

## Impact case study (REF3)

<b>Institution:</b>	Imperial College London	
<b>Unit of Assessment:</b>	12 Engineering	
<b>Title of case study:</b>	Full-waveform Inversion (FWI): from Petroleum Reservoirs to Impact Craters	
<b>Period when the underpinning research was undertaken:</b>	2003 - 2020	
<b>Details of staff conducting the underpinning research from the submitting unit</b>		
<b>Name(s):</b>	<b>Role(s) (e.g. job title):</b>	<b>Period(s) employed:</b>
Michael Warner	Professor of Geophysics	1989 – 2020
Joanna Morgan	Professor of Geophysics	1998 – 2020
<b>Period when the claimed impact occurred:</b>	August 2013 – July 2020	
<b>Is this case study continued from a case study submitted in 2014?</b>	No	
<b>1. Summary of the impact</b>		
<p>Over the past two decades, full-waveform inversion (FWI) has been developed at Imperial College London, from a promising concept into a fully commercialised industrial process capable of imaging physical properties in three dimensions within the heterogeneous shallow interior of the Earth with previously unachievable resolution and reliability.</p> <p>Since August 2013, this research has had multiple impacts:</p> <ul style="list-style-type: none"> <li>I1 FWI has been widely adopted across the petroleum industry where its total value is estimated by BP to be in excess of USD200,000,000,000; a significant fraction of this value relies directly upon software and concepts generated at Imperial.</li> <li>I2 (a) Twenty petroleum companies, and (b) eight oil-field service companies, have licensed FWI software and related technology from Imperial, with billion-dollar impacts on individual companies.</li> <li>I3 Beyond the petroleum sector, FWI technology has been licensed to seven companies involved in mining, off-shore wind-power, carbon sequestration, and medical imaging.</li> <li>I4 In 2014, S-Cube was spun out of Imperial to apply FWI to the most-challenging commercial hydrocarbon targets, subsequently licensing its technology worldwide.</li> <li>I5 Application of FWI to the Chicxulub impact crater led directly to deep drilling of the impact site, quantifying the processes that led to the extinction of the dinosaurs.</li> <li>I6 China Petroleum &amp; Chemical Corporation launched the Resource Geophysics Academy in London to immerse their future post-graduate employees in FWI-related research.</li> </ul>		
<b>2. Underpinning research</b>		
<p>Unlike conventional travel-time tomography, full-waveform inversion (FWI) is a tomographic scheme that fully accounts for the physics of finite-frequency wave propagation; this feature dramatically improves both its resolution and its accuracy. While the fundamental concept of FWI was developed in the 1980s, the intellectual challenges addressed at Imperial have been to render this concept computationally tractable in 3D, to apply it successfully to imperfect real-world data, to overcome the many limitations of the original simple formulation, and to incorporate into FWI the full range of physics displayed by real materials.</p> <p>In 2003, Michael Warner, Joanna Morgan and their co-workers began a long-term research programme to transform then-existing two-dimensional, mono-frequency acoustic isotropic FWI into a fully three-dimensional technology capable of dealing accurately with the true properties of the real world, successively incorporating the effects of anisotropy, density, attenuation and elasticity. The direct solution of the acoustic wave equation in 2D at single frequencies, originally developed for FWI in the 1990s, is not computationally feasible in three dimensions. Instead, the group developed massively-parallel 3D anisotropic solvers in the time domain. Since the real world is both three dimensional and anisotropic, these developments were fundamental to being able to apply FWI usefully to real data.</p> <p>Michael Warner and his co-authors Ivan Stekl and Adrian Umpleby, also from Imperial, obtained the first FWI results from 3D field data in 2008, for which they were awarded</p>		

the Guido Bonarelli prize by the EAGE, the leading European professional organisation in petroleum geoscience. The results of the first anisotropic 3D inversion of commercial field data were obtained in 2010, and published after a three-year embargo in 2013 [R1]. This paper was awarded the prize for the best paper in Geophysics by the SEG in 2014.

In 2014, Warner and Guasch developed a new approach to waveform inversion, “adaptive waveform inversion” [R2], that was able to overcome the problem of cycle skipping that had long constrained the broad applicability of FWI to real data. Rather than minimising differences between observed and modelled data directly, this new approach maps the data into an extended domain in which the data match is near-perfect, but the resultant model is unphysical. The inversion is configured to collapse this extended model onto the physical world while retaining the match to the real data. This approach proved to be effective on real data [R3], providing the underpinning intellectual property for the launch of the spin-out company S-Cube, and winning the prize for the best paper at EAGE in 2014.

In 2010, a team at Imperial and University of Texas at Austin, led by Joanna Morgan, applied FWI to seismic data they had acquired over the Chicxulub impact crater in the Gulf of Mexico. This was the large impact that terminated the Cretaceous period 66 million years ago, leading directly to the extinction of the dinosaurs and many other species. The results of that work [R4] led the International Ocean Drilling Programme to drill the crater offshore. The drilling took place in 2016 leading to [R5] as the first of over thirty papers including five in Science and Nature, and to extensive worldwide media coverage.

In 2015, the team realised that 3D FWI was likely to have important applications in new areas including neuroimaging, off-shore wind-power generation, monitoring carbon sequestration, and non-destructive testing. Together with bio-engineers and neurologists, they developed transmitted-ultrasound FWI to image the adult human brain using a system that is portable, safe, fast and cheap, and able to produce resolution comparable to the best MRI images [R6]. This patented technology served to underpin the launch of start-up companies in brain imaging (in the UK) and in soft-tissue imaging (in Spain).

### 3. References to the research (\*References that best indicate underpinning quality)

- [R1] **Warner M**, Ratcliffe A, Nangoo T, **Morgan JV**, et al. *Anisotropic 3D full-waveform inversion*, Geophysics, 78, R59-R80 (2013). DOI: [10.1190/GEO2012-0338.1](https://doi.org/10.1190/GEO2012-0338.1)
- [R2] **Warner M**, Guasch L. *Adaptive waveform inversion: Theory*, Geophysics, 81, R429-R445 (2016). DOI: [10.1190/geo2015-0387.1](https://doi.org/10.1190/geo2015-0387.1)
- [R3] Guasch L, **Warner M**, Ravaut C. *Adaptive Waveform Inversion: Practice*, Geophysics, 84, R447–R461 (2019). DOI: [10.1190/geo2018-0377.1](https://doi.org/10.1190/geo2018-0377.1)
- [R4] **Morgan JV**, **Warner MR**, Collins GS, et al. *Full waveform tomographic images of the peak ring at the Chicxulub impact crater*, Journal of Geophysical Research, 116, B06303 (2011). DOI: [10.1029/2010JB008015](https://doi.org/10.1029/2010JB008015)
- [R5] **Morgan JV**, Gulick SPS, and 36 others. *The formation of peak rings in large impact craters*, Science, 354, 878-882 (2016). DOI: [10.1126/science.aah6561](https://doi.org/10.1126/science.aah6561)
- [R6] Guasch L, Calderón Agudo O, Tang M, Nachev P, **Warner M**. *Full waveform inversion imaging of the human brain*. npj Digital Medicine, 3, 28 (2020). DOI: [10.1038/s41746-020-0240-8](https://doi.org/10.1038/s41746-020-0240-8)

### 4. Details of the impact

Research at Imperial into FWI has had two distinct impacts on the petroleum industry: one specific, where individual companies are using software developed at Imperial to apply 3D FWI to their own and their clients' seismic data; and one generic, ranging broadly across the industrial sector, where the uptake and effectiveness of FWI has been increased by the research contribution made by the team at Imperial. In both cases, the application of FWI to seismic data has affected individual drilling and investment decisions across the petroleum

industry worldwide, changing drilling priorities, well locations, sub-surface risk assessment and mitigation, and ultimately influencing which hydrocarbon prospects are drilled and which are not, adding consequent value to individual petroleum assets.

### I1 Generic impact across the petroleum sector [S1]

Prior to the development of 3D FWI at Imperial, there was no capability to undertake 3D FWI of any description within the petroleum sector. Today, every large multinational and most mid-sized international petroleum companies have adopted FWI as part of their technical portfolio for finding and exploiting petroleum reserves.

Without the specific FWI research contribution made by Imperial over the past twenty years, and especially without the dissemination of Imperial's software, and its validation and demonstration on key commercial problems and datasets, the widespread adoption of this technology would not have begun so early, and its uptake would not have developed so rapidly or so successfully. In confirmation of this, a senior technologist at BP stated publicly at a recent European industry workshop:

*"The value of FWI to the petroleum industry worldwide is now in excess of 200 billion US dollars. Within BP alone, the verifiable additional value generated by FWI amounts to several tens of billions of dollars in new resource, reduced subsurface risk, reduced HSE exposure, improved drilling decisions, and less-costly production.*

*"A significant fraction of that value would be traceable back to ideas and software that have emerged from Imperial College over the past two decades."*

### I2 (a) Specific impact in oil and gas companies [S2, S3, S4]

Between August 2013 and July 2020, twenty major oil and gas companies licensed Imperial software and technology for commercial FWI: BG, BP, Chevron, CNOOC, CNPC, ConocoPhillips, DONG, ENI, Hess, INEOS, Maersk, Nexen, Pemex, Petrobras, Shell, Sinopec, Statoil, TOTAL, Tullow and Woodside [S2]. Together these companies represent about 25% of world oil and gas production, and about 44% of non-OPEC production.

A specific example of the value delivered for one mid-size international oil and gas company is provided by the announcement made on 8 November 2019 by Woodside Petroleum Ltd [S3]:

*"The estimated gross contingent resource dry gas volume for the Scarborough field has increased to 11.1 Tcf, up 52% from 7.3 Tcf. The increased volume estimates follow completion of integrated subsurface studies incorporating full waveform inversion (FWI), 3D seismic reprocessing and updated petrophysical interpretation. The new FWI 3D seismic reprocessing improved the reservoir imaging quality and increased reservoir sand distribution."*

Tcf = trillion cubic feet of gas with a 2019 well-head value of about USD3,000,000,000.

The increase announced at Scarborough thus represents about USD10,000,000,000 of new resource. Woodside Chief Geophysicist, Fabio Mancini, said [S4]:

*"The collaboration with Imperial College was invaluable in revealing this increase in resource. At Woodside, we run Imperial's FWI software in-house and on the cloud, and we work with several oil-field service companies whose commercial FWI offerings have their roots firmly embedded within Imperial's software and ideas."*

### I2 (b) Specific impact on oil-field service companies [S2, S5]

Eight oil-field service companies hold licences from Imperial to use FWI technology: BGP, CGG, DMT, DUG, Fairfield, S-Cube, Shearwater and TGS [S2]. Together these companies represent more than half of the total world capacity to acquire and process commercial 3D seismic data. They include both CGG, the company with the largest share of the seismic-processing market, and Shearwater, the company with the largest capability in marine seismic acquisition. All eight companies base their commercial FWI offerings on

software and concepts derived directly from source code developed at Imperial and licensed to those companies.

CGG's FWI services were developed directly from the software package developed at Imperial. They have customised and integrated that package into their core processing and imaging software, and Imperial and CGG have jointly published the results of applying this software to industry seismic data [R1]. As a result of adopting and building upon Imperial's FWI software, CGG moved in the space of a few years, from a position where they did not offer FWI as a commercial service, to become widely acknowledged as the worldwide market and technical leader in this field [S5].

Shearwater licensed Imperial's FWI code in 2016, incorporating it into their commercial Reveal software package through which they now license Imperial's FWI technology to third parties. Prior to licensing the code from Imperial, Shearwater were unable to provide commercial FWI services; they now offer this service routinely to their oil-company clients.

### I3 FWI beyond petroleum [S2]

Imperial's FWI technology is licensed to Equinor, Ørsted and M-TRUST for use in site evaluation for off-shore wind power-generation, and licensed to Equinor, S-Cube and Total for use in monitoring off-shore carbon sequestration. The international mining company Rio Tinto licensed FWI technology from Imperial for applications in metalliferous and diamond mining. The UK start-up company M-TRUST Imaging Ltd has adopted patented FWI technology developed at Imperial for high-resolution ultrasound imaging of the adult human brain within the skull [R6]. The Spanish start-up company, Frontwave Imaging, has licensed Imperial's technology to apply FWI to early the detection of breast cancer in young women with dense breast tissue.

### I4 S-Cube spin-out company [S6]

In 2014, Sub Salt Solutions Ltd was launched as an Imperial spinout company with a brief to apply FWI and related technology to the most difficult seismic datasets and most challenging problems faced by the petroleum industry. The company trades under the name S-Cube. The company has had positive cashflow every year since its launch, and all further investment has been generated directly from income. S-Cube has licensed its Imperial-derived AWI [R2, R3] technology to: BP, Chevron, CGG, ConocoPhillips, DONG, ENI, Hess, Nexen, SENAI-Cimatec, Shearwater, Shell, SIP, Statoil, TGS, Total, Tullow and Woodside, and holds related contracts with a majority of the world's major international oil and gas companies.

In 2019, the company's CEO, Nikhil Shah, won *Young Entrepreneur of the Year* at the Asian Business Awards. S-Cube was a finalist in three categories in the Lloyds National Business Awards 2020: Growth through Innovation, Artificial Intelligence, and Data Excellence.

### I5 Chicxulub impact crater [S7, S8]

FWI applied to seismic data across the 200-km diameter Chicxulub impact crater in the southern Gulf of Mexico provided the underpinning models and data that led directly to the USD 10-million offshore-drilling project IODP 364, jointly funded by the International Ocean Drilling Program and the International Continental Scientific Drilling Program. The drilling project was led by Joanna Morgan (Imperial) and Sean Gulick (UT Austin) as Chief Scientists in collaboration with 38 expedition scientists from 12 countries. This work led to Morgan winning the 2020 Barringer Award from the Meteoritical Society for outstanding work in impact cratering [S7]. The work was voted as one of ten key scientific breakthroughs of 2019 by Science.

The Ocean Drilling Program tracks the media impact and public engagement generated by all its 281 drilling projects using Altimetric scores. The Chicxulub drilling for IODP 364 generated a total Altimetric score more than twice that of the next most impactful ocean drilling project, and reference [R5] has the highest Altimetric score of any ocean-drilling output generated within the last fifty years [S8].

The expedition and subsequent science was filmed by Barcroft for the BBC, PBS Nova, and France 5. The resultant programme The Day the Dinosaurs Died was subsequently transmitted in the UK, US, France, Germany, Japan, Australia, South Africa and much of south and central America.

#### I6 Resource Geophysics Academy [S9]

In 2019, China Petroleum and Chemical Corporation (Sinopec), the world's largest oil-and-gas producing, refining and petrochemical conglomerate, launched the Resource Geophysics Academy in London with an initial GBP11,250,000 investment over five years to train future post-graduate employees in Imperial's FWI and related techniques.

### **5. Sources to corroborate the impact**

- S1 Letter from INEOS confirming and endorsing the public statement made by a senior BP technologist at the FWI technical workshop during the annual EAGE meeting in Copenhagen, June 2018 [I1].
- S2 Letter from CNOOC (formally Nexen) confirming the list of companies that have licensed Imperial's FWI software [I2a, I2b, I3].
- S3 Announcement from Woodside, 8 November 2019, of increased reserve estimates for the Scarborough field confirming the role played by FWI in that reassessment [I2a]. PDF available [here](#).
- S4 Letter from Woodside confirming the specific importance of Imperial's contribution to the increase in reserves for the Scarborough natural gas field [I2a].
- S5 Letter from Osokey outlining specific impacts for oil-field service companies [I2b].
- S6 Letter from the Chairman of S-Cube confirming FWI software licensing, the company's history, and Imperial's significance to S-Cube [I4].
- S7 Barringer Award from the Meteoritical Society awarded to Joanna Morgan in 2020 [I5]. Link to the award citation here: <https://tinyurl.com/ybjlapke>. Link archived [here](#).
- S8 2019 Scientific Ocean Drilling Impact Report, Table 5, Page 15, shows three outputs from the Chicxulub IODP 364 expedition having Altmetric scores in the top seven generated by all ocean-drilling project outputs over a fifty-year period [I5]. PDF available [here](#).
- S9 Letter from the President of the Sinopec Group, confirming the Academy launch, explaining the rationale and outlining the importance of FWI to the company [I6].