

Institution: University of Aberdeen
Unit of Assessment: 5 - Biological Sciences
Title of case study: Changing the way nations manage the impacts of human disturbances to protect the conservation status of wild animals
<p>1. Summary of the impact</p> <p>Dr Lusseau's work at the University of Aberdeen into the impact of man's activities on wild animals has led to changes in public and environmental policies in several nations as well as changes in international policies. He developed insights as well as modelling approaches to understand the consequences of human disturbances on the viability of animal populations.</p> <p>The Aberdeen work has led to a change in the way the environmental impact of a range of industries - including tourism, marine renewable energy and oil & gas - is assessed. Lusseau developed best approaches to manage the disruptions of animal behaviour that those activities created to ensure that those disturbances do not endanger the viability of wild animal populations.</p> <p><i>Specifically this research resulted in impact that influenced international policy development and international planning processes. It also informed planning decisions and changed the way environmental risks and hazards are managed in the UK, USA, and New Zealand, and informed changes in legislations and regulations in the USA, UK and New Zealand.</i></p>
<p>2. Underpinning research</p> <p>Research conducted by Dr David Lusseau, Senior Lecturer, and his team at the University of Aberdeen has changed our perception of the risks for the viability of animal populations caused by the impact from man's activities on the behaviour of long-lived, slow reproducing marine species such as whales and dolphins. Previously, such disturbances were perceived to be only a welfare issue. However, work - dating back to 2003 - by Lusseau and his team has demonstrated that repeated exposure to human disturbances leads to significant changes in the amount of time animals spend carrying out vital activities. This can alter their probability of survival, their reproductive success, and the way they use their habitat [1, 2, c]. Also when significant numbers of individual animals are affected, the growth rate of the targeted population can be negatively impacted [c]. This work showed that disturbances that cause changes in animal behaviour can affect the conservation status of animal populations [2, c]. Lusseau's work has led to a complete change in the way disturbances on marine mammals caused by human activities are managed at a global scale (International Whaling Commission [e, f]).</p> <p>This work forms the basis for a paradigm shift in the way human disturbances are managed. Rather than taking a risk-adverse precautionary approach to management of these activities, Lusseau developed an approach that can effectively estimate likely effects on targeted animal population conservation status within the time scale needed for management decisions. This now ensures that the regulation of human disturbances is less open to interpretation and strives to have the same regulatory targets as other form of impacts. This shift in regulatory target interpretation rationalises the impact assessment process, thereby reducing the risks investors have to take during the application process for new developments. At an international level, the findings have prompted a change in the management of developments and activities that could impact on animal behaviour. The burden of proof has shifted from having to demonstrate that such impacts exist, to demonstrating that such impact does not occur [e, f].</p> <p>Since 2008, the Aberdeen team has been directly involved in several impact assessment studies in the USA [a], the UK [2, g, h], Canada, New Zealand [b, c], and Iceland [3], particularly focusing on marine tourism and marine renewables. These have led to changes in management and regulatory frameworks for the maintenance of the conservation status of cetaceans [a, b, d, e, g].</p> <p>Since this seminal work, Lusseau's team at Aberdeen has developed mechanistic models linking behavioural disturbances to population dynamics, as part of a working group funded by the US Office of Naval Research, developing models to assess and predict the population consequences</p>

of disturbances on cetaceans.

In collaboration with others, these models have been used to determine under which conditions the growth rate of certain animal populations would be affected by disturbances caused by man's activities. Lusseau, and colleagues at Aberdeen and other institutions, developed a statistical approach to fit these mechanistic models to observations [2, 5]. This work has been translated in the UK to develop the scientific foundations for an adaptive management scheme for the development of marine renewable energy plants in the light of existing cumulative impacts on wildlife populations living in the area of these developments. This was used for the first time in August 2013 to advise Scottish Natural Heritage and Transport Scotland and Marine Scotland ministers on the likely cumulative effects of the developments of three ports in the Moray Firth on the conservation status of the only bottlenose dolphin population in the North Sea. These developments are deemed of national importance [i].

Finally, Lusseau has instigated a research programme [j] at the International Union for Conservation of Nature Sustainable Use and Livelihoods specialist group, (IUCN-SuLi) to extend this modelling approach. This extension aims to account for the interaction between conservation status targets and the economic viability of activities and local community welfare in defining levels of activities such socioecological systems can sustain.

3. References to the research

- [1] Lusseau D. 2003. The effects of tour boats on the behaviour of bottlenose dolphins: Using Markov chains to model anthropogenic impacts. *Conservation Biology* 17(6): 1785-1793. *156 cites. For the first time shows that tourism interactions affect wildlife population activity budget.*
- [2] New L.F., Harwood J., Thomas L., Donovan C., Clark J.S., Hastie G., Thompson P.M., Cheney B., Scott-Hayward L. & Lusseau D. (2013) Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance. *Functional Ecology* 27: 314-322. *This article is one of several emerging from the following grant: the article and grant developed the first implementation of a simulation platform to inform management by linking disturbances to annual physiological condition of individual dolphins. This modelling approach is now required in Scotland for Environmental Assessments and Habitat Regulation Appraisal.*
- [3] Christiansen, F., Rasmussen, M. & Lusseau, D. 2013. Whalewatching boats disrupt the foraging activities of Minke whales in Faxaflói bay, Iceland. *Marine Ecology Progress Series* 478: 239-251. *This study shows for the first time that baleen whale activity budget can be impacted by boat exposure.*
- [4] Lusseau D. & Higham J.E.S. 2004. Managing the impacts of dolphin-based tourism through the definition of critical habitats: the case of Doubtful Sound, New Zealand. *Tourism Management* 25(6): 657-667. *111 cites. Proposed multi-level spatial planning as management tool that is now used in many locations.*
- [5] Lusseau D., Christiansen F., Harwood J., Mendes S., Thompson P.M., Smith K. & Hastie G.D. 2012. Assessing the risks to marine mammal populations from renewable energy devices – an interim approach. <http://tinyurl.com/bxazp8b>
- [6] Higham J.E.S., Bejder L. & Lusseau D. 2008. An integrated and adaptive management model to address the long-term sustainability of tourist interactions with cetaceans. *Environmental Conservation* 35(4):294-302. *22 cites. This provides the scientific foundation for the development of adaptive management schemes for disturbance-related impacts.*

Impact case study (REF3b)

Research funding:

- Lusseau D. (PI), et al. 2011-2012. The development of a framework to understand and predict the population consequences of disturbances for the Moray Firth bottlenose dolphin population. Scottish Natural Heritage (£40k) <http://tinyurl.com/a4j95pb>.
- Lusseau D. (PI) 2012. Developing an interim approach to assess the risks to marine mammal populations from renewable energy devices. JNCC, CCW and NERC Knowledge Exchange (£28k)
- Lusseau D. (PI) 2013. Effects of development at three ports in the inner Moray Firth on the bottlenose dolphin interest of the Special Area of Conservation. Scottish Natural Heritage (£18k)
- Lusseau D. (co-PI) 2012-2014. Determining the factors contributing to human-dolphin interactions in a long-term resident inshore bottlenose dolphin community. NOAA Seagrant (\$111k)
- Lusseau D. (PI) 2013-2014. Predicting the ability of marine mammal populations to compensate for behavioural disturbances. US Office of Naval Research (\$167k)

4. Details of the impact

The research led to several changes in laws and regulations in the USA [a,d], New Zealand [b,c], and in the inter-governmental organisation responsible for advising nations on the sustainable use of whale stocks (International Whaling Commission, IWC [e]). For example, (i) in 2008, the New Zealand government established the Doubtful Sound Marine Mammal Code of Management [b], including the establishment of our proposed Dolphin Protection Zone [4]. (ii) In 2011, US Federal regulations were changed to introduce protective regulations for killer whales in the Northwest Region under the Endangered Species Act and Marine Mammal Protection Act [a]. (iii) In 2011, the International Union for Conservation for Nature listed the Fiordland subpopulation of *Tursiops truncatus* as critically endangered following our recommendations [c].

The International Whaling Commission shifted the burden of proof in whalewatching impact assessment in 2006 [e] and established the Large-scale Whalewatching Experiment (LaWE) project initiative in 2008 [f] to inform the international management of tourism centred on interacting with whales and dolphins. On the basis of his research Lusseau was elected to chair this research programme for the Commission. This international research initiative provides scientific information to inform an adaptive management framework proposed by Lusseau [6]. It focuses on defining sustainable levels of tourism whale and dolphin populations can support [b] depending on their habitat and their life history characteristics.

As a direct result of Lusseau's findings, the IWC established the inter-committee Joint Working Group for Whalewatching in 2011 [f]. This included changes in rules and procedures of the International Whaling Commission to develop management procedures for whalewatching by allowing direct communication and collaboration between its Scientific and Conservation Committees. Finally, following Lusseau's research [10], the Group is, since 2012, developing an adaptive management plan for whalewatching to coordinate the management of the industry in the 89 member nations [f].

This research also led to a paradigm shift in the way non-lethal impact on cetaceans is managed in the UK [g, h]. The management objective for disturbances have been clarified and aligned to favourable conservation status. Adaptive management schemes [6] have become preferred for these activities. A unified scientific foundation for monitoring and assessing objective compliance has been adopted in 2012 [5]. A series of management tools has been developed in direct response to Lusseau's research. In July 2013, the Joint Nature Conservation Committee (JNCC) established the UK Marine Mammal Renewable Advisory Committee [5]. The role of this national committee will be to implement the management scheme we have developed for the JNCC, NERC KE and CCW, in relation to the development of marine renewable energy plants. From 2012, our scientific and management advice to the Scottish government and SNH [2] has been implemented. Those institutions now use our modelling approach and management framework to consent and manage multiple development proposals in the Moray Firth, UK. Lusseau advised Scottish ministers, in August 2013, on the likely effects of the development of three harbours in the Moray

Impact case study (REF3b)

Firth, to supply windfarm and oil and gas exploitation sites in the North Sea, on the Moray Firth Special Area of Conservation using this modelling approach [i].

Finally, this modelling approach is also adopted at the International Union for the Conservation of Nature (IUCN) with the creation in 2012 of a modelling working group by the IUCN SSC/CEESP Sustainable use and Livelihoods Specialist Group (initiated and now led by Lusseau) to further apply this approach to other socioecological systems within the remit of IUCN [j].

Claimed impact as defined by REF: influenced national and international environmental policy decisions and informed national and international planning decisions. Also led to changes in both the management of natural resources and the management of an environmental risk and hazard.

5. Sources to corroborate the impact

[a] Federal Register entry of the new Rule: <http://www.gpo.gov/fdsys/pkg/FR-2011-04-14/pdf/2011-9034.pdf>. *Following demonstration of impacts on killer whale's activity budget by Lusseau new regulations guiding boat behaviour around whales are imposed and zoning proposed.*

[b] NZ new Code of Management: <http://tinyurl.com/a7s5jlp>. *Following demonstration of impact of tourism on bottlenose dolphin population by Lusseau, new boat behaviour regulations are imposed and the zoning advised by Lusseau proposed.*

[c] IUCN listing of Fiordland subpopulation of bottlenose dolphins: <http://tinyurl.com/6f42k99>. *Bottlenose dolphin populations inhabiting Fiordland are listed as critically endangered with wildlife tourism being listed, for the first time at IUCN, as a key cause for the population's conservation status and a key threat to the population recovery.*

[d] Changes to criteria for Environmental Impact Statement for Oil and Gas operations (pertaining to cumulative impacts): e.g., Recommendation of the US Marine Mammal Commission to the US Bureau of Ocean Energy Management, Regulation, and Enforcement <http://tinyurl.com/ao9rn2k> International Whaling Commission reports detailing steps above:

[e] IWC/58/Rep1 2006 Report of the Scientific Committee, p.54, (<http://tinyurl.com/a4umhdi>): *"The Committee agrees that there is new compelling evidence that the fitness of individual odontocetes repeatedly exposed to whalewatching vessel traffic can be compromised and that this can lead to population level effects. The Committee recommends that similar studies looking at individual fitness of cetaceans be carried out where ever possible. However, in the absence of these data it should be assumed that such effects are possible until indicated otherwise."*

[f] IWC/60/Rep1 2008 Report of the Scientific Committee p.57, (<http://tinyurl.com/a4umhdi>): *Establishment of the LaWE Steering Group* and subsequent IWC/63/CC3 2011 Report of the Standing Working Group on Whalewatching of the Conservation Committee (<http://tinyurl.com/a74bk2t>): *Propose the establishment of the Working Group on Whalewatching as a joint Working Group between the Scientific and Conservation Committees to develop worldwide management procedures for whalewatching.*

[g] JNCC development of interim guidance for English and Welsh territorial waters and the UK offshore marine area on the deliberate disturbance of marine European Protected Species (2007): <http://tinyurl.com/b3c4z9q>. *Research used to define a disturbance offence under the EU Habitats Directive (pp.9;13)*

[h] The Moray Firth Special Area of Conservation Management Scheme: <http://tinyurl.com/amc7muc> and <http://tinyurl.com/a6a5chn> *Changes in management action plan in response to Lusseau's research*

[i] Marine Scotland consideration of a proposal affecting a designated SAC or SPA (11 Oct. 2013) <http://www.scotland.gov.uk/Resource/0043/00436017.pdf> *Scottish government decision on port development based on Lusseau's research and advice.*

[j] Creation of a modelling working group IUCN SSC/CEESP Sustainable use and Livelihoods Specialist Group: <http://tinyurl.com/9wen3w2> and <http://tinyurl.com/b7bktzi>.

Institution: University of Aberdeen

Unit of Assessment: 5 - Biological Sciences

Title of case study: Aberdeen research underpins guidelines for assessing and lessening impacts of offshore energy developments on protected marine mammal populations

1. Summary of the impact

Achievement of energy security and the UK's 2020 carbon targets economy depends upon a mix of new offshore oil and gas and renewable energy developments, but concern that seismic survey and construction noise could pose an unacceptable risk to marine mammals threatens to delay these plans.

University of Aberdeen ecologists, under the direction of Paul Thompson, have developed long-term studies of marine mammal population dynamics that now underpin frameworks for assessing and mitigating the impacts of such developments on marine mammals in EU protected areas.

The specific impact on commerce and the environment is that this assessment process has been adopted by industry within their consent applications. As a result of academic consultancy in industry, planning decisions have been informed by the research, and the management of environmental risks has changed. This has reduced the consenting risk for industry and provided an assessment framework that allows regulators to ensure that they are implementing current government policy within international legal frameworks for environmental protection.

2. Underpinning research

As a result of the University of Aberdeen's long-term ecological studies of coastal harbour seal and bottlenose dolphin populations in Scotland's Moray Firth, these species are now two of the most intensively studied marine mammal populations in the world. Professor Paul Thompson of the University of Aberdeen initiated and has led this integrated research programme for over two decades, using tracking [1] and observational [2] techniques to identify key foraging habitats, and sustained population level studies to understand how distribution and abundance vary through time [1, 3 and 4]. Studies of harbour seals were initially developed through a series of Scottish Office contracts that supported Thompson as a research fellow, and have been maintained between 1993 and 2011 through 6 PhD studentships at Aberdeen, including collaboration with Hammond (St Andrews) and Armstrong (Marine Scotland Science). Studies of bottlenose dolphins were developed in collaboration with Hammond (St Andrews) and have been maintained through 4 Aberdeen-based PhD studentships and 6 externally-funded Research Fellows.

In 2004, Thompson used this understanding of population ecology to develop studies that addressed uncertainty over the potential impacts of offshore energy developments on new marine protected areas (EU Special Areas of Conservation), established in response to the EU Habitats Directive. Research carried out with two EU funded Research Fellows (Bailey & Lusseau) during the installation of the world's first offshore deep-water wind turbines tested acoustic propagation models, and confirmed the potential for far-field disturbance of marine mammals [5]. At the same time, this research demonstrated weaknesses in traditional assessments of impacts using impact and control areas, and the need for analyses along gradients of impact [6]. Recommendations resulting from this work underpinned the development of a large-scale assessment of behavioural responses of small cetaceans to industrial noise, involving a gradient design across a study area of over 2000 km², and an assessment of the spatial scale at which these animals responded to a full-scale commercial seismic survey. This programme was funded by the UK's Department of Energy & Climate Change (DECC) and has been developed and co-ordinated by Thompson, working with Aberdeen-based Research Fellows [Brookes (2009-2012), Graham (2011–Present) & Cordes (2011-2012)] and commercial sub-contractors at Kongsberg Maritime & WWT Consulting Ltd. The survey approaches developed and validated for this study provided the additional data required by the UK Government to licence the seismic survey, and represented the first field test of alternative survey approaches available to underpin consenting of deepwater offshore wind farms licensed through the Scottish Territorial Waters and Round 3 licensing rounds. In 2011, this field test was further developed to compare novel digital survey technologies in collaboration with Borchers and

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Hammond (St Andrews) through a contract from Marine Scotland. Between 2010 and 2012, industry (Energias de Portugal Renewables, Scottish & Southern Energy Renewables & Repsol) also invested in additional research on the offshore distribution of marine mammals to support consent applications for their major joint venture windfarms (Moray Offshore Renewables Ltd and Beatrice Offshore Wind Ltd). Thompson also worked with their environmental teams [Maclean (Natural Power), Hastie (SMRU Ltd) & Nedwell (Subacoustech)], extending modelling work previously used to assess impacts of fisheries [4] and led the development of new frameworks for assessing the population consequences of noise from wind farm construction, allowing comparison of alternative construction options and demonstrating to regulators that proposals will meet international agreements on environmental protection. Since 2012, with funding from the NERC MREKE programme and industry, Thompson and Lusseau at Aberdeen have subsequently worked with collaborators at the University of St Andrews to develop these frameworks for other populations which lack the detailed baseline data available from the Moray Firth research programme.

3. References to the research

- [1] Cordes, LS, Duck, CD, Mackey, BL, Hall, AJ, & Thompson, PM. (2011). Long-term patterns in harbour seal site-use and the consequences for managing protected areas. *Animal Conservation* 14, 430-438. *Paper based on a 20-year time-series of data that demonstrates a shift in distribution at terrestrial breeding sites but consistent use of foraging areas by tagged female harbour seals.*
- [2] Bailey, H & Thompson, PM. (2009). Using marine mammal habitat modelling to identify priority conservation zones within a marine protected area. *Marine Ecology Progress Series*, 378, 279-287. *Paper that uses survey-based data in habitat association models to identify key areas for bottlenose dolphins within the largest marine Special Area of Conservation in UK waters.*
- [3] Wilson, B, Hammond, PS & Thompson, PM. (1999). Estimating size and assessing status of a coastal bottlenose dolphin population. *Ecological Applications*, 9, 288-300. *Paper that used mark-recapture analysis of individually identified bottlenose dolphin in the Moray Firth to provide the first estimate of population size for any cetacean in European waters, and assessed the power of different monitoring schemes to detect future population change.*
- [4] Thompson, PM, Mackey, BL, Barton, TR, Duck, C & Butler, JRA (2007). Assessing the potential impact of salmon fisheries management on the conservation status of harbour seals in NE Scotland. *Animal Conservation*, 10, 48-56. *Paper that identified a significant decline in abundance within an EU Special Area of Conservation for harbour seals. Collaboration with key fisheries organisations identified high levels of previously unreported shooting, which population modelling indicated was sufficient to drive observed declines.*
- [5] Bailey, H, Parvin, S, Senior, B, Simmons, D, Rusin, J, Picken, G & Thompson, PM. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, 60, 888-897. *Paper that reports the first far field recordings of pile driving noise during construction at the world's first deep water wind turbine, highlighting that pile driving noise could be detected at distances of up to 70 km, potentially disturbing small cetaceans at distances of 20 km from source.*
- [6] Thompson, PM, Lusseau, D, Barton, T, Simmons, D, Rusin, J & Bailey, H. (2010). Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Marine Pollution Bulletin*, 60, 1200-1208. *Paper that demonstrates how passive acoustic monitoring can be used to assess responses of cetaceans to wind farm construction, highlights the constraints of traditional approaches to impact assessment and recommends alternative monitoring programmes.*

The publications underpinning these impacts were all in international peer-reviewed journals.

Although several have only been published within the last 2 years, they have collectively attracted 147 citations.

Key grant funding associated with the research:

- [i] *Moray Offshore Renewables Ltd & Beatrice Offshore Wind Ltd* (2010-2012) Assessing the impact of windfarm construction on Moray Firth marine mammals. £325,000
- [ii] *DECC* (2009-2013) Assessing the impact of seismic surveys on cetaceans. £1,957,600
- [iii] *Scottish Government & Scottish Natural Heritage* (2006-2009) Abundance and population structure of Scottish Bottlenose Dolphins £464,944

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- [iv] *EU 6th Fr & Talisman Energy (UK) Ltd* (2005-2007) Assessing the impact of demonstration offshore wind turbines on seabirds and cetaceans. £166,974
- [v] *Scottish Natural Heritage* (2004-2012) Bottlenose dolphin site condition monitoring in the Moray Firth SAC £135,370
- [vi] *NERC* (1993-1995) Molecular-based studies of individual differences in the diet seals. £115,945 Thompson, Co-PI with Amos (Cambridge).
- [vii] *Scottish Office* (1993-1997) Population and foraging ecology of Moray Firth seals. £252,665

Studies of the effects of marine renewable have developed through a continuous series of grants and contracts that have been obtained through open competition involving peer-review. More recently, these have sometimes attracted invited single tender contracts from government and industry [grants ii-iii], which has required detailed scrutiny and, for government bodies, ministerial approval. Such projects were subsequently overseen by a broad steering group of external academics and stakeholders.

4. Details of the impact

The research programme has been designed to maximise impact on public policy, commerce and society through direct interaction of researchers and management organisations, industry support for research and academic consultancy, and the integration of research output into education, media and public arts programmes.

Influencing environmental policy decisions and the management of natural resources The presence of Aberdeen's comprehensive research programme in important marine mammal habitats led to Thompson joining groups that developed frameworks to manage EU Special Areas of Conservation [SNH Regional and Science Board Member (1993-1997) and Scientific Advisor for the Moray Firth SAC Management Group (2000-2009)]. Work with this broad range of stakeholders facilitated dissemination of relevant research on population drivers and underpinned subsequent policy changes in the way that Scottish Government manages these natural populations when regulating offshore energy developments. Working through a broader group led by the Scottish Government, Aberdeen research demonstrated that population declines were linked to high levels of shooting [4]. This led to a paradigm shift in the way Scottish seal populations are managed through the 2005 Moray Firth Seal Management Plan and the new 2010 Marine (Scotland) Act [b].

Industry support for research The impact of Aberdeen's research on offshore energy developments arose through Talisman Energy (UK) Ltd. jointly funding a PhD. Talisman subsequently contracted Aberdeen to conduct offshore cetacean surveys that were completed in 2001, supporting work on their Beatrice Oilfield. This led to an invitation to join a multi-disciplinary consortium, partly funded by the EU Framework 6 programme, to assess the impacts of deepwater wind farms during construction of the Beatrice Demonstrator Turbines. A key output of this work [6] recommended new approaches for assessing cetacean responses to industrial noise. At this time, public and scientific concern over potential impacts on EU protected populations of bottlenose dolphins had resulted in DECC freezing plans to further develop oil and gas production in the region. As a result, Thompson was invited by DECC to design a £1.9 million research project that, in 2010, provided them with sufficient understanding of cetacean populations in the affected areas to allow further seismic surveys [a] and, in 2011, studied cetacean responses to those surveys.

Academic consultancy This research has directly impacted the consenting process adopted by the two offshore wind farm companies developing projects within the Moray Firth - Moray Offshore Renewables Ltd and Beatrice Offshore Wind Ltd, international leaders in this sector. No procedures previously existed for assessing construction impacts on EU protected populations of marine mammals, resulting in a serious consenting risk for these and other UK offshore wind farms. Thompson worked with these environmental and engineering teams [c], liaising closely with regulatory bodies, and led the development of a framework for assessing impacts on protected seal populations [d]. This has been used in consent applications during 2012, demonstrating how planning decisions have been informed by this research [a]. Other developments are now generalising these processes for use in areas which lack the local data available to the Moray Firth

developers through Aberdeen's research programme.

Public understanding of environmental and policy issues In parallel to these developments, recent outreach has focused on activities that improve stakeholder and public understanding of underwater noise issues, and inform debate on balancing the demands of EU legislation on nature conservation and carbon emissions [e]. An arts-science collaboration funded by Creative Scotland and Highlands & Islands Enterprise attracted national media coverage for works by sound and visual artists, and Aberdeen researchers co-organised workshops for schools and for the regulators and statutory advisors who are dealing with offshore renewable planning applications.

Claimed Impact as defined by REF: Decisions by regulatory authorities have been influenced by research, industry has invested in research and development, new assessment processes have been adopted, and public understanding has improved.

5. Sources to corroborate the impact

[a] **Influencing regulatory decisions.** The DECC Appropriate Assessment for further oil exploration in the Moray Firth (https://163.164.19.97/environment/aa_2212.pdf) includes extensive reference to Aberdeen research that underpinned this consent decision (See Sections 8.3-8.7, Figs 8-12 and Section 9.7, fig 16). A testimonial from Marine Scotland explains that "*Aberdeen University's research has changed the way which developers are assessing the long-term impacts of offshore wind farm developments...clearly indicating that developments can be consented without affecting the long-term status of protected marine mammals*"

[b] Changes in the way that seal populations are managed in the Moray Firth are described in Butler et al. (2008) *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18: 1025-1038, and subsequent changes in national seal management are outlined at:

www.scotland.gov.uk/Topics/marine/marine-environment/species/19887/20814

[c] **Industry investment in R & D.** Environmental Statements supporting consent applications for the first offshore wind farm applications under the Scottish Territorial Waters (Beatrice Offshore Wind Ltd and UK Round 3 (Moray Offshore Renewables Ltd) each contains sections outlining how Aberdeen research underpinned their environmental assessment. For example see pp 20-29 of MORL Marine Mammal EIA Appendix (<http://morayoffshorerenewables.com/getmedia/37a382ddf907-420f-902b-8e399fc7ca97/Appendix-7-3-A---Marine-Mammals-Impact-Assessment.pdf>),

Chapters 3, 5 & 6 of MORL Marine Mammal Baseline Technical Document

(<http://morayoffshorerenewables.com/getmedia/82ead15-7f65-4505-802a-bd9023fb3a7d/Appendix-4-4-A---Marine-Mammals-Baseline.pdf>).

A testimonial from the CEO of MORL highlights that "*MORL is highly cognisant of the benefits of The University of Aberdeen's marine mammals research programme which has not only made an invaluable contribution to the assessment of the MORL projects in terms of the baseline information available, but which also has enabled the development of the Moray Firth Seal Assessment Framework through the close collaboration of academia and industry.*"

[d] **Adoption of new procedures.** These Environmental Statements also describe the Aberdeen-led development of new procedures to assess population level impacts on EU Protected marine mammals. A description of this process has been published in Thompson et al. (2013) *Environmental Impact Assessment Review* (<http://dx.doi.org/10.1016/j.eiar.2013.06.005>). As outlined in a testimonial from the Director of Natural Power, Thompson's "*academic consultancy with Natural Power produced an agreed assessment methodology that enabled both Moray Offshore Renewables Ltd and Beatrice Offshore Wind Ltd to submit robust impact assessments to inform Marine Scotland's consenting and HRA processes*".

[e] **Impacts on society, culture & creativity.** Since 2007, two UK networked TV programmes and two BBC Radio 4 programmes have used Aberdeen research to improve public understanding of science and environmental issues (see www.abdn.ac.uk/lighthouse/about/). The wider cultural impact of the Aberdeen arts-science collaboration is highlighted in a BBC Radio 4 "Saving Species" feature (www.bbc.co.uk/programmes/b01mqp1p), a collaboration that has been described as "*one of those inspired mix-and-match exercises that place artists alongside scientists with illuminating results.*" (HeraldScotland, 10/11/12). An SNH testimonial confirms that Aberdeen researchers' "*willingness and ability to engage at different levels to convey and promote the key findings from this research has led to improved understanding of environmental and policy issues*"

Institution: University of Aberdeen
Unit of Assessment: 7 (Earth Systems & Environmental Sciences)
Title of case study: Stratigraphic techniques to develop untapped oil & gas reserves
<p>1. Summary of the impact</p> <p>Research by the University of Aberdeen's research group on Stratigraphic Evolution of large Igneous Provinces (StratLIP) has guided the successful development of new oil-producing fields in the North East Atlantic that were previously not in production, aided by an improved understanding of the geological context within which the reserves were discovered. The research has informed every phase of exploration and development by several of the UK's leading energy companies, in one project saving the partners £600m and proving the financial viability of a major oilfield development deemed important to the UK's oil supply. The findings have contributed to an increase in the UK's energy security and the strength of the UK's oil and gas industry, especially in the context of the local economy of Aberdeen, the energy capital of Europe.</p>
<p>2. Underpinning research</p> <p>The Faroe-Shetland Basin, located in the North East Atlantic, is one of the world's largest lava fields and constitutes a major new frontier for oil and gas exploration. However the natural resources that lie beneath the sea in this Large Igneous Province (LIP) remain largely untapped. Unlike in purely sedimentary basins, traditional techniques employed for oil exploration, such as seismic imaging, are adversely affected in volcanic terrains due to layers of lava up to three kilometres thick. It is these lavas that seal off the oil and gas reservoirs.</p> <p>Since 2006, multidisciplinary research by the University of Aberdeen's StratLIP (Stratigraphic Evolution of Large Igneous Provinces) research group has formulated predictive models of reservoir development and distribution in order to facilitate hydrocarbon exploration and exploitation of LIPs. Led by Professor David Jolley, Chair in Geology (at Aberdeen since 2005), the academics have studied environmental system processes in large lava fields and mapped sediments between the lava flows to identify the location of oil and gas reservoirs. Through extensive fieldwork, the team mapped the stratigraphy of the North Atlantic Igneous Province (NAIP) and carried out subsea volcanological, lithological and palynological analysis (1,2) to identify stratigraphical hydrocarbon traps, informing applications by oil and gas companies for drilling licences within Faroese waters.</p> <p>Interdisciplinary research demonstrated the impact of large-scale volcanism on atmospheric forcing, plant ecosystem dynamics and eutrophication events (2, 3). By building a comprehensive picture of previous climate change in LIPs, Jolley and colleagues were able to identify the different climatic events that had occurred within specific regions of the lava field; for example, by studying the effects of a hypothermal event on plants within the ecosystem. This work allowed the research team to devise a predictive model of intra-volcanic reservoir distribution and contributed to greater understanding of the location of oil and gas reservoirs in the Rosebank field, located offshore northwest of the Shetland Islands, and Corona Ridge in the Faroe-Shetland Channel.</p> <p>Further research into spatial recognition and mapping of plant ecosystems within LIPs (2), allied to more traditional geophysics-based flowfield mapping techniques, underpinned major reinterpretations of the distribution of oil and gas reservoirs within the Rosebank and Cambo oil fields. Stratigraphical analysis revealed that the reservoir sands had come from the south, not the</p>

east as previously thought, and that reservoirs could be found within river valleys in the lava field itself. Jolley's analysis of the Cambo oil field showed that the site was higher in the drainage system than initially predicted. This led to the repositioning of the drilling well and fundamental changes to the mapping models used by Chevron, the energy company leading the exploitation of the field, to improve their accuracy. Studies of changing vegetation patterns identified the location of reservoir sands and where they are likely to extend to, thus guiding exploration companies in their future drilling activities and reducing the risk of costly but unproductive drilling.

3. References to the research

Key Publications in Refereed Journals:

1. Passey, S. & Jolley, D.W. 2009: "A revised lithostratigraphic nomenclature for the Faroe Islands Basalt Group, NE Atlantic Ocean." *Transaction of the Royal Society of Edinburgh, Earth and Environmental Science* 99, 127-158.
This reference contains a fundamental shift in the understanding of the eruptive and depositional history of the lava fields which host the hydrocarbon source rocks.
2. Jolley, D.W., Passey, S.R., Hole, M.J. & Millett, J. 2012. "Large scale magmatic pulses drive plant ecosystem dynamics." *Journal of the Geological Society, London*, 169, 703-711.
This breakthrough paper establishes the link between magma pulsing, sedimentary (reservoir) systems and spatial ecology.
3. Jolley, D.W., Widdowson, M., & Self, S. M. 2008. *Volcanogenic nutrient fluxes and plant ecosystems in Large Igneous Provinces. "An example from the Columbia River Basalt Group."* *Journal of the Geological Society, London* 165, 955-966.
A breakthrough paper demonstrating the range of, and links between ecological and geochemical trends in a lava field, providing an analogy for Rosebank/Camo reservoir modelling.
4. Jolley, D.W. Bell, B.R., Williamson, I.T. & Prince, I. 2009. "Syn-eruption vegetation dynamics, palaeosurfaces and structural controls on lava field vegetation: An example from the Palaeogene Staffa Formation, Mull Lava Field, Scotland." *Review of Palaeobotany and Palynology* 153, 19-33.
The principal publication defining the range of ecological gradients in a lava field defining some of the parameters used to constrain Rosebank and Cambo reservoirs.

Grant examples

1. Jolley D.W. & Passey S. Sediment transfer and drainage systems in the Late Paleocene – Early Eocene of the Faroe – Shetland Basin (2009-11, Sindri £246,556)
2. Jolley D.W. & Huuse, M. Lava sediment interaction in a nearshore environment: an analogue for offshore exploration (2009-11, Sindri £226,169).

4. Details of the impact

The StratLIP group's role in advancing the understanding of the stratigraphy of the north-east Atlantic has been integral to the exploration of oil and gas fields in the north-east Atlantic Ocean. The findings have informed every phase of the development process: licensing applications, planning of drilling programmes, drilling of wells and post-drill evaluation.

Leading energy companies Chevron and Statoil confirm (1, 2) that without Aberdeen's research, their joint development of the Rosebank oil and gas field – heralded by Chevron as "one of the last great resource areas for the UK" at 240 million barrels of oil equivalent – would not have been

Impact case study (REF3b)

possible. The Rosebank project, a joint venture between Chevron North Sea Ltd, Statoil (UK) Ltd, OMV (UK) Ltd and DONG Exploration and Production (UK) Ltd was approved for development by Chevron in July 2012. UK Energy Minister at the time, Charles Hendry, described the project as a “pioneer development” with the potential to substantially increase the UK’s proven oil reserves, and create more than a thousand jobs (3). Chevron’s own reservoir mapping model originally showed that the development of Rosebank was not economically viable. According to the Leading Geoscientist at Statoil, new data from Aberdeen suggested greater intra-reservoir sand connectivity than previously calculated, effectively reducing the element of risk in drilling for oil. They reran the reservoir model by inputting Aberdeen’s data and found that the number of producer wells required to commence production had fallen to nine from 15 at a saving of £600m (£100m per well). Ellis says: “*The greater confidence in reservoir connectivity ... increased the recovery factor from 25 per cent to 40 per cent, again having a significant increase on the reserve base and project profitability.*” In effect this 15 per cent increase proved the difference between the continuation and abandonment of the Rosebank exploration.

Aberdeen’s work on the Rosebank field had a direct impact on the development of neighbouring field Cambo, jointly operated by Chevron and Hess. The stratigraphic framework devised by StratLIP was applied during the drilling of an appraisal well and as a Chevron Geologist confirms (2), “*the decision to continue (with the project) was greatly influenced by the application of the framework*”. Ablard says an ecosystem model developed by Aberdeen for Cambo has been “*instrumental in informing reservoir models giving a clearer understanding of potential recoverable volumes*”. In other words StratLIP’s input has enabled Chevron to better identify the location of oil and gas deposits in the Cambo field, which contributed to a decision in November 2012 to drill the Cambo-5 oil well (4).

In the wider Northeast Atlantic, StratLIP has greatly increased the regional understanding of the relationship of the dominantly volcanic Flett Formation to that of the underlying marine sedimentary rocks of the Lamba and Vaila formations. This has given energy companies much greater confidence in pursuing deeper exploration targets than would be possible if they relied on seismic data alone. In particular, the stratigraphical and palaeoenvironmental context provided by StratLIP’s research has, according to Statoil (1), given the oil industry the confidence to drill deeper in areas of thick basalt lava cover. Statoil, with partners ExxonMobil and Atlantic Petroleum, began drilling its Brugdan II Well into a sub-basalt section offshore the Faroe Islands in June 2012. As the Leading Geoscientist at Statoil put it: “*The cost of a typical well drilled in thick basalt areas can be in excess of £100 million and therefore not undertaken lightly.*”

An example of the risk involved in deep-water drilling in frontier provinces came with the abandonment in 2011 of Chevron’s Lagavulin well, west of the Shetland Islands, which cost £170m to drill. Findings by Jolley regarding the geology of the wider region are informing Chevron’s explorations further afield, including more effective planning, to reduce the risk of a similar outcome in the future.

As well as benefitting the UK government’s efforts to revive the UK’s oil and gas industry, StratLIP’s research has enabled the Faroese government to maximise the economic potential of the oil and gas resources situated within its maritime boundaries. The SINDRI Group (5), set up by the Faroese government, comprises oil companies operating in the Faroese region. Its main objective is to carry out joint projects to explore oil and gas reservoirs in the Faroese continental shelf. Oil companies pay the Faroese government substantial fees for each well drilled. Reflecting Aberdeen’s influence in driving forward development of the NAIP, Sindri granted StratLIP a total of £792,579 in funding between 2008 and July 2013 (Grant examples 1, 2 above). The funding

decision in 2008 was covered by the Press and Journal and BBC Scotland News.

5. Sources to corroborate the impact

1. A Lead Geoscientist, Statoil UK Ltd, will corroborate the benefits and economic impact to Statoil with regard to their Rosebank North Atlantic field development, and the value of the underpinning research.
2. A Geologist at Chevron North Sea Ltd can corroborate the benefits and economic impact to Chevron with regard to their Cambo North Atlantic field development, and the value of the underpinning research.
3. *Article in Wall Street Journal dated 9th July 2012:*
<http://online.wsj.com/article/SB10001424052702304022004577516800838931944.html>
This is an independent media source verifying the economic value of Chevron's development, demonstrating the significance of the impact beyond the UK.
4. *Article in Shetland Times, dated 7th July 2012*
<http://www.shetlandtimes.co.uk/2012/11/07/chevron-given-go-ahead-for-west-of-shetland-drilling>
This is an independent media source verifying the economic value of Chevron's development, demonstrating the significance of the impact within the UK.
5. An Administration Coordinator at Sindri Group, can corroborate the impact of the underpinning research for international oil & gas exploration in fields beyond the UK.

Institution: University of Aberdeen**Unit of Assessment: 7 (Earth Systems and Environmental Sciences)****Title of case study: Stability of ice sheets****1. Summary of the impact**

This case study details the impact of current glaciological research at the University of Aberdeen on the Earth's polar ice sheets on practitioners and services in the non-academic science community, specifically the British Antarctic Survey (BAS) and European Space Agency (ESA). In addition, the research has informed public understanding of the stability of the polar ice caps under the influence of climate change. The beneficiaries of our research are professional scientists in Environmental and Earth Sciences working at BAS and ESA who have used our findings to constrain computer modelling of ice sheet dynamics and to calibrate and validate measurements of ice sheet mass change. We have been involved in major international collaborative field research on the Antarctic and Greenland Ice Sheets to better define the current basal and surface boundaries of the ice sheets and to improve the understanding of the sensitivity of the ice sheets' boundaries to climate change over a range of timescales.

2. Underpinning research

Glaciologists at the University of Aberdeen (UoA) have for over ten years undertaken field-based research on the Antarctic Ice Sheets (AIS) and the Greenland Ice Sheet (GrIS). Their published work has made an impact on the non-academic science community, in particular the British Antarctic Survey and the European Space Agency, by improving understanding of (i) the current surface and basal geometries and properties of the ice sheets, and (ii) the sensitivity of the surface and basal processes to climate change over a range of timescales. This work has informed, and continues to inform, the scientific basis for assessment of the threat posed by anthropogenic climate change on ice sheet mass balance and consequently on global sea level rise. Through press interest and public outreach their work has contributed to the improvement in public understanding of the issues and uncertainties associated with glacial polar science and the environmental impacts of climate change.

West Antarctic Ice Sheet

The West Antarctic Ice Sheet is bounded on three sides by ocean and is predominantly grounded below sea level. This geometry gives rise to complex and poorly understood physics that control the flow of ice from the interior to the oceans. To be reliable predictors of ice sheet stability, computer models require much better knowledge of the geometry and physical properties of the bed of glaciated catchments that drain to the ocean. To this end, **Bingham** (Lecturer 2009-2012; Senior Lecturer since 2013) undertook the first systematic over-snow radar and seismic surveys of the vast **Pine Island Glacier** (PIG), West Antarctica's most rapidly thinning region (1,2), with colleagues including post-doctoral researcher **Scott** (employed at Aberdeen 2004-2006). Bingham mapped new regions of basal topography and differentiated wet and dry basal sediments. He also analysed data from airborne radar surveys to infer past ice-flow dynamics. **Bingham** also undertook the first systematic geophysical data acquisition across Ferrigno Ice Stream, a key region of high surface velocity and ice mass discharge from the Bellingshausen Sea margin of West Antarctica. His field investigations and subsequent analyses revealed that a spatially distinct region of high glacier ice velocities is steered far into the interior of the ice sheet by the existence of a significant tectonic rift that underlies the ice (3). The work has brought into focus the importance of the long-term geological antecedent conditions in determining the sensitivity of contemporary ice sheets to marine forcings and provided an important contribution to Antarctic bed mapping in a previously unsurveyed area.

Greenland Ice Sheet

The European Space Agency's (ESA) CryoSat mission is the first satellite radar altimeter dedicated to measuring change in the Earth's land and marine ice masses. The mission aims to provide cm-scale accuracy in measurements of ice-sheet elevation change. An integral component of achieving this aim was a dedicated field measurement campaign to undertake validation experiments (CryoVex) to "ground truth" an airborne version of the satellite radar altimeter before the launch of the satellite itself. In 2004 and 2006 **Mair** (Lecturer 2002-2006, Senior Lecturer since 2006), post-doctoral researcher **Scott** and colleagues completed a range of geophysical field experiments along a transect of the GrlS. They quantified the amount of summer surface melt that subsequently refreezes in the snowpack, the impact of this on the derivation of ice sheet mass change from surface elevation change (4), and used this information to help develop improved methods for deriving ice sheet surface elevation measurements from radar measurements. They demonstrated that radar reflections from ice layers below the ice sheet surface can create a stronger signal than from the ice sheet surface (5); explained their cause, temporal and spatial variability; and highlighted potential for erroneous surface elevation change measurements by satellite radar altimeters where these phenomena are not accounted for (6).

3. References to the research

1. Smith, AM., Bentley, CR., **Bingham, RG.** & Jordan, TA. (2012). '*Rapid subglacial erosion beneath Pine Island Glacier, West Antarctica*'. Geophysical Research Letters, vol 39, pp. L12501. *One of several papers reporting key geophysical products from surveying of Pine Island Glacier that are being used in BAS ice-sheet modeling of the glacier's future.*
2. Fretwell, P.T. and 55 authors inc. **R.G. Bingham** (2012) *Bedmap2: improved ice bed, surface and thickness datasets for Antarctica*. The Cryosphere Discussions, 6, 4305-3361. *This paper reports on the construction of the Scientific Committee for Antarctic Research (SCAR) product BEDMAP2, with several Aberdeen-acquired-and-analysed surveys forming key inputs to the final product.*
3. **Bingham, R.G.**, Ferraccioli, F., King, E.C., Larter, R.D., Pritchard, H.D., Smith, A.M. & Vaughan, D.G. (2012). '*Inland thinning of West Antarctic Ice Sheet steered along subglacial rifts*'. Nature, 487, 468-471. *Providing a new subglacial topographic dataset in a previously unexplored area that has formed a direct input to BEDMAP2, this paper also formed the basis for raised public understanding of Antarctic ice loss through associated press reporting in 2012 (Funded by NERC-Antarctic Funding Initiative Collaborative Gearing Scheme Grant Ice flow into Eltaning Bay, Bellingshausen Sea, West Antarctica)*
4. Parry, V., Nienow, P., **Mair, D., Scott, J.**, Hubbard, B., Steffen, K. and Wingham, D. 2007. '*Investigations of meltwater refreezing and density variations in the snowpack and firn within the percolation zone of the Greenland Ice Sheet*'. Annals of Glaciology, 46, 61-68.
5. Scott, J.B.T., Nienow, P.W., **Mair, D.W.F.**, Parry, V., Morris, E.M., and Wingham, D.J. 2006. '*The importance of seasonal and annual layers in controlling backscatter to radar altimeters across the percolation zone of an ice sheet*', Geophysical Research Letters, **33**, L24502, doi: 10.1029/2006GL027974. (NERC-Consortium Grant "Validation and Provision of CryoSat Measurements of Fluctuations in the Earth's Land and Marine Ice Fluxes")
6. Scott, J.B.T., **Mair, D.W.F.**, Nienow, P.W., Parry V.L. and Morris. E.M. 2006. '*High frequency ground based radar measurements in the percolation zone of the Greenland Ice Sheet*'. Remote Sensing of Environment. **104**, 361-373 (NERC-Consortium Grant "Validation and Provision of CryoSat Measurements of Fluctuations in the Earth's Land and Marine Ice Fluxes").

4. Details of the impact

Our cryospheric research offers benefits to the non-academic scientific community and to the public, through improved understanding of the stability of polar ice sheets and via our contributions

to public debates and understanding of sea level change and climate change.

Non-academic scientific beneficiaries

Over the last decade, the findings of our research have been disseminated to the scientific community via several pathways, and have had direct impact on the work of non-academic scientific institutions. The scientific output from Antarctica (Bingham) is being used by the **British Antarctic Survey** to reduce the uncertainty surrounding ice sheet boundary conditions and processes, and to improve constraints on future model-based predictions of ice sheet response to climate change. The scientific output from the Greenland Ice Sheet (Mair) is currently still being used by the **European Space Agency** Cryosat programme to calibrate and validate satellite radar based ice sheet measurements models. Additionally, Mair had central input to the design of ESA's CryoVex field experiments. As a result, over the REF-reporting period Bingham has been invited, on the basis of his geophysical findings, to contribute to glaciology/Antarctic tectonics workshops at NASA (Washington D.C., February 2009) and the Polar Research Institute of China (Beijing, October 2010), and Mair was invited to participate in the ESA/NASA workshop on satellite ice sheet altimetry in Reykjavik in June 2009.

British Antarctic Survey (BAS)

Our acquisition, processing, analysis and provision to BAS of key ice-penetrating geophysical datasets across some of West Antarctica's most remote regions has contributed to greatly-reduced uncertainties in BAS's programme of numerically modelling the ice-sheet's future. BAS ice-sheet modelling activities over the last six years have been dedicated to providing greatly improved predictions of the ice-sheet's fate and contribution to global sea-level rise over the next 200 years, to be included in the Intergovernmental Panel on Climate Change's 5th Assessment Report (IPCC AR5, due 2014). A key deficiency of earlier generations of models was the dearth of key model-input data such as basic subglacial topography in some of West Antarctica's most rapidly diminishing regions. Since 2006, our multiple-month field campaigns across these areas have provided the key input datasets most required by BAS modellers to meet the IPCC AR5 goal. The radar and seismic data that we have collected have also been integral to the construction and 2013 release of the Scientific Committee for Antarctic Research (SCAR) product "BEDMAP2", a new digital map of subglacial topography that is central to a range of core activities conducted at BAS, including "whole ice-sheet" modelling, geological reconstructions and ice-core palaeoclimatic interpretations. The Science leader of the IceSheets programme at BAS confirmed: "[...] *the datasets you collected have assisted in filling a crucial data gap [...] and supported our ice sheet modelling activities[...] which in turn were prepared to support the upcoming assessment of the IPCC*" (1).

European Space Agency

Our early involvement with the ESA CryoSat Calibration and Validation experiments from 2004 to 2006 has contributed to the eventual success of CryoSat2 in mapping the elevation of the GrIS with unprecedented accuracy in April 2012. Our ground radar measurements were made at the same frequencies and wavelengths as the airborne radar equivalent of the CryoSat radar altimeter (ASIRAS) which flew across our transects directly over metallic corner reflectors which we erected and measured with differential GPS to determine precise elevations. From 2007 until the launch of CryoSat 2 in November 2010, ESA radar processing teams used our understanding of the temporal and spatial variations in the relative strength of natural surface and near-surface radar reflectors to help devise the most appropriate surface retracking algorithms and compared airborne and ground measurements of artificial corner reflector elevations to help determine absolute elevation accuracies. ESA also continue to use our accumulation and density measurements made across Greenland in 2004 and 2006 to characterise temporal and spatial covariance of annual

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accumulation across the ice sheet and to constrain near surface densification models that are used to convert the ongoing CryoSat2 mission's elevation and volume change measurements to mass change outputs. The head of the Campaign Section at the ESA has clarified: "*the main goal of the CryoSat mission [...] is to provide cm-scale accurate measurements of ice sheet elevation changes to determine the changes in the land and marine ice masses. Achieving this challenging goal requires the collection of independent measurements on the ground [...]. For this the European Space Agency relies strongly on co-operation with scientists such as Dr. Mair*". ESA confirm the importance of the research findings in contributing to their work: "*valuable information on surface melt and refreezing of the snowpack during the summer season [...] was and continues to be extremely useful both to better understand the nature of the CryoSat radar echos from the ice sheet, as well as transform ice sheet surface elevation measurements into ice sheet mass change*" (2).

Public Understanding of Science

Our research has also achieved significant wider societal impact. We have used radio, television, the internet and printed media to raise awareness of our work and explain the importance of polar science to different segments of the public. For example, **Bingham's** recent research on the influence of subglacial rifting on the diminishing West Antarctic Ice Sheet was reported in >200 international media outlets, including the BBC Website (3), BBC World and BBC Scotland Radio, Scientific American (4), Time Magazine and NERC Planet Earth Online. An explanatory video of the work was placed on YouTube and received 75,000 views in 3 days (5). **Bingham** has also appeared on Sky News (2009) and the BBC Website (2008) reporting on his research in West Antarctica (6). **Mair** has taken part in radio (BBC Scotland), TV (BBC, ABC) and newspaper interviews (Sunday Telegraph) both in the field and from the UK about his glacial research and its wider significance. In September 2012 **Bingham** and **Mair** organised, chaired and were panel members of a British Science Festival event, watched by an audience of over one hundred, presenting and debating the future of our polar regions.

5. Sources to corroborate the impact

1. Sources within the Science Leader Ice Sheets Programme, British Antarctic Survey will corroborate the contribution of the research to the wider British Antarctic Survey ice sheets programme, especially in providing data sets.
2. The Head of the Campaign Section, Directorate of Earth Observation Programmes, European Space Agency can corroborate the contribution of the research to the wider ESA CryoSat programme.
3. BBC News July 2012: <http://www.bbc.co.uk/news/science-environment-18959399>. *This source reports on the findings from research towards a public audience*
4. Scientific American 23 July 2012: <http://www.scientificamerican.com/article.cfm?id=scientists-uncover-grand-canyon-in-antarctica>. *This source, in a US publication, demonstrates the reach of interest in the research findings*
5. YouTube July 2012: <http://www.youtube.com/watch?v=VZd47qfsfuA>. *This source is a re-formatting, in a form accessible to the public, of the findings from research on the Antarctic Ice Sheet. It received 75,000 views in the first 3 days after it became available, coinciding also with the publication by UK and US media outlets.*
6. BBC News 24 February 2008: <http://news.bbc.co.uk/1/hi/sci/tech/7261171.stm>. *This source is an early report on public media of the results of research, concentrating specifically of the work of University of Aberdeen scientists.*

Institution: University of Aberdeen
Unit of Assessment: 7 (Earth Systems and Environmental Sciences)
Title of case study: Turbidites: Deep-water hydrocarbon reservoir prediction
<p>1. Summary of the impact</p> <p>This case study describes the economic impact to sections of the hydrocarbons industry resulting from research into deep water sediment transport and depositional processes. <i>turbidites.org</i> 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.</p>
<p>2. Underpinning research</p> <p>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.</p> <p>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 <i>turbidites.org</i>, 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.</p> <p>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</p>

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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*

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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

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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.