Institution: University of Aberdeen

Unit of Assessment: 7 (Earth Systems and Environmental Sciences)

Title of case study: Informing decision-making and training in subsurface industries

Period when the underpinning research was undertaken: 2008-2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Clare Bond	Reader	2010-present
Rob Butler	Professor	2008-present
Juan Alcalde	Research Fellow	2015-2018

Period when the claimed impact occurred: 2013-2018

Is this case study continued from a case study submitted in 2014? N

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

Seismic data are used globally by energy companies, and other subsurface industries, to explore for, develop and produce hydrocarbons, mine resources and store waste. These activities are costly and interpretation of seismic data underpins the decision-making processes. Aberdeen's Interpretation Uncertainty Group's research has enabled companies to generate improved interpretations of seismic datasets. Improved assessment of uncertainties ultimately leads to considerable cost-saving and mitigation against harmful environmental and economic outcomes. The companies have utilised the research to run training course for employees, as do recognised training consultants, leading to refined geological interpretation workflows and enhanced decision-making regarding subsurface uncertainties.

2. Underpinning research (indicative maximum 500 words)

Safe and economically viable management of the subsurface requires detailed knowledge of the geology. Seismic images, generated by recording sound waves that reflect-off geological boundaries underground, provide a fundamental source for generation of subsurface knowledge. The acquisition and processing of seismic data is time-consuming and costly (c. Total spent USD163,000,000 acquiring wide-angle 3D seismic data for a single block, offshore Angola in 2013/14[1]), with exploratory wells (used to aid interpretation of seismic imagery) also costing upwards of USD 30,000,000 million per offshore well. Shell, one of the largest hydrocarbon producers in the world, spent approximately USD13,000,000,000 on exploration between 2015 and 2019. Despite the cost of acquisition, seismic images are used extensively by both extractive (e.g. hydrocarbons, water, minerals) and subsurface storage (e.g. CO_2 and radioactive material) industries as a key source of geological information.

Aberdeen's Interpretation Uncertainty Group (led by Clare Bond) have established a global reputation for applied research into the uncertainties associated with interpretation of seismic images. Outputs generated by the Interpretation Uncertainty Group include joint/academic industry papers [1, 3, 4], invited webinars and seminars [S4], input into industry continued professional development (CPD) training courses [S1, S2] and knowledge exchange sessions [S6]. These research outputs have underpinned key outcomes for industry and policy makers in both energy and underground waste storage industries, reflected by uptake of the research recommendations for workflows and training by global energy companies including Schlumberger, BP, Shell, Equinor and Wintershall Dea.

[1] https://www.ep.total.com/en/expertise/exploration/subsalt-imaging-optimized-design-wats-acquisition-method

Research by the Interpretation Uncertainty Group aims to mitigate against the negative outcomes brought about by interpretational uncertainty across a range of subsurface industry sectors (e.g. nuclear waste disposal, hydrocarbon extraction, CO_2 storage), which is an area of great expense to the industry. Bond has led research on interpretational uncertainty internationally, integrating techniques and theories derived in the social, psychological and statistical sciences with Earth science. In doing so, she has developed a new interdisciplinary approach to evaluating subsurface interpretation. Since joining Aberdeen in 2010, Bond has built a group working on interpretational uncertainty of subsurface data that engages effectively with industry and policy stakeholders. Research methods include testing approaches of multiple cohorts to interpretation of seismic data [1, 2], assessing differences in approach and techniques [1, 2, 3, 4], and testing the impact of creative space on interpretation and reasoning [1, 5, 6].

Key Research findings:

Collaborative research and published outputs by the Interpretation Uncertainty Group at the University of Aberdeen has demonstrated that:

- Several factors may influence interpretation outcome. These include interpreter biases and heuristics [2, 6], background, education and training experience [3, 5, 6]
- Data quality impacts interpretation uncertainty and the prediction of features such as faults in the subsurface [1, 4].
- Explicit use of reasoning techniques is critical in ensuring a geologically robust interpretation [5]. Recommended strategies include consideration of multiple scenarios, sketching geological diagrams and considering geological evolution and setting [1, 2, 4, 5, 6].
- Work with industry demonstrates the impact on reservoir volumetric predictions as a consequence of interpretational uncertainty and consequently the range in economic risk [3, 4].

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

References (citations via Scopus):

[1] **Alcalde, J**., **Bond, C.E**., Johnson, G., Ellis, J.F. and **Butler, R.W**., 2017. Impact of seismic image quality on fault interpretation uncertainty. *GSA Today*, doi: https://doi.org/10.1130/GSATG282A.1, 13 citations.

[2] Macrae, E.J., **Bond, C.E**., Shipton, Z.K. and Lunn, R.J., 2016. Increasing the quality of seismic interpretation. *Interpretation*, *4*(3), pp. 395-402, doi: https://doi.org/10.1190/INT-2015-0218.1, 14 citations.

[3] Richards, F.L., Richardson, N.J., **Bond, C.E**. and Cowgill, M., 2015. Interpretational variability of structural traps: implications for exploration risk and volume uncertainty. *Geological Society, London, Special Publications*, *421*, pp. 7-27, doi: https://doi.org/10.1144/SP421.13, 14 citations

[4] **Bond, C.E**., Johnson, G. and Ellis, J.F., 2015. Structural model creation: the impact of data type and creative space on geological reasoning and interpretation. *Geological Society, London, Special Publications*, *421 (1)*, pp. 83-97, doi: https://doi.org/10.1144/SP421.4, 19 citations.

[5] Torvela, T. and **Bond, C.E**., 2011. Do experts use idealised structural models? Insights from a deepwater fold–thrust belt. *Journal of Structural Geology*, *33*(1), pp. 51-58, doi: https://doi.org/10.1016/j.jsg.2010.10.002, 19 citations.

[6] **Bond, C.E**., Philo, C. and Shipton, Z.K., 2011. When There isn't a Right Answer: Interpretation and reasoning, key skills for twenty-first century geoscience. *International Journal of Science Education*, *33*(5), pp. 629-652, doi: https://doi.org/10.1080/09500691003660364, 53 citations.

Grants:

[i] 2018-2019. Geocognition - Visualising and Interpreting Sub-Surface Image Data. Royal Society of Edinburgh, research sabbatical grant (GBP62,691).
[ii] 2018-2019. Research contract with Nagra (Swiss Nuclear Waste Body) on structural interpretation uncertainty (GBP11,000)
[iii] 2017-2021. Evaluating consistency in complex structural models in areas of high interpretation uncertainty. Total (GBP108,000).
[iv] 2014-2015. Improving Interpretation Outcomes: quantifying biases and designing workflows for better seismic interpretation. NERC - NE/M007251/1 (GBP93,215).
[v] 2013-2017. Uncertainty in expert interpretation of geological cross-sections and its propagation into 3D geological framework models. BGS-BUFI NERC algorithm and University of Aberdeen College of Physical Sciences, PhD studentship (GBP73,000)
[vi] 2011-2013. Learning from experts - the interpretation of seismic datasets. Scottish Higher Education Academy (GBP10,705)

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

Unsuccessful exploration based on seismic interpretation can cost a energy company USD5,000,000 to USD20,000,000 per exploration site, this added to the cost of acquisition and processing of seismic data (c. USD25,000 per km^2 [S1]) can incur substantial losses for the industry. Interpretation of seismic image data is not straightforward and interpretations are subject to considerable uncertainty, meaning that geological interpretations of seismic image data cannot be validated prior to exploratory drilling. This has significant cost implications due to the expense associated with drilling wells.

Seismic interpretations are sensitive to both human factors (e.g. data processing decisions, interpretation bias) and non-human factors (e.g. rock velocities). Interpretational uncertainty relating to subsurface projects may significantly impact the economic viability and the expected integrity of exploratory drilling campaigns and the viability of hazardous waste storage sites, therefore there is considerable interest in new methods to increase certainty. Full consideration of the risks with misinterpretation in geological interpretation of seismic data (including management strategies and potential impacts) is thus critical to mitigate against negative environmental, economic and societal outcomes.

(a) Aberdeen research results used to develop in-house training courses at energy and subsurface service companies.

Training based on the Group's research findings has been shown to improve understanding and reliability of interpretation among companies' employees, leading to better decision-making in immediate projects and ultimately through careers, about interpretation of subsurface uncertainties. This allows companies to build in-house expertise and more readily rely upon human-led assessment to improve risk mitigation. As a consultant, Bond has had direct input into the design and formulation of training materials for Wintershall Dea [S1] and has input into BP and Schlumberger training content through webinars designed to supplement internal training offerings [S4]. At Wintershall Dea, Bond's research underpinned the development of a tool for seismic interpreters to improve their awareness of bias (from 2015-present). This tool lead "…*to a better uncertainty management along the […] life cycle of Exploration, Development and Production projects*." and is now available to 400 professionals within the structural geology and seismic interpreter community of practice [S1]. Bond's research has been incorporated into a wide range of training materials delivered to industry professionals in the energy sector. This includes continued professional development courses delivered with major energy companies such as Shell, ConocoPhillips and BP, which are three of the seven largest energy companies in the world, as well as with Equinor and Wintershall Dea [S1, S3, S4, S5], and via training courses provided to energy companies by external contractors and consultants [S2, S5, S6].

Principal Structural Geologist at ConocoPhillips who previously delivered training based on Bond's research to 400 geoscientists has stated:

"*We have evidence that this training […] benefits seismic interpreters. Many of these steps are now a formal requirement in many oil companies during technical review stages and as such*

exposing employees to Dr Bond's research both improves the quality of individuals' work and provides a set of recommendations for meeting technical review requirements." [extract from testimonial, S2]. Development of employees' seismic interpretation skills leads to direct economic benefit for energy companies [S1, S2, S5] through improved geological interpretation and greater leverage of seismic data since 2014 [S1].

A Senior Structural Geologist at Shell has corroborated that, "*Dr Bond's work provides specific guidelines for improving seismic interpretation and mitigating against the negative effects of conceptual bias. This work has allowed us to tailor and focus our training material, and by doing so, improve the technical capabilities of our geoscientists.*" [Extract from testimonial, S3]

(b) Quality control, evaluation and technical review – petroleum, geological storage of waste, mineral exploration

Results from the Interpretation Uncertainty Group at the University of Aberdeen are increasingly used by the energy industry to better constrain geological uncertainties in the subsurface. Consultants and technical advisors within the sector have used this research to aid technical review of subsurface interpretation within large energy companies to reduce the uncertainties associated with exploratory drilling campaigns [S5, S6]. Bond's expertise has led to contracts with BP, Total [iii] and ConocoPhillips and attracted significant internal investment in the development of new tools and techniques at Wintershall Dea to assess the quality and consistency of subsurface interpretations and to further develop workflows for constraining subsurface uncertainty [S1].

The hazardous waste storage industry both in the UK and in Europe. Nagra (Swiss Nuclear Waste Body) has funded Bond's research into storage site selection through consultancy services [ii] and input into policy development working with the British Geological Survey and Radioactive Waste Management on managing geological uncertainty in the managing radioactive waste safely process. Finally, Bond and her groups' research has been used in the mineral exploration industry to aid interpretation and reduce uncertainties around the occurrence and estimated volumes of reserves in the subsurface [S7].

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

[S1] Testimonial from Head of Reservoir Management, Wintershall Dea, corroborates Bond's input into the design and formulation of training materials for Wintershall Dea and the value of CPD courses
[S2] Testimonial from a Senior Associate, Rose & Associates (LLP) (risk assessment experts), corroborates the development of employees' seismic interpretation skills and direct economic benefit for energy companies
[S3] Testimonial from a Senior Structural Geologist, Shell, corroborates that the research has underpinned guidelines for improving seismic interpretation and mitigating against the negative effects of conceptual bias
[S4] Testimonial from a Senior Structural Geologist and Petroleum Systems Analyst, Schlumberger: corroborates Bond's input to Schlumberger training content through webinars
[S5] CEO and Chief Scientist at GeoStructure (LLC) testimonial, corroborates that Bond's research has been used to aid technical review of subsurface interpretation within large energy companies
[S6] Testimonial from Geophysicist, corroborates that Bond's research has reduced the uncertainties associated with exploratory drilling campaigns
[S7] Introduction to the special issue on geophysics applied to mineral exploration (https://doi.org/10.1139/cjes-2018-0314)