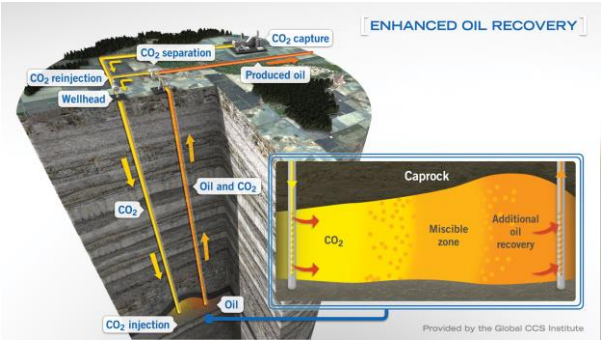
Note #7: Carbon Capture & Storage - the Industry Wavefield Inversion has been waiting for?

I will admit to bias as this is a combination of two major interests in my life, but as described in this opinion piece I honestly think we could be at the start of a new geophysical renaissance.

The importance of carbon capture is almost universally acknowledged as being a good thing - disagreements about the impact and approaches notwithstanding, the world has woken up to the need to mitigate our hydrocarbon-dependent society.

Several countries have started programmes to store CO2 within reservoirs - Northern Lights in Norway and Porthos in the Netherlands being two of the most recent European examples but worldwide there are dozens of carbon capture projects - ranging from variations in Enhanced Oil and Gas Recovery to CO2 sequestration.



All of these projects are huge engineering concerns, but the monitoring of the CO2 going into the rocks isn't being explicitly addressed and the public, wary from a history of fraccing induced seismicity and opposition to nuclear waste disposal, may choose not to "Trust us". We in the Energy Industry need to accept that and be more pellucid in our submission of evidence and justifications. I believe that geophysics will help in adding much needed transparency to the storage and monitoring of CO2.

Carbon Capture & Storage: Successes & Challenges

Concern amongst policymakers and the wider public about the possibility of containment failure makes the need for "quantitative" measurements of fluid movements within and around the reservoir key.

The Sleipner Field in Norway has a wonderful caprock that has been holding back injected CO2 for 20+ years. Geophysical evidence, in the form of multiple repeated seismic surveys ('time-lapse' or '4D'), has shown this to be the case - providing the confidence needed by participants and regulators that the technology to succeed exists.

On the other hand, the Snøhvit Field, also in Norway, saw unexpected changes from gas injection within 3 years, emphasising the need for caution and close monitoring. We only have to look at the Groningen gas field in the Netherlands to observe that movement of gases within a human lifespan can have serious implications: plans are being made to shut the field in, not because of a lack of reserves, but because of the subsidence and induced seismicity experienced by people and businesses at the surface.

There are still many technological challenges to overcome and advances to be made in order for Carbon Capture to be a success: pumping gases into rocks is not as easy as extracting them - the reservoir cannot be considered as just a "tank of sand" - pressures, temperatures and the geochemical changes means pumping tonnes of acidic gas into rocks is not a simple operation.

In rock physics, it would appear that the beloved Gassmann equation doesn't really hold up to scrutiny with injection of carbon gases into rocks; better understanding of patchy fluid substitution and more detailed measurements are going to be required to investigate this quandary further. .

Geophysical Monitoring

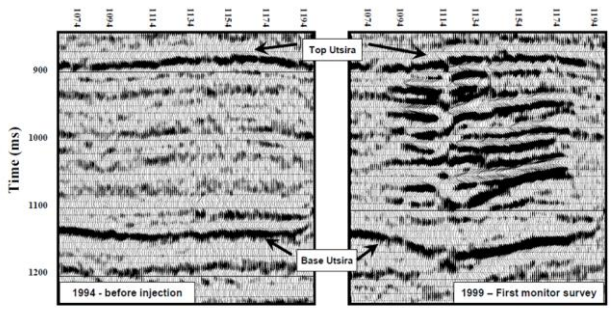
Downhole measurements will always give the most detailed subsurface information, but their lateral extent is limited, hence the need for more areally detailed investigation; geophysics fulfils that requirement.

Various mitigations to the problems of monitoring carbon-capture have been and are being actively considered for CO2 sequestration; all of which include geophysical monitoring. Historically, this focussed on interpretation of reflection seismic

CO2 accumulating in porous stratigraphy should be readily detectable by these existing seismic methods. However, leakages into lower permeability rocks may be difficult to detect from conventional techniques. Similarly, faults or fractures generated from the pumping of gases could be difficult to detect.

Time-lapse seismic has allowed quantification of fluid movement in the reservoir - injected and produced - allowing determination of areas where hydrocarbons remain unswept or where there has been pressure build-up.

This has made it possible to link the reservoir engineering world with that of geology and geophysics, providing an easily translatable language communicating quantified images of what is likely to be happening below the mudline. This makes the technology perfect for Carbon Capture and storage: it is an easily useable tool for monitoring the injection and movement of CO2.



Other good, complimentary geophysical techniques exist, such as crosshole seismic: seismic source and receivers down different wellbores can create a high-resolution mesh through the subsurface. This results in higher resolution and gives the potential to identify leakage from faults directly in the subsurface, but only if sufficient well penetrations exist.

Seismic inversion is a technique which attempts to determine the properties of the rocks and fluids within the subsurface, and aims to marry up the increased resolution of techniques like crosshole into the conventional seismic domain.

Over the last decade and a half, seismic and its derivatives have been replaced by probabilities: lithology, fluid type etc. Advances in seismic acquisition have significantly reduced the *a-priori* information or bias from wellbore interpolation – creating an excellent way of disseminating information that be utilised in a more cohesive, integrated approach.

As mentioned, seismic data has blossomed in acquisition speed, aperture, frequency content and sampling density. But what happens to a lot of the data?

It gets canned: turning rays, converted waves, multiples and refractions are routinely removed leaving only reflections. Processing this data takes time. There are numerous challenges and copious amounts of QC that goes into getting the correct seismic output - seismic data is not colour-by-numbers painting with a simple set of instructions to follow, but bespoke restoration of an image.

Furthermore, things can and do go wrong: stacking of data that wipes out polarity reversals, smoothing algorithms that reduce fault offsets and belief that reprocessing can render a problem with the acquisition obsolete are just some I've come across over the years.

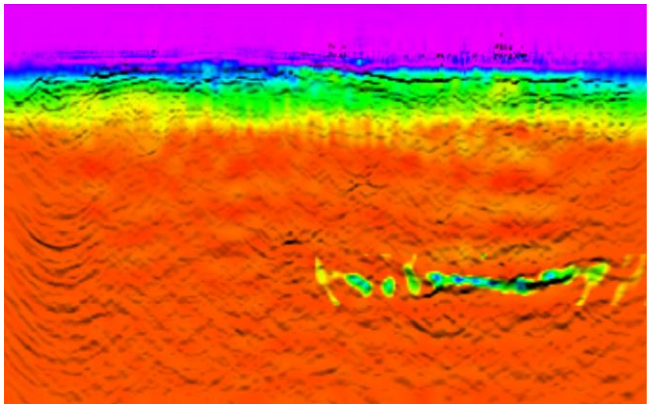
This is not a slight on convention, it's worked remarkably well up to now; but with the dawn of a new energy era, it's time to expand our thinking.

Wavefield Inversion

The ultimate goal of seismic inversion is to translate raw seismic data directly into subsurface velocity and density. This approach is known as wavefield inversion – a process in which the entire wavefield, not just the reflections, are used to create the result.

There are two generalised perspectives: frequency-domain and time-domain wavefield inversion. The former allows for the fast computation of velocities and is used by seismic service companies to aid in velocity modelling for migrations, often called Full Waveform Inversion (FWI).

Time-domain wavefield inversion has several advantages: it does not require wavelets derived from subjective well-to-seismic ties and, while regular seismic processing is limited to a constant sampling rate (usually 4ms) wavefield inversion can vary the vertical sampling - going from a coarse grid in the overburden to a much finer grid within the zone of interest, only limited by the acquisition sampling, typically 1 or 2 ms.



Computationally expensive when first developed, time-domain wavefield inversion is emerging into the mainstream, and just in time: monitoring the injection of gas into the subsurface will need the highest resolution and best images as quickly as possible.

Huang et. al, in the May 2021 issue of the SEG Leading Edge point to commercial success in getting acoustic full waveform inversion results from 3D data in weeks after acquisition – the algorithms and computational power is there to generate a new geophysical renaissance.

Way Forward

Current plans to mitigate the effects of climate change include Carbon Capture and Storage, using oil and gas technologies to store rather than produce gas.

Putting gas into a reservoir is not new - it's the type of gas that has changed and the implications of leakage are significant. Wavefield inversion holds the potential to get higher fidelity results, more quickly, to help establish clear, communicable images of successful carbon dioxide sequestration to the public and policymakers.

Capitalism will always drive industry so having an economic carbon price will help. Recent prices are approaching that of oil ($50) and this allows our industry to contribute to the solution to the problem exacerbated by our consumption of hydrocarbons; giving geoscientists a continuing role, through acquisition, processing and interpretation of seismic data to monitor CO2 storage.