Institution: University of Cambridge

Unit of Assessment: UoA17B

Title of case study: Impacts on mapping agencies and the hydrocarbons industry of marine-geophysical, bathymetric and geological investigations of polar continental shelves

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

Research based on unique marine-geophysical, bathymetric and geological data from the previously little-known polar shelf seas, collected and analysed by **Dowdeswell** and colleagues, has had significant impacts on the work of British and international charting agencies and on the activities of multi-national hydrocarbons companies. In terms of hazards in polar seas, these high-resolution water-depth data from offshore of Greenland and Antarctica have proved invaluable for use by the UK Hydrographic Office and international sea-floor mapping agencies in formal navigational charts that have wide international reach. Industry has also used Dowdeswell's satellite-derived measurements of iceberg dimensions and drift tracks, together with evidence on iceberg-keel ploughing of the sea floor, to assess hazards of operating ships and sea-floor structures in Arctic waters. Dowdeswell and colleagues' interpretation of seismic data has generated understanding of Quaternary sedimentary geometry and architecture on glacier-influenced shelves. This has been used in collaborative projects with hydrocarbons companies in applications to identify sorted sandy sediments (significant as oil and gas traps) in hydrocarbon-bearing ancient glacial rocks, for example in North Africa.

2. Underpinning research (indicative maximum 500 words)

Original marine-geophysical and -geological data were collected on a series of competitively won NERC-funded cruises of up to 40 days on the UK's ice-strengthened research vessel *James Clark Ross* (1994, 2000, 2002, 2003, 2004a, 2004b, 2006, 2007, 2009) by **Dowdeswell** (Assistant Director of Research at the Scott Polar Research Institute (SPRI), University of Cambridge, 1989-94, Professor of Geography and Director of SPRI, 2002-present). A number of academic colleagues, post-doctoral researchers and PhD students have been involved in this research, particularly in data acquisition and analysis. Dowdeswell has led the group throughout.

Mapping the floor of the polar seas using high-resolution swath-bathymetric methods is a state-of-the-art approach, providing the most detailed evidence available on sea-floor topography and water depth (resolution 1-2 m vertically, 5-30 m horizontally) (Dowdeswell et al., 2006). The well-preserved submarine glacial landforms identified and analysed from these data have been used to reconstruct the dimensions and flow of full-glacial ice sheets and the pattern of subsequent deglaciation across high-latitude shelves. Glacier-influenced fjord and shelf sediments were also sampled by coring during these nine NERC-funded cruises (Dowdeswell et al., 2004), and the geometry, stratigraphy, geotechnical properties and chronology of the deposits were described and interpreted from shallow acoustic records and cores. These observations have provided significant new information on the nature of ice-sheet beds that is an important boundary condition for ice-sheet modelling (Dowdeswell et al., 2004, 2008).

Extensive shipboard and satellite-derived observations of the dimensions and frequency-distribution of modern icebergs in polar waters have also been made (Dowdeswell and Bamber, 2007). Systematic data on both iceberg plan-form and keel depths have been derived from a number of locations in the polar seas. Detailed swath-bathymetric mapping of the occurrence of iceberg-keel ploughmarks on polar shelves has also allowed inferences to be made on the nature and timing of ice-sheet breakup and, through the past drift tracks of these icebergs, the direction of past ocean currents.

Dowdeswell has also used 2- and 3-dimensional seismic-reflection datasets acquired by industry and national agencies on Arctic continental shelves to describe and understand the geometry and stratigraphy of sediments derived from ice sheets and their significance in the context of past ice-sheet form and flow (Dowdeswell et al., 2007; Dowdeswell and Fugelli, 2012). Since 2005, Dowdeswell and several post docs have spent extended periods working with industry (BP Canada, BP Norway, BP Algeria, Eni) and national agencies (e.g. Canadian Geological Survey, Norwegian Geological Survey) on the analysis and interpretation of these seismic records. The results have enabled Dowdeswell and his team to develop a detailed understanding of the internal

structure and formation of major glacially produced landforms; for example, the large grounding-zone wedges that enable the reconstruction of rates of ice-sheet retreat across continental shelves during deglaciation (e.g. Dowdeswell et al., 2008; Dowdeswell and Fugelli, 2012). Dowdeswell has also worked in hydrocarbons industry laboratories, analysing seismic records from the Beaufort Sea and northern Norwegian margins to shed new light on the intensity of glaciations during the past 2.5 million years of the Quaternary Ice Age. In addition, data from the Beaufort margin are being used for planning new International Ocean Drilling campaigns, collaborative between academics and industry, to reconstruct past climates and stratigraphic architecture.

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

Dowdeswell has been supported as PI by major research grants and has published extensively in ISI-listed scientific journals; a total of 38 papers on hazards in polar seas (sea-floor bathymetry and icebergs) and the geometry and stratigraphy of ice-sheet derived sediments from 2008-2013 with him as an author. Since 1993, eight papers on this topic (in *QSR, GSA Bulletin, Geology, Geophysical Research Letters)* have been cited over 100 times and seventeen more (in, for example, *Geology, GSA Bulletin, Geophysical Research Letters, Sedimentology, Marine Geology*) in excess of 50 times (Google Scholar).

Dowdeswell, J.A., Ó Cofaigh, C. and Pudsey, C.J., 2004. Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream. *Geology*, 32, 13-16, doi:10.1130/G19864.1

Dowdeswell, J.A., Evans, J., Ó Cofaigh, C. and Anderson, J.B., 2006. Morphology and sedimentary processes on the continental slope off Pine Island Bay, Amundsen Sea, West Antarctica. *Geological Society of America, Bulletin*, 118, 606-619, doi:10.1130/B25791.1

Dowdeswell, J.A. and Bamber, J.L., 2007. Keel depths of modern Antarctic icebergs and implications for sea-floor scouring in the geological record. *Marine Geology*, 243, 120-131, doi:10.1016/j.margeo.2007.04.008

Dowdeswell, J.A., Ottesen, D., Rise, L. and Craig, J. (Eni), 2007. Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. *Geology*, 35, 359-362, doi:10.1130/G23200A.1

Dowdeswell, J.A., Ottesen, D., Evans, J., Ó Cofaigh, C. and Anderson, J.B., 2008. Submarine glacial landforms and rates of ice-stream collapse. *Geology*, 36, 819-822, doi: 10.1130/G24808A.1

Dowdeswell, J.A. and Fugelli, E.M.G. (BP), 2012. The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. *Geological Society of America Bulletin*, 124, 1750-1761, doi:10.1130/B30628.1

Grant to **J.A. Dowdeswell**, Ice-rafted debris on the Antarctic continental margin and dynamics of the Antarctic Ice Sheet, Natural Environment Research Council, 2001-04, k£181.

Grant to **J.A. Dowdeswell**, Marine geological processes and sediments beneath floating ice shelves in Greenland and Antarctica: investigations using the Autosub AUV, Natural Environment Research Council, 2001-07, k£369.

Grant to **J.A. Dowdeswell** and J. Craig (Eni)**,** Slope stability on Europe's passive continental margins, Natural Environment Research Council, 2004-08, k£105.

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

A major impact of the Dowdeswell group's unique depth measurements is through their incorporation into new, widely used navigational charts. These swath-bathymetric data were calibrated and processed in Cambridge after each geophysical cruise (e.g. Dowdeswell et al., 2006), released to the UK Hydrographic Office, and incorporated in their official navigational charts of the polar oceans. These bathymetric data have had a particularly significant navigational impact in isolated parts of the polar seas, where the lack of depth data is a serious hazard to shipping (see 5.1). The wide reach of the data is through its use for safe navigation by ships operating in the polar seas (e.g. c. 30,000 international cruise-ship visitors to Antarctica each year). In addition, the Arctic bathymetric data have been incorporated into the International Bathymetric Chart of the Arctic Ocean (with Dowdeswell invited as editorial board member – see 5.2). This is *the* definitive

regional bathymetry for the Arctic Ocean and is used widely by governments (e.g. for questions concerning the Law of the Sea and associated economic zone claims) and industry (e.g. for exploration of these hostile waters and regional base maps for detailed seismic surveys). The UK National Hydrographer commented (see 5.1): 'Many of the areas you have surveyed, especially around the Antarctic and Greenland, were hitherto unknown or very poorly mapped. Your data are, therefore, a vital contribution to the safety of navigation.'

A major hazard to navigation in the polar seas is presented by icebergs. In addition, the below-water keels of the largest icebergs from the Greenland and Antarctic ice sheets can extend downward about 500 m (Dowdeswell and Bamber, 2007), implying that sea-floor engineering structures (cables, pipelines) are also at risk when these keels contact and plough through the soft sediments of the sea floor. Dowdeswell has been commissioned by industry to assess iceberg hazard in the Arctic seas because of his unique previous observational work on the dimensions and keel depths of icebergs (Dowdeswell and Bamber, 2007). This has included a series of quantitative reports on modern iceberg size-frequency distributions using digital satellite data and numerical-model predictions of iceberg delivery rates and how the flux of icebergs may change over the coming century. These reports (e.g. see 5.3) have been delivered to Eni and to a consortium of hydrocarbons companies. Industry has used these reports to assess the hazards and viability of exploration for, and extraction of, hydrocarbons from the Arctic seas, and as part of their decision-making process in terms of whether to bid for specific blocks in ice-infested waters. The Vice-President for Exploration of Eni (9th largest oil producer in the World) commented: 'Your work on iceberg flux and drift has been particularly critical given its tremendous impact on our ability to conduct offshore operations safely in this remote Arctic area' (see 5.4).

Dowdeswell's unique high-latitude work, on the internal architecture and sedimentology of continental shelves across which major Quaternary ice sheets have grown and decayed (e.g. Dowdeswell et al., 2004, 2006, 2007), is distinctive and important to the hydrocarbons industry, because traditional industry models of sedimentary basins are derived from fluvial/deltaic systems and not from glacial systems. Industry is using these basin-scale models of polar continental shelves, derived from the bathymetric, acoustic and sedimentary evidence acquired from shipborne work in the Arctic and Antarctic (Section 2). These models, of both glacial landforms and landform assemblages, indicate the process environment under which debris was deposited, and also the geometry and structure of specific sedimentary landforms (Dowdeswell et al., 2008; Dowdeswell and Fugelli, 2012). The detailed description and understanding of, for example, glacial depositional features such as grounding-zone wedges, from modern and Quaternary Arctic shelves, has led directly to applications to ancient glacial sediments proven to contain large quantities of oil and gas.

These ancient rocks are the subject of continuing exploration and exploitation by the hydrocarbons industry. Industry needs to know the sedimentary and seismic geometry, or architecture, of these ice-sheet influenced rocks so that companies can understand, model and then drill into the most productive oil and gas traps, which are generally associated with sorted sand and gravel sediments. Typical examples are the 450 million year old rocks of Northern Africa and Arabia, deposited when the area was in a polar position due to plate wandering. The Quaternary work by Dowdeswell and colleagues (e.g. Dowdeswell et al., 2004, 2007, 2008; Dowdeswell and Fugelli, 2012) has led directly to: i) the identification of features of similar dimensions and internal structure in the Late Ordovician glacial rocks of BP's Algerian blocks and Eni's Libyan assets; ii) the location of high-amplitude seismic reflectors in industry's 3-D seismic data; iii) the interpretation of these reflectors as likely sandy sediments by analogy with our Quaternary examples from the Greenland shelf and, significantly, iv) to specific decisions on the choice of drilling sites for wells. Eni's Vice-President for Exploration commented (see 5.4) that this work: 'has been used to understand glacial depositional systems and, specifically, to identify sorted sandy sediments (significant as oil and gas traps) in the hydrocarbon-bearing 450 Myr old glacial rocks of North Africa' (see 5.4).

The impact of our research has been secured through: i) a series of confidential reports to industry (e.g. see 5.3); ii) workshops and seminars on, for example, the interpretation of sediment cores from glacial environments (e.g. see 5.5), delivered to groups of hydrocarbons-industry personnel at research centres such as BP Sunbury (8/10, 10/10, 8/12, 3/13), Calgary (6/11) and Stavanger (7/11), and through visits to Cambridge University by, for example, the Arctic group of Eni (3/10,

10/10, 10/11, 3/12, 4/13, 10/13); iii) working directly with industry in their seismic-processing laboratories in London, Norway and Canada in order to investigate and analyse specific seismic interpretation problems involving the Canadian Beaufort, Greenland and Norwegian continental shelves; iv) papers in the scientific literature which, published after a contractually agreed period in confidence to specific industrial sponsors with whom we have worked (and often co-written with industry scientists; e.g. Dowdeswell et al., 2007; Dowdeswell and Fugelli, 2012), are a further important means of dissemination to the wider industrial community (Section 3).

The extensive knowledge-base derived by Dowdeswell and co-workers from data acquired on modern and Quaternary polar shelves, where the processes of sediment delivery and deposition from ice sheets can be best understood, is therefore of key significance to industry. The Norwegian margin group at BP (6th largest oil producer in the World) noted (see 5.6) the potential for 'an important transfer of knowledge to BP, in that the Scott Polar Research Institute has detailed expertise in modern and Quaternary patterns and processes of glacial deposition in marine settings which is important to BP's evolving understanding of ice-sheet sedimentary systems.' More recently, the Vice-President for Exploration of Eni wrote (see 5.4): 'Your work has been of particular value in reducing exploration risk and in improving hydrocarbon recovery in some of our largest North African oilfields.'

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

Corroboration of impact is provided by the users of our unique bathymetric data from polar seas and of confidential research-based reports and workshop presentations to industry on the sedimentary architecture of high-latitude continental margins (note that sources 3 and 5 are included as evidence that reports and presentations were given to industry and that source 3 will be supplied on request but *is to remain confidential*):

1. Letter from person 1 (the UK National Hydrographer, UK Hydrographic Office).
2. Paper in *Geophysical Research Letters* by Jakobsson et al. (2012), (doi: 10.1029/2012GL052219).
3. Dowdeswell, J.A. and van der Wal, N., 2011. Modern environmental conditions on the East Greenland offshore margin (70-79°N): modelling iceberg flux to 2100, 125 pp, confidential report to Eni. Deliverable to Eni contract of kEuro150.
4. Letter from person 2 (Vice-President for Exploration, Eni).
5. Dowdeswell, J.A. and Hogan, K.A. Glacigenic diamict facies from the marine environment. Workshop at BP, Sunbury, 10/10. Deliverable to BP Algeria contract of k£30.
6. Letter from persons 3 & 4 (Exploration Team Leader & Geologist, BP Norway).