ADR – an EM tool for surface based remote sensing of deep subsurface geology

Contents are shown for ease of navigation and overview of the draft.

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PART A: Theory

Introduction

History of ADR

Atomic Dielectric Resonance (ADR) is a radio wave technique for remote sensing of the deep subsurface (up to ~ 3km). The ability of radio waves and RADAR to penetrate the subsurface was first recognised about 1910 and was used to measure glacial ice thicknesses in the 1920's in the Alps **(Mansilla C., 2006).** Military interest in the sub-surface applications of RADAR eventually led in the 1970's to the advent of commercial ground penetrating radar techniques (GPR) focussed on the shallow subsurface. During the 1980's air and space borne applications of synthetic aperture radar (SAR) showed the subsurface could be remotely imaged, and the importance of using narrow beams and lower frequencies to do so **(Stove, G. 2009, 2011 & 2012)**. More recently the ESA Mars Express probe MARSIS has detected ice layers and subterranean lakes at the Martian Poles to depths of 1km **(Lauro et al. 2010; Trautner and Grard, 2003).** The emergence of beamed LIDAR technologies in the 80's and 90's raised awareness of the potential for similar approaches with radio and microwave frequencies **(Stove G., 2012).**

Founded in 1994, Adrok Ltd is engaged in ongoing electromagnetic (EM) tool development, with its key objective being commercial application of metre to decametre scale imaging of the subsurface with low frequency radio waves, to km-scale depths. Projects undertaken have involved the minerals, hydrogeology, geothermal, and hydrocarbon sectors.

Theory of ADR

When electromagnetic waves (EM) encounter a ”barrier” of matter, one or more of three things happens – reflection, transmission, or absorption. These processes also polarise the reflected or transmitted EM to varying degrees. The relative proportion of each response depends on the signal frequency and wavelength, it’s intensity and the barrier itself – its chemistry, physical structure and thickness. Visible light is obstructed by solids because its wavelengths interact with the molecular structures, leading to rapid dissipation and scattering. Radio waves travel through solids with less disruption because their wavelengths are too large to care about these smaller details, just as a large ship cares little about a choppy sea, whereas a dinghy might.

Materials absorb electromagnetic waves differently, depending on their molecular level structures. Atomic dielectric resonance technology exploits this material specific response by transmitting electromagnetic waves to a subsurface material and recording the reflected signal. The subsurface responses are recorded in time, and spectrally analysed for energy, frequency and phase, utilising Fast Fourier Transform analysis (FFT). From this information, and by utilising Maxwell’s equations and Debeye polarisation models, three key variables for the material can be derived – the relative permittivity, magnetic permeability, and electric conductivity **(Stove G., 2012; Stove G. et al. 2018)**. The most interesting of these is the relative permittivity. This is also sometimes called the relative permittivity (relative to a vacuum) or dielectric constant. The former term is used in the rest of this paper.

The EM reflection processing is similar in some respects to seismic – the velocity of EM waves within low energy loss materials is controlled by the relative permittivity **(Chang-Min, 2012, Martinez & Byrnes, 2001)**, and so depth conversion can be completed through similar ray tracing or normal moveout techniques, and the relative permittivity can ultimately be backed out from TWT **(Stove G., 2011)**. EM waves and their associated quantum scale effects leads to differences with purely acoustic waves. One key difference is the additional frequency response generated at the target related to the resonant frequency of the material illuminated and useful for target identification **(Toribio et al 2003; Liu & Shuley, 2006; Stove G. et al., 2009; Stove C., 2010; Stove G. 2012,)**.

Differences with other EM

ADR is a time-domain based electromagnetic method like ground penetrating radar (GPR). They both utilise radio waves, but GPR is omnidirectional and uses higher frequencies with less depth penetration. GPR is concerned only with the top few metres of the subsurface and primarily with reflector geometry. Unlike ADR it is less concerned with backing out the relative permittivity to help ascertain material character.

Other EM techniques such as marine controlled source electromagnetic methods (CSEM) or magnetotellurics, measure the polarisation or resistivity changes induced by external electric and magnetic fields – from natural or controlled artificial sources. Unlike the instantaneous changes of ADR reflections, these responses happen slowly in time and hence resolve spatially large objects rather than high detail. ADR is fundamentally different in pursuing metre to decametre scale changes at km scale depths.

Tool acquisition and types of scan

The tool itself is easily deployable, transported by backpack if necessary, to any terrain people can reach. There are three distinct types of scan, which serve different purposes, and these are discussed in more detail in multiple Adrok publications **(e.g. Stove G. et al 2011, Stove G. et al 2013, Stove G. et al 2018)**. To complete thorough time-depth calibrated studies all three are usually conducted.

A STARE scan is a detailed spot location scan. It addresses noise reduction and statistical analysis of return signal at a particular site. It performs a repeat pulse transmission typically about 5000 times and receives a set of time domain traces to allow stacking and correlation analysis. The transmitter and receiver reside at the same location.

The P-scan is a less detailed linear scan. Like GPR it moves the transmitter and receiver assembly at a constant speed along a surface scan line. It is essentially the same procedure as a STARE but spread over a slice of the subsurface.

The WARR scan differs from the previous types in having a separation between the transmitter and receiver. This enables use of hyperbolic move-out techniques and ray-tracing velocity analysis like those used for seismic. These are used to map time to depth and to derive the relative permittivity as a function of depth.

Field work for a set of scans is usually accomplished in a matter of weeks. Further information on the different processing algorithms can be found in **Stove et al 2018**. The versatility and negligible environmental impact of the tool is a great bonus for geophysical exploration in areas where it might not otherwise be considered, such as in remote or rugged areas, or in urban and industrial developments. As with other electromagnetic techniques, the abundance of noise in such areas is an issue and the treatment of noise issues is covered in a later section. The extent to which noise has been successfully eliminated during processing is another subject of enquiry for this study, and certainly remains an ongoing aspect of tool and data processing workflow.

Curve types

Figure 1 shows example output from a well in Weald Basin. A total of 17 basic ADR curves are routinely used in this study's analysis, capturing different elements and analyses of the returned signal. These different elements provide a method of enhancing uniqueness associated with individual lithological and pore fluid responses. The curves employ use of time bins to stack data, typically corresponding to depth bins of about 40-60 m.

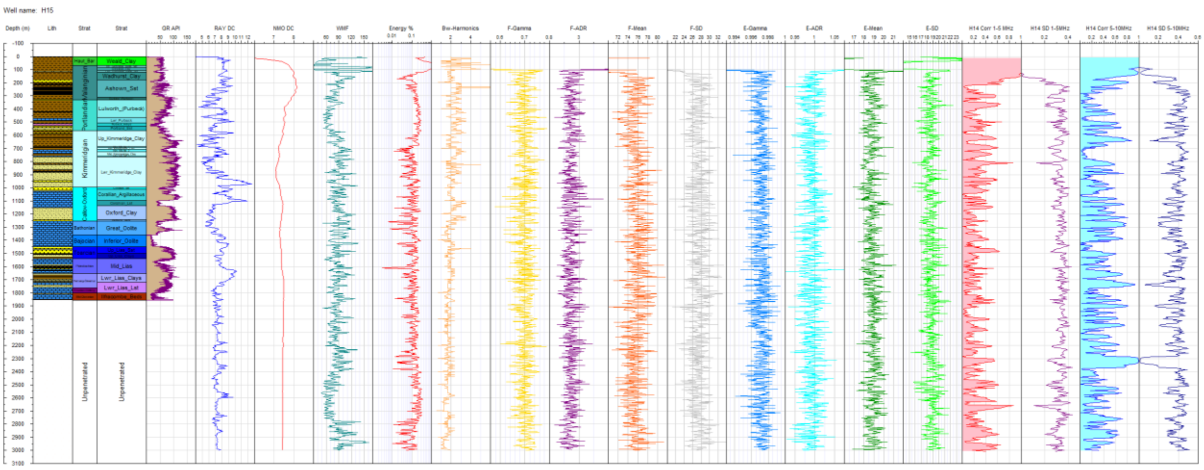


Figure 1: Example ADR output from the ADR basin

RayDC & NMO DC

Two independent estimates of the relative permittivity or dielectric constant (DC) are produced from the analysis, allowing DC curves to be plotted as a function of depth– RAY DC and NMO DC. The former is provided by ray-tracing and finite-difference techniques and the latter by normal moveout. These curves require a WARR scan. The RAY DC workflow produces a higher resolution curve than the NMO one.

WMF & ElogA

The weighted mean frequency curve or WMF is an average frequency response for a given depth, weighted towards those energies that are especially energetic. In contrast, the ElogA curve is related to the total energy response of the depth in question.

E&F curves

Fgamma and Egamma curves are concerned with the frequency and energy reflectivity of the interval. Fmean, FSD, Emean, and ESD record the mean and standard deviation of frequencies and energies over the measured thickness and include information from the whole range of frequencies. FADR and EADR measure the resonant frequency and energies of the subsurface and are related to the means divided by the standard deviation.

Correlation curves

Correlation curves require a STARE scan. During such a scan, 1000 frequency traces can be repeated up to 100 times producing 100000 wave packets. This increases the signal to noise ratio, filtering out any short-term temporal variations. For the stacked traces, correlation and standard deviation curves are produced for various frequency bins, typically 1-5MHz and 5-10MHz. Intervals where the correlation value is high, or exceeds the standard deviation, are attributed a higher reliability.

Bandwidth Harmonics

Fast Fourier Transform (FFT) analysis of the received signals into constituent frequencies is performed. The number of bandwidth harmonics recognised above noise levels is analysed for each interval and produced as a trace.

Key Technical Issues

Character

ADR logs, as illustrated in **Figure 1**, are different in character to typical logs. The number of distinctive responses are less. This is to be expected and does not detract from the usefulness of responses that are distinctive. A good understanding of what is being measured is important in this context.

Relative permittivity of rocks

Laboratory experiments have established the relative permittivity of a large number of minerals, liquids, gases, and rocks. Some of these are shown in **Figure 3 and Figure 3 .**The relative permittivity controls how polarised a dielectric material becomes in the presence of an applied electric field – which is itself dictated by the distribution of charge within a molecule. Water is a highly polar molecule (uneven internal distribution of charge), so in liquid form this means it is highly polarised when subject to electromagnetic fields.

This gift to electromagnetic exploration means that the relative permittivity of water is 80 to 81, which compares with most rocks and minerals, in the range 4-16, and with hydrocarbons in the range 1-2. Hence, if the relative permittivity can be ascertained at depth, it potentially allows resolution of porosity and fluid saturations, including both water and hydrocarbons.

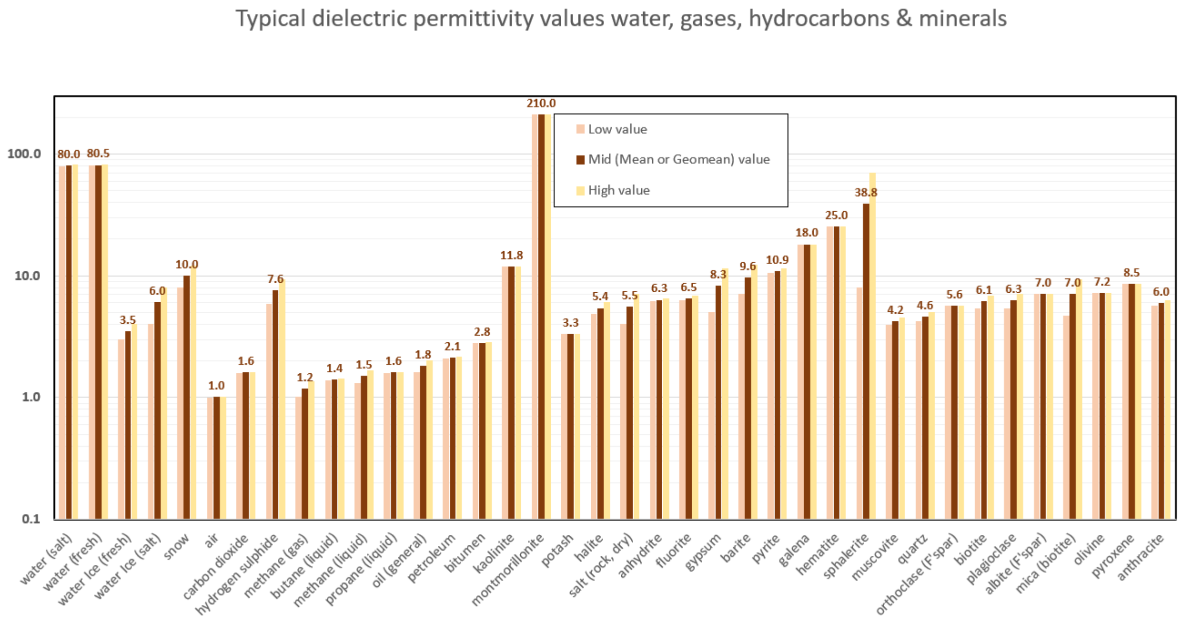


Figure 2: Relative Permittivity (dielectric constant) values for fluids and minerals in typical sedimentary basins

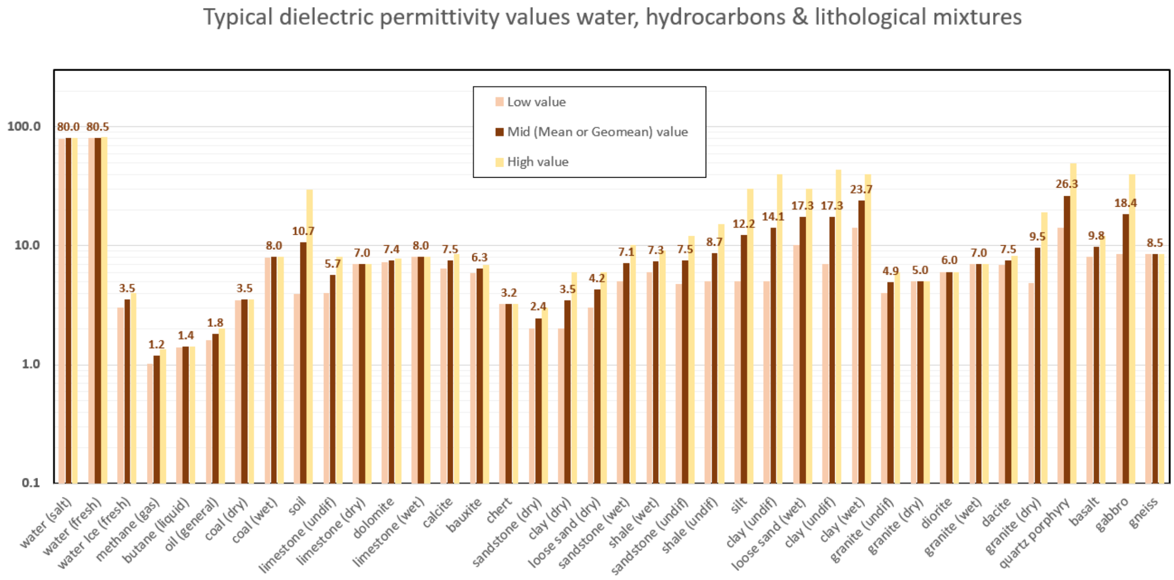


Figure 3: : Relative Permittivity (dielectric constant) values for fluids and rock types in typical sedimentary basins

The relative permittivity of a sandstone is a direct function of porosity **(Knight & Mur, 1987; Martinez & Byrnes, 2001).** While it is sometimes regarded as constant, it does vary with temperature, pressure, and frequency. These changes are mostly very slight over atmospheric and sedimentary basin subsurface ranges, and tool frequency ranges and so reference to a constant is not a bad approximation **(Martinez and Byrnes, 2001)**. In practice, variations due to material composition and structure in a complex rock mixture likely overwhelm any variations due to temperature or pressure.

It is important to review ADR data in this context of a strong influence from water content. A key difficulty is that rock forming minerals of any rock matrix have a large degree of overlap for relative permittivity value and the backing-out unique solutions for lithology from the relative permittivity alone can be difficult. For example, some shales and sandstones might have similar mineralogy and overall water content, in which case a relative permittivity contrast between them may not be pronounced.

The spectroscopic analysis of frequencies and their energies, and lithostratigraphic calibration with multiple wells, is therefore useful in constraining uniqueness. With time, understanding the relative permittivity contrasts and other curve responses peculiar to a local basin stratigraphy allows extrapolation away from known well sites - but the initial calibration with these areas of known geology is necessary and is driven not just by gross lithology, but by the details of chemical composition.

Modern well log acquisition and associated petrophysical analysis for lithology and fluid volume fractions allows independent modelling of the relative permittivity at a given depth from first principles. This is subject to many uncertainties but anticipates the key dielectric contrasts that one would expect ADR tools to detect, before any acquisition is undertaken. The modelling algorithm and uncertainties are discussed in more detail in later sections. Their improvement is the subject of ongoing experiment.

Uniqueness of solution

The recognisable detection of subsurface geology by the ADR tool does not itself guarantee an ability to predict geology in the absence of calibration. A sharp dielectric contrast resulting from a known geological contact may be observed and recorded by the tool, but to back out a particular set of lithologies occurring at the contact, when this is not already known, is much harder. To reduce this problem, any information which constrains and differentiates response uniqueness is helpful. This includes a basin stratigraphic framework to limit the types of contacts anticipated, forward relative permittivity modelling of the stratigraphy from first principles to anticipate likely contrasts, and utilising all the various ADR curve responses, not just the one(s) with the most prominent response.

Implications of DC variability in typical sedimentary basins

Large changes in water content, hydrocarbon content, and significantly different matrix mineralogy, are therefore the things which we would expect to show up best in ADR tool analysis of relative permittivity. Recalling that it is total porosity, not effective porosity that controls the water response, shales and sands with similar total porosity and mineralogy, may not respond very distinctly. However, hydrocarbons will preferentially charge the best effective porosity, and so large saturations, they can be expected to respond distinctly, and indeed this seems to be the case for even smaller saturations **(Figure 17)**. The different mineralogy of calcite suggests limestone-shale or limestone-sandstone contacts should be more evident – and this is borne out be results. Likewise for evaporite or igneous rock contacts with other sediments. A hydrocarbon filled highly porous sandstone overlain by limestone and/or evaporite, might be expected to produce the most pronounced response – but a striking example of this is lacking from the study areas – however note that even when a small HC saturation is indicated, this scenario does seem to produce a response **(Figure 17)**.

Surface Soils

Materials with high electrical conductivities incur high rates of signal attenuation with depth. In hard rocks this is of a less concern, but in surface soils it can be very important. The key driver is water content, including the amount, distribution, and chemistry of soil water. High salt levels can be a problem, especially in arid and carbonate rich areas. For this reason, a site with only shallow soils and bedrock close to the surface is optimal for signal penetration. For these reasons the tool is hence best suited to onshore applications. Offshore application is feasible, but signal transmission from the seabed is required, and transmission through saltwater saturated seafloor sludge poses challenges.

Depth error

In low loss materials with little signal attenuation (low conductivity and low relative permittivity), the velocity of an electromagnetic signal is provided simply by the speed of light in a vacuum (c) times the reciprocal of the relative permittivity's square root for that material. This effect on common rocks and pore fluids is given in Error! Reference source not found.. Similar to acoustic wave analysis for seismic, normal move out hyperbolae allow definition of EM wave velocity, and hence relative permittivity layer model – though this is completed over much shorter lateral distances than for seismic (a few hundred m). The high-resolution time analysis then allows a backing out of depth, and finite element ray-tracing techniques allow construction of a higher resolution relative permittivity model. However, rocks are not perfectly "low loss", given the water content, and so some depth error may result. These effects are thought to be small, but well calibration allows a way of checking – when contacts with strong dielectric contrasts correspond to recognisably strong responses. The forward dielectric modelling supports such inference and can occasionally provide even stronger evidence of the depth error, if the forward modelled form closely resembles that of the observed, but with a depth offset. On the occasions when this does occur, errors up to 20 m are sometimes implied **(Figure 17).**

Material	Dielectric Constant, ε (Farads/m)	Matrix Propagation Time (ns/m)	Fluid Propagation Time, (ns/m)
Sandstone	4.65	7.2	
Limestone	7.50	9.1	
Dolomite	6.80	8.7	
Anhydrite	6.35	8.4	
Halite	5.6 to 6.35	7.9 to 8.4	
Shale	5 to 25	7.5 to 16.6	
Oil	2.2		4.9
Gas	3.3		6.0
Fresh water (at 25℃)	78.3		29.5

ns/m = nanoseconds/meter.

Table 1: Dielectric constant (relative permittivity) effect on EM propagation velocity common rock materials (after Chang-Min 2012)

Noise treatment

The electromagnetic radio wave environment is a noisy one. It includes noise from man-made, meteorological, solar, and cosmic sources. Treatment of noise, and resolution of the geological signal is a critical issue. The frontline battle for this takes place at acquisition, simply by taking thousands of repeated measurements to increase the signal to noise ratio. Correlation analysis then serves to help differentiate signal from noise and the most reliable intervals. There are wider issues which make repeatability a key test – as discussed in the next section.

Electromagnetic noise in our context represents any signal that is not related to subsurface geology. It can take several forms. It can be short duration random noise variations, which will be tackled by the many repeat measurements taken at acquisition. Other noise sources may consist of a regular time-repeating pattern, in which case they are also easily recognised. Harder to eliminate are those types of noise which may be relatively constant over the period of acquisition but which are nonetheless not related to subsurface geology. Recognising and eliminating the extent and "loudness" of such noise requires duplicate measurements at different times - a non-trivial exercise in terms of time and cost.

Repeatability

In any scientific experiment, repeatability is a critical verification. We expect the geology to remain constant over the relevant acquisition timescales (excepting production related pore fluid changes), so we would expect repeatability of results over all time periods if a geological signal is dominant. If a detection of prominent signal cannot be repeated at different times, then it is of no use for lateral extrapolation of a geological interpretation, because if the response has changed and the geology hasn't, the response is noise, not geological signal.

Device repeatability

A first step is to deduce the reliability of the tool itself – that it measures the same thing consistently. This is confirmed in **Figure 4**.

Figure 4: ADR tool device repeatability

Method repeatability

The method of acquisition can also be tested for repeatability by using two different tools at the same place. This indicates how subtleties in the individual device construction and measurement – perhaps by a different team - can vary response. Results confirm that the method itself, not just the individual device, also gives adequate repeatability **(Figure 5)**. This however, is only part of the story - to be able to use the tool in a predictive sense for subsurface geology we need the subset of responses that are considered geological to be resolved consistently.

Figure 5: ADR Method repeatability

Short-term temporal repeatability

Repeatability of the signal over the short-term period of the acquisition is established by taking thousands of measurements and using statistical analysis for verification of consistency. This might indicate some levels are more consistent that others – their signal is “louder” above any noise.

Spatial repeatability

Spatial repeatability is also helpful. We know that geology does vary spatially, but in stratified sedimentary layers, so we do expect some lateral consistency with distance. Hence if we can move our tool a short distance and observe similar results, it also increases confidence in the repeatability of signal dominated by geology. This is typically demonstrated in the WARR scan results or adjacent P-scan results **(Figure 6).**

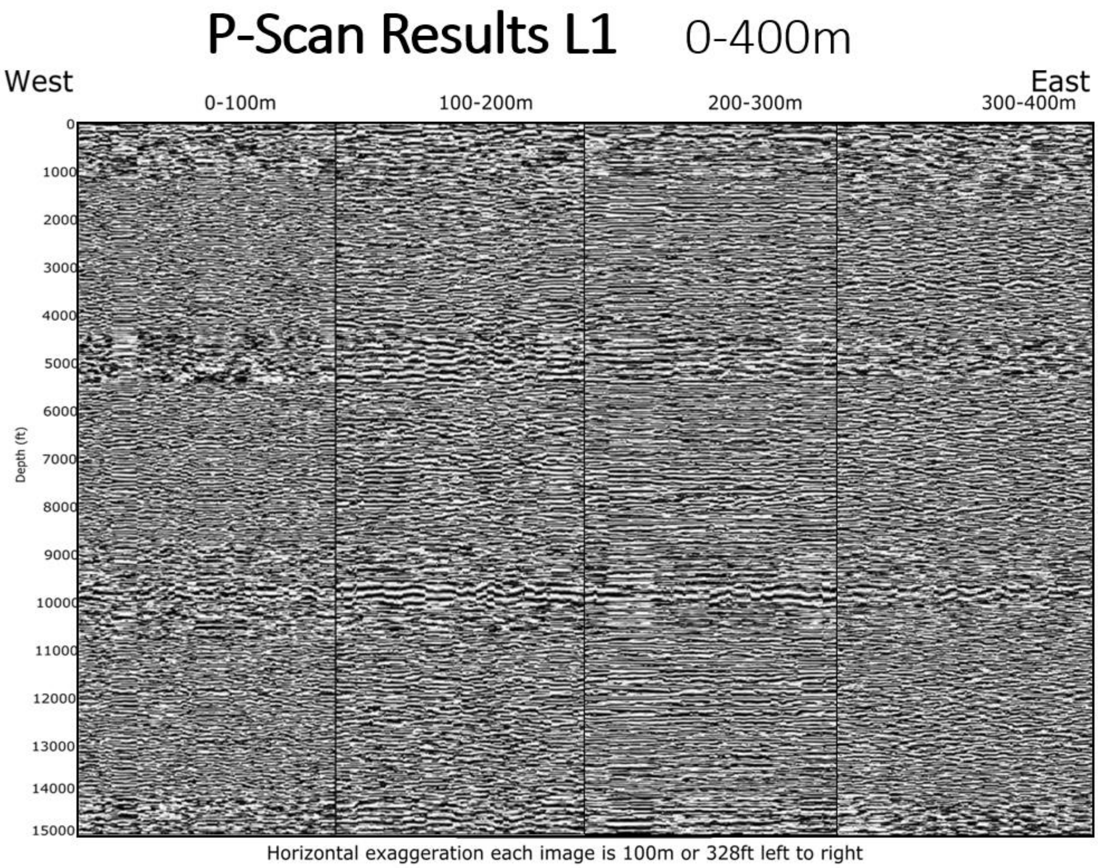


Figure 6: Spatial repeatability demonstrated by adjacent P-Scans at one of the Lancashire wells - consistent changes in character response occur at subsurface layers of known lithological contrast.

Long-term temporal repeatability

Demonstrable repeatability over a longer time period, with a repeated measurement using the same tool, in the same place, but some weeks or months later, is important. This separates and confirms the geological component of a signal from any longer duration noise elements that might be present throughout the timescale of an initial acquisition period.

If responses over a longer time period are similar at key points, we can increase our confidence that the geology is responsible at those points.

Km-scale Depth penetration

Shallow depth penetration of the tool through several meters of concrete have been unambigously achieved **(Stove, 2014).** More in question is the efficacy over large depths. The European Space Agency MARSIS tool has already demonstrated the generic ability of radar-based tools to observe important dielectric constants at depths of 1.5 km within the permafrost of the Martian south pole **(Lauro et al. 2010; Trautner and Grard, 2003)**, but what of the ADR tools ? Adrok has tested transmission and receipt of signal from the Pen-Oreille lead-zinc mine in Washington state (and confirmed both over distances on a scale of hundreds of metres **(Van den Doel et al., 2014).** Adrok has also achieved convincing surface-based detection of a borehole-calibrated sulphide vein at 460 m depth in Australia **(Richards et al., 2015).**

The principle of significant 100-m scale depth penetration is already demonstrated for mineralisation with a strong dielectric contrast. The current study is concerned with more general detections of sedimentary basin geological signal at km scale depths, utilising calibration with wells. This approach places the tool close to the relevant well sites and calibrates remote responses with the interpedently known deep geology. Such geology will have more subtle dielectric contrasts than exotic mineralisations.

Enhancing depth penetration

Several techniques are used to assist depth penetration of the ADR signal. Selection of a site where surface soils or other high-loss materials are thin also aids greater depth penetration.

Air and space-borne synthetic aperture radar (SAR) experiments have demonstrated the greater depth penetration possible with lower frequencies **(Stove, G. 2009, 2011 & 2012)**. Consequently Adrok tools work mainly in the lower 1-100 MHz radio wave frequency, similar to MARSIS **(Lauro et al. 2010; Trautner and Grard, 2003).** Such frequencies have wavelengths in the 1-100m range. A capability to also work in the higher 0.3 to 300 GHz radar frequency exists when required for shallower work (wavelengths of the order 1mm – 1m).

The tool focuses as much energy as possible in the head of the pulsed wave – as this is where least energy is lost during transmission. Also important is the beam-like nature of the signal about 0.4m wide, and approximately 0.1 m wide at its most intense. This allows an illumination the subsurface like a torch, unlike omnidirectional ground penetrating radar (GPR).

The signal delivered is multi-spectral, unlike a monochromatic laser, with different frequencies combined to give a pulse **(figure XX)**. These frequencies are coherent – i.e. with the same wave-form and phase difference. The coherent multi-spectral nature minimises loss of energy to the surroundings **(Stove G. et al 2013)** and facilitates depth penetration **(figure XX)**. The resulting pulse has two components – a longer wavelength standing-wave form to go deep, and shorter waves within it to enhance vertical resolution **(Figure 7).**

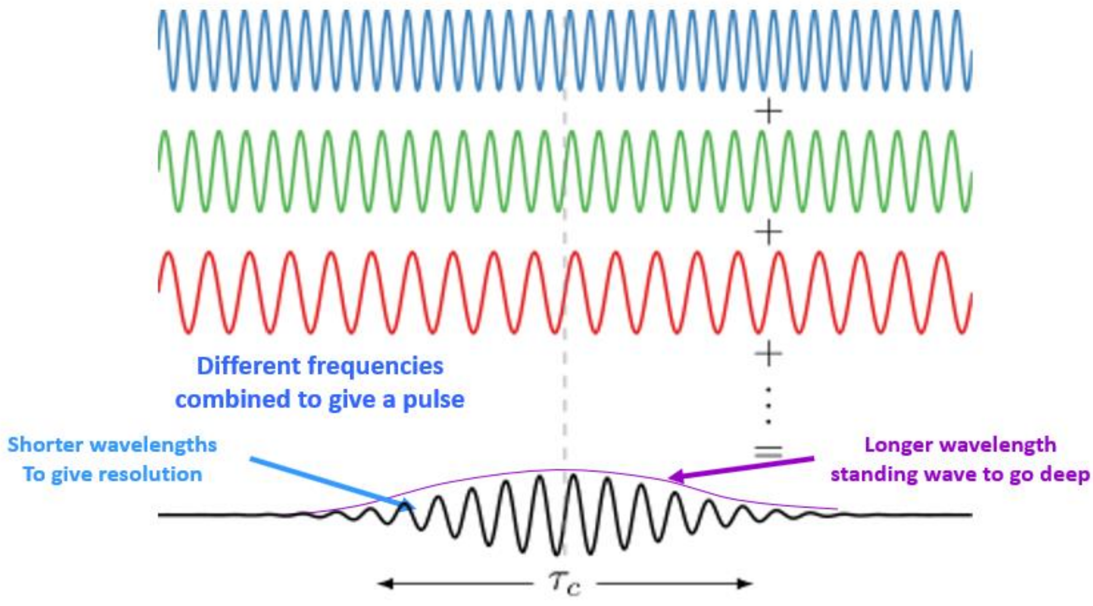


Figure 7: Different frequencies are combined to give a pulse of dual shorter wavelength and longer wavelength nature directed beam-like into the subsurface

The extent to which these strategies succeed in taking signal to depth is a key aspect of this study. Unavoidably, higher frequency components of the signal will be attenuated with depth. Strategies help minimise this attenuation, but they cannot prevent it. The best way to ascertain how big a problem this represents, is through borehole-calibrated case studies such as this one.

Depth resolution

The depth resolution achievable by a signal of a certain frequency and wavelength has a well-known relationship. Resolution of features less than a quarter of the signal wavelength becomes difficult. Attenuation and scattering of wave – especially shorter wavelength hi-resolving power wave signal is inevitable with depth, as physically heterogeneous subsurface materials are encountered. Central to the ADR tool's ability to resolve at depth, is the dual wavelength nature of the pulse delivered (**Figure 7**), and resonant responses generated at the materials encountered. This latter point, stemming from the quantum nature of electromagnetism, is different to acoustic signals which experience no comparable excitation at the reflected material. This is potentially important, as any resonant response generated at the target will be subject to only half the propagation distance of the original signal – with implications for the amounts of scattering and attenuation.

The signal includes frequencies in the 100 MHz range – with wavelengths of the order of a few m, packaged within a lower frequency standing wave, to assist depth penetration. The transmitted signal also utilises X-band and C-band radar frequencies that enhance a material's resonant response **(Stove, C., 2014),** amplifying the signal returned. As the highest remaining frequencies are increasingly attenuated and scattered, a central question is how much of this pulsed signal remains intact at depth to allow resolutions on a metre to decametre scale. This study seeks empirical evidence of this from independent calibrating data.

Statistical significance

Interpretative bias - "seeing what we want to see" is a constant danger in any kind of log interpretation, but especially in noisier environments. The approach in this study is to highlight correlations that seem worthy of further investigation using basic statistical tests such as correlation coefficient to assess significance. The workflows adopted make every effort to remain quantitative and auditable, prioritising mathematical analysis of the data preferred over visual selection, however the vulnerability to interpretative bias is recognised.

Further analysis of statistical significance where a correlation is supposed - including a library of response types in many wells and many basins – to help document consistency or lack of - is part of the ongoing work programme.

Mathematical visualisations

Given a highly variable character of curve which is sometimes very different to that of conventional well logs, we commonly compute average and standard deviation curves over a sliding “moving window” bin, to complement but not replace the raw data. These help to discern underlying trends. Sometimes the technique is also used to produce correlation coefficients in a similar fashion for a pair of curves, including non-ADR well logs. Such analyses require that the curves have common depth points, interpolated where necessary in MATLAB using “pchip” algorithms.

To accentuate lithological responses suspected from empirical observation, curves are sometimes combined to provide “lithological metrics”. Incorporating the responses of multiple curves into a metric increases the chance of observing unique behaviours related to lithology. To ensure numerical values of one curve do not overwhelm another, curves are normalised below a cut-off depth of 150m to facilitate such combination, below the variations due to near surface effects. To avoid division by near zero values, a 1-2 normalisation is used.

Workflow Summary

See **Figure 8** summarising the workflow.

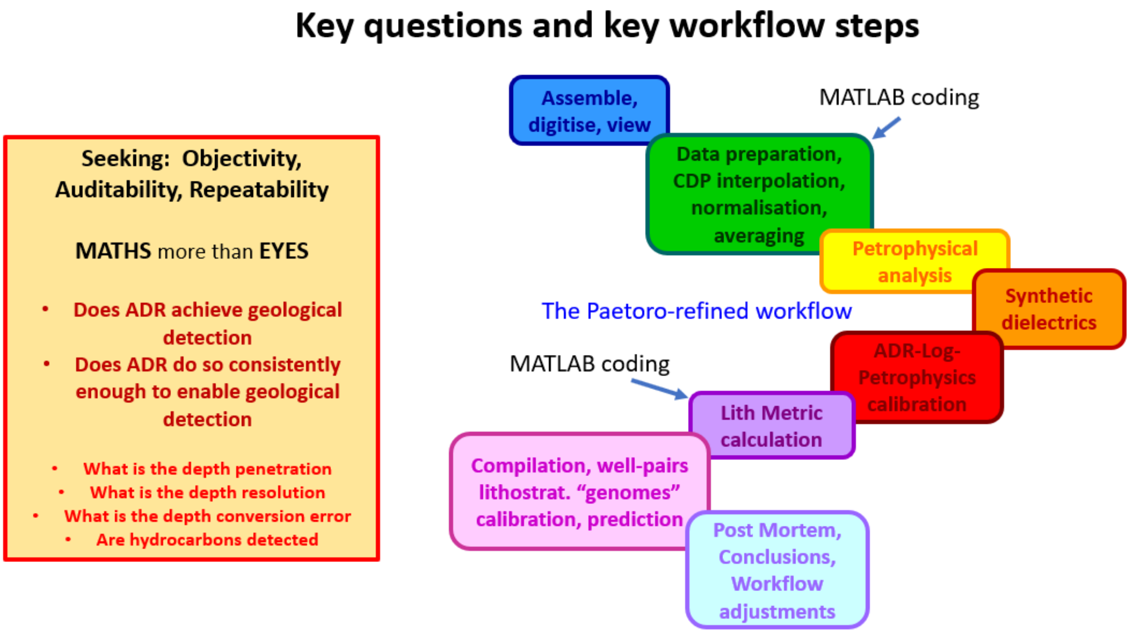


Figure 8: Key workflow steps

ADR data acquisition at calibration wells

Selection of suitable wells, ideally with modern and comprehensive log suites is made, and ADR scans are undertaken from the surface at the well site, or very close to it (typically within ~ 100m). A small distance of separation from the original borehole may be necessary to optimise soil conditions for acquisition and depth penetration. Acquisition is completed over a period of several weeks.

Data processing & Depth conversion

Data processing is the most time-consuming aspect of an ADR study and can take several months depending on the number of wells. Processing details are outside the scope of this paper and are described more fully in numerous Adrok authored publications **(Stove, G., 2011 & 2012; Stove G. et al, 2011, 2013, Stove G. & Stove C. 2018).** It is important to note that while there are similarities with acoustic waves, the spectroscopic analysis conducted by Adrok is achieved through a quantum electrodynamic approach **(Feynman, 1985),** comparable to the tuning of musical instruments (Stove, G., 2012) but similarly classifying rocks by an equivalent of their notes and octaves. This quantum dimension of the electromagnetic wave response takes ADR analysis into different realms of physics to that of seismic processing, particularly in respect to resonant responses **(Stove G. et al., 2009).**

Once completed, the raw data is visually inspected against all available well data, including existing well logs, stratigraphic tops, lithology logs, and any client petrophysics. Using independent normal move out and ray tracing techniques, the two way times are used to provide time-depth information from WARR scans, and provide depth conversion in a fashion similar to seismic depth conversion **(Stove, G. et al 2011)**.

CDP, normalisation, averaging

MATLAB "pchip" interpolations create common depth points (CDP) across all curves where this is not already the case. Curves are normalised to facilitate curve combinations and lithological metrics to help highlight suspected lithological response. Average and standard deviation curves are produced from the curves over a variety of "moving window" data bins, to supplement the raw data and ascertain underlying trends over larger interval. Correlations between selected pairs of ADR curves and a well log or petrophysical curve are sometimes also investigated.

Petrophysical analysis

While geologist interpreted lithological logs are a useful first guide to lithostratigraphy, they are subjective interpretations and can impose discrete boundaries or lithologies on contacts that are in truth gradational and/or thinly interbedded. Well logs and derived petrophysical curves better capture the real natural variations that occur and form a superior basis for calibration with ADR data. Petrophysical analysis is not without its own uncertainty, but the relationship to raw high depth resolution data is clearer and more auditable. If client provided well logs are of sufficient quality, an independent petrophysical analysis of the well logs is therefore conducted. The well log suites are often of differing vintages so a new set of independent petrophysical analysis ensures conformity of petrophysical approach across different wells from different operators.

Forward modelling of relative permittivity

Provided with a petrophysical analysis of the lithology and fluid volume fractions as a function of depth for a well, it is in possible to estimate from theoretical first principles the relative permittivity characterising a rock-fluid mixture at a given depth. This is not a simple pro-rata'ed volume-weighted calculation, although that has some merit as a simple first pass model. The subject is treated in more detail by **Martinez and Byrnes (2001)** and we adopt their method for relative permittivity calculation. Each volume component is multiplied by the square root of its estimated relative permittivity. These terms for each component are summed, and then the sum squared, to estimate the relative permittivity for the whole mix.

The large range of dielectric values possible for any given lithology **(Figure 3)** means this is usually an uncertain estimate in absolute terms, and a variety of permutations are trialled. However, the principal objective of this forward modelling step is not to precisely match values, but to predict whether major contrasts occur and to detect if modelled forms of dielectric curve are locally replicated by ADR tool acquisition. The workflow is adequate for this purpose.

Where such matches occur, they provide a wholly independent confirmation of signal depth penetration by the tool. They also serve as a pre-acquisition feasibility step for clients wanting to know whether the tool can be useful with their particular basin stratigraphies and targets. In the future stochastic processes for this forward modelling, to capture a fuller and probabilistic range of possibilities for comparison with observations, may prove useful.

The simplest dielectric forward modelling assumes any given gross lithology has the same relative permittivity through a well's section, when in reality this is an oversimplification and a function of a unit's detailed geochemistry and microstructure. Likewise, whether the dielectric permittivities of the solid phase component in any way dominate over the pore fluid component is not extensively studied or understood. Understanding the subtleties of these phenomena is an ongoing science. Although they do not measure exactly the same frequencies, the increasing number of downhole dielectric tools now provided by most major well logging service providers **(Chang-Min, 2012)** gives an additional opportunity to answer these questions directly for modern wells. This is achieved by comparing ADR tool remote surface logging with proximally acquired downhole observations of the relative permittivity.

The variability of dielectric response within complex rock and pore fluid mixtures should not be underestimated. Many aspects of these variations still remain poorly understood within the scientific community, but study is accelerating (e.g. **Misra and Tathed 2017, Zhang et al**

2012) and the growing body of down-hole and remotely sense data available holds promise for vastly increased understanding in the future.

Data collation and comparison

A number of key data sets therefore exist for comparison and calibration:

- ADR curve data suite of 17 curves
- Geologist interpreted well tops and lithostratigraphy
- Original well logs and associated petrophysics
- Independent petrophysical analysis
- Forward modelling of relative permittivity from petrophysics

The datasets are compared, and suspected correlations noted and documented. Given the large number of well-defined raw and calibrating data sets available, future prediction with machine or deep learning has potential applications. Computer algorithms will be better suited to trawling the large number of curves and recognising statistically significant correlations with geology – and will be able to do so more efficiently and objectively than the human eye. The time-consuming and trial and error nature of attempting the same thing manually is less satisfactory.

Uncalibrated "Blind" prediction tests

Although AI routes may be a better approach in the log term, "manual" blind prediction can be attempted on wells for which calibrating data is available, but without using it – and then comparing predictions against the known results. The approach uses a pair or multiple pairs of calibration wells to qualitatively extract responses and character changes in all the different curves, focussing on those that are shared and corresponding to lithology or fluid changes.

Where patterns are defined across many curves and locations, a multi-curve litho-stratigraphic “genome” emerges, uniqueness is increased and therefore assists use in a predictive capacity.

Such shared patterns are then used as a “bridge” to another uncalibrated site, where the same relationships are looked for, and used to predict lithostratigraphy. There is no guarantee such similarities are not spurious but repeating the process across many curves and well pairs increases the likelihood that they are not. Such a process is necessarily qualitative. The objective at this stage is to explore the conceptual workflow as a framework for more rigorous AI-based approaches, essentially doing the same thing but much faster and more efficiently across a much larger tensor of data sets.

PART B: Onshore UK Case Studies

Study objectives

This set of case studies investigates two key questions. Firstly whether the ADR technique is indeed remotely detecting any (not necessarily all) lithostratigraphy and pore fluid (HC/water) changes at km-scale depths within three sedimentary basins onshore UK. If confirmed, the next step is to ascertain whether the responses show sufficient consistency to be used in a predictive capacity. Where there are issues that hinder such application, suggestions for improvement are considered. Secondary objectives include evidence for the extent of depth penetration, depth resolution, and hydrocarbon detection. Theoretical modelling is sometimes employed to assist with these objectives, but the approach of this study is predominantly an empirical one, examining the raw data for correlation with geological contrasts.

Field areas

Three key areas onshore UK were investigated with the ADR tool, for a variety of clients, including the East Midlands, Weald Basin, and Lancashire **(Figure 9)**. Generic stratigraphies for these basins are provided in (**Figure 10)**. . The investigated wells are assigned codes in this study. Three from the East Midlands analysed in 2017 are referred to as H7, H8, and H9. Six wells from the Weald Basin, analysed during 2018, are H13, H14, H15, H16, H19, and H22. Three wells from Lancashire, analysed during 2019, are L1, L2, L3.

Figure 9: Location of UK onshore basins investigated in this study

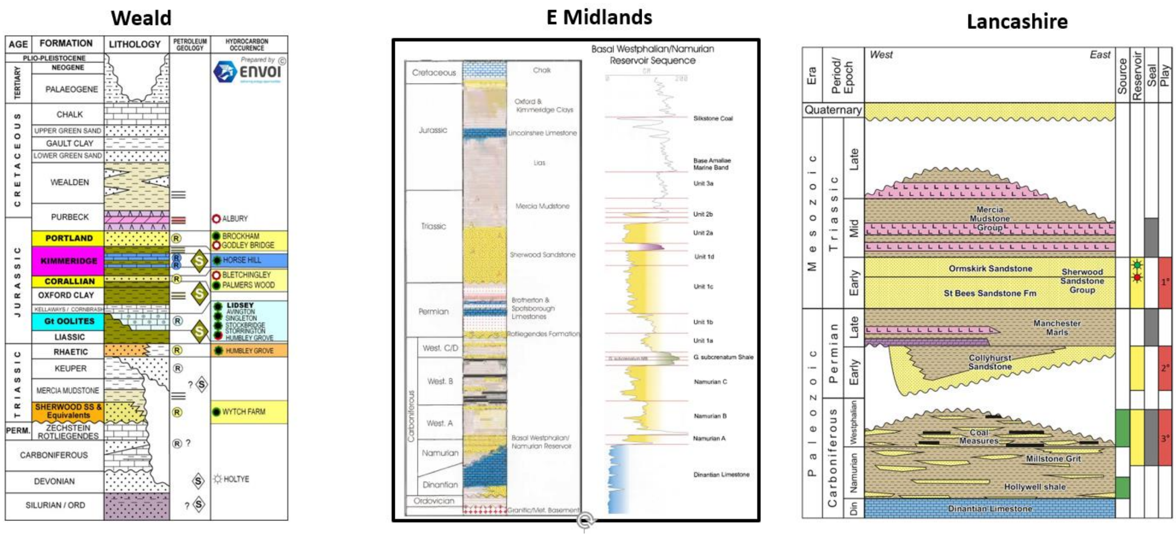


Figure 10: Representative stratigraphies of UK onshore basins investigated in this study

Response Analysis Overviews

Completion pending full analysis of curve responses, all studies

Calibration well log and petrophysical curves are used to define the key lithostratigraphy contacts and intervals and are compared with responses are occurring at the same level in the ADR data. Responses characterised by type – peak, trough, peak-trough couplet, or trough-peak couplet, or no response. These responses are further qualified as either prominent, moderate, or indistinct. A prominent response is one which markedly stands out in relation to the rest of the curve. A moderate one is one which stands out as distinct relative to nearby parts of the curve. An indistinct one could have a small or moderate amplitude response but is not of a character to stand out from other similar responses nearby in the curve. That's is a pre-requisite for it to be of any use in prediction. Responses are then logged against the stratigraphic contact name, the lithological change occurring, and its abruptness. Though qualitative, these allow crude statistics to be calculated for all responses over all wells, to ascertain any lithostratigraphically-driven commonality of response.

The time to depth processing of the WARR scan can result in a depth conversion error that will be the same magnitude for all ADR curves. If there are hints that a prominent response on a number of curves is slightly offset from the exact marker, the deviation is recorded in four categories:

1) at the well log defined, contact,
2) within +/- 5m of it,
3) within +5 to +20m i.e. deeper, or
4) within -5 to -20m, i.e. shallower.

An error tolerance greater than 20m is not considered in this study. Such an error may be possible, especially in deeper parts of the section, or areas of non-layer cake structural complexity on the scale of the WARR scan (some hundreds of m from the primary acquisition site). Metrics are also calculated incorporating every curve's response at a given lithostratigraphy marker. Though arbitrary in nature these allow an approximate relative scoring regime of all the responses for usefulness.

For the major stratigraphic and lithological changes investigated, and for a given curve, typically about a fifth to a quarter are moderate or prominent **(Figure 11)**. Given the non-uniqueness of the relative permittivity across many lithologies **(Figure 3)** this is not unexpected. It tells us that in three quarters to four fifths of cases, the non-uniqueness of the rock-mineral matrix and fluid composition is insufficient to produce a marked response in the ADR tool. That does not detract from the good responses which do occur. Such statistical analysis allows us to understand more fully the key drivers for the most responsive lithostratigraphic contrasts.

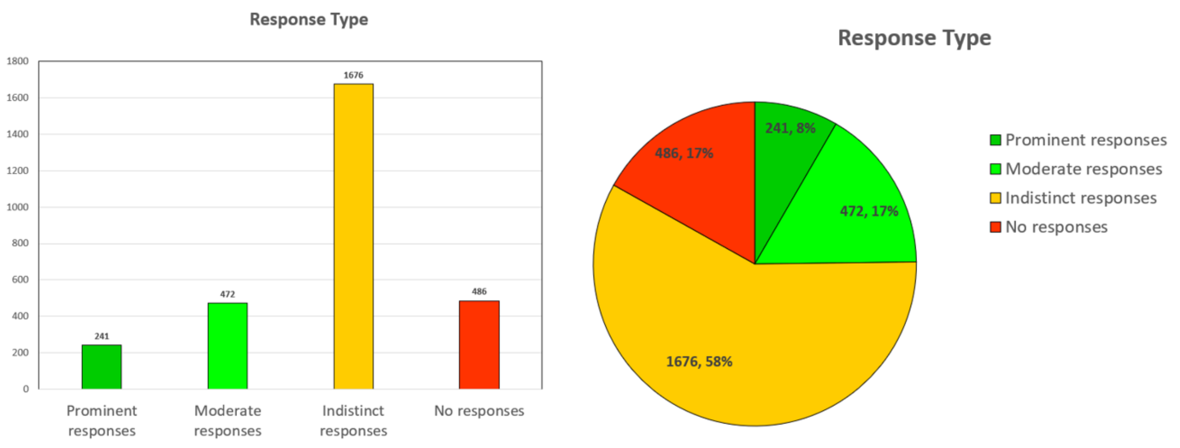
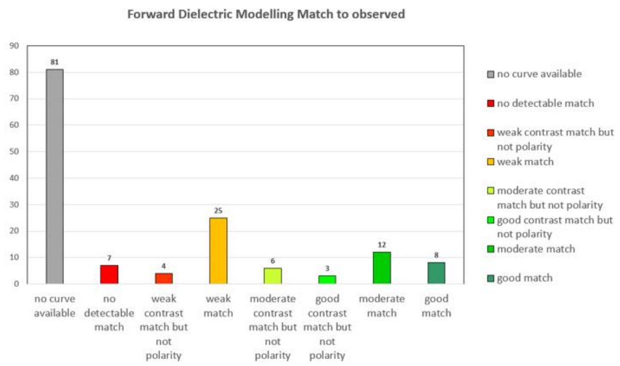


Figure 11: Response type statistics, all wells, all contacts

Dielectric forward modelling success

Completion pending full analysis of curve responses, all studies

Any matching points of change between the modelled and observed DC curves give independent verification of tool detection success. Matches are characterised at a contact in terms of whether they are is strong, weak, the same polarity to that modelled, or the opposite. About 30% of contacts studied showed a moderate to good match (**Figure 12**). The latter is allowed given the range and overlap of dielectric values possible – particularly for sand-shale boundaries. Some observations have shows a match in from of the modelled and observed curves, but offset by some depth. These can independently provide an indication of likely depth error.



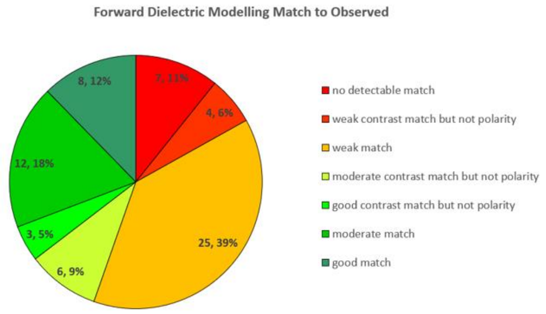


Figure 12: Forward Dielectric modelling to observed

Sensing Geology

Completion pending full analysis of curve responses, all studies

About 20% of responses give encouragement that a geological change is being detected (**Figure 13**). The success of some forward modelling is also an encouragement of geological detection (**Figure 12 and Figure 15**). If the contact responses analysed are characterised by the lithological change involved, for example, from an overlying shale to an underlying limestone, there is often, though not always, a systematic type of response for each individual ADR curve **(Figure 16**). As suspected from forward modelling analysis, it is the units with a strong mineralogical or pore fluid type contrast that show up best – and limestones in particular often show up well **(Figure 14)**

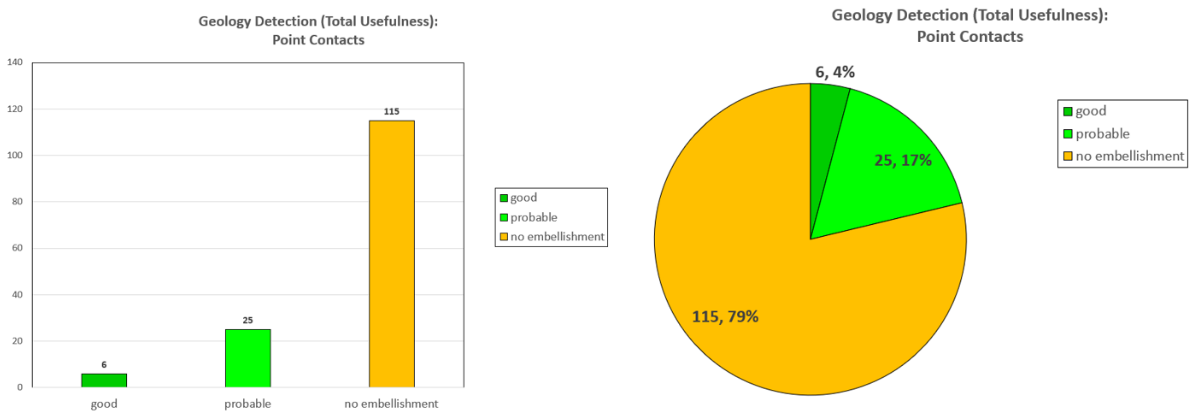


Figure 13: Contacts thought to be detecting geology in a distinctive fashion

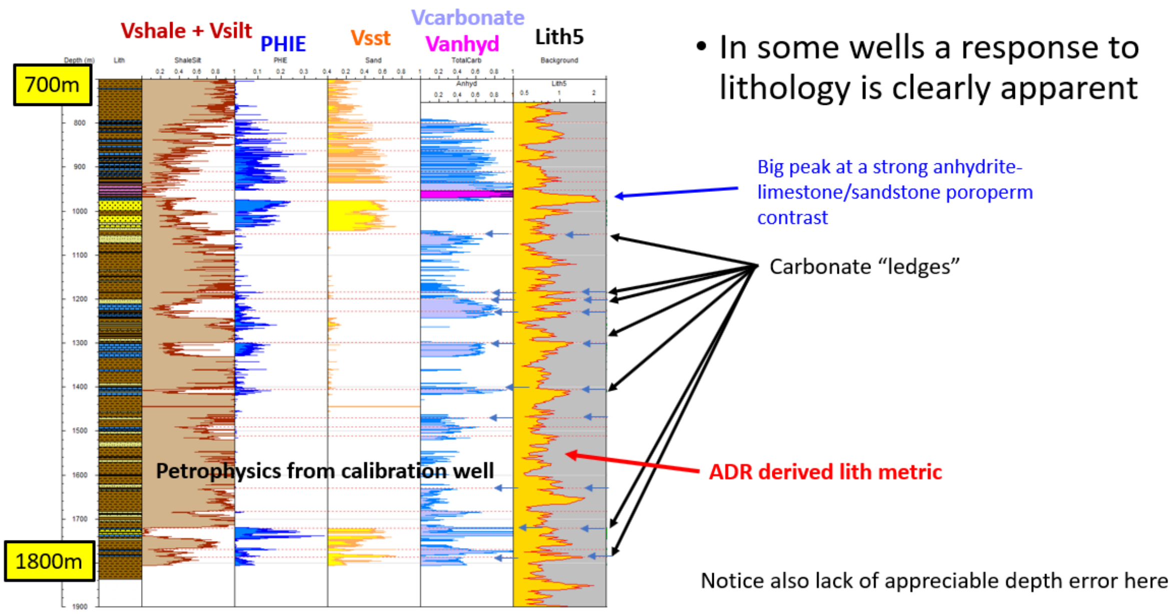


Figure 14: The use of lithological metrics combining ADR curves to accentuate lithological responses, in this case highlighting distinctive carbonate ledges and a carbonate-anhydrite contact with underlying sandstone reservoir

- Dielectric responses (pink) forward modelled from calibrating well petrophysics independently of Adrok acquisition sometimes show a marked, if not exact, similarity in form to the observed dielectric constant.
- The slight offset indicated by black lines hints at a likely depth conversion error (~20m)

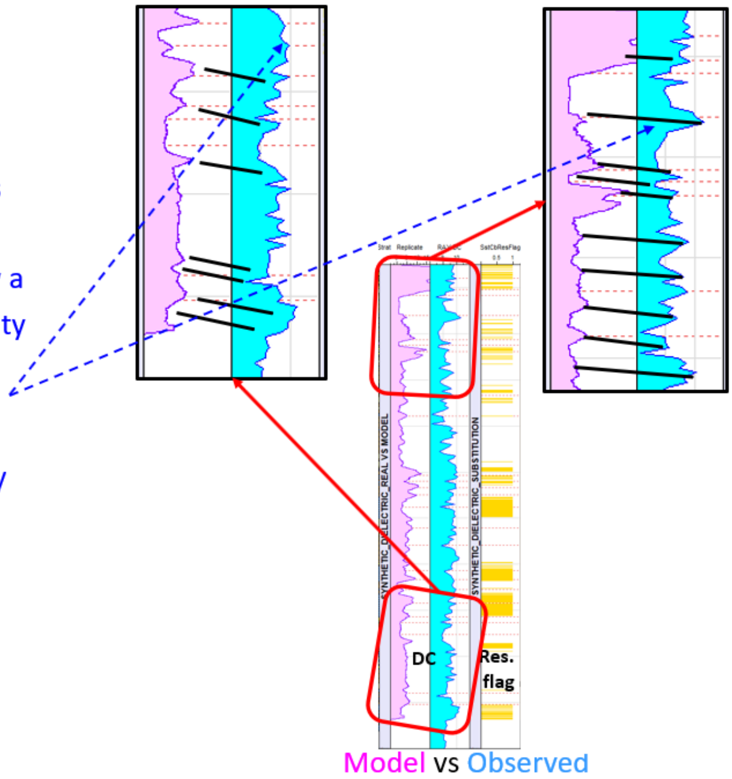


Figure 15: Similarity in form of responses from petrophysically derived forward modelling of well data, compared to surface remote sensing of the Adrok tool, sometimes shows good similarity in from, suggesting geological detection, and allowing estimate of depth conversion error.

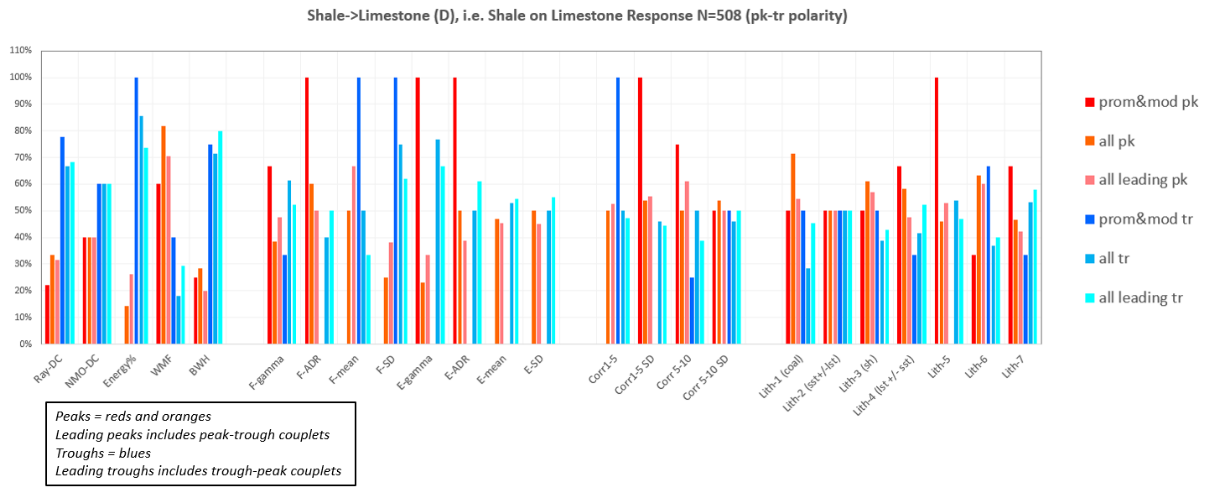


Figure 16: Bar chart of the type of response encountered for shales overlying limestone, for each ADR curve, all basins, all wells.

Sensing Hydrocarbons

Completion pending full analysis of curve responses, all studies

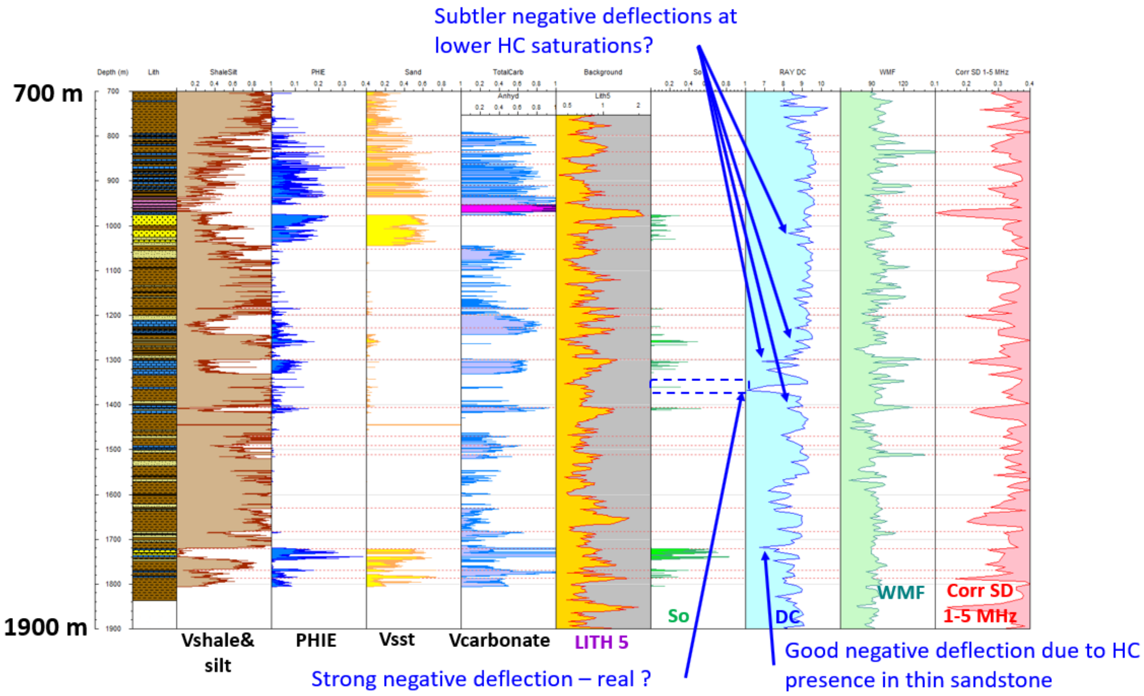


Figure 17: Example of thin and sometimes weak HC saturations lowering the Ray-traced DC response, as would be expected

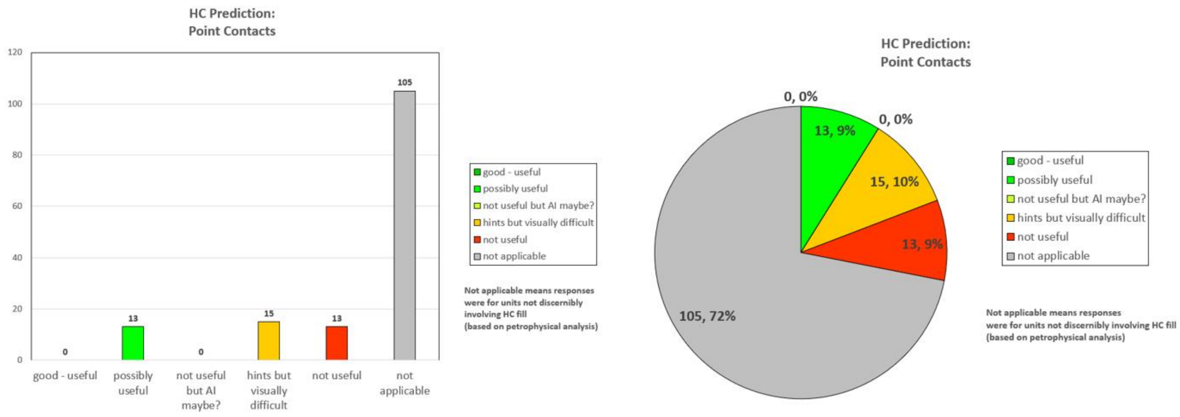


Figure 18: There are not a large number of thick very strong saturation in the wells studied, nevertheless where some HC saturation was perceived by petrophysical analysis, about a third of these showed some manifestation in the ADR curves.

Prediction

Completion pending full analysis of curve responses, all studies

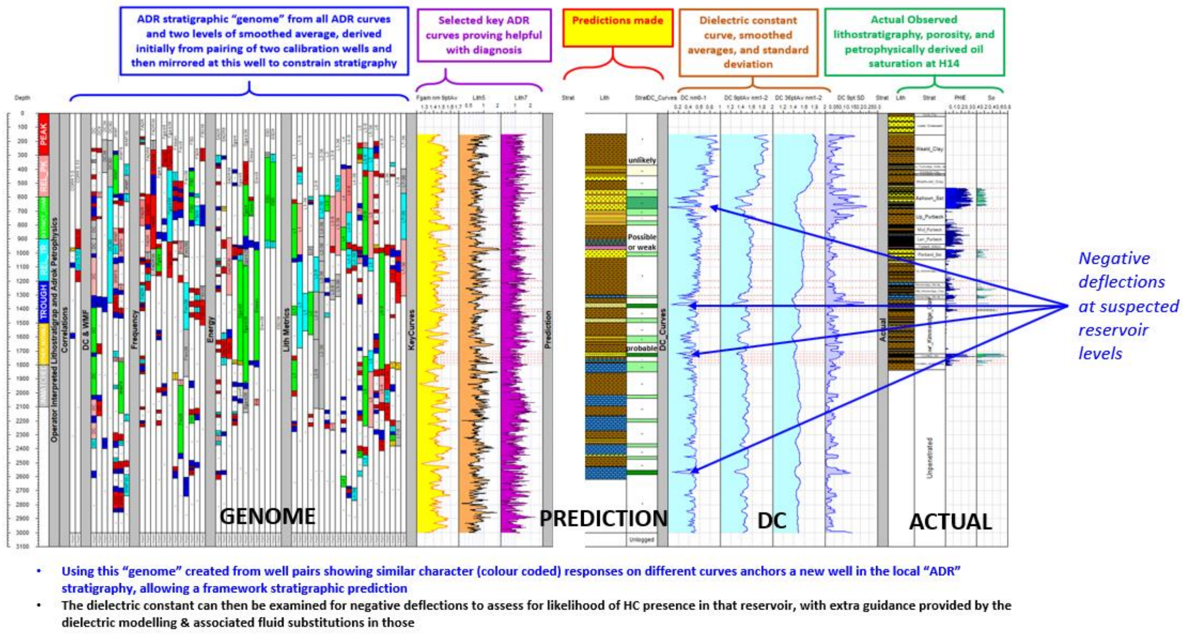


Figure 19: Example of how a lithostratigraphic "genome" characterising the ADR curve response in a basin from a pair or pairs of wells, and be applied to a new well to make an independent "blind" prediction, which can then be compared with actual well borehole information. In practice, in the longer term, AI techniques may prove a more efficient way of doing this than more subjective manual inspection.

Summary of Further Work & Potential

Dielectric contrast feasibility studies

The forward modelling of relative permittivity from petrophysical analysis at calibrating wells has to date been a simple approach. The option to do so more stochastically would better capture the most significant dielectric contrasts for a range of values and give an improved capability to test against observed results.

AI assistance

The use of AI techniques to systematically, efficiently, and objectively trawl the large number of ADR, well log, lithological interpretation, and dielectric modelling data sets for relationships holds promise for better identification of diagnostic correlations.

Down hole dielectric tool calibration

The increasing use of downhole dielectric tools in modern wells provides a much better chance to compare "like with like" in terms of downhole well log calibration with surface remote sensing by ADR tools. It can help verify lithological responses and clarify issues related to depth error. Amounts of signal attenuation as a function depth, and differential signal attenuation in matrix versus pores.

Hydrogeology, geothermal, and petroleum applications

A key feature of the ADR tool is an ability to record quickly and with low impact in environments that onshore seismic acquisition finds challenging both technically and from a cost point of view. This includes rugged terrain and urban or industrial areas – although the higher electromagentic noise levels nearer to high population densities can prove a challenge.

The very distinct dielectric character of water means highly porous reservoir units will typically have a significant dielectric contrast more easily resolvable by the ADR tool, with obvious benefits for geothermal and hydrogeology applications. This comes with a caveat that total, not effective porosity is being resolved, and so the contrasts might not be as great as expected if high porosity shales are also present. If hydrocarbons are involved though, these preferentially seek the good effective porosity, and given the very low hydrocarbon dielectric values compared to water, should be resolvable at significant saturations and column thicknesses. The relative permittivity of water does vary with temperature and phase with implications for geothermal prospecting. This is discussed more fully in **(Stove G. & Stove C., 2018).**

It is pore fluid and mineralogically driven compositional differences with strong accompanying dielectric contrast that drive the best ADR tool responses. While at a global level the overlaps between carbonates, evaporites and clastic unit permittivity values is substantial, hindering differentiation, in a local basin setting, these responses can be a lot more distinct. In general, from the existing study, it is differentiation of carbonate-clastic and evaporate-clastic contacts that seem to be the most prominent. Intra-clastic shale-siltstone-sandstone contacts that are not at major unconformities and without hydrocarbon saturation can be harder to resolve, probably because the total porosities and the matrix composition do not very that much, in spite of changes in grain size.

The introduction of hydrocarbons into the system dramatically assists differentiation though. This means that petroleum system sequences where carbonate-clastic and evaporite-clastic contacts play an important role in reservoir-seal pairing are those most conducive to detection – such as many of the evaporite sealed clastic & carbonate reservoirs, shale sealed carbonate reservoirs in the Middle East, or tight carbonate sandstone sealed reservoirs. Turbiditic and deltaic sand-shale sequences with good amounts of hydrocarbon charge in the system, should also be fruitful areas for investigation. In general, basins where the lithological variation is relatively simple assists interpretation, since here the calibrating wells can be extrapolated laterally more effectively and confidently.

Full field simple case

Case studies to date have typically involved three to six wells. To more conclusively demonstrate the tool effectiveness, a larger study 10-20 well study over a large and simply structured field with good dielectric contrasts and the neighbouring areas of purely water-leg would be invaluable. Large fields in Saudi, Iraq, and Kuwait could form excellent case studies.

Water/steam front advance during production

The tool has the potential to monitor changes in pore fluid composition at individual sites occurring with production, as reservoir hydrocarbons are replaced by reservoir or injected fluids. The tool is currently being used by clients for injected steam front monitoring at Kern River in California (**Stove G. et al, 2018**).

Conclusions

We assert, based on these onshore UK studies, that a deep geological signal from the subsurface relating to relative permittivity variation, is being resolved at the surface to depths up to a at least 2 km. It is possible that greater depth signal is being resolved, but our calibration is limited by well TD's to ~ 2.5 km. Such responses do not occur for every lithological contact but rather are best resolved where prominent dielectric contrasts occur. In a sedimentary basin context, these are mostly driven by pore-fluid content and porosity. Mineral occurrences with strong dielectric constants, and/or porous aquifers, form the best targets for the technique. The non-uniqueness of relative permittivity value is an issue, and the prediction of geology from an uncalibrated raw ADR log where no a-priori idea of stratigraphy is available will be challenging - but modern resource plays are rarely without calibrating well information and surface geological mapping to help constrain likely response.

Efforts are being made to enhance recognition of geological signal for predictive purposes. Visual inspection and character extrapolation from calibrated well pairings can help but is time consuming and vulnerable to interpretation bias. Moving forward, in the presence of abundant calibrating well data sets, artificial intelligence (AI) techniques appear better placed to advance recognition of the geological signal and to do so in an objective mathematically auditable fashion. Trial acquisitions over fields with multiple calibration wells and relatively simple and laterally consistent stratigraphy (e.g. deltaic or turbiditic sand-shale sequences, or shallow marine carbonate-shale sequences), would from a good basis for further investigations of this nature.

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Appendices

Abbreviation	Explanation
ADR	Atomic Dielectric Resonance
AI	Artificial Intelligence
CDP	Common Depth Point
DC	Dielectric Constant (= relative permittivity)
EM	Electromagnetic [waves]
FFT	Fast Fourier Transform analysis
GPR	Ground Penetrating Radar
MARSIS	
NMO	Normal Move-Out
PHIE	Effective porosity
PHIT	Total porosity
SAR	Synthetic Aperture Radar
TD	Total Depth (of well)
TDEM	Time Domain Electromagnetic Method
TWT	Two-Way [travel] Time

Table 2: Abbreviations used