Institution: Cardiff University

Unit of Assessment: 7

Title of case study: Understanding the properties of caprocks to improve hydrocarbon exploration and CO_2 sequestration

1. Summary of the impact

Economic gains by oil and gas companies, improvements in professional practice in hydrocarbon exploration, and environmental benefits from identifying CO_2 disposal sites have been achieved through a Cardiff-led consortium with industry. Building on research carried out since 2004, ten of the largest oil companies in the World have contributed to and benefited from understanding how faulted caprocks behave under specific geological conditions. Research at Cardiff has shown which families of faults and fractures make caprocks highly permeable, thus improving Industry's ability to predict if caprocks are able to prevent oil and gas reaching the surface.

2. Underpinning research

Faults and fractures are universally attributed to tectonic stresses, where the *in-situ* stress state of rocks is perturbed by tectonic or gravitational forces. In 1994, Professor Joe Cartwright, then at Imperial College, discovered a type of fault system that did not conform to this standard model. These faults were identified using geophysical imaging of 3D seismic data; firstly in the North Sea Basin and, subsequent to Cartwright's move to a Chair at Cardiff in 1999, in over 200 basins worldwide [3.1]. The faults are characterised by their polygonal pattern, similar to shrinkage cracks on a dried-out lake bed, albeit developed at a much larger scale. Research then focused on establishing their effect on the integrity of caprocks and the compartmentalisation of reservoirs. The caprocks are especially important for resource exploitation (hydrocarbons, groundwater and latterly subsurface CO_2 sequestration) because they have intrinsically low permeability, hindering the movement of fluids in the subsurface and providing potential barriers to the escape of resource or toxic fluids to the Earth's surface.

After a first stage largely funded by the hydrocarbon Industry (CAPROCKS consortium) and NERC, research undertaken at Cardiff focused on the development of models for the formation of polygonal faults. The first possible triggering processes considered were a) high pore fluid pressure or b) syneresis (a process by which gels spontaneously contract under inter-particle forces) [3.1]. Neither explanation was fully satisfactory from a theoretical viewpoint. Polygonal faults could not be explained using standard rock or soil mechanical theory, since they defined a bulk volumetric contraction of the medium in which they formed [3.1]. More recent work has implicated volumetric contraction during diagenesis [3.1]. Following the award of a NERC grant on the genesis of polygonal faults, efforts concentrated on recognition of the timing of fault formation from 2008 to August 2012. Tiago Alves (lecturer) also started to make a contribution to this work, which is on-going. Between 2007 and 2010 he added quantifiable geophysical and structural data to the initial results [3.2].

This led to the discovery of significant controls on the reactivation of early faults on both reservoir and caprock intervals [3.3] and, later, on the recognition of an important degree of internal organisation in blocky and faulted submarine mass-flows, which are commonly part of

caprocks [3.4]. Cardiff's work has now demonstrated conclusively that faulted and blocky caprock intervals have important implications for the degree of connectivity between reservoir units, and to the seal competence of caprocks [3.5].

From this research, a novel approach to assessing seal quality has been developed by Alves and Cartwright in conjunction with Aplin (Newcastle) (http://research.ncl.ac.uk/caprocks/). Cartwright left Cardiff in 2012, but the work is being continued by Alves. The value of the research on seal quality was recognised by The Royal Society and the Wolfson Foundation, which invested £200K in a new laboratory for CO_2 sequestration in Cardiff in 2008. This research has also led to new NERC-funded studentships.

3. References to the research

[1] **Cartwright, J.A.** 2011. Diagenetically induced shear failure of fine-grained sediments and the development of polygonal fault systems. *Marine and Petroleum Geology*, **28**, 1593–1610. http://dx.doi.org/10.1016/j.marpetgeo.2011.06.004

[2] **Alves, T.M., Cartwright, J.A.** & Davies, R.J. 2009. Faulting of salt-withdrawal basins during early halokinesis: Effects on the Paleogene Rio Doce Canyon system (Espirito Santo Basin, Brazil). *AAPG Bulletin*, **93**, 617–652. http://dx.doi.org/10.1306/02030908105

[3] **Alves, T.M.** 2012. Scale-relationships and geometry of normal faults reactivated during gravitational gliding of Albian rafts (Espírito Santo Basin, SE Brazil). *Earth and Planetary Science Letters*, **331–332**, 80–96. http://dx.doi.org/10.1016/j.epsl.2012.03.014

[4] **Alves, T.M.** 2010. 3D seismic examples of differential compaction in mass-transport deposits and their effect on post-failure strata. *Marine Geology*, **271**, 212–224. http://dx.doi.org/10.1016/j.margeo.2010.02.014

[5] **Alves**, **T.M.**, Kourtev, K., Moore, G.F., Strasser, M. 2013. Assessing the internal character, reservoir potential and seal competence of mass-transport deposits using seismic texture: a geophysical and petrophysical approach. *AAPG Bulletin*, in press, http://dx.doi.org/10.1016/j.margeo.2013.07.011

4. Details of the impact

Cardiff University research into caprocks, building on the paradigm-changing work by Cartwright on polygonal fault systems and seal integrity (awarded the Wallace E Pratt Medal in 2009) and Alves's subsequent research, has had a direct impact on the global petroleum industry. This has led to:

- Economic gains, through a more effective approach to oil and gas exploration and extraction, building on more effective risk analysis
- Changes in professional practice in the petroleum industry, including a new approach to the risk analysis of caprock seal integrity
- Environmental benefits, through improved location of sub-surface gas accumulations, and identifying potential CO_2 sequestration sites.

Economic impact

Cardiff's work has been focused on the development of models for the formation of polygonal faults. Of key importance was establishing the effect that these faults would have on the integrity of caprocks and the compartmentalisation of reservoirs. Caprocks are especially important for resource exploitation (hydrocarbons, groundwater and subsurface CO_2 sequestration) because they have intrinsically low permeability, hindering the movement of fluids in the subsurface and providing potential barriers for the escape of resource or toxic fluids to the Earth's surface.

This work allowed Cardiff to capture new investment from major international hydrocarbon exploration companies. An example is the new Block 17/06 oil field in offshore Angola, the largest oil field in West Africa and one of the largest in the world to be affected by polygonal and associated fault families. In 2012 TOTAL, Sonangol P&P, Partex Oil and Gas, SSI Seventeen, Falcon Oil and ACR funded a new large Cardiff-led consortium to analyse the interaction between deeper fault families and the polygonal faults dissecting caprocks that develop within reservoirs in the Angola Block. In presenting a new model for the formation, evolution and sealing properties of polygonal and other types of faults, data produced by Cardiff is directly informing the development planning for this major resource, part of a project costed at in excess of $10Bn.

The Block 17/06 project is working to minimise the geological uncertainties of key reservoir succession in offshore Angola. The study is looking at the role of fault systems in the migration of fluids between pre-salt, Albian rafts and Oligo-Miocene channels, in which some of the largest oil fields in Angola are located (such as CLOV, Girassol, Dalia, Rosa), and indicating the regions of larger connectivity between reservoir intervals. This involves investigating distinct structural architectures and styles of compartmentalization as these may cause significant variations in reservoir volumes, wettability and pressures that can have a profound impact on CO_2 production and underground injection. The project follows the methods extensively proven in the pioneer work in rafts from SE Brazil by Alves (2012) and provides the consortium with a *Connectivity Index* to assess exploration risks prior to drilling.

Professional practice

The risk of seal failure is difficult to assess and is a significant concern for the hydrocarbon industry; it is responsible for many failed exploration boreholes, and accounts for billions of dollars annually. The research on polygonal faulting has shifted the risk assessment approach from a laboratory-scale investigation of the physical properties of samples of seals to a more holistic approach in which petrophysical data is used to calibrate three-dimensional seismic data. Through its geological analysis of seismic data to characterise seal integrity, Cardiff has been fundamental in this shift of emphasis within the industry.

The methodology established by Cardiff has been disseminated to industry through the CAPROCKS and Block 17/06 consortia. CAPROCKS was originally funded by ten major oil companies (including Shell, BP, ExxonMobil, Statoil, BG Group and Total). Block 17/06 is sponsored by five major oil companies. These companies apply the results produced by Cardiff to redesign workflows used to assess the quality of caprock seals, and develop new software and models of reservoir and seal units.

Environmental impact

The wider societal and environmental impacts of this research include identifying sites for the underground disposal of CO_2 as a climate change mitigation activity. For underground CO_2 disposal, the long-term containment capability is predicated on seal integrity to prevent the leakage of CO_2 back to the surface. It has the potential, according to the International Energy Agency (2008), of reducing greenhouse gas emission by 20% by 2050.

The Cardiff approach to assessing seal quality has also helped secure funding for a consortium of twelve academic and civil protection institutions, sponsored by the European Commission, to assess oil spill risks and set up workflows for marine pollution accidents in the Eastern Mediterranean (Cyprus, Israel, Lebanon and Greece). The work of CAPROCKS and Block 17/06 consortia on seal quality is also being used to predict the areas where the possibility of seal fracturing as a result of CO_2 injection is much reduced.

5. Sources to corroborate the impact

All work carried out from 2008 onwards by the CAPROCKS consortium is reported in: CAPROCKS website - http://research.ncl.ac.uk/caprocks/

Industry contacts are :

[1]. Exploration Manager at TOTAL for Block 17/06, Luanda, Angola will confirm the impact of the Block 17/6 consortium on TOTAL

[2]. Deputy Director of International Exploration at TOTAL, Pau, France will confirm the impact of the Block 17/6 consortium on TOTAL

[3]. Exploration Manager at Partex Oil and Gas, Lisbon will confirm the impact of the Block 17/6 consortium on Partex.

[4] Senior Geophysicist at Partex Oil and Gas, Lisbon will confirm the impact of the Block 17/6 consortium on Partex

[5]. CAPROCKS coordinator, Durham and Newcastle Universities will confirm the importance of Alves' research to CAPROCKS in the impact period