Onshore UK detection of subsurface geology to metre scale resolution and km scale depth, without drilling or seismic

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The potential

A dramatic revolution for subsurface mapping onshore would result from the development of a non-destructive tool that is portable, quick to deploy and which can discern geology from the surface in ways previously possible only through seismic and drilling.

Adrok is working towards realising this ambition with field studies similar to that presented here. If successful the applications are widespread within all subsurface industries - including exploration for mineral, hydrocarbon, geothermal, and aquifer resources. This is especially true in areas where normal seismic acquisition is difficult; or where there are political and environmental sensitivities to more disruptive techniques.

A new EM technique, fundamentally different to previous approaches

An InnovateUK supported project involving Adrok and IGas Plc provided an opportunity to conduct fieldwork and a feasibility study into innovative remote sensing onshore UK. Adrok's core technology is called Atomic Dielectric Resonance ("ADR"). ADR is a patented investigative technique (Stove, 2005) which involves the measurement and interpretation of resonant energy responses of materials to the interaction of pulsed electromagnetic radio-waves (Stove et al., 2012; Doel et al. 2014; Stove & Doel, 2015). The tool has already enjoyed successes most notably in coal and mineral exploration, but the purpose of this project has been to test the applicability to hydrocarbon exploration and sedimentary sequences.

Adrok's technology involves a portable tool which scans the subsurface using a focussed beam of electromagnetic radiation at radio wave frequencies (see Figure 1).

From ground level the tool measures subsurface dielectric permittivity, spectral data (energy, frequency and phase) and material resonance, *without* physically boring the ground. The materials encountered respond differently at atomic scales – absorbing, reflecting and resonating in different ways. The responses are recorded in time and depth converted with algorithms similar to seismic processing. These data produce "Virtual Boreholes" which can be calibrated with known geology to build up a reference database to assist understanding of lithologies, fluids, and geometries present in the subsurface. These facilitate lithostratigraphic interpretation of data from new, unknown locations.

This electromagnetic (EM) surveying technique is fundamentally different to lower resolution surveys of subsurface resistivity undertaken offshore (CSEM - controlled source electromagnetic surveying). The Adrok technology is higher resolution and higher frequency in nature, as well as being easy to apply onshore. While the tool uses similar parts of the EM spectrum to ground penetrating radar (GPR), it differs from GPR in utilising novel transmitter and receiver antennas and low power, pulsed transmissions with multiple centre frequencies that resonate the material it encounters.

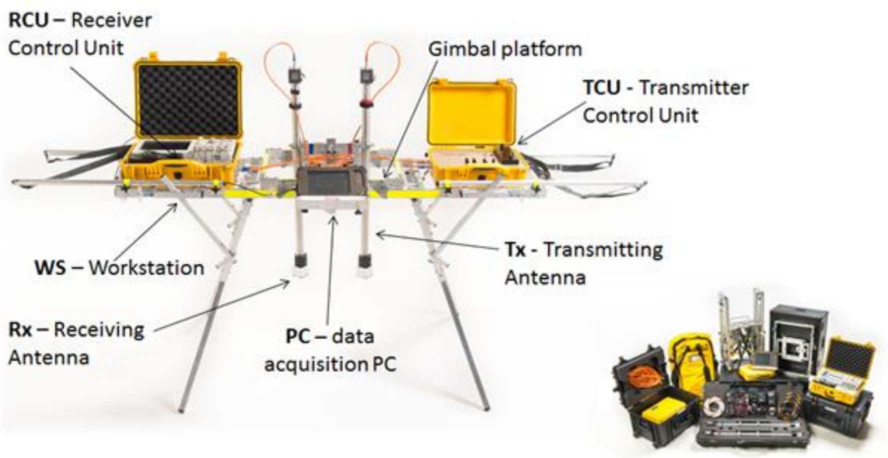

Figure 1: The portable ADR field scanner

Practicalities of the tool – quick & simple to deploy

The scanning is completed quickly and cheaply over a period of weeks with portable equipment capable of being carried on a backpack through difficult terrain. Scans undertaken at historical well locations are useful to calibrate responses, but the scans do not themselves require any drilling, or any of the disruption associated with seismic surveys. Any subsurface information is achieved at a fraction of the cost of normal methods. The tool is especially relevant for de-risking areas of difficult terrain, complicated geological structure, high population density, or environmental sensitivity, where conventional subsurface seismic is difficult to acquire. The cost and time advantages make it worthy of consideration as a precursor tool even when those other avenues are feasible.

Objectives of this onshore UK study

The tool does remain at early stages of development so both its potential and its limits are still being explored. Focussing on a number of wells onshore UK, some involving hydrocarbon reservoirs, the principal aims of this study therefore included:

- Ascertaining whether the tools are responding to known subsurface geology and fluids.
- Advancing understanding of what is/isn't driving the tool responses at a fundamental level.
- Ascertaining whether responses are happening consistently enough for correlation when calibrated with a known well.
- Ascertaining whether responses are happening consistently enough to predict lithology, stratigraphy, and fluid fill, when no local calibration well is available.

Preliminary results of ongoing work

For this project, Adrok successfully deployed the ADR scanner at 22 localities at IGas' onshore UK properties in the Cheshire Basin, Gainsborough Trough, and Weald Basin. IGas provided Adrok with calibration data for 10 of these sites, from which subsurface lithologies were assigned and correlated by Adrok. From this, relationships between new and calibration data were established and then applied to interpret 2 "blind-test" holes in the Weald Basin.

The following conclusions have been possible:

- Noise and natural variability in atomic, microscopic, and macroscopic scale features driving the ADR response make analysis involved, but the tools are responding to subsurface geological features.
- When a calibrating well is available, this can allow broad scale correlation and identification of prominently responding units. Regional knowledge of subsurface and surface stratigraphy helps.
- The best responses occur at clear contrasts between relatively homogeneous beds of different lithology and/or fluid. Sandstone units of this nature are prospective not just for hydrocarbons but also geothermal resource.
- The tools are responding to geology, but non-uniqueness of response means that unambiguously predicting lithology from the data can be difficult. This non-uniqueness is also a feature of many wireline tools in sedimentary sequences so should not come as any real surprise.
- Objective, auditable, repeatable, mathematical data processing techniques for assisting visualisation of the data can significantly help analysis.
- Progress is being made utilising multiple data sets and their mathematical combination, designed to highlight particular lithologies, but prognoses are probabilistic rather than diagnostic in nature.
- A growing library of laboratory and field case studies and further well calibration is the key to increasing confidence in predictions, and to better understanding the theory underlying tool responses.
- Basins with a limited number of lithologies - limiting the number of variables (e.g. deltaic settings) would seem the best places to continue trial the tool.

Examples of some of the ADR results produced for this project are shown in Figures 2 and 3. Fuller results will be presented and discussed in the presentation.

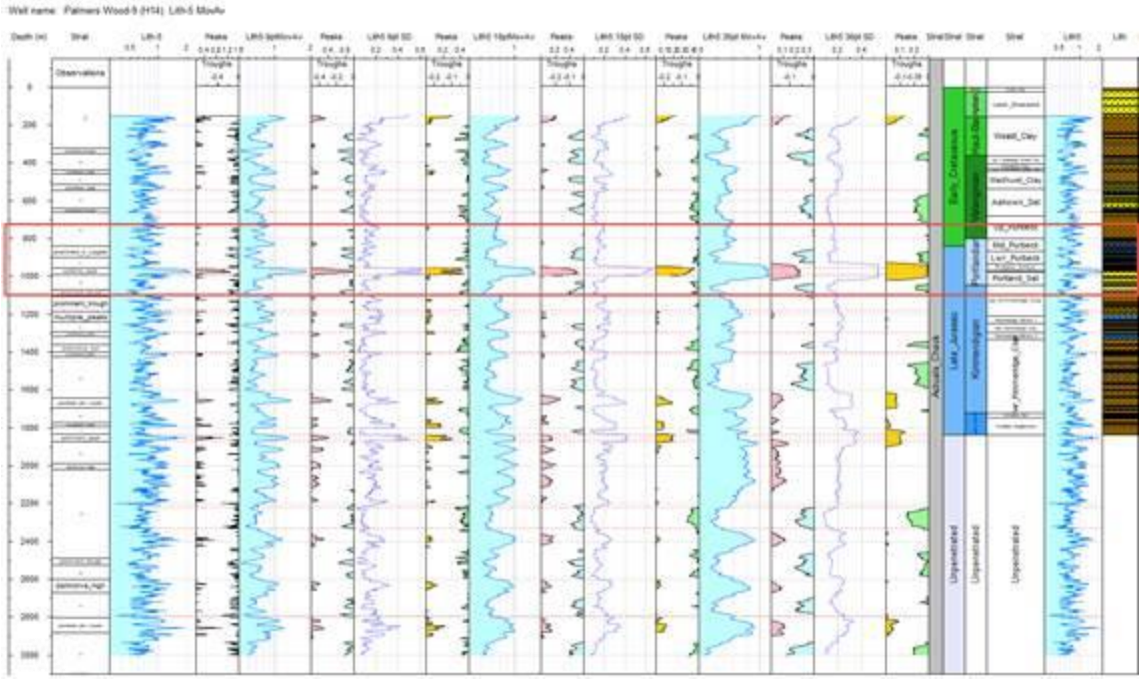

Figure 2: Weald Basin response from just one of the many possible metrics available from analysis, in this case nicely highlight a boundary between Purbeck Anhydrite and Portland Sandstone

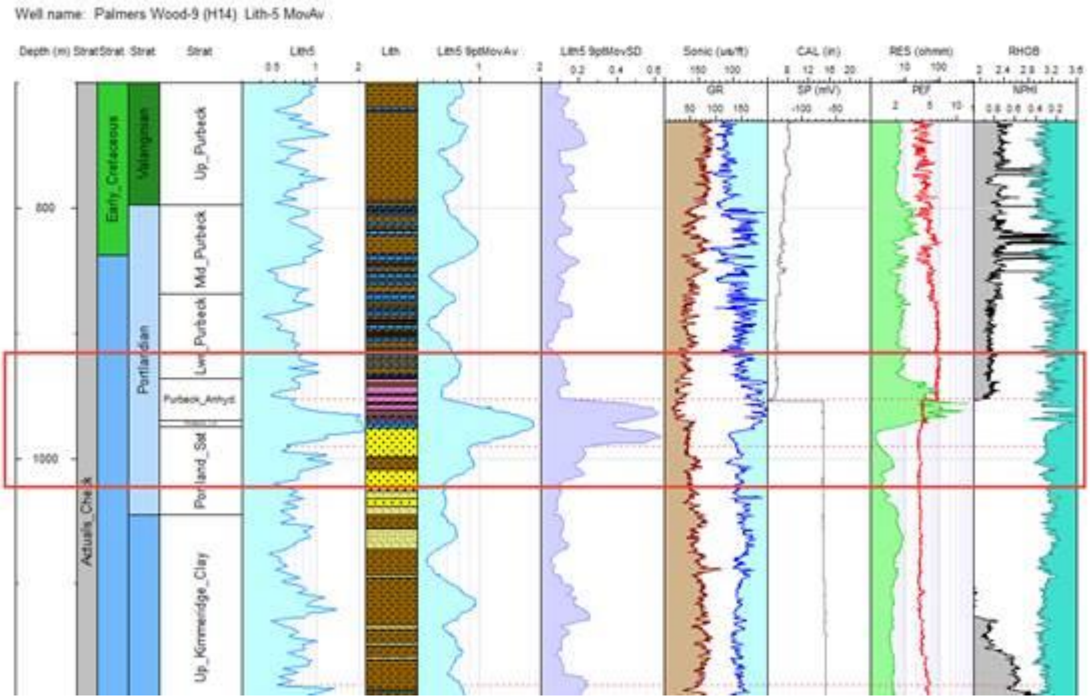

Figure 3: Understanding precisely what the tool is seeing with different metrics and why is the subject of ongoing study, assisted by calibration with wireline measurements when available. For example, here, comparing with the resistivity, is it the anhydrite causing the response, or is there a HC signature in the top of the sandstone?

No panacea, but a useful addition to the exploration arsenal

The tool is not a one-stop shop solution to geological problems but holds promise as another part of the risk-mitigation toolkit for subsurface professionals. It is at a comparable stage of development to deployment of the very first wireline tools, with scope for future expansion as subtleties are better understood.

This portable cheap sub-surface tool is responding to geological boundaries up to 3000 m deep with m-scale resolution. The analysis is non-trivial, but this should catch the notice of any geoscientist with an eye for innovation. The tool warrants further development and field testing. A number of major companies worldwide are already working with Adrok to do that.

Exciting scope for future testing and development

Onshore UK with its ample supply of wells, diverse geology, and onshore mineral, geothermal, and hydrocarbon resources, is just one good place to further investigate this exciting new technology. Globally, onshore stacked deltaic or turbiditic plays and massive sands for geothermal exploitation may represent other "low hanging fruit" in the sedimentary context. Twenty-first century advances in data analysis, including machine learning capabilities, give a sense that the technology is poised to grow in importance in subsurface resource exploration and monitoring.

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Sedimentology of the Lower Carboniferous Breagh gas field (Southern North Sea) and age-equivalent onshore outcrops (Northumberland, UK)

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Introduction

Exploration success in nearshore waters off the Yorkshire Coast has led to gas discoveries in Early Carboniferous reservoirs at Crosgan, the development of the Breagh gas field (Figure 1) and has reignited interest in prospectivity along the southern margin of the Mid North Sea High (MNSH). The Breagh gas field contains sandstone reservoirs belonging to the Yoredale Formation (Figure 2). These are dated as late Visean (late Asbian and Brigantian) based on miospore analysis (McLean *et al.* 2005; Mclean & Martin 2009). The dating constraints allow for detailed sedimentological analysis to be carried out within the Breagh wells, linked to neighbouring wells and prospects (e.g. Crosgan; Figure 1). Due to the regional uplift of Britain and the easterly tilt that resulted from Palaeogene tectonic events, age-equivalent onshore exposures crop out along the Northumberland coast from Berwick-upon-Tweed in the North to Beadnell in the south. These outcrops belong to the Tyne Limestone and Alston formations (Yoredale Group) and are laterally equivalent to the Yoredale Formation in the UKSNS (Figure 2). These localities are well known to geologists, have been the subject of several publications (Leeder 1974; Holliday *et al.* 1975; Johnson 1984; Reynolds 1992; Turner & Scrutton 2004), and provide an exceptional training ground to allow students and industry professionals alike to visualise and investigate fluvio-deltaic deposits.

The key to understanding the play fairway is the sedimentological and tectonic evolution of the Early Carboniferous deposits in the UK Southern North Sea (UKSNS). Here we present a detailed sedimentological interpretation of these deposits in the Breagh gas field and surrounding region, including the onshore age-equivalent and sedimentologically analogous exposures. Understanding the nature and evolution of these sediments has important implications for de-risking future Carboniferous prospects and for understanding the wider pre-Variscan tectonic framework across the UK and Europe.

Data

This work involved a detailed and systematic sedimentological analysis of approximately 350 m of conventional core and electrical well logs from the Yoredale Formation in wells within, and close to, the Breagh Field. Over 620 m of section has been logged onshore in Northumberland. We have integrated traditional fieldwork techniques such as facies, palaeocurrent and stacking-pattern analyses with new biostratigraphic data collection on the coastal outcrops. This has allowed us to characterise the sedimentology in greater detail and in three dimensions. Results have then been integrated with and informed our offshore interpretations.

Seismic interpretation of the Carboniferous over the Breagh Field is hampered by imaging problems produced by three variables: differences in thickness of the Cretaceous Chalk Group; the presence of deformed evaporates belonging to the Zechstein Supergroup, and; fast velocities, which lead to reduced resolution. However, it is still possible to identify the major tectono-stratigraphic megasequences and determine the structural evolution of the greater Breagh area from the Carboniferous to the present day. This forms the focus of a separate presentation here: Grant et al. 2018. Structural and stratigraphic controls on the Breagh gas field, UK Southern North Sea.

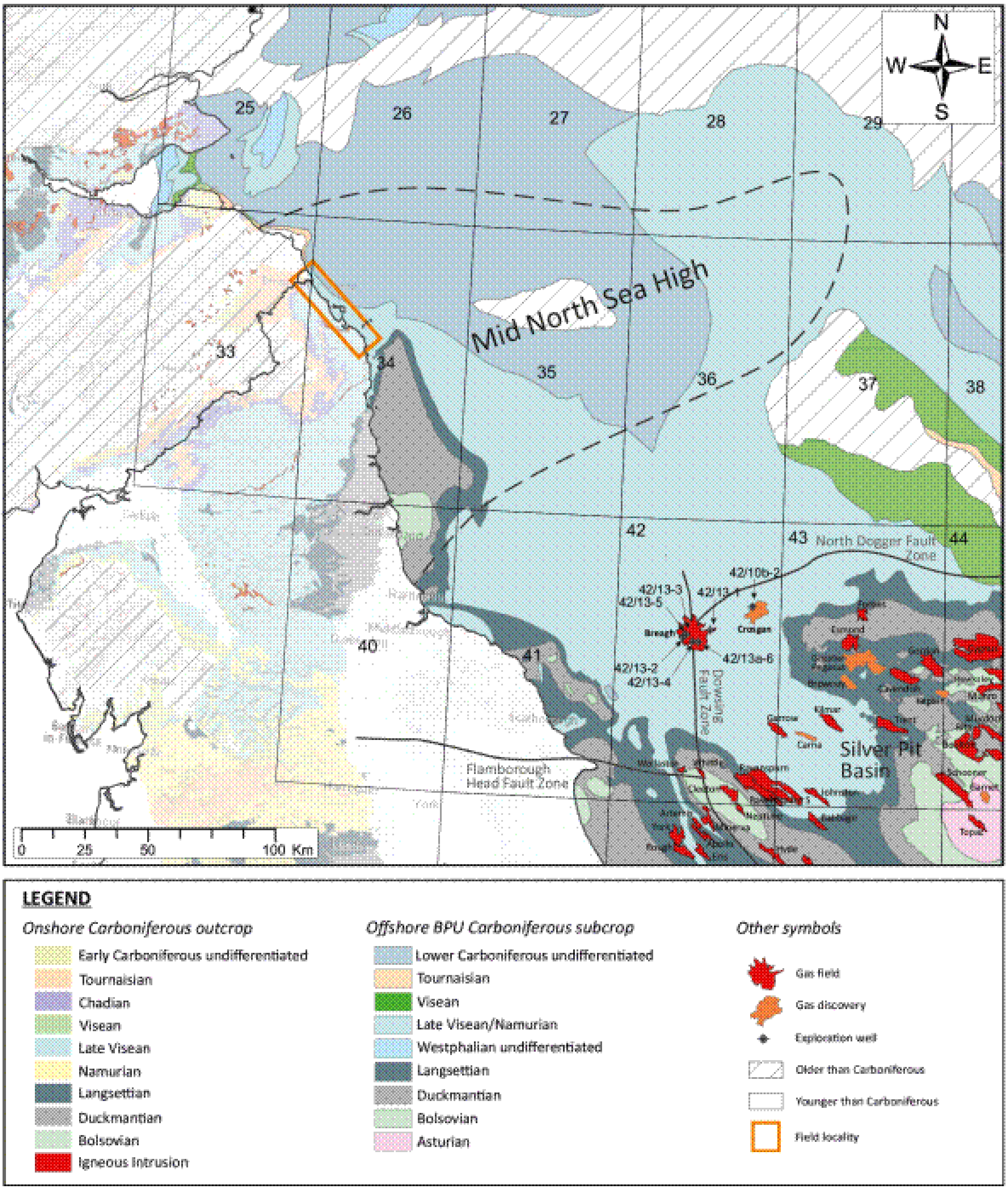

Figure 1- Location map showing the UK coastline and offshore quadrants. The colours onshore represent the various ages of Carboniferous rocks at outcrop. Offshore the colours represent Carboniferous deposits subcropping the seabed (In more western areas) and beneath the Base Permian Unconformity (BPU) where there is younger cover. The outline of the coastal section where we have undertaken fieldwork is denoted by the orange box (with detailed maps shown in figure 6). Also shown is the location of the Breagh gas field (near the centre of quad 42) and some of the exploration wells with core that have been utilised during this work. Data compiled from various sources including freely-available OGA and BGS data.

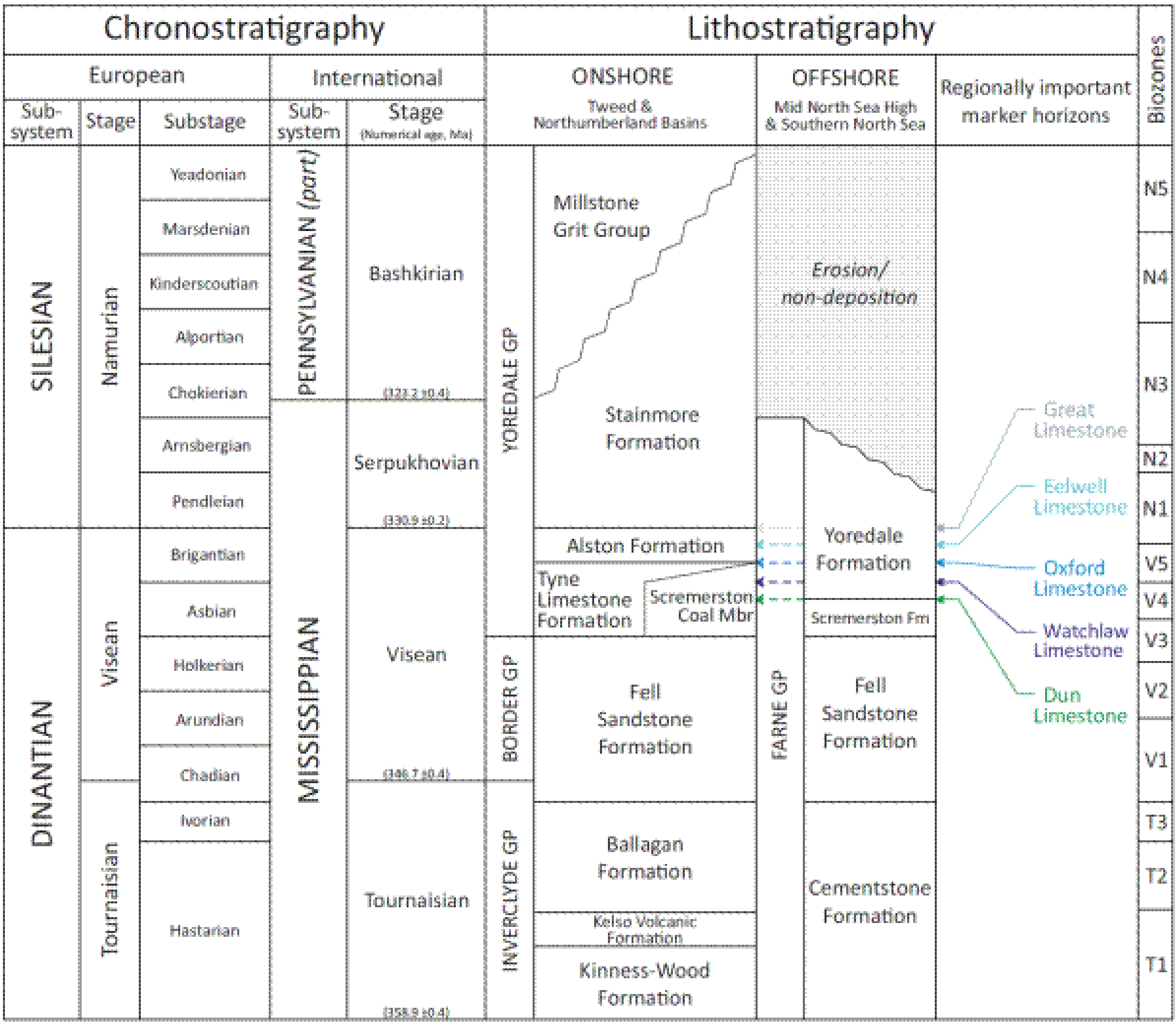

Figure 2- Chronostratigraphic and lithostratigraphic nomenclature for the onshore Tweed and Northumberland basins and the offshore UKSNS. The stratigraphic level of important, regionally-extensive limestone markers is indicated.

Results

The general depositional palaeoenvironment was a recurring deltaic system with variable depositional processes and multiple sub-environments. Our field and core-based sedimentological studies have allowed seventeen individual facies to be recognised. The facies are grouped into four facies associations based on their interpreted depositional environment, these are: Upper Delta Plain (including fluvial channel, lacustrine, floodplain and delta top facies), Lower Delta Plain (including tidally influenced distributary channel and interdistributary bay facies), Delta Front (including prodelta, mouth bar and laterally developed shoreface facies) and Open Marine (including limestone and offshore mudstone facies). The Open Marine Facies Association represents the most distal marine deposition, with the Upper Delta Plain Facies Association being entirely terrestrial. In a generally prograding wedge, elements of each facies association should stack to form a ‘cycle’. Facies and facies associations are summarised in Table 1.

The results demonstrate that the main reservoir facies in the Breagh Field are formed of erosive-based, medium- to coarse-grained, pebbly, tabular and trough cross-bedded, amalgamated sandstone beds interpreted as braided (low-sinuosity) river deposits that may have infilled incised valleys. However, significant additional sandstone bodies are represented by mouth bar, distributary and barrier-island deposits. These have different depositional geometries and lithological characteristics which are important to understand in order to maximise recovery from these fluvio-deltaic reservoirs.

Environment (Facies Association)	**A - Open marine**	**B - Delta front**	**C - Lower delta plain**	**D - Upper delta plain [& coastal plain]**
Sub-Environment (Facies)	A1 - Carbonate Shelf	B1 - Prodelta	C1 - Bay [lagoon] Floor	D1 - Braided Fluvial Channel
		B2 - Lower Shoreface	C2 - Bay [lagoon] Margin	D2 - Low-Sinuosity Fluvial Channel
		B3 - Upper Shoreface		D3 – Abandoned Channel
	A2 - Offshore Muds	B4 - Mouth Bar	C3 - Interdistributary Bay Delta	D4 - Lake
		B5 - Tidally-Influenced Distributary Channel	C4 - Distributary Channel	D5 - Non-Marine Delta Top [inc. Floodplain, Crevasse Elements, Palaeosol and Mire]

Table 1 – Summary of interpreted facies, facies associations and depositional environments.

Discussion

Late Visean sedimentation in Northumberland, the Southern North Sea and the wider region (e.g. Netherlands, Belgium and as far afield as Nova Scotia), is characterised by repeated Regressive-Transgressive-Regressive (R-T) 'cycles' of stacked facies. Each cycle is characterised by a package of coarsening and cleaning upwards clastic sediment that form a progradational-retrogradational package bounded by two maximum flooding surfaces (typically associated with fossiliferous limestone beds). It is possible to assign a dominant, depositional process (e.g. river-dominated) to each cycle. The stacking of these cycles and changing dominant deltaic process enables us to investigate the Gross Depositional Environments (GDE) for each genetic stratigraphic sequence (sensu Galloway, 1989) and produce palaeogeographies and play fairway maps through which to better understand the prospectivity and tectonic evolution of the Early Carboniferous basins. Our interpretations are consistent with results from studies of Asbian and early Brigantian, fluvio-deltaic deposition in a series of river-dominated deltaic cycles within tectonically confined depocentres in northern England and southern Scotland (Fraser & Gawthorpe 2003). Palaeocurrent data record sediment transportation towards the south and southwest within these confined basins (Gardiner 1983). The cyclicity of these successions is normally attributed to either allogenic (eustatic, tectonic) or autogenic (sedimentary) processes, or a combination of these. However, the Northumberland and Tweed basins were elongate and narrow (c. 60 km wide), approximately equating to the width of some modern river-dominated delta lobes (Elliott 1975; Gardiner 1983). Being confined within such narrow basins suggests that there was little room for autogenic processes to occur and points towards allogenic controls on the deposition of these river-dominated deltas. Onshore seismic profiles demonstrate that a significant switch from localised extension-controlled deposition within these narrow grabens, to a regional-scale phase of thermal subsidence occurred later in the Brigantian (Fraser & Gawthorpe 1990, 2003; Leeder & Hardman 1990). This change in tectonic style appears to coincide with a change in deposition from river-dominated deltas to mixed wave-, tide- and river-influenced deltas. We interpret this as a shift from extensional to post-rift tectonics prior to the development of a broad foreland basin setting associated with the early Westphalian onset of the Variscan orogeny. The change is marked by the Oxford Limestone (figure 2), which is correlated from Northumberland into the UKSNS (this study) and the North Pennines, where it is recorded as the Jew Limestone (Frost, 1968; Holliday et al., 1975; Johnson, 1984; Gardiner 1983) and it represents a major marine incursion in the Midland Valley of Scotland, where it is recorded as the Hurlet Limestone (Dean et al., 2011; Holliday et al., 1975; Johnson, 1984).

A thorough understanding of the tectono-sedimentary evolution of the Lower Carboniferous is critical for future near-field hydrocarbon exploration and the re-appraisal of other potential hydrocarbon accumulations within the UKSNS and further afield. Additionally, depleted reservoirs in the UKSNS may also provide exciting opportunities for future energy and carbon storage.

Acknowledgements

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MagPI – A new tool for the determination of permeability in clastic reservoirs

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The study presented here summarises a joint industry project between the University of Derby and Advanced Downhole Petrophysics Ltd, undertaken by two students for their MSc independent studies. The project looked at the use of a relatively new tool, the Magnetic Permeability Indicator (MagPI) as a method for permeability measurement on cores from two North Sea wells (Figure 1). This tool induces a magnetic field into a rock sample and measures the degree of resultant magnetisation, so that the magnetic susceptibility (magnetisation/applied magnetic field) can be obtained. This magnetic susceptibility is primarily controlled by the mineralogy of the zone of investigation; minerals such as quartz have very low and negative magnetic susceptibilities in contrast to illite and haematite which have higher and positive magnetic susceptibilities. For this study, the MagPI tool yielded a suite of measurements of bulk volume magnetic susceptibility; the trends from a variety of runs through the core were compared with lithology, mineralogy, and Routine Core Analysis (RCA) measurements that had previously been taken from plugs.

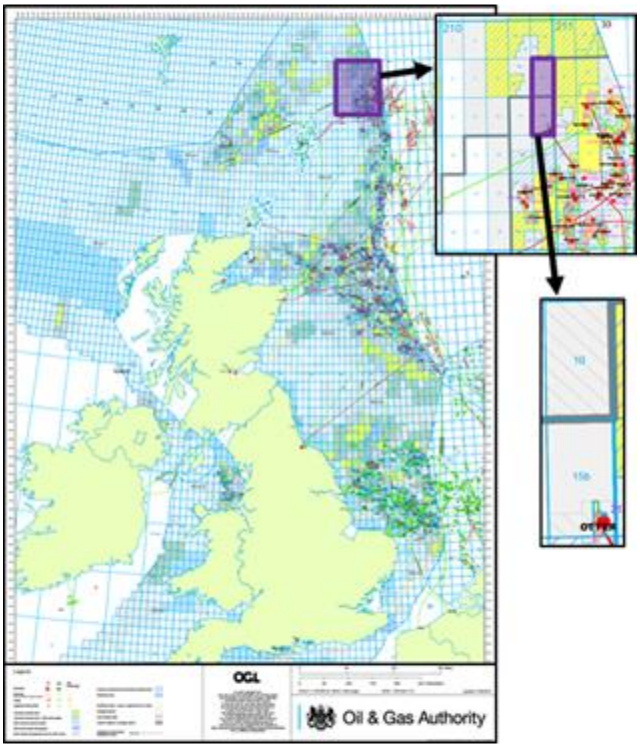

Figure 1. UK North Sea licensing area and all the blocks within the study area. Inset shows block 210/10- 1 and 210/15- 2. Modified from Oil and Gas Authority (2016).

Rationale

One of the most challenging facets of sub-surface analysis is the determination of permeability within a reservoir interval. While bulk porosity is arguably the most important factor that governs the overall volume of hydrocarbons within a structure, it is permeability that determines the likely flow rate from a given reservoir and thus the longer term commerciality of any discovery.

In contrast to porosity measurements, permeability itself can only be accurately gauged from physical testing of recovered core material, or long-term drill stem tests. However, there are some remote tools that can be used as a proxy for establishing the permeability of an interval. Nuclear Magnetic Resonance, for example, can help establish the distribution of pore sizes within the zone of investigation, which can then be used to infer the likely permeability. Tools which can similarly provide methodologies for the determination of permeability within reservoir intervals are thus of great potential benefit to the oil and gas industry, especially if the results can be obtained quickly and in a cost-effective manner.

Previous applications

Recent studies of magnetic susceptibility on reservoir rocks have demonstrated how the technique can be used in a rapid, non-destructive way to determine key petrophysical parameters (Potter, 2007; Potter, Al-Ghamdi, & Ivakhnenko, 2011; Ivakhnenko and Potter, 2006). The project focused on the ability of MagPI to derive permeability through the use of bulk volume magnetic susceptibility (VMS) readings. Core sections from two Jurassic North Sea wells, 210/10- 1 and 210/15- 2, were used for this study. The MagPI tool was able to detect the variations in mineral content (from magnetic susceptibility values) which can then be converted into a magnetically derived illite (MDI) content. Illite is paramagnetic with a positive magnetic susceptibility and is a significant pore clogging phase in the subsurface. Illite-bearing rocks tend to have a lower permeability than non-illitic clastics which have the same bulk porosity, and it is hypothesised that variations in illite content can be directly correlated with fluctuations in permeability (Potter, 2007).

Results of this study

A variety of magnetic susceptibility measurements at different spacing intervals were taken from the two cores. From this, The Magnetically Derived Illite content was derived for each sample point using the equations of Potter et al. (2004):

$$MDI = \frac{(K_r - K_Q)}{(K_I - K_Q)} \times 100$$

where MDI = magnetically derived illite content (%), K_r = measured VMS of the reservoir rock, K_Q = VMS of Quartz (-1.50e^{-5}), K_I = VMS of illite (+4.10e^{-4}).

The MDI values were then plotted against the Klinkenberg Corrected Air Horizontal Permeabilities (KCAHP) from a suite of corresponding core plug samples from the two cores. This provided a regression equation from which the magnetically predicted permeability (MPP) was calculated. MPP values proved to be reliable when directly compared to both KCAHP values and wireline logs. SEM analysis of core chips was also used to qualitatively assess the validity of the calculated illite amount in a representative batch of samples.

In total four measuring runs were undertaken along the cores. Both wells had two runs, each run being at a different measuring interval. The alteration between a broad and fine resolution allowed for an investigation as to whether the resolution of the tool had an effect on the results. Although the readings of the broader-spaced results were generally reliable, the wide sample separation distance meant there was a higher degree of uncertainty between readings.

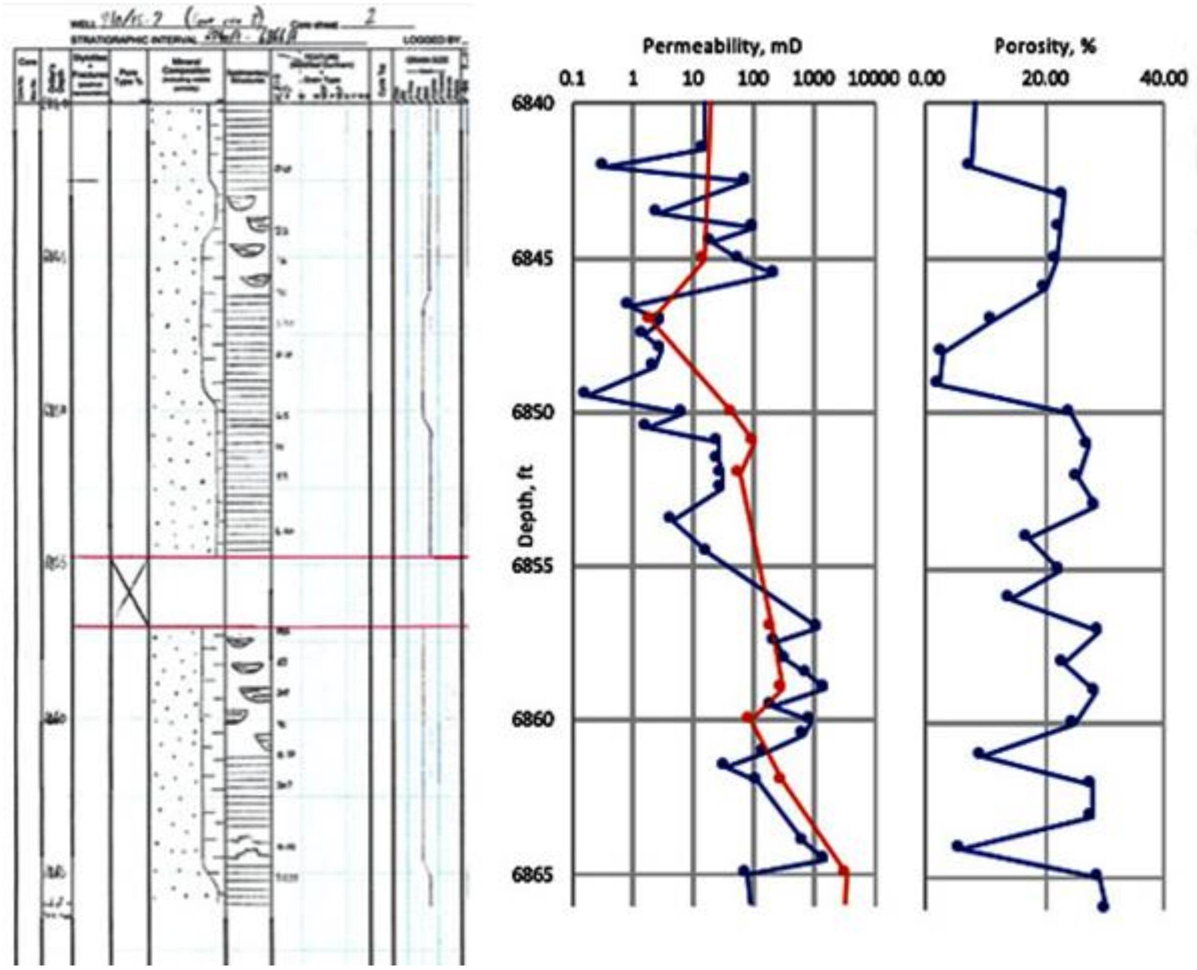

Figure 2. Comparison of logged lithological variations with RCA Permeability and Porosity (blue lines) and Magnetically Predicted Permeability (red line).

Figure 2 summarises the permeability-depth trends for 210/15- 2. There is a strong similarity between the trend measured from Routine Core Analysis (RCA) and the trend calculated from magnetic susceptibility, further highlighted in the crossplot of Figure 3.

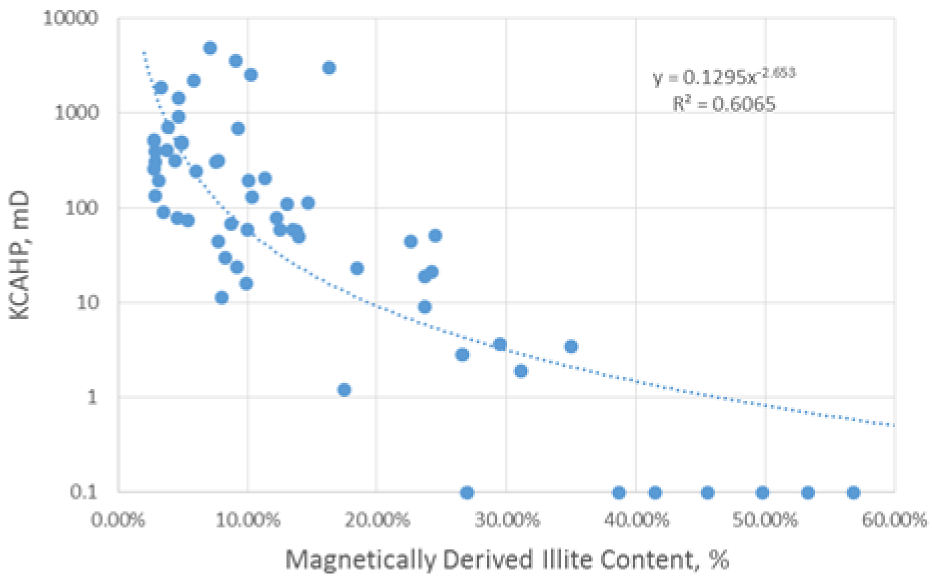

Figure 3. Crossplot of measured permeability against calculated Illite content

Similarly-good correlations were noted across the other intervals of the cores, heralding great promise for this technique as a rapid way to establish permeability trends for clastic core samples.

Future Developments

While the technique shows potential as a tool for quickly establishing permeability trends, further study needs to be done on fine tuning the optimal data acquisition time and resolution. A broader resolution may provide a faster logging time, as would a shorter acquisition time for the sample readings. In this project, each measurement acquired a magnetic susceptibility reading over a seven second interval. Future work may look at the reliability of a faster acquisition time, especially if the tool is to be used in a downhole environment. This trade-off between logging time and accuracy needs to be further explored, but there is potential in utilising this technique as a quick and relatively cheap determinant of permeability within clastic reservoirs.

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Quantitative prediction of sandbody connectivity within distributive fluvial systems through numerical modelling

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Fluvial reservoirs are challenging to characterise due to heterogeneity associated with complex facies architecture. The primary control of reservoir performance is sandbody connectivity that is a result of channel belt stacking. Recent advances by Hartley et al. (2010), Weissmann et al. (2010), and Owen et al. (2015) in understanding the large-scale spatial distribution of fluvial facies from modern and ancient systems have led to the development of the Distributive Fluvial System (DFS) model. This conceptual model provides a framework to predict the distribution of channel stacking patterns depending on location within the DFS (proximal, medial or distal) and accommodation. At present, the model is largely qualitative and does not include accommodation driven controls predicted in the LAB model (Bridge and Leeder, 1979; Leeder, 1977). Quantifying the DFS model through outcrop analogues is difficult due to the limited number of case studies with exposure of the entire system. Flume tank experiments have full parameter control but introduce significant upscaling uncertainty unlike process-based numerical models that allow full parameter control at a range of scales.

Process-based numerical models

Process-based models recreate sedimentary systems from input parameters and governing equations. In the case of DFS modelling, the input parameters are (1) duration, (2) topography of the initial surface, (3) subsidence history, (4) fluid flow characteristics including water discharge, direction and velocity of flow, Manning's roughness coefficient, and sediment concentration and constitution. Fluid flow is computed with variations of the Navier-Stokes equations using the shallow water assumption. The routing of flow is governed by the path of the fluid elements. They follow the gradient from cell to cell. The accuracy of the models depends on the fluid flow equations used. As accuracy is proportional to computing time, a balance of the two parameters is necessary. Models need to be both of a sufficient resolution and be reproducible in great numbers to generate statistically significant results. Multiple modelling approaches are required to cover the full scale of DFS from entire systems to segments of channels. Three software products were selected for this purpose: (1) the stratigraphic forward modelling software Sedsim for the system scale (Griffiths et al., 2012), (2) the fluvial forward modelling source code developed by D. Karssenberg for the channel network scale (Karssenberg and Bridge, 2008), and (3) the fluid flow modelling software Delft3D for specific channel processes (Lesser et al., 2004). The model outputs are generated at every predetermined time step and encompass elevation and grain-size distribution for each cell and channel position and the fluid characteristics therein. These outputs can be combined to create depositional facies and ultimately a time-dependent facies model which allows the analysis of sandbody connectivity.

Modelling approach

To determine the possibilities and limitations of the software, a comparison model was run with each of them. The model recreates a small DFS which terminates in a large body of water. The initial surface is a ramp and the fluvial input comes through a point source at the upper side of the ramp. The slope of the initial surface, subsidence rate and fluvial input parameters were chosen from literature studies of modern systems of similar sizes. To reduce complexity, wave and tidal processes were not included.

Sedsim can model DFS with downstream lengths in the 100s of kilometres at reasonable computing times. The software can also recreate every termination type described by Hartley et al. (2010), such as axial fluvial system, coast, lake, and aeolian dune field. This large-scale modelling approach both in time and space comes at the price of accuracy. Isolated fluid elements are utilized to represent continuous flow which only captures the mean sediment transport within each time step and does not account for flood events (Griffiths et al., 2012). The source code developed by D. Karssenberg specializes on the development of channel networks with a focus on channel bifurcation and avulsion. This allows a direct analysis of sandbody connectivity form the outputs. To reduce computing time, the fluid flow is computed with a simple slope-driven diffusion equation that reduces the accuracy of the solution. The source code is also limited to fluvial environments and can only model a part of the DFS and not the entire system (Karssenberg and Bridge, 2008). Delft3D solves the fluid flow equation very accurately and contains modules for marine environments. If a small delta including channels, flood plains, and marine effects are to be modelled, the computation time is prohibitively long. It can be used for small channel segments though, e.g. to analyse a bifurcation (van der Vegt et al., 2016). To balance out the shortcomings of each individual software, they are used in tandem as a software suite.

Discussion and further work

The current understanding of sandbody connectivity in DFS is purely conceptual (Fig. 1). The forward modelling suite described above is used to compute a series of models which cover the spectrum of accommodation space, sediment supply and climate variations. The parameter sets for these scenarios are gathered from literature studies. The suite allows modelling the full range of scales. Each parameter set is modelled at the system scale first, the outcomes are analysed, and the appropriate software is used to delve into specific aspects of the large-scale model. This creates model families for each parameter set. Each model family is quality controlled against a range of DFS in outcrop and active systems; these include (1) the Ebro system (Spain), (2) the Morrison and (3) Colton Formation, USA, and (4) the modern Mitchell DFS in the Gulf of Carpentaria, Australia. Using numerical modelling to fill the data gaps in outcrop and modern analogues will result in a greatly improved model for understanding and predicting reservoir connectivity in fluvial systems.

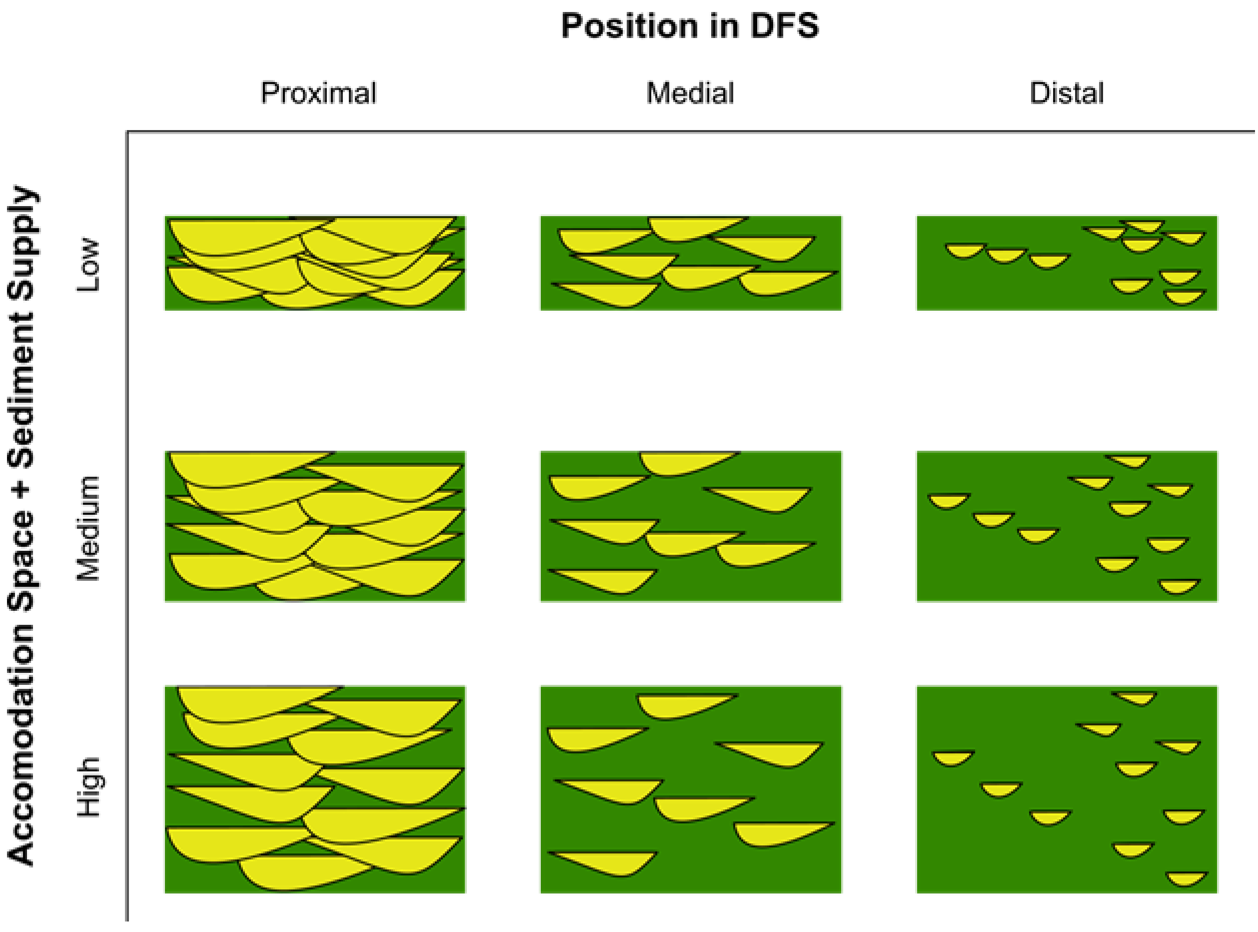

Fig 1. Conceptual model of sandbody connectivity in distributive fluvial systems (DFS) in cross-sectional view perpendicular to the main flow direction. Nine models represent the effect of the position within the DFS from proximal on the left to distal on the right, and accommodation space and sediment supply from low on top to high at the bottom. The yellow bodies are sand-filled fluvial channels and the green represents flood plain. The sandbody connectivity slowly diminishes with higher accommodation space and quickly diminishes the more proximal the position within the DFS.

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The optimal lateral length and well pad size for maximising recoverable reserves of shale gas in northern England.

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Introduction

With the success of shale gas in the US, other more densely populated countries, including several countries in Europe, have begun exploration for shale gas. Within these countries the carrying capacity of the land and competition for land with other uses are important factors to consider as they restrict the amount of gas that could be extracted. That is, in Europe, with its greater population density, there is an increased need to study the well pad footprint (the area covered by the well pad), setbacks and infrastructure.

Within the UK, shale gas is still in the exploratory phase and no commercial operations have yet been authorised (Delebarre et al., 2017). However, in 2016 two sites within the North of England were granted planning permission to drill and explore the potential of shale gas in the area (Delebarre et al., 2017). Thus, in April 2018 Cuadrilla Resources announced the UK's first horizontal shale gas well had been drilled laterally extending 800m (Cuadrilla Resources, 2018). With exploration wells underway the public have concerns with regards to the impact on the land and the surrounding environment. There are a number of studies that assess current and likely future footprints of shale gas sites within Europe (Baranzelli et al., 2015; Clancy et al., 2018) and the US (Drohan et al., 2012; Racicot et al., 2014; Johnson et al., 2010; Martinez and Preston., 2018). However, there are only two studies published on site location limitations due to surface carrying capacity (Clancy et al., 2018; Racicot et al., 2014). Furthermore, based on our review there have been no studies published in the peer-reviewed scientific literature that address well pad spacing and optimal lateral length. Therefore, the main aim of this research was to determine if there is an optimum lateral length and well pad size that limits disruption on the surface but maximises technically recoverable reserves.

Methodology

The approach of this study was to consider the relationship between technically recoverable resources as estimated with various recovery factors and to relate all estimates to lateral length. For the purposes of the study we estimated: direct footprint, indirect footprint, subsurface footprint and technically recoverable reserve estimates using the equations below. Given the range of situations where shale gas is either being exploited or at least considered; and the uncertainty within resource estimates a stochastic approach was taken with ranges for inputs being defined from literature.

- The direct surface footprint of any given well pad is: $S_f = W_a + (L_a L_n)$

Where: S_f - surface footprint; W_a - area required for a single well pad with one well; L_a - area required per lateral; L_n - number of laterals wells on the pad.

- The subsurface footprint of any well pad can be defined as: $S_{sf} = (L_l L_w) L_n$

Where: S_{sf} – indirect subsurface footprint (m^2); L_l - lateral length (m); L_w - the drainage width accessed by any lateral (m); L_n - number of lateral wells on the pad.

- The indirect surface footprint (I_f) is: $I_f = (2B)^2$

Where: I_f = indirect surface footprint (m^2); and B = setback distance (m).

- Technically recoverable reserves, determined from the resource estimates, are limited by the recovery factor and the surface carrying capacity is: $T = \theta\varphi R$

Where: T - technically recoverable reserve per license block (m^3 of gas); θ - surface carry capacity; φ- recovery factor; and R - estimated resource (of lateral).

The carrying capacity of the license blocks over the Bowland Shale was calculated. Carrying capacity is as defined in Clancy et al. (2018) as the number of well pads that could be located, without overlap or disruption of the surface infrastructure (including all roads, buildings, water ways, ponds and woodland) within a 100 km^2 licence block. We assessed physically how many well pads with the following variables could be located within 20 licence blocks: lateral length set at 3 levels - 500 m, 750 m and 1.25 km; setback distance set at 3 levels – 152 m, 305 m and 457 m, these results were plotted and assessed. The number of well pads in each of the 20 license blocks for each of the combinations of lateral length and setback distance were analysed using a two-way analysis of variance (ANOVA) to generate a general linear model.

Results

As one expects, as the lateral length and the number of laterals per well pad increase the subsurface footprint also increases. In addition, as the setback distance increases the indirect surface footprint also increases. Generally, license blocks with higher carrying capacities (licence blocks that have less existing infrastructure and more available space to locate more well pads) show that well pads with multiple wells and with longer laterals are more efficient in terms of the amount of extracted gas compared to the footprint. However, each block differs and increasing the number of well pads and extending lateral lengths does not always result in optimal gas recovery. In certain cases, where licence blocks have a higher carrying capacity (licence blocks with less existing infrastructure and more available space for additional well pads) it is found that well pads with multiple wells are still the most effective but slightly shorter laterals are more efficient. In this latter case, well pads with lateral extending 750 m would potentially yield more gas than laterals of 1.25 km. Our results indicate that for a large number of the licence blocks a lateral length of 1200 m would be an optimal lateral length (Figure 1). Thus it minimises the impact on the surface whilst maximising the volume of gas that can be extracted. It is worth noting that our calculations do not factor in sweet spots and variations in shale thickness across the across the Bowland Basin.

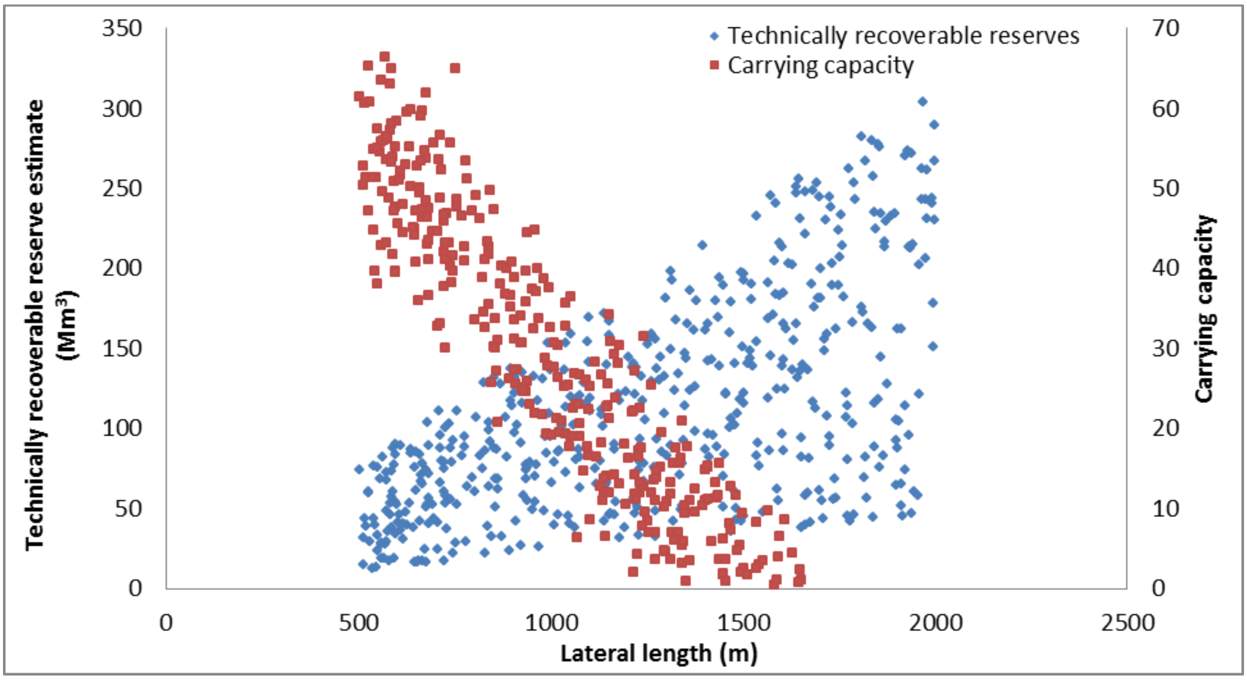

Figure 1. Technically recoverable reserves estimates (Mm^3) and carrying capacity per license block, against lateral length (m).

Conclusion

The number of well sites that can be located within a licence block is largely dependent on the individual license block. Blocks that include large cities and towns have more existing infrastructure limiting the space available for well pads and their associated setbacks. Generally, license blocks with higher carrying capacities show that multi-well pads with longer laterals are more efficient in terms of footprint size. However, as each block differs increasing the number of well pads and extending lateral lengths does not always result in optimal gas recovery. Our results highlight that generally longer laterals reduce the cumulative surface footprint and generate more gas reserves, however, this is not always the case and licensed blocks need to be assessed on an individual basis.

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VardyQuake: Measurement of anthropogenic seismic signals produced at the King Power Stadium during live football matches.

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The VardyQuake project was a collaboration between the British Geological Survey (BGS) and the University of Leicester Geology department. It was conducted by a group of 20 undergraduate geology students, sub-divided into teams with responsibilities for technical work, educational visits, social media and publicity. The project was led by Paul Denton, a leading Geophysicist at the BGS. Seismic monitoring equipment was supplied by SEIS-UK, the Natural Environment Research Council's onshore seismic facility, led by Dr Victoria Lane. Who also provided great support to the technical team throughout the project.

The project entailed the novel application of seismic monitoring equipment by measuring anthropogenic seismic signals produced during live home football matches. During home games, as goals are scored, the crowds celebrate, generating seismic waves, which are detected and quantified using seismic visualisation software. The project was an outreach program conducted in order to encourage more engagement from school students in the geosciences. A key aspect of generating widespread interest in the phenomena was that in 2016, Leicester City Football Club was having a major impact in the Premier League, and as rank outsiders at the start of the season the club and city were already a focal point of sports news. They ultimately went on to win the Premier League Cup at the end of the season in May, drawing more public attention to VardyQuake. The term 'VardyQuake' was coined after Leicester's leading striker Jamie Vardy.

Geophones were set up in a local school, Hazel Community Primary School, approximately 500 m from the local football stadium, King Power Stadium. The equipment worked in unison with a similar system installed in the basement of the University's Department of Geology Bennett Building and another installed set in the New Walk Museum approximately 1.1 km from the stadium, see figure 1. Seismic signals were monitored in real time by hardwire or remotely via an internet connection at the University.

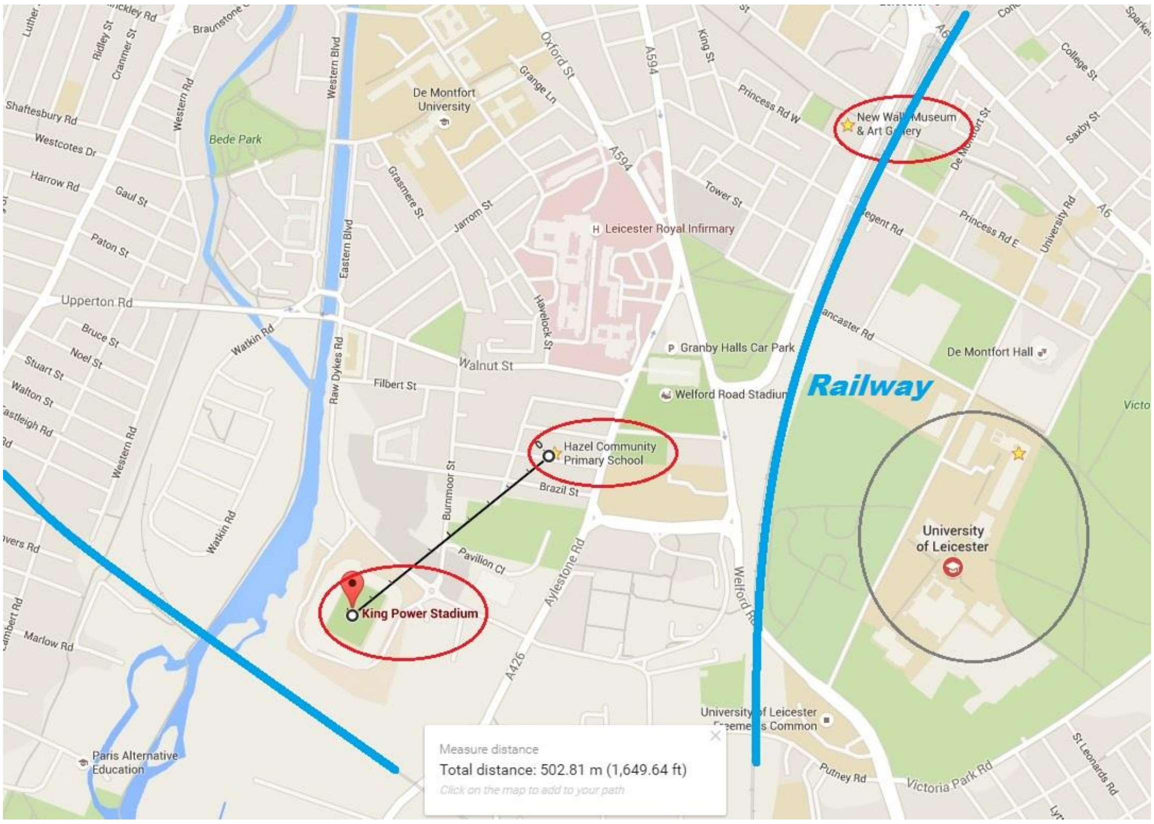

Figure 1. Location map of the football stadium, primary school, local museum and the university, illustrated from Google Maps.

Within the seismic traces recorded by the equipment, several seismic anomalies were detected. It was observed that there was a clear correlation between the occurrence of large seismic signals and the exact times Leicester scored a goal at home. It was concluded that the equipment was measuring small earthquakes produced by the sudden energy release by the cheering Leicester fans celebrating at the moment a goal was scored. The stadium was full for every match with 29,000 home supporters and only 3,000 visiting supporters so goals from visiting teams hardly registered on the seismic system whereas goals from the home team had considerable effects[2].

Signals were recorded at Hazel school for the last 7 home matches of the season, in which Leicester scored in every match at least once. For one of these matches a professional quality broadband sensor (Guralp CMG-6TD) was deployed alongside the 2 Hz geophone at Hazel school by SEIS-UK, to check the calibration values[2]. The seismic anomalies, which correlated with the scoring of goals, were calculated for signal strength and quantified as a magnitude on the Richter scale.

On the 6th of March the seismograph at the Hazel school recorded seismic signals from a small earthquake which occurred in the middle of the night near Oxford, 102 km away. The British Geological Survey national seismic network registered this event and assigned it a local earthquake magnitude value M=2.3, using their modified local earthquake magnitude formula[1]. This was used as a calibration event in addition to the BGS earthquake magnitude formula to make an empirical estimate for the sensitivity of the Hazel school seismograph[2] and thus an equivalent magnitude estimate for the 'VardyQuakes'.

During a match between Leicester City and West Bromwich Albion, the equipment detected strong seismic signals during the first half when Leicester scored a goal, which measured a magnitude 0.1 on the Richter scale, see figure 2. The biggest signal detected during the seasons matches was recorded when Leicester City scored the only goal in the match against Norwich in the 89th minute and this registered a magnitude 0.3, see figure 2.

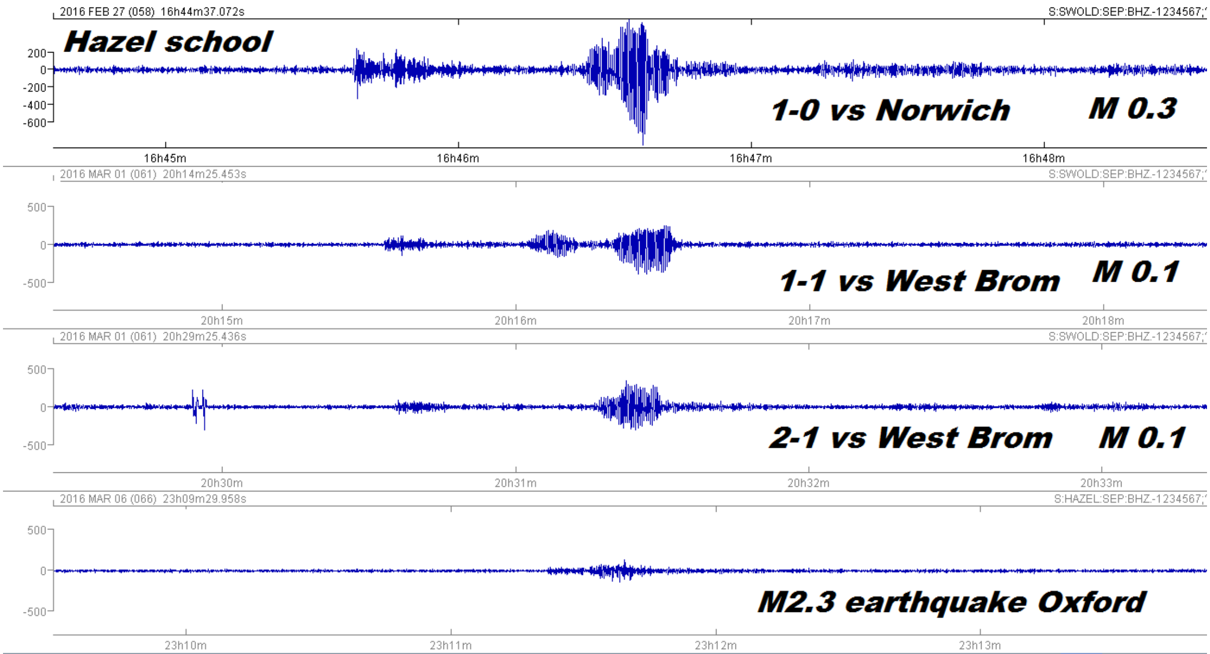

Figure 2. Seismic anomalies detected on seismic trace coincident with goals scored during each respective game and seismic signal produced from the earthquake near Oxford on the 6th of March 2016.

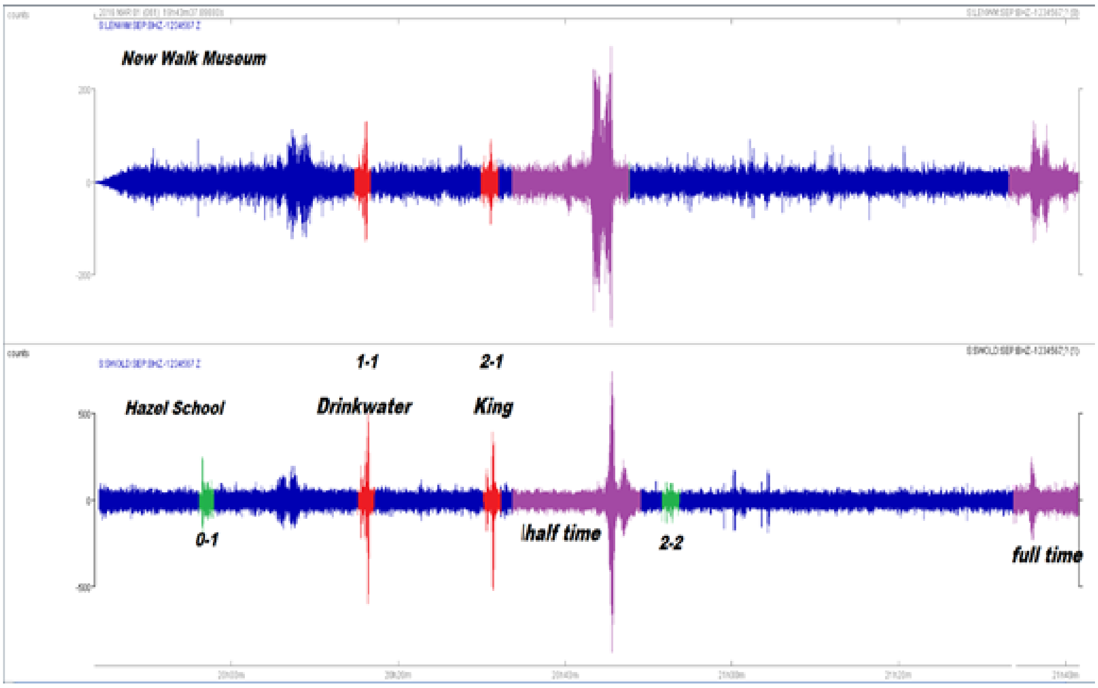

Figure 3. Bottom trace: Seismic trace produced from game against West Bromwich Albion. Highlighted are distinct peaks produced when goal are scored particularly from Danny Drinkwater and Andy King from Leicester City and during half time. Top trace: Seismic trace from seismometers set up at the local museum, used for comparative purposes.

Leicester fans generating the kind of seismic activity is not a new phenomenon, Seattle Seahawks fans caused a minor earthquake between a magnitude of 1 and 2, termed 'Beast Quakes' during an early first-quarter touchdown in the game against New Orleans Saints in December 2013[3], see figure 4.

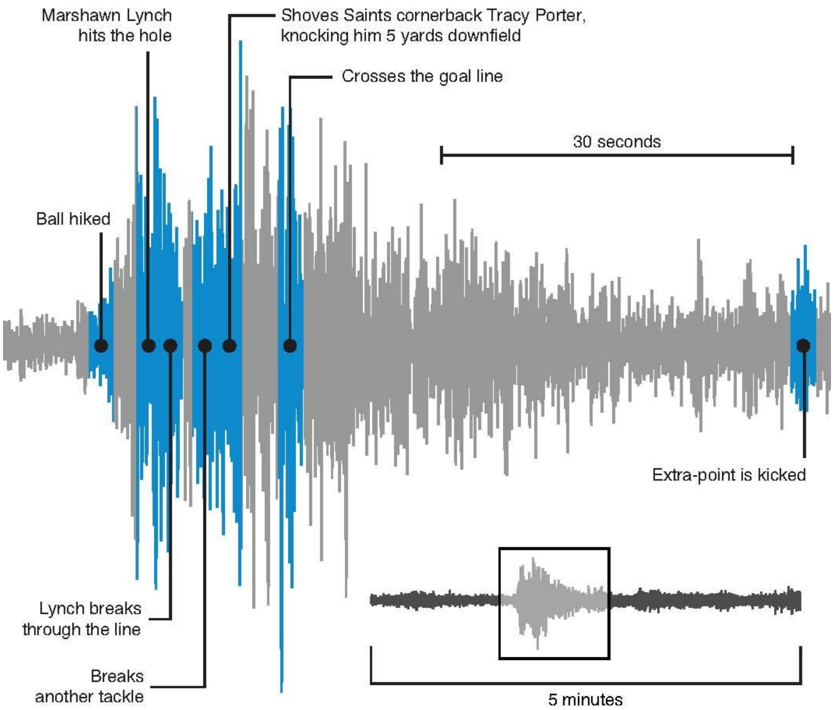

Figure 4. Illustrated section from the seismic trace produced during the December 2013 game between Seattle Seahawks and New Orleans Saints[3].

The head teacher at Hazel Community Primary School was keen to get involved and the education team made several visits to the school and ran education sessions for the pupils there. The school is relatively small with 400 pupils aged 4-11 and located in an impoverished inner city. Often in these schools the rate of progression into higher education is low thus introducing the pupils to current undergraduates as potential role models can help boost their personal aspirations[2].

The education team talked about how the seismic waves had travelled from the stadium to the school, using slinkies as visual aids, and making comparisons and contrasts with sound waves through the air, which the school pupils had been studying in their curriculum[2]. The pupils were highly engaged and asked probing and intellectually charged questions. They were overall very excited about their involvement in the project.

The publicity team started a social media campaign based around Twitter with a @VardyQuake account posting images and information about each match as it happened, it accumulated over 1000+ followers.

The story of VardyQuake was picked up by the local paper, regional TV and the UK national press. Reuters, an international news agency, ultimately released an article which was picked up globally, with over 375 articles published as far afield as Nepal, Uganda, Malaysia, USA and Australia. The project subsequently accumulated over £1.1 million worth of advertising value.

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