



London Petrophysical Society
Presents:



Sounds from the Ground:

Uses and applications of sub-surface acoustics

Thursday 23rd June 2016

The Geological Society, Burlington House, London

Start time	End time	Name	Company	Talk Title
09:00	09:30	Registration		
09:30	09:40	Michael O'Keefe	LPS	Welcome & Introduction
09:40	10:15	Peter Fitch	Imperial College	Beginners guide to the soundtrack of the borehole
10:15	10:45	Said Assous	Weatherford	Borehole Acoustic Processing Methods: A review
10:45	11:15	Break		
11:15	11:45	Saad Kisra	Schlumberger	When can you trust a sonic curve?
11:45	12:15	Marek Kozak	SuperSonic Geophysical	How to evaluate the quality of borehole acoustic data
12:15	12:45	Iain Whyte	Tullow Oil	LWD Sonic Cement Logging: Benefits, Applicability, and Novel Uses for Assessing Well Integrity
12:45	13:45	Lunch		
13:45	14:30	Jennifer Market	SPWLA Distinguished Speaker	Untangling Acoustic Anisotropy
14:30	15:00	Phillip Tracadas	Halliburton	Measurement of Anisotropy Using Advanced Tools & Techniques
15:00	15:30	Break		
15:30	16:00	Geoff Page	Baker Hughes	Away from the borehole - filling the gap between logs & seismic
16:00	16:30	Andy Chadwick	BGS	Understanding the evolution of the injected CO ₂ plume at Sleipner: Integrating high resolution time-lapse seismic imaging and numerical fluid flow modelling
16:30	16:40	Michael O'Keefe	LPS	Closing Comments
16:40 onwards	Refreshments			

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The following pages contain the Abstracts

Beginners guide to the soundtrack of the borehole.

Peter Fitch, Department of Earth Science & Engineering, Imperial College London. (p.fitch@imperial.ac.uk)

Within the *medley* of the logging tools, the *solo* act that forms the focus of this *album* of talks is the Sonic, or *acoustic* log. At the *bass* level, the sonic log is a measure of the time taken for a sound wave to travel through 1 foot of the formation. The *tempo*, or rather the travel time of the sound wave (Δt or DT, normally measured in microseconds per foot, $\mu\text{s}/\text{ft}$) depends on the *harmony* between the world famous *trio* of lithology, porosity and saturating fluids of the formation. Interval travel or *transit time* is the reciprocal of the velocity of a sound wave. Therefore if the *duet* between lithology and fluid type are known then the *crescendo* of the sonic log is an *a-cappella* estimate of porosity. The following track list summarises the key points introduced in this introduction:

Track 1: More than a feeling (Boston) – In the simplest sense, the sonic tool consists of a transmitter that emits a sound wave pulse and one or more receivers at a set distance apart that pick up the wave as it moves past the receiver.

Track 2: With or Without You (U2) – Three main types of sonic wave can be detected by borehole tools: the compressional or *P* wave, the shear or *S* wave, and the Stoneley (*St*) wave.

Track 3: Pinball Wizard (The Who) – In a dense, well cemented and consolidated rock with low porosity *P*-waves will move quickly through the formation, i.e. sound wave velocities (V_p) will be high. As transit time and velocity are inversely proportional, *P*-wave transit times will be low. Typically high porosity formations = high transit times, and low porosity formations = low transit times.

Track 4: Handbags & Gladrags (Rod Stewart) – Sonic tools use ultrasonic transmitters which produce short pulses of sound at regular intervals. The sound waves used are typically in the frequency of 500 Hz to 30 kHz. Typical transmitter(s) used by most wireline tools are piezoelectric transducers that convert sound waves (pressure pulses) into electromagnetic signals.

Track 5: Drove all night (Cindy Lauper) – The transmitter emits sound waves in all directions. The wave which has travelled from the transmitter directly through the mud column in the borehole is known as the *mud* wave. The mud wave will travel at low velocities through the low density drilling mud. Other *P*-waves will move through the drilling mud and into the formation.

Track 6: Are you gonna go my way (Lenny Kravitz) – At the interface between the borehole and the formation, waves intersecting the borehole wall at a critical angle will be refracted into the formation. As the *P*-wave moves through the formation its energy is dissipated and velocity is reduced. When the wave is slowed to a critical velocity the wave is refracted back into the borehole mud and towards the tool receiver.

Track 7: Got the time (Anthrax) – The time elapsed between detection of the first *P*-wave at the first and second receiver is measured. The average value measured by the two transmitters is calculated and presented as the *P*-wave transit time, compensating for any borehole effect (e.g. rugosity).

Track 8: Crazy (Aerosmith) – Qualitative, visual identification of lithology and porous formations. The travel time of the sound wave (Δt or DT, $\mu\text{sec}/\text{ft}$) depends on the rock matrix, porosity and saturating fluids of the formation. Porosity will increase transit times.

Track 9: Don't stop believin' (Journey) – Quantitative estimates of porosity include the Wyllie Time-Average and Raymer-Hunt-Gardner Equations.

Track 10: Cum on feel the Noize (Slade) – We will end by looking at some acoustic problems associated with cycle skipping, borehole damage, and abnormal formation pressures.

Borehole acoustic array processing methods: a review

Said Assous, Weatherford International Ltd.

Borehole acoustic measurements reflect a multitude of reservoir and wellbore properties. Compressional (P), shear (S), Stoneley (St) and flexural (FL) wave velocities (commonly expressed as slowness, inverse of velocity) are used alone or in combination with other measurements to infer porosity, permeability, lithology, pore pressure, anisotropy, fluid type, stress direction, the presence and alignment of fractures and the quality of casing-cement bonds. Compressional and refracted shear slowness from monopole sources are commonly determined using Slowness-Time Coherence (STC) processing, but this is not appropriate for the dispersive Stoneley and dipole flexural modes whose slowness depends on frequency. For these modes there are multiple processing options, including Weighted Spectral Semblance (WSS), Prony, Matrix Pencil, ARPS, and Phase-Moveout. This talk discusses the signal processing challenges associated with the dispersive modes, and highlights the advantages and disadvantages of the principal methods, using both synthetic and field data sets.

When can you trust a sonic curve? Or, why acoustic dispersion analysis is the ultimate QC for slownesses

Saad Kisra, Irina Mikhaltseva, Schlumberger

There are numerous end users of acoustic slownesses, including geophysicists, petrophysicists, and geomechanics and drilling engineers. In our industry, semblance-based processing is the standard, and it is commonly accepted that a slowness curve obtained from a sonic array tool is reliable when it is supported by a strong coherent signal over a number of receiver arrays. However, there are many common occasions when this is not correct, such as in the presence of dispersive modes in multipole signals or when the processing parameters (such as filter bandwidth) are not adjusted to the environmental conditions. In such cases, the analysis of the waveforms in the frequency – slowness space (also known as dispersion analysis) is key to identifying the problematic results and obtaining slownesses that reflect the formation properties.

It is well known that the signal obtained from the excitation of a borehole depends primarily on (1) the formation slownesses; (2) formation bulk density; (3) borehole diameter and shape (4) borehole fluid slowness and density; (5) type of transmitter (monopole, dipole or quadrupole); and (6) more complex effects such as formation alteration, tool presence and tool position in the borehole, and formation anisotropy (fracturing, layering or stress). Typically in dispersion analysis, the measured dispersion curves are plotted on top of a theoretical curve calculated based on a homogeneous-isotropic model recorded in a perfectly circular borehole with a perfectly centralized tool. All differences between the measurement and the model curve are interpreted as a deviation from the ideal scenario described above.

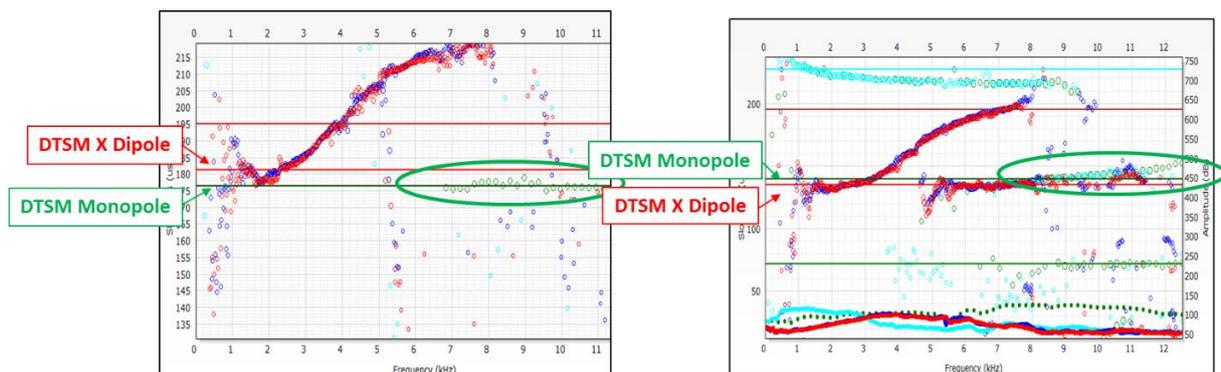


Figure 1: The left figure shows that the dipole shear slowness from the X-dipole is overestimated by 8 us/ft due to non-optimal processing parameters. The right figure shows an example of the shear slowness as extracted from the monopole firing overestimating the formation shear slowness by 5 us/ft due to dispersion.

Using field examples from a wireline dipole sonic tool and a logging-while-drilling (LWD) quadrupole tool, we show various scenarios where the dispersive behaviour of some borehole modes can cause semblance-based methods to estimate the wrong slowness. For instance, the figure shows two examples where dispersion analysis is able to discriminate which arrival is associated with the correct slowness which one is affected by dispersive modes in the borehole.

How to evaluate the quality of borehole acoustic data

Marek Kozak, SuperSonic Geophysical LLC

Modern borehole acoustic tools, both a wireline and LWD, are based on segmented receiver architecture. It means that at each receiver level the sensors are capable of recording the data incoming from various radially separated azimuths. In a wireline case there are typically four of them; in LWD world there is one segment in a Unipole source architecture and up to the four of them in the quadrupole excitations. This concept was developed and implemented due to the need to control the characteristics of received wave form data. For example – a dipole source should excite flexural wave forms that are phase reversed as measured across 180 degree angular separations at each receiver station. From the other hand – the monopole source generated wave forms (e.g. compressional and/or Stoneley) should be arriving in phase. Segmented receiver architecture allows to measure and to verify wave form propagation mode(s) based on the phase characteristics. We propose to augment classic semblance method with processing based on segmented architecture receiver data. In the case of good tool centralization and correct receiver calibration the segmented results are expected to be similar as measured across each segment of the tool (e.g. the travel times, slowness values and semblance peaks). Otherwise; single receiver side processing ought to be used.

***Marek Kozak** is co-owner and Principal Researcher at SuperSonic Geophysical LLC, a California company offering since 2001 consulting, data processing, and software design services to companies developing acoustic well logging technology. His primary area of interest is development and application of methods for processing of acoustic logging data acquired under difficult conditions.*

Dr. Kozak received a M.Sc. in Computer Science in 1978, and PhD in EE/Measurement Systems in 1990, both from the Warsaw University of Technology where he was assistant professor from 1978 to 1990. In 1990 he moved to California and joined Magnetic Pulse Inc. of Fremont where he held various positions, being instrumental in development of pulsed power wireline induction and full wave dipole acoustic tools, and processing software.

LWD Sonic Cement Logging: Benefits, Applicability, and Novel Uses for Assessing Well Integrity

Iain Whyte, Tullow Oil

With the ongoing changes affecting the global drilling industry, well integrity has become an area of great engineering focus and development. Cement bond analysis is of key interest as the consequences of failed, or partially complete, cementing operations can, at best, be a costly delay in drilling operations and, at worst, an extremely hazardous safety issue.

Traditionally, wireline acoustic tools have been used to analyze the quality of the cement bond between the casing and the formation. Wireline tools have been developed over many years to produce high-quality assessments of cement bond, which can then be confidently used to confirm well integrity. However, the conveyance method requires that the analysis be performed on the critical path and also that additional methods be used in high-angle wells. Logging-while-drilling (LWD) technology offers a potential alternative without these issues, provided the current limitations of the technology are understood and its applicability properly assessed as a fit-for-purpose solution. As a minimum, the LWD logging technique can provide a trigger as to whether more advanced logging techniques must be deployed or can be avoided.

This presentation explores the applicability of LWD sonic tools to the analysis of cement behind casing. It considers both the currently accepted deliverable of top of cement (TOC) analysis, along with examples of more advanced processing techniques and their comparison to wireline cement evaluation, providing case study examples in each case. The benefits and limitations of these methods will be discussed, along with operational considerations to aid in successful logging, including the use of repeat logging passes to indicate changes in cement quality with time. The use of LWD sonic tools to identify casing collar connections on driller's depth, enabling the safe positioning of cased-hole whipstocks, is also covered, demonstrating a novel and little-used application of LWD technology.

Iain Whyte is the Group Operations Petrophysics Lead for Tullow Oil based in London, supporting all Tullow locations globally. Iain joined Tullow in 2010, having previously worked for BP in a variety of roles over a 7-year period, originally an Operations Petrophysicist in Turkey, Angola, Norway, and Caspian Sea for BP and lately a Petrophysicist for Shah Deniz massive gas exploration and development project in Azerbaijan. Prior to his time at BP, Iain worked for Weatherford Wireline as a logging engineer for 1 year and Baker Atlas for 7 years. Iain is a member of SPWLA and SPE and is Past President of Technology for the London Petrophysical Society. Iain is also the Assistant General Chairman of the SPWLA 2018 Annual Symposium organising committee which will be held in London in 2018.

Untangling Acoustic Anisotropy

Jennifer Market, Weatherford International Ltd. SPWLA Distinguished Speaker 2015

Acoustic anisotropy analysis is used in a wide variety of applications, such as fracture characterisation, wellbore stability, production enhancement, and geosteering. However, the methods by which acoustic anisotropy are determined are not always well understood, both by the end user and the data analyst. Azimuthal variations in velocities may be due to stress variations, intrinsic anisotropy, bed boundaries, or some combination thereof. Environmental effects such as hole inclination, centralization, wellbore condition, dispersion and source/receiver matching affect the viability of the data and must be considered in the interpretation. Untangling the various acoustic anisotropy factors is essential to effectively interpreting the results.

The presentation begins with a discussion of the types of acoustic anisotropy, followed by a review of common industry methods for extracting anisotropy from wireline and LWD azimuthal sonic data. Environmental factors such as tool centralization, irregular borehole shape, poor tool calibration, and dispersion are considered, paying particular attention to the practical limitations of acquiring data suitable for high quality anisotropy analysis in adverse conditions.

Quality control techniques are discussed in some detail, as there are various causes of “false anisotropy” that should be recognized so as not to incorrectly interpret processing artefacts as formation features. Quality control plots are suggested to aid the non-specialist in determining whether the anisotropy results are viable. Intrinsic, induced, and geometric anisotropy are discussed in detail, along with consideration of the depth if sensitivity of acoustic measurements. Finally, a case study is presented to illustrate the art of untangling overlapping acoustic anisotropy responses.



Jennifer Market is the global acoustics advisor for Weatherford. Her role involves acoustic data processing and interpretation, along with development of software and new application. She also provides industry training seminars to widen the understanding of acoustic data acquisition and applications. She has 15+years' experience in borehole acoustics, working in a service company to develop acoustics tools and applications. She frequently publishes articles for both SPWLA and SPE and was an SPWLA lecturer in 2008-2009, 2011-2012, and 2015-2016 as well as a SPE Distinguished lecturer 2014-2105.

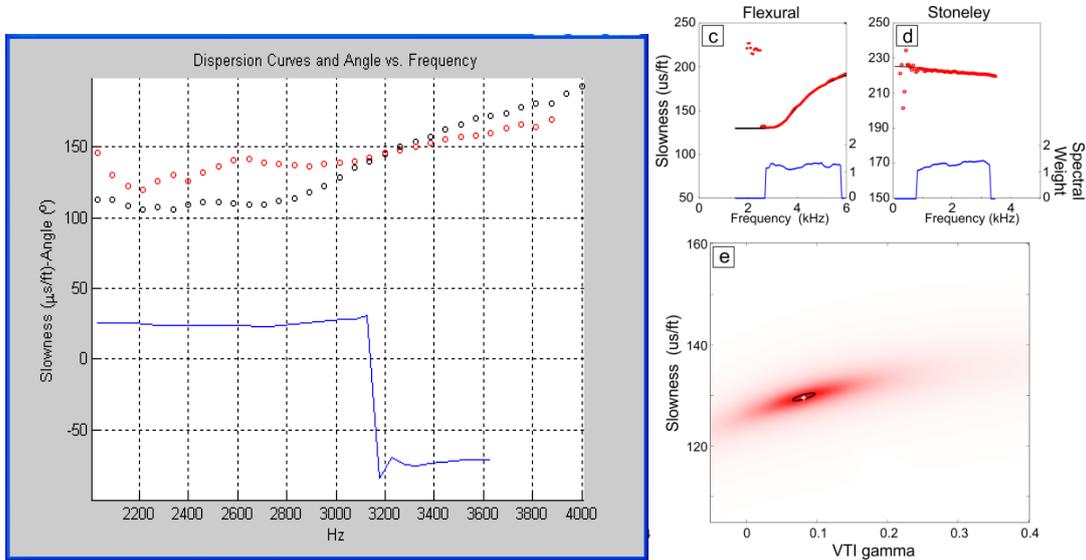
Measurement of Anisotropy Using Advanced Tools and Techniques

Philip Tracadas (presenter) Global Acoustics Product Champion, Halliburton, Mark Collins, Ruijia Wang (authors), Halliburton

Two types of acoustic anisotropy can be directly measured by wireline sonic tools and recorded into logs. For cross-dipole acoustic log waveforms in boreholes oriented in formations with horizontal transverse isotropy (HTI), an analytic algorithm has been developed that gives a precise global minimum solution that measures fast axis direction and related error estimate. For low-frequency monopole (Stoneley) and dipole (flexural) log waveforms in boreholes oriented in formations with vertical transverse isotropy (VTI), an inversion algorithm that matches theoretical to waveform-derived dispersion curves gives a log of the Thomsen gamma parameter.

Conventional algorithms for HTI measurement work by minimizing an objective function using numerical search methods (such as very fast simulated annealing) or by evaluating the objective function on a fine grid in the parameter space (ie. brute force); however, this is never necessary with cross-dipole waveforms as an analytic relation exists for the angle between a tool's dipole axis and the formation's fast axis. Analytic computation relative to numerical computation provides several advantages including assured global minimum finding in the objective function, related error bars, and both time and frequency-domain solution configurations. The frequency versus fast angle solution helps to quantify the anisotropy mechanism (i.e. stress, fabric, etc.). Vertical depth resolution and measure point of the algorithm are also clarified.

The measurement of VTI anisotropy depends on high-fidelity waveforms with wide-band (~1 to ~7 kHz, depending on formation slowness) dispersive content, characterization of the tool effect on the mode dispersion curves, and an accurate measurement of mud speed. In the low-frequency portion of the waveform band, the Stoneley mode is sensitive to horizontal shear slowness and the flexural (dipole) mode is sensitive to vertical shear slowness. Mud slowness must be directly measured or globally inverted from the data in order to anchor the inversion in the high-frequency portion of the waveform band.



(Left) Frequency versus HTI fast angle solution (blue) can assess the anisotropy mechanism reflected in the fast (black) and slow (red) rotated waveform dispersions. (Right) VTI gamma solution (lower right) based on inversion of high-fidelity dispersion curves (upper right, red) with models (black) using an adaptive weighting scheme (blue).

Away from the Borehole – Filling the gap between logs and seismic

Geoff Page, EARC Region Petrophysics Advisor, Baker Hughes Incorporated, Aberdeen.

The majority of logging instruments, whether wireline or LWD, only see a few feet (or even inches) away from a wellbore, and have a similar vertical resolution. Seismic data can see an entire reservoir but with a resolution of 10's or even 100's of feet. How can we fill the gap between?

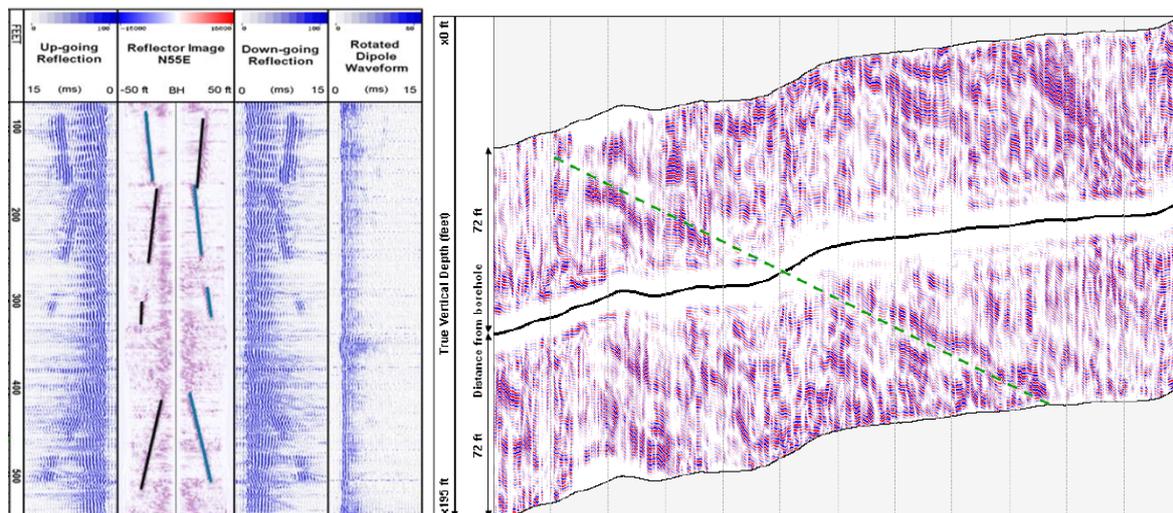
Recent developments of deep reading resistivity instruments allow wells to be navigated relative to bed boundaries, and help fill the gap, but also use fairly crude layered models. These have been discussed in detail at previous Symposiums.

In the early 1980's people were experimenting with using specialist acoustic wireline instruments with extreme transmitter-receiver spacings (25m) to attempt to take seismic imaging downhole, use higher frequencies, and get a better structural image of the near wellbore. These were successful in seeing up to 10 or 20ft away.

More recently standard array type acoustic logging instruments have been used in this mode. As well as acquiring "Delta-T" type data, they could acquire data that could be processed to image near wellbore structures. This was considerably improved a few years ago when the introduction of imaging using shear waves enabled not only seeing deeper – up to 60ft, but also azimuthally in order to determine the strike of imaged "features". This has now been enhanced to "see" over 100ft away from the wellbore, at higher frequencies and in far more detail than wellbore seismic.

Another important benefit of using shear waves is that fractures have a very high shear energy reflectivity; hence this type of imaging has been used extensively in wells which are to be hydraulically frac'd – either to target the frac to/away from natural fractures pre-treatment, or to image the results of the stimulation.

Combining wellbore imagers, (resistivity and Ultrasonic), with Acoustic imaging, resistivity and seismic now allows us to see the reservoir structure at all scales from <1" to the entire reservoir.

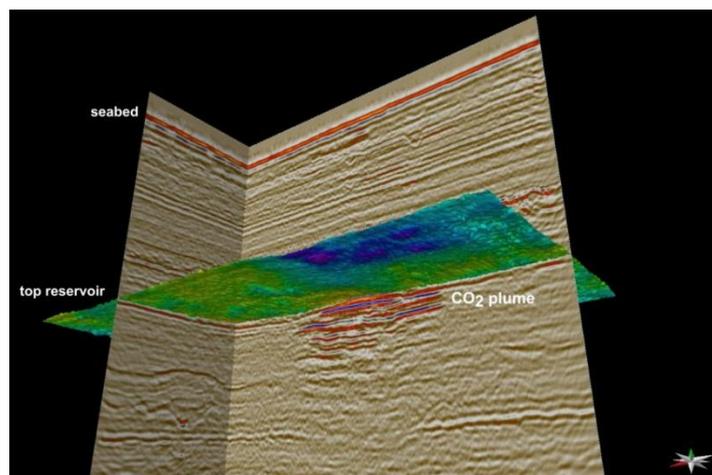


Understanding the evolution of the injected CO₂ plume at Sleipner: Integrating high resolution time-lapse seismic imaging and numerical fluid flow modelling

Andy Chadwick, British Geological Survey, Keyworth

Since 1996, the Sleipner CO₂ storage operation in the Norwegian North Sea has injected more than 15 million tonnes of CO₂ into the Utsira Sand, a major saline aquifer. Time-lapse 3D seismic monitoring datasets provide unique images of a developing CO₂ plume in a sandstone reservoir of relatively simple structure. The plume is imaged as a tiered feature, comprising a number of subhorizontal layers of CO₂ each trapped beneath a thin intra-reservoir mudstone. The CO₂ layers vary in thickness from zero at their outer edges to more than ten metres thick in the axial part of the plume.

The topmost CO₂ layer is accumulating beneath the reservoir topseal with its lateral spread closely controlled by buoyancy-driven flow beneath the topseal topography. Recent higher resolution 3D data, acquired with a dual-sensor streamer, have explicitly resolved reflections from the top and from the base of this layer. The unprecedented imaging detail has allowed accurate mapping of layer geometry and independent estimation of layer velocity. The monitoring results are used to calibrate high resolution numerical fluid flow models of the layer evolution, enabling verification of migration and trapping processes in the storage reservoir, and prediction of future behaviour. This level of understanding is required to satisfy the European regulatory regime for underground CO₂ storage.



Seismic image of the CO₂ plume at Sleipner, extracted from the 2006 3D dataset with over 8 million tonnes of CO₂ stored.

Andy Chadwick has nearly forty years' experience in most aspects of seismic geophysics, structural geology and basin analysis and is currently an Individual Merit Research Scientist at the British Geological Survey. Since 1998 he has become increasingly involved with underground CO₂ storage, participating in many European CO₂ research projects and a number of others funded by the UK and overseas governments, research councils and industry. Andy's main interests lie in storage site performance prediction and monitoring. Current research directions include quantitative analysis of time-lapse seismic data to characterise CO₂ plumes, and history-matched flow modelling to understand detailed modes of CO₂ migration in reservoirs. Andy has advised a number of national and international regulatory bodies and is particularly interested in developing pragmatic integrated monitoring systems and strategies for industrial-scale storage sites that meet anticipated regulatory requirements. He has published over 150 scientific papers and books on a range of topics including more than sixty on CCS.