Institution: University of Aberdeen

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

Title of case study: Sand Injectites

1. Summary of the impact

Researchers in petroleum geology at the University of Aberdeen have since the mid 1990's been investigating the characteristics and geological context of sand injectites. The geological contexts within which injected sands are discovered have permitted a step change in the production potential in some oil fields (up to c. 1 billion barrels oil), and to define new exploration targets (up to 250 million barrels oil) to make a significant increase to the overall proven reserves of hydrocarbons in any given province (e.g. the North Sea). The findings of this research have been utilised by a number of multinational oil & gas companies to optimise their exploration and field development strategies to maximise the commercial production of hydrocarbons. This case study describes the economic impacts resulting from two projects in particular in the North Sea, the Volund field (Marathon Oil) and the Mariner Field (Statoil) resulting in the enhancement of strategy, operations and management practices; improvements in performance and adoption of new processes; and creation of new employment as a direct result of research facilitating the development of new assets that would otherwise have remained fallow.

2. Underpinning research

Despite being described in a paper in 1827, sand injectites received little attention and was given almost no scientific or commercial attention for the next 170 years. The paucity of scientific understanding meant that any practical or commercial implications that sand injectites might have were overlooked. However, in 1998 high-quality 3D seismic reflection surveys over the Alba oilfield (Statoil/Chevron) revealed the common occurrence of sandstone intrusions as entire or significant components of oilfields, allowing the field development strategy for that field to be optimised. Since that time Professor Andrew Hurst has created the Sand Injectites Research Group (SIRG) at the University of Aberdeen to investigate these phenomena, and this group has become the global focus of knowledge for understanding the geological conditions that lead to formation of sand injectites, their significance in petroleum systems and, specifically, their potential for holding commercial volumes of hydrocarbon and hence as targets for exploration and field-development drilling. An invited 2007 Memoir (AAPG 87) documented the early stages of research by SIRG and associates, including oil industry partners. The Sand Injectites Research Group (SIRG) has more than 12 years continuous activity funded by the international oil industry (BG, Cairn, Chevron, Det Norske, DONG, EnQuest, JX Nippon, Kerr McGee, Lundin, Maersk, Marathon, Premier Oil, Shell, Statoil, Total, and Wintershall), to a total value of £2.2 million.

By examining never-previously-described outcrop and examining oil-industry subsurface data (1,2) SIRG developed predictive models for the occurrence and geometry of sand injectites that previously were deemed random (3). Through understanding the relationships between sandstone distribution and their mechanism of formation it was recognised that regionally-developed instability in the very shallow (<2 km burial) crust was caused by the focussing of anomalously-high pore-fluid pressure that caused the hydraulic fracture of low-permeability strata and concomitant fluidisation and upward injection of sand into the fractures. This group of processes occur rapidly (from days to weeks) and frequently mobilise 10-100's km^3 of sand. Such intrusions have occurred in sedimentary basins globally throughout geologic time (2). As a result of the research undertaken, sand injectites are no longer considered to be occasional anomalous features, but

often constitute the predominant occurrence of sandstone in many petroleum-bearing basins, and are hence of direct importance in hydrocarbon exploration and production.

SIRG's research has been undertaken through oil-industry-sponsored Joint Industry Projects. Of direct significance to hydrocarbon exploration-drilling SIRG's research during phase 1 (2000-2003) defined *intrusive traps* a new class (type) of hydrocarbon trap (1). Specifically this stimulated exploration for *intrusive* targets on the NW European Continental Shelf and contributed to the discovery (2003) and development of Volund field on the Norwegian Continental Shelf (NCS) and other exploration projects globally.

During phase 2 (2005-2009) SIRG's cross-disciplinary research team determined the pore-fluid pressures at which hydraulic failure occurred and the velocity, rheology and turbulence of the fluidised sand (3, 4). Thus for the first time the conditions of formation of the external and internal structures associated with sand injectites could be inferred (4, 5). Relating the physical model to characteristics of sand injectites preserved in the rock record provides the key to understanding why and if large-scale sand injection occurs and how to differentiate them from depositional sandstones when encountered in the subsurface, which is of critical importance to the oil industry when modelling the evolution of pore-fluid pressure and predicting sandstone distribution in petroleum systems. A further new hydrocarbon trap – extrusive - was defined (6).

Current and future research (phase 3 commenced in 2013) examines in more detail the significance of sand injectites in basin/petroleum system evolution, in particular focussing on mechanisms for the development of regional pore-fluid overpressures in the very shallow crust (5). Elevation of pore-fluid pressure is the driver of hydraulic fracturing and sand fluidisation. Constraining the geological conditions under which it occurs will allow better pre-drill prediction of the likelihood of occurrence of sand injectites as both discrete sedimentary units or as modifiers of depositional units.

3. References to the research

1. **Hurst**, A., Cartwright, J.A., Duranti, D., Huuse, M. & Nelson, M. 2005. "*Sand injectites: an emerging global play in deep-water clastic environments In: Petroleum Geology: North-West Europe and Global Perspectives"* – Proceedings of the 6th Petroleum Geology Conference, Dore, A. & Vining, B. (eds.), Geological Society, London, p.133-144. *This was the first documentation and quantification of sand injectite plays and definition of intrusive traps*.

2. **Hurst**, A. and Cartwright, J.A. 2007. "*Sand Injectites: Implications for hydrocarbon exploration and production*," Hurst, A. & Cartwright, J. (eds.), AAPG Memoir 87, Tulsa. *This was the first compilation of original papers on sand injectites in petroleum systems.*

3. Vigorito, M. and **Hurst**, A. 2010. *"Regional sand injectite architecture as a record of pore pressure evolution and sand redistribution in the shallow crust: insights from the Panoche Giant Injection Complex, California."* Journal Geological Society of London 167, 889-904. *This included a critical evaluation of the relationship between pore-fluid pressure and the architecture and external geometry of a giant sand injection complex.*

4. **Hurst**, A., Scott, A. and Vigorito, M. 2011. *"Physical characteristics of sand injectites, Earth-Science."* Reviews 106, 215-246. *This is the first ever review of the sand injectites and their mechanism of formation.*

5. Scott, A., Vigorito, M. and **Hurst**, A. 2009. *"The process of sand injection: internal structures and relationships with host strata (Yellowbank Creek injectite complex, California)."* Journal of Sedimentary Research 79, 568-583. *This provided a detailed analysis of the origin of granular textures in a sandstone intrusion and their relationship to the process of sand emplacement.*

6. **Hurst**, A., Cartwright, J.A., Huuse, M. and Duranti, D. 2006. *"Extrusive sandstones (extrudites): a new class of stratigraphic trap?"* In: in, M.R. Allen, G.P. Goffey, R.K. Morgan and I.M. Walker eds., The deliberate search for stratigraphic traps: where are they now? Geological Society (London) Special Publication 254, p. 289-300. *This was the first definition of associated stratigraphic traps.*

4. Details of the impact

Hurst and his collaborators have established a global reputation for identifying the presence and significance of sand injectites in petroleum systems. Direct practical implications of the models include:

a) improved pre-drill prediction of sandstone distribution that leads to more successful exploration;

b) more accurate and appropriate description and modelling of reservoirs in which sandstone intrusions occur;

c) targeting of "sand injectite exploration prospects" – **intrusive traps** - by the direct application of the scientific basis from their occurrence developed by SIRG;

d) definition of criteria for identifying sand injectites in boreholes (Duranti and Hurst 2004) now in widespread use in the oil industry and academia;

e) a programme of workshops and courses with industry partners to ensure transfer of science and technology into their environment.

New exploration and field-development drilling targets have been identified that led to the generation of completely new exploration plays, the discovery of new oilfields and improved recovery from existing oilfields. Currently several oil company sponsors, including Marathon, Premier Oil, Total and Statoil, amongst others, use SIRG's concepts and data routinely in their exploration programmes. Four case studies from these named companies offer examples of this.

Marathon Oil participated in Phase 1 of the Sand Injectites research programme. As a result of the research findings concerned with intrusive traps Marathon discovered Volund field in 2003, with an expected gross value >$6Bn (7). Following discovery SIRG worked closely with the Volund field development team, supporting validation of quantitative models of oil production and advising on appropriate geological procedure for drilling (7). The Chief Geoscientist at Marathon Oil has confirmed that SIRG's "*analogue data were a critical component of the pre-exploration de-risking of Volund and had a direct impact on the eventual approval to sanction funding an exploration well given by Marathon's Head Office, Houston*" (2).

This exploration success prompted new sponsor involvement with an injectite exploration focus. Encore (now Premier Oil) have used the results of research to confirm the production potential of the greater Catcher field in 2010, and have commented that "*EnCore's discovery of Catcher, Varadero and Burgman fields in Block 28/9 was the UK exploration success story of 2010 ..... there is believed to be 400mmbo* [million barrels of oil equivalent] *in place*" in which "*Prof Hurst's research has had immediate effect on our evaluation of the Greater Catcher area and we plan to develop our working relationship with him. It appears that Sand Injectite research is a rather special feature of UK geological research with high relevance to the oil industry and well deserving of international recognition*" (3).

Statoil have financially supported Sand Injectites research from the outset in the late 1990's. As a result of research findings, Statoil were able to identify the widespread presence of injected sands within their field development areas, and were able to re-frame and optimise their field development strategies accordingly. The generic benefits of SIRG's research to Statoil have been summarised by a Senior Research Scientist (Exploration) for Statoil, in a communication to the University of Aberdeen: "*Statoil recognised the lack of research on the enigmatic but often*

regionally-developed features known as sand injectites. By investing in the Sand Injectites consortia at the University of Aberdeen Statoil has increased its understanding of when, where and how sand injectites form thus enhancing our understanding of their role in basin evolution. Equally important has been the generation of the first ever large outcrop database of sand injectites that helps all aspects of our subsurface evaluation, including seismic interpretation, and reservoir characterisation. In my daily work I use pictures and ideas from these outcrops to educate and illustrate how sand injectites are formed and expressed in the subsurface" (1). Most recently Statoil's development of the Mariner field in the UKCS has been approved, with a field development strategy based around exploitation of reserves within sand injectites, which is a direct consequence of collaboration with SIRG. The field is believed to hold reserves of approximately 300 million barrels with a commercial value of some $8 billion. As a result of this field development 700 new jobs will be created (6). Statoil have confirmed that the SIRG "*group has made tangible contributions to Mariner's commerciality and allowed an appreciation of the main uncertainties and how to best geologically model them*" (5). Whilst production from the field will not commence until 2017, the impact generated from government approval of development plans is considerable in guaranteeing future economic returns.

In the context of oilfield development SIRG research has played an important role supporting operators with well placement and optimising hydrocarbon recovery. In 2002, prior to development of Girasol (offshore Angola, 1.55 MMB OOIP), Total Research in Pau invited SIRG to examine core data from Girasol and other offshore fields/discoveries that "*confirmed the presence of significant sub vertical sandstone intrusions …… their identification gave the possibility of much higher than expected vertical permeability between the main sandstone reservoirs and consequent improved aquifer support. This interpretation proved to be correct and participated to the understanding of the oil production and water-handling characteristics of Girasol*" (4).

SIRG's transfer of research results to the oil industry is a prioritised activity and has an increasingly global impact. Company-specific workshops and field courses are also common activities (in 2013 4 field trips are organised for the benefit of Premier Oil, Wintershall, Cairn Energy, Maersk, Det Norske, Statoil and Tullow Oil). Since 2008 approximately 150 oil-company personnel have attended field courses led by Hurst and colleagues and many more have attended office-located workshops. Courses are typically associated with specific oil fields or are used to heighten the awareness of sand injectites within companies.

5. Sources to corroborate the impact

1. A Senior Research Scientist (Exploration), Statoil Norway corroborates the impact and benefits generally of sand injectites research, and especially the early impact related to the Alba field development.
2. The Chief Geoscientist at Marathon Oil UK corroborates the impact and benefits to Marathon of the Volund field development.
3. A former member of staff at EnCore corroborates the impact and benefits to the Catcher field development.
4. Staff at Total E&P, Pau confirms the impact on the Girasol development offshore Angola.
5. A member of staff at Statoil, Aberdeen confirms the impact and benefits to the Mariner field development.
6. *See* http://www.bbc.co.uk/news/uk-scotland-scotland-business-21474052 *for the media impact of the Mariner field development announcement.*
7. Schwab et al. (in press) Volund Field: Development of an Eocene Sand Injection Complex, Offshore Norway. Special Publication Geological Society of London.