. Prof. White's insights, algorithms and methodology are used by hydrocarbon companies, in particular BP Exploration, to predict hydrocarbon potential and to gain access to exploration acreage.

2. Underpinning research (indicative maximum 500 words)

The academic research on deep-water margins and extensional sedimentary basins which underpins this impact case study was carried out at the Bullard Laboratories, of the Cambridge Department of Earth Sciences, by Prof. White and his group during the post-1993 period. His research has concentrated on interrogating the stratigraphic record of deep-water sedimentary basins and continental margins to develop a quantitative understanding of their thermal evolution in time and space. The approach of this group has been to: (i) use innovative theoretical insights to develop associated algorithms and quantitative models; and (ii) demonstrate their use in interpreting sub-surface seismic and stratigraphic data.

Key steps in the development of this research are:

1. The formulation in 1993, and subsequent development, of a novel one-dimensional inversion algorithm which relates the subsidence history of a well to the duration, timing and rate of lithospheric extension at that location within a sedimentary basin or margin [1, see references in section 3].
2. Applications of this algorithm to well data and seismic reflection surveys in sedimentary basins to determine histories of subsidence, uplift and deformation, and to validate geological interpretations [2].
3. The development in 2000 of a two-dimensional inversion algorithm to model the history of subsidence, normal faulting and crustal thinning along profiles across highly extended continental margins; its application to calibrated regional seismic profiles worldwide, and calculation of its associated consequences for thermal evolution [3,4,5].
4. Development of a three-dimensional inverse algorithm to model subsidence history, in a way which allows for, but does not require, depth-dependent thinning of crust and lithosphere [6].

These advances were achieved by development of the underlying theoretical, mathematical and algorithmic insights and software tools at Cambridge. The tools were tested on high-quality seismic and well data made available through industrial collaborators, who are the only people with access to data of the appropriate quality. As a result, Prof. White's research group has had continuous and strong links with the hydrocarbon industry for over 20 years and has continued to nurture and develop these links throughout the period of this impact case. The closeness of this interaction, and the resulting exchange, discussion and criticism of insights, data and interpretations between industry and academia, spawned many novel intellectual developments in this subject area, as well as the articulation of problems and gaps in knowledge [e.g. 3].

The group working on this project has been led by Prof. Nicky White (Cambridge: 1984-present

Reader in Basin Analysis since 2003, Professor from 2013) and has involved several young researchers, many acting as co-authors on publications summarising the research outcomes. These included Dr Rowley (1994-1998, now Exploration Manager, Cairn Oil), Dr Bellingham (Cambridge 1995-1999, now Exploration Manager, Hess), Dr Jones (Cambridge 1996-2000), Dr Mackay (Cambridge 2001-2005, now BP Exploration), Dr G. Edwards (Cambridge 2002-2006, now BP Exploration), Dr Crosby (Cambridge 2002-2009, now BP Exploration), Dr Roberts (Cambridge 2009- present).

Industrial and external academic collaborators principally supplied datasets which were used to test and validate new software packages. The external collaborators include:
Dr Barwise (BP), Dr Shillington (Columbia University), Dr Minshull (Cambridge 1986-1989, now University of Southampton), Dr. R. Edwards (Cambridge 2000-2003, now National Oceanography Centre, Southampton).

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

Key peer-reviewed papers in high-impact international journals. *Those which best indicate the quality of the underpinning research are indicated (*)*

1. * **White, N.** 1994. An inverse method for determining lithospheric strain rate variation on geological timescales. *Earth. Planet. Sci. Letts*, 122, 351-71, *doi: 10.1016/0012-821X(94)90008-6* [K*ey one-dimensional inversion routine*].

2. Rowley, E. & **White, N**. 1998. Inverse modeling of extension and denudation in the East Irish Sea and surrounding areas. *Earth. Planet. Sci. Letts*, 161, 57-71*. doi: 10.1016/S0012-821X(98)00137-X [application and validation of one-dimensional inversion routine].*

3. *** White, N**., Thompson, M. & Barwise, T., 2003. Understanding the structural and thermal evolution of deep-water continental margins. *Nature*, 426, 334-343. doi:10.1038/nature02133 *[Scientific challenge that deep-water margins represent].*

4. Shillington, D., **White, N**., Minshull, T., Edwards, R., Edwards, G. & Jones, S. 2008. Cenozoic evolution of the eastern Black Sea: a test of depth-dependent stretching models. *Earth Planet. Sci. Letts*., 265, 360-378. doi: 10.1016/j.epsl.2007.10.033 *[How subsidence algorithms can be applied to wide-angle and reflection seismic data].*

5. Crosby, A., **White, N**., Edwards, G. & Shillington, D. 2010. Self-consistent strain rate and heat-flow modelling of lithospheric extension: application to Newfoundland-Iberia conjugate margins. *Petroleum Geosciences*, 16, 247-256. doi:10.1144/1354-079309-901 *[Petroleum implications of this modelling].*

6. * Crosby, A., **White, N**., Edwards, G., Corfield, R. & Mackay, L. 2011. Evolution of deep-water rifted margins: testing depth-dependent extensional models. *Tectonics*, 30, TC1004. doi:10.1029/2010TC002687 *[Summary of modelling approach and its applications worldwide].*

Key Grants:

Structural and thermal evolution of basins and margins. £350,000 BP Exploration (2006-2011)
Dynamic stratigraphy of margins £513,167 BP Exploration (2010-2014).
Formation of intra-cratonic basins £593,311 BP America Production Company (2013-2016).

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

The impact of this research has been to demonstrate that a quantitative understanding of the thermal and structural evolution of sedimentary basins and continental margins can be

obtained by exploiting a set of software tools, developed at Cambridge, to model the subsidence and crustal thinning behaviour across these regions. The major beneficiaries have been hydrocarbon companies who explore for oil and gas in frontier, high risk, regions such as the UK continental shelf, the Gulf of Mexico and the South Atlantic margins. The know-how, techniques and capability developed during this on-going research effort have helped to reduce the geological uncertainty of a dramatically escalating financial risk. The impact of this research has been to aid materially the decision-making process by assessing hydrocarbon potential and by identifying promising exploration targets. In this way, economic strategy has been firmly coupled with scientific knowledge. With regard to BP Exploration, this research has yielded significant financial impact in the following deep-water regions:
(a) **Beaufort Sea, offshore Alaska:** two-dimensional subsidence and crustal thinning model enabled a series of heatflow scenarios to be tested. A major question centred on the thickness of the lithospheric plate undergoing stretching. The success of these tests played a vital role in helping the decision-making process for acreage access. [October - December 2009].
(b) **Brazil-Angola conjugate margins:** combined modelling of data from both margins showed that plate deformation occurred by uniform thinning which affected thermal maturation of the sub-salt play which has been the focus of exploration effort since Petrobras made significant discoveries. Results have impacted exploration strategies. [May 2008 – September 2012].
(c) **Ceduna delta, offshore South Australia:** two-dimensional subsidence modelling of this margin demonstrated the existence of dynamic drawdown which has affected in-house thermal modelling strategies and changed play concepts. [September - December 2012].

The success of Prof. White's approach has resulted in a long-term multi-phase collaboration with BP Exploration. Phase I of this collaboration started in October 2006 and lasted for 5 years with funding of £350,000. Since 2008, specific projects have also been carried out which helped BP to leverage acreage access in different countries (see 5 below). The reach of this impact has been global, affecting BP's international operations. Individual projects typically involved the application of Prof. White's software tools for analysis, interpretation and modelling of seismic profiles and well-log data at the Cambridge Department of Earth Sciences. Results were incorporated into BP's in-house workflow and culminated in an improved understanding of structural evolution and thermal maturation. BP themselves state that it is difficult to assign a precise value to this work, the financial implications of these studies have however, been substantial. Industry acreage access and drilling decisions are typically made on the basis of person-years or -decades of in-house technical work, incorporating impactful University research as appropriate. Offshore exploration is expensive, with seismic programs often costing in excess of $10 million and individual wells frequently costing in excess of $100 million. The depth of our contribution is demonstrated by the level of BP's engagement in formal project meetings with the Cambridge research group; these are held twice a year with on average around 20 BP representatives attending each meeting. In addition more informal meetings and working relationships between BP and Cambridge occur regularly.

The Access Manager, East Africa at BP International Limited will corroborate that *"BP's assessment of the economic potential of a range of frontier, high risk regions has been influenced by the research on sedimentary basins and continental margins which has been carried out by the group led by Dr Nicky White"* and that *"White's ideas and insights have had impact in BP and the wider hydrocarbon industry. White's river inversion profile tool is particularly relevant to industry; because of the ability to predict sediment flux through time it has added a new set of constraints in the development and refinement of dynamic topographic models. By using this and other tools developed in Cambridge, the group has supplied BP with modelled datasets and other information on basins and margins which we have been actively assessing worldwide. This work has been incorporated into the decision making process in a number of areas globally including Alaska, Australia, Brazil and West Africa."*

As well as the two annual day conferences attended by BP personnel, the fruits of this collaboration have been published and disseminated more widely in BP in several ways:
i) by the development, at Cambridge, of an electronic atlas which was supplied for BP's internal usage. This was initiated in 2006 and we have continued to provide regular updates;
ii) quarterly activity reports and presentations sent to BP management;
iii) a two week field excursion to teach BP personnel the principles of dynamic topography and basin dynamics. This hands-on learning experience is based in western North America; White contributed to the original design of this and to the delivery and leadership of the training on each occasion it has been held, in September 2011, 2012 & 2013.

The impact of White's work and its significance in decision-making at BP is reinforced by:

- the comprehensive electronic atlas which was developed for use at BP Exploration. It is *"widely used by at least 30 personnel on an on-going basis"*. This 5 terabyte atlas contains sets of digital maps, analyses of well-log data, interpretations and models (based on the Cambridge research) of deep-seismic reflection and wide-angle profiles.
- Multiple electronic reports on basins and margins worldwide which are referred to by BP personnel. Typically, these reports contain a collation of modeled datasets.
- The development and implementation of a two-week-long field-based training course within BP specifically for their personnel. A pilot excursion was run for senior staff in September 2011. The first full excursion was run in September 2012 and a second in 2013. It features localities throughout Arizona, Utah and Colorado. Six quantitative exercises were developed for evening sessions. This hands-on learning experience was originally developed for North American personnel within BP.

These on-going activities have been accompanied by recruitment of >12 undergraduate, graduate and post-doctoral personnel from Cambridge into BP Exploration. An important consequence has been that software packages developed and tested at Cambridge are now routinely used by BP staff. The success of Phase I led to setting up of Phase II in 2010 which is a 4 year project with funding of £513,167. This project generated a new set of novel software tools for assessing the global importance of dynamic topography produced by the convecting mantle. Initial results have already had an important impact on exploration strategies in the Mediterranean, the Gulf of Mexico, the South China Sea, and the Caspian Sea.

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

The Access Manager, East Africa at BP International Limited and the **Executive Vice President, Exploration**, at BP International Limited will corroborate the impact of White's work and its significance in decision-making in many areas globally including the Alaska, Australia, Brazil and West Africa.