Institution: University of Oxford

Unit of Assessment: 7 – Earth Systems and Environmental Sciences

Title of case study: Reducing the risk of top seal failure and leakage from hydrocarbon accumulations or carbon dioxide storage sites

Period when the underpinning research was undertaken: 2012-2020

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:
Prof. Joseph Cartwright	Professor of Earth Sciences	August 2012-present
Dr Martino Foschi	Research Fellow	2013-present
Dr Claudia Bertoni	Research Fellow	2013-2018
Dr Christopher Kirkham	Post-doctoral research assistant	2017-present

Period when the claimed impact occurred: August 2013 – July 2020

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

1. Summary of the impact

Pre-drill predictions of top seal integrity are fundamental aspects of petroleum exploration and subsurface sequestration of CO_2; incorrect predictions can result in dry holes which cost GBP10,000,000s per well. Traditionally companies have used core and wellbore data to estimate oil and gas column heights that could be supported without leakage. The Cartwright research group has shown how the use of 3D seismic data can be used to better assess leakage bypass systems. The Oxford work has established and quantified the role of seal bypass systems in top seal failure and secondary hydrocarbon migration. This entailed characterising their diagnostic features on seismic data, and developing interpretational techniques to constrain both the timing and flux of hydrocarbons leaking from the reservoirs and the boundary conditions governing leakage. This workflow is now widely used by industry to assess the risk of top seal failure. The resulting data, practical knowledge, training courses and digital analyses are now embedded as fundamental components of workflows for seal risking and exploration play analysis by major international companies (e.g., Shell, ENI, Equinor) as part of their global exploration process and in their carbon capture and storage (CCS) operations. This work has undoubtedly saved many GBP10,000,000s in wasted investment, through reducing the risk of drilling into traps where the bulk of the hydrocarbons have leaked.

2. Underpinning research

Leakage from reservoirs through top seals is one of the major causes of exploration failure in the hydrocarbon industry and is a major negative factor in choosing sites for CO_2 storage. Standard practice for risking top seal integrity prior to drilling is to focus on the physical properties of the sealing sequences and the fluid pressure distribution from reservoir to top seal. Prior to the Cartwright research group, relatively limited emphasis was placed on identifying potential leakage pathways within the sealing sequences that intrinsically pose a risk to seal integrity by virtue of their static or dynamic permeability.

Since 2012 the Cartwright research group has:

1. Identified leakage from a large range of sub-surface reservoirs, documented the variability of seismic characteristics of leakage phenomena, and determined the key factors influencing leakage potential and top seal integrity in the presence of seal bypass systems **[1-3]**.
2. Shown how the development of extremely high overpressures resulting from rapid loading and unloading of sedimentary basins can be a cause of high flux leakage through thick evaporitic top seals. Evaporite sequences had been considered by the petroleum industry to be ‘perfect’ seals, but the Cartwright research group showed that hydrocarbons can and do leak at high fluxes through such seals, under conditions of exceptional overpressure **[4,5]**.

3. Quantified the pressure regime leading to catastrophic breaching of hydrocarbon accumulations and demonstrated the range of geological processes that can lead to significant loss of hydrocarbon volumes from reservoirs **[3,5,6]**.

The research was undertaken by Cartwright's (Shell Professor of Earth Sciences 2012-2017) group between 2012 and 2020, funded by Phase 3 of CAPROCKS (2012 to 2013; by a consortium of major oil companies) **[G1]**, and three major grants from Shell (2012-17; 2018-20; 2019-2021) **[G2, G3, G4]**, with major contributions by Cartwright's PDRAs Foschi (2013-2020), Bertoni (2013-2018), and Kirkham (2016 - 2020). Additional NERC funding for field research **[G5]** has helped to further quantify leakage. The work is underpinned by nearly 100 papers since 2012 in collaboration with a range of industry and academic partners.

Five papers published between 2014 and 2020 **[1-5]** established the conceptual framework for identifying and risking leakage phenomena using seismic data. This research was undertaken with collaborators in industry (BHP, **[1]**; Shell, **[2]**; Statoil, **[5]**) and in academia (Georgia Tech, **[4]**). Significant advances included the identification of major direct hydrocarbon indicators hosted in non-reservoir facies **[1,2],** the development of a genetic model for the origin of fluid escape pipes **[4],** and the development of a systematic workflow integrating seismic observations of leakage with hydrocarbon column heights and distributions to establish leakage volumes **[3].** This latter work also established the importance of dating leakage events using seafloor expulsion phenomena. Dating leakage is critical if trigger mechanisms are to be elucidated and flux is to be calculated, and dating is also an integral part of predicting leakage phenomena and for providing constraints for petroleum system modelling. Three papers **[1-3]** set out the workflow for analysing leakage timing and fluxes. The research on hydrocarbon prospects **[2]** and known hydrocarbon accumulations **[3]** identified clear end members in leakage structures that link directly to the driving pressure in the reservoir and the permeability heterogeneity structure of the sealing sequences. For example, **[3]** documents a major leakage of gas from the Scarborough Field, offshore Australia, dating this to the past 200 Ka, and explaining the distribution of leakage phenomena as being due to aquifer overpressuring. This is critical knowledge for making better predictions of seal integrity ahead of the drill bit.

Abnormally high aquifer pressures are found to lead to highly focused leakage plumes, expressed typically in fluid escape pipes **[4-6],** whereas more diffuse leakage occurs under lower pressure gradients in more heterogeneous top seals **[2].** This work is directly relevant to CCS operations where CO_2 injection could lead to unexpectedly high aquifer pressuring. Extreme aquifer pressures were shown to be responsible for large flux, episodic leakage of reservoired hydrocarbons through thick evaporitic sealing sequences, demonstrating for the first time that the most efficient petroleum seals can be breached under specific, albeit rare conditions. This work was published in Basin Research in 2018, and won the best paper award from the EAGE **[5].** Fluid escape pipes crossing evaporite seals were shown to be the result of rapid loading and unloading of the basinal succession, or to abrupt changes in the stress regime (tectonic overpressuring). Identification of leakage through hydraulic fracture networks allowed the first reconstruction of paleo-pressure evolution in a reservoir, a novel method for basin-scale fluid pressure analysis, undertaken in collaboration with SpectrumGeo **[6].** The seal analysis workflow allows explorers and sub-surface engineers to establish the timing, priming and triggering mechanisms and migration processes involved in leakage events, which underpins Oxford's current research aimed at further quantifying leakage fluxes, funded by Shell **[G4].**

3. References to the research (References 1-6 are all journal articles; Cartwright research group personnel are in **bold**.)

[1] **Foschi**, **M**, **Cartwright, JA**, Peel, FJ, (2014) Vertical anomaly clusters: Evidence for vertical gas migration across multilayered sealing sequences. *AAPG Bulletin,* 98 (9), 1859-1884. doi:10.1306/04051413121

[2] **Bertoni, C**, **Cartwright, J**, **Foschi, M,** Martin, J, (2018) Spectrum of gas migration phenomena across multi-layered sealing sequences. *AAPG Bulletin*, 102 (6), 1011–1034. doi:10.1306/0810171622617210

[3] **Foschi, M & Cartwright, J**, (2020) Seal failure assessment of a major gas field via integration of seal properties and leakage phenomena. *AAPG Bulletin*, 104(8):1627-1648. doi:10.1306/02282018111

[4] **Cartwright, J** and Santamarina, C, (2015) Seismic characteristics of fluid escape pipes in sedimentary basins: implications for pipe genesis, *Marine and Petroleum Geology,* 65, 126-140. doi:10.1016/j.marpetgeo.2015.03.023
[5] **Kirkham, C, Cartwright, J**., Hermanrud, C & Jebsen, C, (2018) The genesis of mud volcano conduits through thick evaporite sequences, *Basin Research*, 30, 217-236 doi:10.1111/bre.12250 *Won the R. Mitchum Award of the EAGE in 2019.*
[6] **Cartwright, J, Kirkham, C, Bertoni, C,** Hodgson, N, and Rodriguez, K**,** (2018) Direct calibration of salt sheet kinematics during gravity-driven deformation, *Geology*, 46, 623-626, doi:10.1130/G40219.1

Projects:

Evidence of the quality of the Cartwright group's success is in it being contracted by various petroleum companies to undertake research throughout the REF period.
[G1] CAPROCKS Consortium Funding Phase 3, 2012-2013. Sponsors: Anadarko, BHP Billiton, BG, BP, Chevron, ConocoPhilips, ENI, Equinor, Petrobras. GBP360,000 [Cartwright is founding PI on this project, with co-Investigators: A. Aplin (Durham); Q Fisher (Leeds); G. Couples (Heriot-Watt)]
[G2] Shell Grant USD9,700,000 2012-2018 [Task 1 PI Cartwright, USD3,200,000]
[G3] Shell Grant USD1,200,000 2018-2021 [PI Cartwright USD420,000]
[G4] Shell Grant USD600,000 2019-2021 [PI Foschi].
[G5] NERC grant (NE/R016615/1) [PI Cartwright, GBP50,148]

4. Details of the impact

'Impacts on practitioners and delivery of professional services'

From 2013, Oxford research has led to conceptual frameworks being adopted by hundreds of explorers, achieved through training courses and leading to changes in how the risk of reservoir leakage is assessed. Traditionally core analysis of capillary pressures and leak-off tests were used to assess column height. The use of 3D seismic data has provided a step-wise improvement in top-seal and by-pass systems analyses on a field-wide scale. Block grant funding from Shell to Oxford has provided a major catalyst for this impact. Professor Cartwright has delivered 8 courses on the seismic workflow since 2013 through Nautilus Ltd to 150 explorers and seismic interpreters from 17 different exploration companies, in London, Stavanger, and Kuala Lumpur. In-house knowledge transfer workshops have been delivered through exchange visits with Equinor, ENI, Anadarko, BP and Shell in 2013/14, and for Shell in 2015/16/17/18 in Houston, Holland and Kuala Lumpur (12 courses and 247 attendees). The Chief Scientist and Vice President Research Strategy for Shell notes: *"The material provided by Oxford was initially transferred by workshops and courses, secondments, and an atlas to specific staff in Shell. It has now (from 2018 on) become an integral part of the in-house training programme."* **[TL1]**

From 2015, Oxford research discoveries led to industrial partners using the results in screening of exploration acreage for new plays and opportunities through better identification of leakage phenomena on seismic data. The Exploration Discipline Lead within Shell notes: *The research has directly contributed to the improved conceptual understanding of seal risk within Shell, and this background knowledge has been widely disseminated. The confidential final report sets out the theoretical foundations of seal bypass and leakage from reservoirs and presents valuable case studies from Shell's exploration portfolio (plus other non-proprietary sources) that demonstrate the mechanisms of secondary (cross-stratal) hydrocarbon migration and the processes leading to leakage from hydrocarbon reservoirs. This is the first comprehensive and consistent guide to the interpretation of the seismic anomalies that reflect vertical fluid migration and as such is an important aide to our existing seismic interpretation workflows. . . . our seismic interpreters are now more generally aware of seal bypass features and the risks they can pose for exploration prospectivity. The Atlas has been incorporated into the Shell Exploration Guidelines and Standards and is used as a reference to help explorers interpret seismic anomalies in a consistent manner.* **[TL4]**

Longer-term dissemination of the Oxford research into professional practice has taken place through the training of PhD graduates supervised by Cartwright, many of whom have taken up senior positions in exploration companies globally. Since 2013, he has supervised 13 PhD students, in projects linked to the risking of top seals or hydrocarbon migration, 7 of whom have entered the petroleum industry.

'Impacts on production – research leads to improvement in productivity and resource-use efficiency'

Seal Risk Analysis: The research undertaken by the Cartwright research group has led to the adoption during the review period of a more systems-based approach to top seal risking by Shell International, Equinor and ENI, along with a group of companies that participated in the CAPROCKS consortium **[G1].** Shell is ranked second largest oil company in the world by revenue by the oil and gas journal, Equinor is the largest oil company operating in Norway, and ENI was ranked the most successful oil exploration company for replacing reserves for the last few years by the Financial Times. This approach involves identifying the seal bypass systems classified by the Cartwright research group and assigning risk of failure values to prospects using the novel seismic interpretational workflows developed at Oxford. The Chief Scientist and Vice President Research Strategy for Shell International notes: *"They* [Oxford] *have recently (2019/20) also established a rigorous and repeatable workflow based on automated 3D seismic interpretation whereby the specific leakage paths feeding hydrocarbons into seismically detectable reservoirs can be mapped and estimates made of the relative timing of leakage."* **[TL1]**

From 2013, the Cartwright group developed systematic methods for the assessment of seal risk based on seismic interpretational workflows. Seal risk analysis is a critical and poorly understood component of assessing the commercial potential for an exploration prospect, and analysing the risk of seal failure is largely a question of managing the unknowns in the complex processes that lead to a viable seal being present.

The Cartwright research group provided to the global exploration community a framework or workflow for risking the role of seal bypass systems in the overall analysis of seal integrity. ENI have deployed this workflow across the company: "*[Cartwright's] latest work at Oxford (post 2015) has been to more directly link observations with risk analysis by quantifying the timing and effective permeability of the bypass systems…The direct benefits of Professor Cartwright's research are widely rooted in ENI in the higher level understanding of the processes that can compromise seal quality…..and also in highlighting to our seismic interpreters the range of geological features that can lead to seal bypass. Professor Cartwright and his team has undoubtedly saved ENI many 10s of millions of pounds in wasted investment …"* **[TL2]**

The significant impact of the quantitative nature of the research at Oxford from 2018 onwards is also clearly highlighted by an Exploration Vice President (Brazil) for Equinor who says: "*His latest work in particular is of significant commercial value in exploration in salt basins, because he has been the first to identify and quantify major seal breaching, of really thick evaporite sequences…..His quantification of seal integrity and overpressure development in the case study of the Eastern Mediterranean has wide application potential for the petroleum exploration industry, because there is so much activity in major salt basins. Professor Cartwright's work on topseal characterization is widely used by explorers and seismic interpreters within Equinor."* **[TL3]**

Exploration Play Analysis: The conceptual advances on seal risk and the translation of those into seismic interpretation workflows, through new insights into the mechanisms of dominantly vertical secondary hydrocarbon migration, have also been adopted by a number of oil companies from 2016 onwards in exploration play analysis. Play analysis (the analysis of the distribution of reservoirs, traps, seals and migration pathways on a basin scale) is the process by which explorers identify regions with petroleum exploration potential and involves an analysis of all the possible migration pathways for oil and gas to be transported from the source region to the trap. By way of commercially contextualising this work for global hydrocarbon exploration, the loss of hydrocarbons through the seal failure has been estimated in a recent Exxon study of dry holes to account for >50% of all failed exploration wells **[S1].** Given that each well typically costs more than USD50,000,000, the conceptual advances in seal risk achieved by the Cartwright research group can lead directly to more realistic exploration risk analysis with huge concomitant commercial potential. These advances result in more efficient exploration to conserve the environmental impact of drilling (by drilling fewer wells).

The Cartwright group research during 2012 to 2020 led to a breakthrough in understanding of vertical migration pathways, an essential component in deciphering hydrocarbon plays in any basin. The research results produced since 2015 **[1-6]** have allowed explorers to identify migration pathways directly from seismic data, and also identified novel processes by which hydrocarbons can migrate vertically across thick evaporate sequences, opening up new potential in many salt basins. The Senior Vice-President Exploration Strategies for ENI highlights the significance of the impact of this research: "*Evaporite seals have traditionally been viewed by the petroleum industry as the most effective of all seal types, so it was a really significant finding that large fluxes of pre-salt fluids can penetrate these seals to migrate into the post-salt stratigraphy. This has wide potential significance for exploration in the many salt basins in the world (both in seal integrity and secondary migration into post-salt traps), and for safe drilling (since it points to extreme overpressure). ENI has considerable exploration acreage in such basins (e.g. Eastern Mediterranean), so this work is of direct and immediate relevance in our exploration campaigns in the region."* **[TL2]** The Chief Scientist and Vice President Research Strategy for Shell International adds: *"This work has contributed to a new consistency amongst Shell workers in the prospect-risking process for frontier exploration plays. It has greatly enhanced value generation from the program in itself, but also Shell-internal programs in for example sea floor scanning of fluid systems as well as more general interpretation of reservoir fluid effects were greatly helped by this work. The commercial benefit of the work lies in improved decision-making: which prospects to drill, which not to drill, and, though hazard avoidance, where specifically to drill them. The commercial value of the work derives from improved drilling efficiency and lower finding costs and will average out to tens of millions of dollars per year for a company the size of Shell. There are also the intangible benefits for example increasing capability with staff as well as increase safety and reduced environmental exposures related to better-targeted drilling."* **[TL1]**

Carbon capture and storage (CCS): In addition to the impact on hydrocarbon seal risking, safe drilling, and commercial exploration viability, the Cartwright research group work can be directly transposed into a similar workflow for seal prediction in subsurface siting of CO_2 disposal by injection into shallow aquifers. The work has implications for UK Net Zero efforts, described by the Exploration Discipline Lead within Shell as "*This improved understanding of seal risk is also applicable to CO_2 storage at scale – an area identified by the Committee on Climate Change that will have relevance to the UK as it strives to meet its Net Zero target*" **[TL4]**. Whilst noting future impact, this statement indicated that the work of Cartwright's group is influencing Shell's current decision-making with respect to CO_2 storage.

5. Sources to corroborate the impact

Testimonial Letters and sources:

[TL1] Vice President Research Strategy, Chair Shell Science Council and Chief Scientist, Shell International. *Impact Oxford research has had on Shell's prospect-risking processes, including staff training.*
[TL2] Senior Vice President Exploration Strategies, ENI. *Impact of Oxford research on ENI's efforts to de-risk top-seal failure, especially in evaporite settings.*
[TL3] Vice President Exploration, Brazil, Equinor. *Impact of Oxford research on Equinor's efforts to de-risk top-seal failure, especially impact in recent years.*
[TL4] Exploration Discipline Lead, Shell International. *Describes Shell's funding to Oxford (2012-2017) and the wide impact it has had on the company.*
[S1] Rudolph, K. W. and F. J. Golding, (2017) Benchmarking exploration predictions and performance using 20+ yr of drilling results: One company's experience. *AAPG Bulletin*, 101, 161-176 doi:10.1306/06281616060