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Sleipner CO_2 securely stored deep beneath seabed, in spite of unexpected Hugin fracture discovery

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Summary

*General readers of Nature may now think that the proposition to store carbon dioxide in deep geological strata is doomed to fail (*Monastersky 2013*). This is far from the case, as a more balanced review could easily have pointed out. It is now important to provide an alternative perspective, based on published information, that geological storage of CO_2 by deep injection for CCS is both sufficiently secure, and knowable in its environmental impacts. Furthermore, research has shown that there is good support from many parts of the public, although qualified, for CCS as an essential part of a response to the threat of global climate change and ocean acidification.*

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There is definitely an essential role for journalistic media to challenge CCS developers to explain and to justify their proposition. However, the Monastersky news review seeks to link spatially disconnected observations as cause and inevitable consequence, with no analysis of the evidence, or the feasibility. The ECO_2 project has attempted to conflate a seabed fracture seeping shallow CH_4 with future leakage of CO_2 from the Sleipner project deep storage site 25km distant. This is not the first sensationalist news comment from the ECO_2 project (Reitz 2012), but we are still waiting, several years after "discovery", for the peer-reviewed evidence to demonstrate the implied causality. The framing of these recent assertions needs to be formally challenged as a science process.

The Sleipner project examined here is the first purpose-engineered sub-sea geological CO_2 storage site in the world. Commencing in 1996, the Norwegian oil company Statoil has injected about 1 million tons of CO_2 per year, driven by the commercial imperative to avoid offshore carbon taxes combined with the ambition to behave in a more sustainable way.

The progress of this injection has been closely monitored by eight seismic reflection surveys, at approximately 2 year intervals. These high resolution records clearly show that CO_2 is being retained within the intended sandstone formation, with no sign of leakage (Chadwick et al 2011). The ascent and lateral dispersion of this CO_2 plume can be accurately modelled and mass-balanced (Cavanagh & Haszeldine 2014), demonstrating that CO_2 security is achieved and understood.

The ECO_2 project has obtained interesting and high resolution images of a fracture, open at the seabed, emitting small volume seeps of water and dissolved gases - which is not unusual in hydrocarbon provinces, (Judd and Hovland 2009). The fracture is observed on 1996 seismic reflection surveys for region around the Sleipner oilfield (Furre et al 2013), and so pre-dates engineered CO_2 injection. The feature was discovered separately in 2011 by a University of Bergen cruise, which named this the "Hugin Fracture"; that was visited twice more in 2012 by the ECO_2 project to obtain high resolution sonar images (Reitz 2012). Published images show the Hugin Fracture is about 5m wide and 3.5km long, as a zig-zag of ENE and NW linear subsets (Baumberger 2013).

However, post-glacial fractures or faulting are not particularly new, and can have several causes. Post glacial ice sheet unloading, stress relief and rebound, forms fault scarps onshore (Lundqvist & Lagerback 1976). Additionally, seabed subsidence is well documented due to hydrocarbon extraction (Mes 1990), as are linear fissures and chains of sea bed pockmarks due to dewatering of deeper sands or ascent of deep gas (Judd and Hovland 2009). In this case (Furre et al 2013), the Hugin

Fracture overlies the edge of a shallow buried sub-glacial tunnel valley, which is likely to be partially filled with sand, and contains shallow methane. The fracture may have formed as a compaction drape over more resistant sand.

It is therefore not surprising that the Hugin Fracture seeps fresh water and biogenic methane of shallow provenance (Reitz 2012); this is what would be expected. No CO_2 from injection at Sleipner has been detected. Traces of thermogenic (deeper) methane are stated to be present (Schaps 2012), although these are common around this part of the North Sea (Heggland 1997). The overall seepage is tiny, about 1 tonne of gas per year (Retiz 2012). Methane can be derived, through geological time, vertically or laterally from beneath the Utsira CO_2 storage reservoir, migrating vertically, then laterally through a complex spaghetti of glacial tunnel valley conduits. Clear fingerprinting of tracer gases could assist, but the identification of specific methane sources is elusive. Consequently the article title and graphic (Monastersky 2013 Fig 1) juxtaposing stored CO_2 and fracture leakage, is entirely misleading.

ECO_2 have specifically conflated the discovery of a seabed fracture with the possibility of leakage from the Utsira Sand CO_2 store for the Sleipner project. We consider that is rather disingenuous. Even though disclaimers are written into the article, the subliminal suggestion of leakage is being made, to the point of claims that are neither supported nor quantified: *"We are saying it is very likely some thing will come out in the end,"* says Klaus Wallmann, ECO_2 coordinator.

However ECO_2 provide no depth profile beneath the fracture, indicating the downwards extent, which is what we would like to see, to support assertions of connectivity and potential leakage. Additional information might include chemical analyses of emitted gases, and especially their isotopic signatures of H, C, O and fingerprints of trace noble gases, which are diagnostic of specific CH_4 or CO_2 origins (Gilfillan et al 2011). The geological setting is important to remember: the Utsira storage reservoir is overlain by primary seal mudrock from seabed to 800 mbsl, so there is still 550 m of mudrock sealing between the engineered CO_2 store and the supposed base of the Hugin Fracture at 150 mbsl. In other regions of the North Sea, older and more compacted mudrocks have clearly retained natural CO_2 accumulations for tens of millions of years (Lu et al 2009). That is much longer than the thousands of years required here for the purpose of carbon abatement. We would like to see a much better assessment of why one fracture of limited depth, far distant from the well-known CO_2 plume, is expected to be a problem, when it can be seen that the huge additional over-engineering of the mudrock topseal above Utsira Sand is, according to all the evidence to date, adequately retaining all CO_2. The story can readily be spun in the opposite direction: viz "CO_2 securely stored in spite of unexpected discovery". This indicates an unbalance in the way that the ECO_2 findings are reported. The ECO_2 hypotheses are highly speculative, and an interpretation is offered, but is unsupported by data. What is required is an academically balanced and impartial discussion.

The short discussion about vertical chimneys and pipes (Monastersky 2013), which could act as conduits for rapid gas or water escape through sediments overlying the Utsira sand CO_2 reservoir, is also very old news (Heggland 1997, Zweigel 2000, Judd & Hovland 2009). To bring something additional, ECO_2 could be looking to demonstrate that vertical fluid chimneys from the Utsira CO_2 reservoir are active, rather than dormant, and link CH_4 or CO_2 migration pathways to seabed features which currently seep. These are potentially much greater potential conduits for vertical CO_2 movement than the Hugin Fracture singularity. Fluid chimneys around the Sleipner site were recognized before injection started (Heggland 1997, Zweigel 2000), and sequential surveys during CO_2 injection enable confident statements to be made that there is no change in gas above the CO_2 reservoir. This demonstrates the value of baseline data and appropriate monitoring.

The article then correctly states that even if CO_2 leaks, it does not seem to be a problem, and finally drifts off into vague economic speculation without any clear relevance or conclusion. What the focus should be, is that more than 60% of injected CO_2 is inevitably trapped as small bubbles in sediment pores by residual saturation (Goater et al 2013) and cannot leak. The other 40% of CO_2 is structurally trapped far away from the Hugin Fracture. Even if leakage occurred, this CO_2 could migrate for only short distances, as it rapidly dissolves by interaction with subsurface porewater; this has been quantified by geochemical studies of natural CO_2 accumulations (Gilfillan et al 2009). Even if CO_2 does leak to the surface (or seabed), then on-land it is dispersed by wind, such that the effects on human health are minimal (Roberts et al 2011). On the North Sea shelf, subsea CO_2 leakage would be dispersed by ocean currents, such that direct local environmental impacts are modelled to be insignificant (Blackford et al 2009).

Monastersky (2013) chooses to quote that that any leakage *"would be a disaster for public opinion".* A deeper dive into the evidence, provided by social science researchers on the same ECO_2 project (Mabon et al 2014), suggests that leakage – whilst of course undesirable – need not in itself be a show-stopper for the geological storage of CO_2. Many members of the public do understand that environmental systems are complex and that scientists and engineers do not know everything. What publics want to see is not a reassurance that a site will *not* leak, rather that adequate monitoring, control and remediation procedures are in place *should* any leak be discovered (Brunsting et al, 2012; Mabon et al, 2014). Indeed, attempts to convince publics that a site will *never* leak can induce skepticism, and may even reduce public support for CO_2 storage if an impression is created that scientists and/or developers have given insufficient attention to the possibility of an unexpected scenario occurring (Howell et al, 2014).

Furthermore, although it is true that offshore CO_2 storage removes some of the factors that can drive public opposition to CCS (van Noorden 2010) – effects on real estate prices, perceived immediate risks to human health – it is important to caution against over-stating the claim in Monastersky (2013) that offshore CCS will be 'easier' in terms of public acceptability. Many drivers of public perception, such as place-attachment and perceptions of fairness, do not correspond easily to land-sea boundaries. To say that offshore CO_2 storage is always going to be 'easier' in terms of public acceptability thus flattens the very complex, dynamic and contingent nature of public perceptions of energy infrastructure.

Prudent, stage-by-stage testing (as opposed to excessive precaution which means that nothing is ever achieved) is what is needed. Then, as more is learned about the risks, and how they can be managed, the endeavour can be scaled-up. For leakage of CO_2 from engineered storage to have any effect on stimulating climate warming, then leakage would need to be at the scale of a percentage a year or greater (Teng & Tondeur 2007, Stone et al 2009); that requires such a large number of mistakes to occur at a majority of CO_2 storage sites that the proposition becomes unfeasible. The Hugin Fracture, seeping at 1 tonne/day (Reitz 2012) falls well below that threshold. As a long-term risk, geological CO_2 storage will out-perform most types of carbon mitigation, such as forestry.

In summary, we find that Monastersky (2013) takes an unduly negative view of the Sleipner CO_2 storage experiment, and the quoted researchers offer a mixture of alarmism and innuendo. A seabed fracture has been imaged by a novel technique, and forms one of many fluid conduits beneath the shallow North Sea. There is no evidence of methane movement in the overburden, or unplanned CO_2 migration from the reservoir, during the Sleipner CO_2 storage project history. The multiple barriers to CO_2 leakage – residual saturation in the reservoir, thick and multiple seal rocks, dissolution in overburden porewaters, laterally extensive migration dispersion in overburden tunnel valleys, and lack of environmental impact modelled for CO_2 at the seabed, all provide good reasons for public confidence. The abundance of baseline and monitoring data, also give confidence that irregularities can be detected, and solved, long before events become problems. Many things are not perfectly explained. Many things could go wrong. But nothing has. Therefore, it is very encouraging that the immature science, which pragmatically selected the Utsira sand reservoir as storage for the Sleipner project, has proven robust. The subsequent 18 years of global endeavor gives high confidence in the ability of geo-science and engineering systems to identify good CO_2 storage, to operate that safely, and monitor secure retention (Scott et al 2012). We remain skeptical of science by press-release, and wait to evaluate the publication of convincing data on the Hugin Fracture; ECO_2 have to put up or shut up; the Sleipner project seems to be storing CO_2 securely in the Utsira reservoir.

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