Institution:	Imperial College London	
Unit of Assessment:	12 Engineering	
Title of case study:	Digital Rock Analysis	
Period when the underpinning research was undertaken:	2002 - 2020	
Details of staff conducting the underpinning research from the submitting unit		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Martin Blunt Branko Bijeljic	Professor of Petroleum Engineering Principal Research Fellow	2002 - present 2002 - present
Period when the claimed impact occurred:	2014 - 2020	
Is this case study continued from a case study submitted in 2014?	Yes	

1. Summary of the impact

Digital Rock Analysis – imaging and modelling fluid flow in rocks from the microscopic scale upwards based on research by Prof. Blunt FREng, Dr. Bijeljic and their team at Imperial College – has transformed how oil companies characterise rock samples, make decisions on reservoir management, and design recovery. The concepts are also used to design secure carbon dioxide storage in the subsurface.

Examples of impact since 2014 include:

1. estimated savings of USD200,000,000 in operations for Shell, not including the benefit of improved recovery [E1];
2. saving USD32,500,000 and additional reserves (producible oil) of twenty million barrels (worth approximately USD800,000,000) from a single field in Kuwait [E2];
3. application as a service to the oil industry by iRock Technologies with 60 employees, founded by a former Imperial PhD student and Prof. Blunt, with one example project resulting in additional revenue of USD2,800,000,000 for the client [E3];
4. additional revenue of USD400,000,000 from one field after the application of digital rocks technology [E4];
5. adoption of the technology in other companies [E5-7] (BP quotes potential business impact of over USD1,000,000,000 [E6]).

2. Underpinning research

Over the last 20 years Prof. Blunt, Dr. Bijeljic and their Imperial College colleagues have developed an integrated package of modelling, imaging and analysis tools devoted to the study of fluid flow in porous rocks. The principal breakthrough has been the ability to observe oil, water and gas within a rock at the high temperatures and pressures seen in oil reservoirs, and to use this as the basis for predictive numerical modelling. In the industry, the results are used in computer simulation tools to predict and design oil recovery and carbon dioxide storage processes.

The research was funded by industrial research grants with a total value of approximately GBP90,000,000 to Imperial College: the Qatar Carbonates and Carbon Storage Research Centre, Shell Digital Rock Programme, Total Digital Rocks and Imaging projects, and ADNOC (Abu Dhabi National Oil Company).

Overall, this work has received over 30,000 citations in the scientific literature (see https://scholar.google.com/citations?user=vMSqj1AAAAAJ&hl=en) and contributed to Prof. Blunt's election to the Royal Academy of Engineering in 2019: the citation reads *"Professor Blunt and his research team have pioneered the use of X-ray micro-tomography to image rocks and fluid displacement within them"* https://www.raeng.org.uk/about-us/the-fellowship/new-fellows-2019/fellows/martin-blunt

Six major research achievements led to the development of new imaging, analysis and modelling techniques which created the impact described in section 4.

1. The development of accurate predictive models to simulate flow at the pore scale through rock samples and compute averaged properties which are used to determine the recovery potential from hydrocarbon reservoirs [R1]. This has formed the basis of the technology used in industry – see, for instance, impact item I1 in section 4.

2. The development of image analysis methods to extract a pore network representation of a rock from a three-dimensional X-ray micro-tomography image. Without this extraction method the models could not represent the complex internal geometry of a rock accurately: the universally-adopted methodology was first published and tested in [R2] by Prof. Blunt and Hu Dong, one of Prof. Blunt's PhD students. Dr. Dong then established a company, iRock Technologies, to apply the knowledge of this technology using [R1,2] (see impact items I2 and I3 in section 4).

3. The next major milestone was to image both the rock and the fluids within it at reservoir conditions of high temperature and pressure, as shown in the picture – [R3] describes the first reliable method to do this, applied to the study of carbon dioxide storage. This research was performed by one of Prof. Blunt's PhD students Matthew Andrew who now works for Zeiss Microscopy where he has adapted these ideas into a commercial product sold to industry (impact I6).

4. Pore-scale images can also be used determine the contact angle between two fluid phases and the solid: this wettability controls flow behaviour and had hitherto been one crucial missing input into pore-scale models. The first accurate measurements of contact angle *in situ* were published in [R4] allowing first-principles predictions to be made by pore-scale models. This work has been widely applied in industry, see impacts I4-I7.

5. The next step was to apply these imaging and analysis techniques to reservoir samples: this was described in [R5] where contact angle and surface roughness were characterized in three samples from a large producing oilfield in the Middle East and related to oil recovery. This is the work of two PhD students sponsored by ADNOC (Abu Dhabi National Oil Company), leading to impact I5.

6. The culminating item of research was to combine imaging and analysis to measure, directly, averaged flow properties of interest, namely relative permeability and capillary pressure, and to use this to validate advanced numerical models [R6], contributing to impact items I1 and I7.

3. References to the research

[R1] P H Valvatne and M J Blunt, "Predictive pore-scale modeling of two-phase flow in mixed wet media," Water Resources Research, 40, W07406 (2004). https://doi.org/10.1029/2003WR002627

[R2] H Dong and M J Blunt, "Pore-network extraction from micro-computerized-tomography images," Physical Review E 80, 036307 (2009). https://doi.org/10.1103/PhysRevE.80.036307

[R3] M Andrew, B Bijeljic and M J Blunt, "Pore-scale imaging of geological carbon dioxide storage under in situ conditions," Geophysical Research Letters, 40 3915–3918 (2013). https://doi.org/10.1002/grl.50771

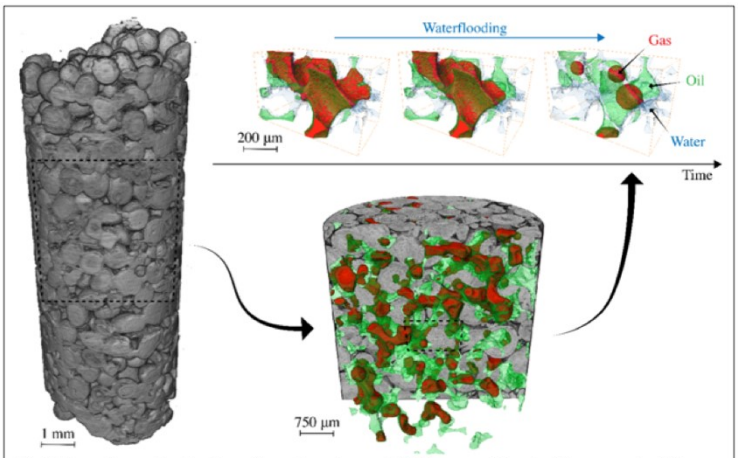
[R4] M Andrew, B Bijeljic, and M J Blunt, "Pore-scale contact angle measurements at reservoir conditions using X-ray microtomography," Advances in Water Resources, 68 24–31 (2014). https://doi.org/10.1016/j.advwatres.2014.02.014

[R5] A AlRatrout, M J Blunt, and B Bijeljic, "Wettability in complex porous materials: the mixed-wet state and its relationship to surface roughness," Proceedings of the National Academy of Sciences 115 (36) 8901-8906 (2018). https://doi.org/10.1073/pnas.1803734115

[R6] A Q Raeini, B Bijeljic, and Martin J. Blunt, "Generalized network modeling of capillary-dominated two-phase flow," Physical Review E 97, 023308 (2018). https://doi.org/10.1103/PhysRevE.97.023308

4. Details of the impact

Over the past 10 years Digital Rock Analysis has become established in the oil industry. This technology, **illustrated in the figure,** involves making use of three-dimensional images of rocks combined with sophisticated modelling tools to predict flow, transport and mechanical behaviour. The work has application in improved oil recovery from sandstone and carbonate reservoirs; the same ideas have also been adopted to design carbon dioxide storage in the subsurface, to help prevent dangerous climate change.



Digital rock analysis: Imaging of rocks and fluids, combined with numerical flow modelling to design improved hydrocarbon recovery and carbon dioxide storage.

These ideas have been applied in three ways: (i) directly by major oil companies I1-2, I6-7; (ii) through oilfield service companies, I4-5; and (iii) specifically by iRock Technologies, an oilfield service company founded by a former Imperial PhD student and Prof. Blunt, I3.

Examples of impact since 2014 include:

I1. Shell. A Shell manager from the Middle East states [E1]: "*I would like to focus on how Digital Rock Physics and ongoing research led by Imperial have made a significant business impact……With the aid of digital rock physics, we can optimize our special core analysis programs leading to cost savings of typically over $1 mln each program and underpinning field development plans to add over 100 mln barrels of improved recovery for each of such complex carbonate reservoirs. Our latest internal estimate of the NPVs attributed to Digital Rock Technology applications in our upstream exploration and production business units leads to a figure of over $200 mln in total that still does not capture the upside in recovery improvement and production enhancement*." This impact comes from continued support of research at Imperial College, particularly from research items [R1, R2 and R6] in the past 7 years.

I2. Kuwait Oil Company. An analysis of asphaltene precipitation using Digital Rock Technology in Kuwait performed by Prof. Blunt in 2012 enabled savings "*in excess of 32.5 million US$"* and "*additional reserves of order 20 million barrels of oil*" [E2] in the management of a single field over the subsequent 8 years. This successful application of the technology encouraged KOC (Kuwait Oil Company) to adopt this technology more widely: iRock (see item 3 below) currently holds an USD8,800,000 five-year (2018-2023) service contract with KOC and has established a core analysis laboratory in Kuwait [E3]. More recent studies in 2019 have been used to characterize rock types and flow barriers in producing fields to aid the management of waterflooding, and the quantitative analysis of regions of the reservoir clogged with tar to assist the design of steam flooding to enhance recovery. Just one project in 2018 has led to direct savings of USD4,700,000 and additional oil recovery worth USD2,800,000,000 by allowing rapid field development [E3].

I3. iRock Technologies, www.irocktech.com was founded in 2010 by Dr. Hu Dong, a former PhD student at Imperial College, to provide digital rock services to the oil industry: the underlying research applied by the company were items [R1] and [R2] above. Prof. Blunt acts as Chief Scientist, while another former PhD student, Dr. Nasiru Idowu, is Head of Technology. The company operates in China, the Middle East and Europe with 60 employees in China, the UK, Kuwait and Norway [E3]. In 2018 iRock secured USD5,000,000 in investment from CNOOC (China National Offshore Oil Company). Clients include ADCO, ADMA, CNOOC, Kuwait Oil Company, Maersk, Petrochina, Petronas, Saudi Aramco, Shell, Total, Schlumberger, Sinopec and Yanchang Petroleum.

I4. Other service companies have also harnessed the ideas and methods developed at Imperial College to help oil companies improve production and reduce costs [R1, R2]. A letter from the CTO of Petricore - http://www.petricore.com/ points to, among other examples, USD400,000,000 in additional income from the rapid development of a field under the Norwegian North Sea [E4].

I5. A Technical Specialist at **ADNOC (Abu Dhabi National Oil Company)** states, in relation to reservoir studies [E5]: "*This work has been transformed by the introduction of digital rock technology (DRP), based on three-dimensional imaging and modelling. Much of this technology is based on research at Imperial College London*." ADNOC has completed successful projects with iRock Technologies including a USD800,000 study in 2018 to 2019 which was the first commercial application of the wettability characterization workflow described in reference [R5].

I6. Reservoir-condition imaging of rocks and the fluids within them is now commercially available through **Zeiss Microscopy** based on [R3, R4] from 2015**.** Senior Expert at Zeiss writes [E6]: "*your developments have truly revolutionized the way that the oil and gas industry views their rocks*" and "*this provides a significant contribution to a total of between $30-40m/yr business for ZEISS microscopy."*

I7. Other major companies, including **BP** are directly implementing digital analysis in their own commercial activities to improve reservoir management based principally on [R1-3 and R6]. A Reservoir Engineering Senior Advisor writes about the technology [E7]: "*BP rates it as "most attractive" in terms of business impact potential (>1$bn BP NPV)".* This application of pore-scale modelling and imaging by oil companies and commercial service companies relies in large part on research at Imperial College, as attested by the sources listed (see Section 3).

5. Sources to corroborate the impact

[E1] **Letter received.** Shell as a user of the technology: Manager, Shell Technology Oman.

[E2] **Letter received.** Kuwait Oil Company as a user of the technology: Senior Consultant, Kuwait Oil Company.

[E3] **Letter received.** iRock Technologies which applied the technology as a service to the oil industry, www.irocktech.com – President, iRock Technologies.

[E4] **Letter received.** Chief Technology Officer, Petricore, which exploits the technology as a service to the oil industry, http://ww.petricore.com/

[E5] **Letter received.** ADNOC (Abu Dubai National Oil Company) as a user of the technology: Technical Specialist, ADNOC.

[E6] **Letter received.** Zeiss as a user and adapter of imaging and analysis methods: Senior Technologist, Zeiss.

[E7] **Letter received.** BP as a user of the technology: Reservoir Engineering Senior Adviser, BP UK.