

## Impact case study template (REF3b)

**Title of case study:** Imaging below basalts

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

Approximately 70% of the continental margins contain significant volcanic flows, created when continents broke apart. Because large quantities of hydrocarbons may be trapped in sediments beneath the lava flows the ability to image through the basalt layers is of tremendous commercial value. However, these lava flows impede conventional seismic imaging by scattering energy, thus blocking the view of what lies beneath. ***Professor White and his team developed a technique, based on work in the 1990's, for imaging through the lava flows which differs radically from the conventional commercial approach.*** Professor White's technique has been widely adopted by the oil industry and has had a dramatic global impact, particularly for companies expanding exploration into deeper waters, including the north-west margin of Europe, the South American coast, particularly off Brazil and the continental margins of India. This approach has now become the norm having been adopted by oil companies globally.

### 2. Underpinning research (indicative maximum 500 words)

Professor White's research has focused on using seismic methods to understand the Earth's subsurface crust. In the 1990's Prof White and his team developed methods, utilising seismic energy propagating at much larger angles than conventionally recorded, for imaging through lava flows in order to study the interactions between rifting and outbursts of massive volumes of molten rock. An essential part of the work has involved the development of ocean bottom seismometers and the new software necessary for processing and modelling wide-angle seismograms recorded at sea. The key insights to successful imaging through basalts which came out of this academic research were:

1. To acquire seismic data at large offsets using either very long hydrophone streamers towed behind a ship or fixed ocean bottom seismometers on the seabed.
2. To use a broad-band seismic source with a large bandwidth including low frequency (below 10Hz) energy because higher frequencies are scattered by the basalts and do not penetrate them.

In the 1990s the oil industry moved into the exploration of new frontiers on the continental margins. In 1995, having become aware of Prof White's work on volcanism caused by rifting of the North Atlantic, the oil company Amerada Hess approached him for help with their exploration of the Faroe-Shetland region which contained large volcanic flows.

Since that time the research has been considerably extended, significantly increased in scope and breadth, and continues to the present day. For example, drawing on his experience in academic surveys of obtaining large offset profiles by using two ships instead of one, Prof White designed a large two-ship experiment on the Faroes shelf which was acquired in 1996, using well-equipped commercial vessels. Results showing successful sub-basalt imaging were announced in October 1997 at the prestigious 4-yearly conference on the Petroleum Geology of the NW European shelf by the CEO of Amerada Hess. As a result of the success of this 1996 survey, Professor White continued to refine the technique, working with Amerada Hess to design another survey which was shot in 1998. This recognition led in 2001 to setting up a large academic consortium (called iSIMM, for 'integrated Seismic Imaging and Modelling of Margins'), jointly with another HEI (Prof N.J. Kusznir of Liverpool University) and two contractor companies, Badleys and Schlumberger Cambridge Research Ltd (SCR). This attracted 8 oil companies to sign up, WesternGeco donated £1 million of ship time and processing to acquire long-offset data (12000 metre streamer) across the Faroes shelf and continental margin.

The survey parameters were designed by Dr Phil Christie (SCR) and Prof White. In addition

to a long offset streamer, they deployed 85 3-component ocean bottom seismometers to obtain offsets out to 120 km. The source design focussed on generating low frequencies because work, directed by Prof White, on seismics recorded down boreholes had shown that low frequencies were required to propagate through basalts. The actual source wavelet was recorded in deep water using a vertical array of hydrophones deployed for the purpose, and compared to the theoretical modelled waveform. SCR subsequently took out a patent on an aspect of modelling the signature from the novel source design (UK patent 2 425 838, in 2007; US patent 7,551,515, in 2010) and another (US Patent 7,961,549, which was granted on 14 June 2011) describing low frequency data acquisition and processing approaches for seismic in applications of sub-salt and sub-basalt exploration.

Much of the research was done during 2002–2010 by a team which included several early career researchers, many of whom now work in the UK hydrocarbon or commercial sectors (see section 5). Members of the group working on this project and acting as co-authors on publications have included: Professor White, (Cambridge academic staff: 1981- present), Professor McKenzie (Cambridge academic staff 1969-2012), Dr Jon Smallwood (Cambridge 1993-1997 and later employed by Amerada Hess), Dr Jenny Maresh (Cambridge 2000-2004), Dr Zoe Lunnon (Cambridge 2001-2005), Dr Lindsey Smith (Cambridge 2002-2006), Dr Alan Roberts (Cambridge 2002-2008), Dr Jennifer Eccles (Cambridge 2004-2008), Dr Helen Lau (Cambridge 2006-2009), Dr Moritz Fliedner (Cambridge 1997-2001), Dr Roman Spitzer (Cambridge 2002-2006). **External Collaborators include:** Prof N.J. Kuszniir (of Liverpool University, who developed margin subsidence software), Dr Phil Christie (of Schlumberger Cambridge Research Ltd, who holds patents connected with this work), Dr B Boslaugh (of Amerada Hess, who arranged seismic acquisition at sea).

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

*Those which best indicate the quality of the underpinning research are indicated (\*)*

White, R. S. & McKenzie, D. (1995). Mantle plumes and flood basalts. *Journal of Geophysical Research*, 100, 17,543–17,585, doi:10.1029/95JB01585. *[sets out the reasons for massive volcanism on rifted margins: 292 citations to date]*

\* Fruehn, J., Fliedner, M. M. & White, R. S. (2001). Integrated wide-angle and near-vertical subbasalt study using large-aperture seismic data from the Faeroe-Shetland region. *Geophysics*, 66, 1340–1348, doi: 10.1190/1.1487079. *[results from two-ship profiles which show large offsets are required for sub-basalt imaging]*

White, R. S., Smallwood, J. R., Fliedner, M. M., Boslaugh, B., Maresh, J. & Fruehn, J. (2003). Imaging and regional distribution of basalt flows in the Faroe-Shetland Basin. *Geophysical Prospecting*, 51, 215–231, doi: 10.1046/j.1365-2478.2003.00364.x. *[regional application of our methods, widely used as a base map for exploration]*

Maresh, J., White, R. S. Hobbs, R.W. & Smallwood, J.R. (2006). Seismic attenuation of Atlantic margin basalts: observations and modeling, *Geophysics*, 71, B211–B221, doi: 10.1190/1.2335875 *[demonstration of why low frequency sources are required to penetrate basalt flows]*

\* White, R. S., Smith, L. K., Roberts, A. W., Christie, P. A. F., Kuszniir, N. J. & iSIMM Team. (2008). Lower-crustal intrusion on the North Atlantic continental margin, *Nature*, 452, 460–464 plus supplementary information at [www.nature.com](http://www.nature.com), doi:10.1038/nature06687 *[results from applying methods for deep sub-basalt imaging]*

\* Lau, K. W. H., White, R. S. & Christie, P. A. F. (2010). Integrating streamer and ocean-bottom seismic data for sub-basalt imaging on the Atlantic Margin, *Petroleum Geoscience*, 16, 349–366, doi: 10.1144/1354-0793/10-023 *[shows benefits for sub-basalt imaging of combining an academic-developed approach to velocity modelling from OBS with industry processing]*

**Peer reviewed grants:1/** (Kuszniur, White, Roberts & Christie) iSIMM: integrated Seismic Imaging and Modelling of Margins (NERC LINK plus DTI and 8 oil companies) (2001–2005) £1,304,173 + seetime + Western Geco acquisition (£1.3 million) = £2.6 million total

**2/** (Japsen, White, Worthington) Petrophysical and seismic properties of Faroes basalts (Sindri – a group comprising oil companies working in Faroes sector) (2002–2005) 10,680,610 DKK (c. £ 1.2M). **Other Grants:** (White) P- and S-wave characterisation of subsurface properties (Schlumberger Cambridge Research Ltd) (2005–2010) £427,500

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

The main impact of our research has been the widespread acceptance that sub-basalt imaging can be greatly improved by a combination of using long offsets and a low frequency broad-band source. The major beneficiaries have been oil companies exploring for hydrocarbons in frontier areas such as the northwest margin of Europe, the Brazilian margin of South America and the continental margins of India. Approximately 70% of all continental margins contain significant volcanic flows, so as oil exploration extends into deeper waters of frontier areas the techniques discussed here have become increasingly important.

The process by which our research has been disseminated was initially by presentations at regular one-day meetings with the oil companies who contributed to the iSIMM project. This gave the participating oil companies advance knowledge of progress, and thus a commercial edge and which some incorporated into their exploration programmes. Exchange of personnel between companies, and the way so many expensive exploration activities like drilling wells are often joint enterprises, means that a 6-month lead is often all they expect or need to obtain a commercial advantage. Our results from the Faroes-Shetland Basin were used in the 3<sup>rd</sup> Faroes Licensing Round in November 2008 at which companies bid for exploration rights, and continue to be used by oil companies to help plan drilling targets. **The Director of the Faroese Earth and Energy Directorate (Jarðfeingi)** will verify *"that several companies bidding for exploration rights have applied this approach and these techniques continue to play an important role in the hydrocarbon exploration effort in the Faroese region"*.

The other main route of dissemination to a wider audience was through presentations at conferences, and particularly those attended by oil companies. These oral presentations often preceded the formal publication in international refereed journals, which often took 12 months, and we typically gave talks on results as fast as they became available. None of our work was restricted from publication in any way, and we believe that this led rapidly to its becoming widely known and used. On several occasions oil companies (specifically Shell, Amerada Hess, Total), having seen presentations of our results, directed the seismic contractors acquiring data under contract to use the same parameters as we worked out for iSIMM. Many other companies have also adopted the same principles we developed in planning their surveys. **Schlumberger Cambridge Research** will attest that this work *"motivated clients to purchase proprietary acquisition by Schlumberger of at least 5,000 line-km of low-frequency, long-offset seismic data in the basalt-covered regions of the Atlantic Margin"* and will provide evidence of the impact of our work on sub-basalt imaging, the importance of the patents taken out, and the connection with US Patent 7,961,549, which was granted on 14 June 2011, describing low frequency data acquisition and processing approaches for seismic acquisition in areas of sub-salt and sub-basalt exploration.

The benefits of improved survey design were clear in subsequent surveys shot by oil companies from 2003 onwards. Since 2008 the long-offset, low frequency strategy is now widely used as standard in surveys on volcanically-dominated continental shelves, and new acquisition technologies continue to be developed to generate and record low-frequency, broad-band data. Further advances also come in improved methods of processing, modelling and inverting the data. This is seen already from the fact that older seismic surveys, albeit with

shorter maximum offsets (typically only 2.4 km) have been reprocessed commercially by oil companies to bring out the low frequency information, with noticeable improvement in the sub-basalt image. **The Exploration Team Leader at GDF-Suez** will corroborate that “*broad-spectrum seismic sources as developed for sub-basalt imaging by the Cambridge group and related seismic processing techniques have gone on to be applied widely across other areas of the UK including the Central North Sea where the additional frequency content can reduce risk on the exploration process*” and that “*Several wildcat exploration wells costing £50M + have been drilled in areas where the sub-basalt imaging techniques pioneered by the Cambridge group have been applied, for example Lagavulin (217/15-1 in 2010/2011).*”

The precise financial value of the work is difficult to quantify but the typical licencing costs for broadband 3D seismic surveys are now in the range of £10,000 per km<sup>2</sup> (with a typical survey being 200-1000km<sup>2</sup>). It is estimated that over 8,000 km of low-frequency 2D long-offset data, directly informed by the techniques we developed, have been acquired on the northwest European continental margin alone, with revenue of \$80 million for the seismic contractors. Worldwide, the sub-basalt imaging market is much greater with important basins offshore South America, West Africa, Greenland and India. On land the Siberian Traps, Karoo, Columbia River and Parana basins have major sub-basalt prospectivity. The ability to image beneath basalts developed by this research has led to increased industrial activity to exploit sub-basalt oil reservoirs.

A further important benefit has been the supply of trained researchers into industry. Many oil companies tell us that this is of equally great importance to the research results we obtain. Three out of four postdocs employed on this research at Cambridge University now work in the hydrocarbon industry and are still active in sub-basalt research. This has led to continued interaction between the industry and academics. The oil companies and contractors have benefitted from the much longer periods of time and more focussed effort that the academic postgraduate and postdoctoral researchers are able to devote to a single study, free from the commercial deadlines in a corporate setting which require industry workers to move on to other projects. The academic research has benefitted from access to state-of-the-art seismic acquisition systems owned by oil company contractors, which are otherwise out of their reach.

Destinations of researchers after they left the Department of Earth Sciences, Cambridge University: OMV; PriceWaterhouse Coopers; Universities of Auckland, Cambridge and Durham; Dalhousie; Statoil; BP; GXT; WesternGeco; 3DGeo; UK Civil Service (Environment).

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

The impact of this work can be corroborated by: a) **The Director of the Faroese Earth and Energy Directorate (Jarðfeingi)**, b) the **Exploration Team Leader at GDF-Suez** and c) **Schlumberger Cambridge Research**.

- Dr Philip Christie, past-President of the European Association of Geoscientists & Engineers, can corroborate impact and also published a paper on the benefits of joint academic-industry projects, focusing on this work: Christie, PAF (2009) A Bumpy Road? *European Union Public Service Review* vol. 18, pp 524–527, published by PSCA International.
- Statoil put out in 2011 an appeal on their web site for innovative ways to improve sub-basalt imaging: a large number of the references and illustrations in their background material and presentation were to research by the Cambridge research group, showing the impact on this area of work. See: <http://innovate.statoil.com/challenges/Pages/Challenge.aspx>
- **Patents:** "Source signature deconvolution method" by Phil Christie and Zoe Lunnon, filed as US patent 7,551,515, in 2010 and as UK Patent Application 29 April 2005, granted as UK patent 2,425,838 on 27 June 2007 are directly derived from this work [*Phil Christie is an industry collaborator at Schlumberger Cambridge Research and Zoë Lunnon was at Cambridge (2001-2005) and played an active part in the iSIMM project*].