Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 8. Full-waveform seismic inversion: improving resolution in oil & gas exploration

1. Summary of the impact (indicative maximum 100 words)

Full-waveform inversion (FWI) is a seismic technique for exploring the interior of the Earth; it has been developed at Imperial College over two decades, from a promising concept into a fully commercialised industrial process that has been widely adopted across the petroleum industry. The technique improves both the spatial resolution and the fidelity with which the sub-surface can be imaged in three dimensions. All the major multinational petroleum companies now use FWI internally, and all the major oil-field service companies offer the technology to the wider industry. Since its first commercial uptake in 2008, its application has influenced at least one hundred drilling decisions worldwide, and as a consequence it has generated additional value of at least $500M within the petroleum industry.

2. Underpinning research (indicative maximum 500 words)

Unlike conventional travel-time tomography, full-waveform inversion is a tomographic scheme that fully honours the physics of finite-frequency wave propagation; it is principally this feature that improves its resolution and its accuracy. The fundamentals of the method have long been understood; the intellectual challenge has been to render this theory computationally tractable and to apply it successfully to imperfect data using realisable computer hardware configurations. In the mid 1990's, Gerhard Pratt (Elf Lecturer, Imperial College, 1993-1998) and co-workers at Imperial College developed the first practical implementation of acoustic isotropic FWI in two-dimensions [1]. They developed an algorithm in the frequency domain that was orders of magnitude faster than hitherto, and demonstrated that this could successfully invert both synthetic and field seismic datasets in 2D [2].

A decade later, Professors Michael Warner (Imperial, 1993-2013), Joanna Morgan (Imperial, 1998-2013), Yanghua Wang (Imperial, 2003-2013) and their co-workers built upon these early successes to extend the method into three-dimensions, first in the frequency domain, and then into the more-effective time domain, successively incorporating attenuation, anisotropy and elastic effects. Although the extension from two to three dimensions is conceptually simple, its practical computational implementation is not. The direct solution of the wave equation that Gerhard Pratt used in 2D is not computationally feasible in 3D. Instead, the group developed iterative 3D solvers in the frequency domain, and later, massively-parallel solvers in the time domain. Since the real world is three dimensional and anisotropic, these developments were fundamental to being able to apply the methodology usefully to real industrial problems.

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 [3], for which they were awarded the Bonarelli prize by the EAGE, the leading European professional organisation in petroleum geoscience. Since then, the range of problems, targets and datasets to which the methodology can be successfully applied has continued to grow [4, 5, 6]. The first 3D anisotropic results from field data were obtained in 2010, and the first elastic results appeared in 2012.

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

[1] R.G. Pratt, Z.-M. Song, P. Williamson, M. Warner, “Two-dimensional velocity models from wide-angle seismic data by wavefield inversion”, Geophysical Journal International, Vol124, Issue 2, pp. 323-340, (1996) DOI: 10.1111/j.1365-246X.1996.tb07023.x
(The first application of 2D FWI to surface seismic data.)

* [2] R.G. Pratt, "Seismic waveform inversion in the frequency domain, Part 1: Theory and verification in a physical scale model", Geophysics, Vol 64, pp. 888-901, (1999) DOI: 10.1190/1.1444597. **(Developed FWI theory into a usable tool.)**

* [3] M. Warner, I. Stekl, A. Umpleby, "Efficient and effective 3D wavefield tomography", Paper presented at the 70th European Association of Geoscientists and Engineers Annual Conference, Rome, (2008) . http://www.earthdoc.org/publication/publicationdetails/?publication=9831
(This presentation demonstrated the first ever successful application of 3D FWI to field data. The paper was awarded the Bonarelli prize by the European Association of Geoscientists & Engineers (EAGE). Within a year of this paper, the method was being applied commercially by BP and others.)

[4] Y. Wang, Y. Rao, "Reflection seismic waveform tomography", Journal of Geophysical Research, Vol 114, Issue B03304, (2009) DOI: 10.1029/2008JB005916
(Demonstrated FWI on reflection data, thus widening the range of problems that are amenable to this technique.)

* [5] M. Warner, A. Ratcliffe, T. Nangoo, et al., "Anisotropic 3D full-waveform inversion", Geophysics, Vol 78, pp. R59-R80, (2013) DOI: 10.1190/GEO2012-0338.1
(This joint Imperial/industry paper is the first that describes how 3D FWI can be applied to invert anisotropic field data. The work was completed in 2010; full publication was embargoed by the industrial sponsors until 2013.)

[6] Members of the FWI research team appear as inventors on nine patents related to FWI: GB 1101345.5, GB 1121934.2, GB 1121932.6, GB 1206073.7, GB 1219828.9., US 2012/028470, US 2012/028504, US 2012/039057, US 2012/039077, and have held over thirty grants supporting the development and application of FWI with a total value of over £6M from three research councils, seventeen commercial partners, two government departments and two charities.

4. Details of the impact (indicative maximum 750 words)

Research at Imperial into full-waveform inversion has had two distinct impacts on the petroleum industry: one specific, where individual companies are directly using software developed at Imperial College 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 direct research contribution made by 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, borehole locations, sub-surface risk assessment and mitigation, and ultimately influencing which plays are drilled and which are not, adding consequent value to individual petroleum assets.

Generic across the petroleum sector

The petroleum industry worldwide has adopted 3D full-waveform seismic inversion as a new tool with which to improve the quality of images and interpretations of the subsurface for petroleum exploration and production. A decade ago, there was no capability to undertake 3D FWI of any description within the petroleum sector. Today, every large multinational petroleum company (BP, Chevron, ConocoPhillips, ExxonMobil, Shell, TOTAL), and many mid-sized (BG Group, DONG, ENI, Hess, Maersk, Nexen, Statoil, Tullow Oil, Woodside) and national oil companies (CNOOC, Petrobras, Saudi Aramco, Sinopec, among others), have adopted 3D FWI as part of their technical portfolio for finding and exploiting petroleum reserves. All the largest oil-field seismic service companies (CGG, ION, PGS, TGS, WesternGeco) now offer FWI as a commercial service to their oil-company clients.

Without the specific FWI research contribution made by Imperial over the past twenty years, and especially without its dissemination, validation and demonstration on key problems and datasets, the adoption of this technology would not have begun so early, and its uptake would not have developed so rapidly, so widely or so successfully.

The head of FWI research at BP and now with TOTAL [7], writes:

> "*I have been working on the topic of Full waverform inversion for about 15 years with both BP and Total. My research, and its direct application to industry problems, was made possible thanks to the technology for FWI that Gerhard Pratt conceived and developed during his time at Imperial College: which includes key publications and more practically, a 2D frequency domain FWI software that pioneered the way that the industry currently performs FWI. To this date, Gerhard's work remains the reference in the field and his outstanding contribution to the community has been recognized by the EAGE Conrad Schlumberger award* ".

The head of FWI development at Chevron [8], writes:

> *"In 2007, FWI was an untried, unproven, and potentially unaffordable technique in 3D. The paper presented at EAGE in Rome, by Warner et al in 2008, demonstrated to a sceptical industry audience that 3D FWI could be made to work efficiently and effectively on real 3D seismic data. This success convinced several companies of the value of FWI, and within a year BP was able to demonstrate the full commercial value of the technique when applied to a large field dataset. This provided a huge impetus to others to follow this early lead, and today everyone has the technology. Without this paper, and the research at Imperial that underpinned it, 3D FWI would still have happened eventually, but not so quickly, and perhaps not yet."*

Between 2008 and 2012 the industry was estimated, in a public statement made by WesternGeco at the 2012 SEG conference in Las Vegas, to have spent more than $200M on seismic data acquisition, data processing, bespoke computer hardware, software development, and novel acquisition platforms, specifically to support 3D FWI [9].

During the same period, in a public statement made on 9 June 2013 during the "Robust FWI Workshop" at the 75th EAGE Conference & Exhibition in London, BP estimated that additional value of at least $500M had been generated for the petroleum industry through the application of FWI to specific seismic datasets that have influenced at least one hundred individual drilling decisions [9]. This value is realised because improved imaging leads to improved interpretation, reduced sub-surface risk and HSE exposure, more discoveries, and more-effective oil and gas development and extraction.

<u>Specific impact in particular companies</u>

Since 2008, eighteen companies have licensed 3D FWI computer software from Imperial: BG Group, BP, CGG, Chevron, ConocoPhillips, DONG, DUGS, ENI, Hess, Ion-GX, Maersk, Nexen, Rio Tinto, Shell, TGS, TOTAL, Tullow, and Woodside [9].

Around a third of all the 3D seismic data worldwide, to which FWI has been applied, was estimated in a public statement made by CGG during the "Advances in Model Building, Imaging, and FWI Workshop" at the 2013 SEG conference in Houston, to have been analysed using software derived from that written at Imperial [9].

The head of global technology at Hess [10], writes:

> *"By 2010, a few successful 3-D Full Waveform Inversion (FWI) results had been published on modern seismic surveys. Hess conducted a worldwide review of academic consortia, and discovered that Imperial College was the only group to have FWI results on a real 3-D seismic data set. The Imperial College Fullwave consortium was, and still is, the leading academic group in 3-D full waveform inversion. Hess joined the consortium in the fall of 2010 to collaborate and learn about ways to apply FWI to real-world problems. With the assistance of Mike Warner and his staff, we immediately and successfully applied their industrial-grade code to one of our major assets, leapfrogging many companies who were trying to climb the FWI learning curve by themselves."*

The head of geophysics for BG-Group [11], writes:

> *"BG Group have supported the work at Imperial in 3D FWI since its initiation in 2006. The team at Imperial are world leading, and the results of their research and their*

software are now being used, both within BG and by our sub-contractors, to assist our exploration and production worldwide. We are also involved with Mike Warner's group in a new initiative within Brazil in commencing in 2013, which involves a >$20m investment from BG Group, and participation from the Federal University of Rio Grande Norte in Brazil and the University of British Columbia. As part of this large ongoing project, there is an advanced plan to purchase the largest high-performance computer in South America specifically to run the FWI software that Mike Warner's research team have developed."

Among the companies that have licensed the software, CGG is an oil-field service company with the largest share of the seismic services market. They offer extensive FWI services from seven centres worldwide based in London, Massy, Oslo, Houston, Rio de Janeiro, Singapore and Perth. Their FWI services are built around the software package developed at Imperial [9]. Since 2010, they have customised and integrated this 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 [5]. As a result of adopting Imperial's software, CGG has moved in three years, from a position where they did not offer FWI as a commercial service, to become the market leader in this field worldwide [9]. In order to ensure the continued development and availability of FWI as a valuable industrial tool and maintain a clear pathway to impact the spin –out company Sub –Salt Solutions is in the process of being developed.

5. Sources to corroborate the impact (indicative maximum of 10 references.)

[7] Former Head of FWI research at BP, now with Total to confirm use of the full waveform in BP and Total

[8] Head of FWI Development, Senior Staff Geophysicist with Chevron to confirm the industrial use of 3D FWI and its link to Imperial College research

[9] The Industry Technology Facilitator (ITF) act as brokers between research providers and the international petroleum industry. Their lead facilitator for exploration and production is able to provide corroboration of unpublished public statements made by the petroleum industry, and to corroborate the specifics of software licensing, software development, publication embargoes and related issues linked to FWI at Imperial College.

[10] Head of Global Technology at Hess to confirm the successful application of the industrial-grade code to their major assets.

[11] Head of Geophysics for BG Group to confirm BG plan to purchase the largest high-performance computer in South America specifically to run the FWI software that Mike Warner's research team have developed