Impact case study template (REF3b)

Title of case study: Quantifying the risk of CO_2 leakage from Carbon Capture and Storage Sites

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

Geological storage of CO_2 requires prediction of the fate of stored CO_2 for ~ 10,000 years after injection, a period much longer than can be observed in injection experiments or modelled. The only way to directly observe the behaviour of CO_2 in crustal reservoirs over such time periods is to study accumulations of natural CO_2. This case study developed from research undertaken in the Department of Earth Sciences by Bickle between 2006 and 2011 on one such natural accumulation at Green River, Utah, USA. As a result of this research, ***Shell Global Solutions International BV, identified Green River as a location where they could evaluate the long-term response of caprocks to CO_2 accumulations. In 2011 they commenced a major drilling and research program to recover and study caprock, reservoir rocks and fluids. The data we have generated from this work is being used to evaluate large-scale CCS projects including the proposed Goldeneye project in the UK North Sea***.

2. Underpinning research (indicative maximum 500 words)

The key research and insights which have led to the impact and commercial investment described have been underpinned by Bickle's research since the 1980's into the modelling of fluid movement in rocks, in particular the development of methods to infer past fluid movements in crustal settings using natural geological examples.

An important step in this research was the modelling of CO_2 degassing from Himalayan hot springs in the early 2000s (published in 2008). This led onto work, which commenced in 2006, on the natural CO_2 system at Green River, Utah. Our work on Green River entailed careful documentation and interpretation of all the geological aspects that were available for study at the surface; these included fluids sampled from the CO_2 geysers as well as exhumed outcrop which had previously held similar CO_2 reservoirs. A key paper on the Green River system, published in 2009, demonstrated that it was possible to:

a) recover both the nature and rates of the fluid-mineral reactions in the underlying CO_2-charged reservoir by sampling, analysing and modelling the fluid compositions of cold CO_2 geysers sampled at surface;
b) show that reaction rate was critically dependent on the proximity of the fluids to chemical equilibrium with the reservoir minerals.

This and other work on the natural CO_2 system gave the Cambridge group an international reputation for research on natural analogues for geological carbon storage. Funding for our CCS research came from a NERC national consortium CCS grant in 2005, a Marie Curie Training network (2006-2010) and a £3.2 million NERC consortium grant (2008-2015), led by Cambridge.

The work was brought to the attention of Shell Global Solutions International BV as a result of a presentation of our research at a meeting of our Industrial Associates Scheme in 2009 (see our impact template for information about this scheme) attended by key company employees. This led to their subsequent invitation to join an academic consortium researching geological analogues for CO_2 storage. Shell recognised that available studies of the caprocks overlying geological CO_2 reservoirs were totally inadequate for addressing the key questions of long-term reservoir integrity. On the basis of our earlier research, as well as a review and a field visit led by Cambridge, Shell chose the Utah site for a drill hole to sample caprock.

The drilling was carried out by DOSECC, the US continental drilling facility, and had 100% core recovery through the critical caprock and reservoir intervals. Fluid sampling was carried out by Cambridge and led to the successful recovery of samples at formation pressure enabling the critical pH and dissolved CO_2 concentration measurements to be carried out at pressure, the first such measurements in a drill hole to study geological carbon storage.

Members of the group working on this project and acting as co-authors on publications have included: Professor Bickle, (Cambridge 1983-present and Professor of Tectonics since 2000), Dr Holland (Cambridge 1979-present, Reader in Petrology since 2001), Dr Galy (Cambridge 2000-present, University Senior Lecturer since 2007), and Research Associates Dr Chapman (Cambridge 1984-present), Dr Becker (Cambridge 2001-2007), Dr Kampman (Cambridge 2006-present) and Dr Dubacq (Cambridge 2010-2012). Dr Assayag (Cambridge 2008-2009 as Marie Curie Experienced Researcher) was part of the research group as were two young researchers, Wigley and Nicholl).

External Collaborators include:
Prof Ballentine (of Manchester University, now at Oxford, who has carried out noble gas geochemistry), Dr Sherwood Lollar (University of Toronto who has carried out stable isotope geochemistry), Prof Ellam (SUERC, East Kilbride who carried out U-series dating), Prof Shipton (Strathclyde), and Dr Burnside (Edinburgh) who have been involved with the U-series dating.

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

Those which best indicate the quality of the underpinning research are indicated (*), Cambridge co-authors are shown in bold.

1/ **Becker, J. A., Bickle, M. J., Galy, A.,** and **Holland, T. J. B.**, 2008, Himalayan metamorphic CO_2 fluxes: Quantitative constraints from hydrothermal springs: Earth and Planetary Science Letters, v. 265, p. 616–629, doi:10.1016/j.epsl.2007.10.046

2/ **Bickle, M. J.**, 2009, Geological carbon storage: Nature Geoscience, v. 2, no. 12, p. 815-818, doi:10.1038/ngeo687.

3/ *** Kampman, N., Bickle, M., Becker, J., Assayag, N., and Chapman, H.**, 2009, Feldspar dissolution kinetics and Gibbs free energy dependence in a CO_2-enriched groundwater system, Green River, Utah: Earth and Planetary Science Letters, v. 284, no. 3-4, p. 473-488, doi:10.1016/j.epsl.2009.05.013.

4/ *** Dubacq, B., Bickle, M. J., Wigley, M., Kampman, N.**, Ballentine, C. J., and Sherwood Lollar, B., 2012, Noble gas and Carbon isotopic evidence for CO_2-driven silicate dissolution in a recent natural CO_2 field: Earth and Planetary Science Letters, v. 341–344, p. 10–19, doi:10.1016/j.epsl.2012.05.040.

5/ *** Kampman, N**., Burnside, N. M., Shipton, Z. K., **Chapman, H. J., Nicholl, J. A.**, Ellam, R. M., and **Bickle, M. J.**, 2012, Pulses of carbon dioxide emissions from intracrustal faults following climatic warming: Nature Geoscience, v. 5, p. 352-358, doi:10.1038/ngeo1451.

6/ **Wigley, M., Bickle, M., Kampman, N., and Dubacq, B.**, 2012, Fluid-Mineral Reactions in an Ancient CO_2 Reservoir, Green River, Utah.: Geology, v. 40, p. 555-558, doi: 10.1130/G32946.1.

Peer reviewed Grants:

- 2005-2008: NERC, 'The UK Carbon Capture and Storage Consortium' (£130,000 to Cambridge).
- 2006-2010: EU Marie Curie Training Network 'GRASP', (£213,673 to Cambridge).
- 2008-2013: NERC Consortium Grant led by Cambridge: 'Predicting the fate of CO_2 in geological reservoirs for modelling geological carbon storage'. (£2,957,549 total Cambridge, Manchester, Leeds, BGS; £901,212 to Cambridge).
- 2012-2015: DECC "£20 million Innovation grant": 'The Long Term Performance of Geological Seals to Carbon Storage'. (£735,533 total Cambridge, Manchester, BGS, £401,000 to Cambridge).

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

The main impact of this research has been to enable a multi-national oil company (Shell) to ***apply evidence-based research results to the major problem of predicting the long-term integrity of geological storage sites***.

Our detailed and ground breaking research on the Green River site clearly demonstrated to Shell the value of research on a geological analogue for CO_2 storage and was critical in establishing the site's suitability for extensive investment. Shell Global Solutions International reallocated internal budgets to fund work on the Green River site and to redeploy company scientific staff to work on the project. Their commercial investments to develop and research this bore-hole site, providing them with a geological analogue for CO_2 storage, have already amounted to direct expenditure of over £1M, including £330k on the drilling and £750k on associated research. The work has allowed a new and improved assessment for use in the evaluation of risk in storage sites. In particular, ***the results of the research have been used to test and verify Shell's in-house reactive-transport modelling codes which have increased understanding of long-term CO_2 plume migration e.g. for storage in the Goldeneye field from the Peterhead project being assessed in the UK North Sea as part of the DECC-funded £1 billion CCS Commercialisation Competition.***

The unquantified risks of ensuring that '*that the stored CO_2 will be completely and permanently contained*' (DIRECTIVE 2009/31/EC) have been previously cited as key obstacles to implementation of geological carbon storage. The costs of such risks include the significantly enhanced insurance premiums against leakage from storage, a high cost/low risk event, the costs of mitigating such leaks, as well as public opposition, engendered by the concern that the CO_2 stores may leak. All the major reports on implementing CCS published in the UK during 2011 and 2012 identify security of storage including caprock (geological seal) behaviour as a key uncertainty which should be a high priority for research. The DECC CCS Roadmap, 20122 lists '*Improve understanding of geological seal integrity and subsurface CO_2 behaviour*' as a high priority under R&D needs for storage. The APGTF Report, 20117 (Table 4) cites caprock integrity as a high priority for immediate research. The FEED Report (20118 ,Table 7.1.4-2), the most authoritative assessment of a commercial storage site to date, lists '*post-closure consent uncertainties*' as risk No. 4, '*adverse public reaction*' as risk No 9 and '*migration of CO_2 from storage site*' as risk No. 17, in the list of the top 50 Post-FEED risks. Each of these depend on demonstration of caprock and seal integrities. The outcomes of the FEED report are particularly important as this establishes that the long term risks were one of the causes of the failure of the first DECC £1 billion CCS program.

The eventual importance of carbon capture and storage to the UK economy has been estimated at £42 billion a year by 2050 (DECC interim report '*The potential for reducing the costs of CCS in the UK'*, DECC, November 2012). Shell now leads one of the two proposals for major government-subsidised storage schemes currently being evaluated in the UK under ***DECC's £1 billion CCS Commercialisation Competition***. ***Our work on caprock integrity is a fundamental element in the risk assessments necessary for this scheme to go ahead*** and these new and improved methods of risk assessment and management have been crucial to ensuring the mitigation of potential future losses.

The Manager for CO_2 Storage Technologies at Shell Global Solutions International will verify that *"the extensive field and laboratory work on natural CO_2 analogues in Utah, together with an advanced process understanding, has led to the decision by Shell management to invest into drilling a research well into the CO_2-charged formations in Green River"* and that the data generated "*will be used to test and verify in-house modelling codes*" for industrial scale CCS operation. He will also corroborate the level of the company's financial investment.

The initial dissemination of our research, which impacted on Shell, was a presentation at the Department of Earth Sciences in Cambridge to the Earth Sciences Industrial Associates at our annual meeting. This was followed by several meetings and presentations to Shell Global Solutions International BV in Rijswijk, the Netherlands.

A further impact of this research is the contribution to the UK industrial sector of an on-going, regular supply of highly trained post-doctoral students and researchers. Three of the post-doctoral researchers are now either employed by major oil companies (Becker, Exxon) or have permanent academic research positions, in the UK (Kampman) and France (Dubacq).

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

The Manager for CO_2 Storage Technologies at Shell Global Solutions International.