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Passive, continuous monitoring of carbon dioxide geostorage using muon tomography

Jon Gluyas[1], Lee Thompson[2], Dave Allen[3], Charlotte Benton[4], Paula Chadwick[3], Sam Clark[1,5], Joel Klinger[2,6], Vitaly Kudryavtsev[2], Darren Lincoln[2,7], Ben Maunder[1,7], Cathryn Mitchell[4], Sam Nolan[3], Sean Paling[9], Neil Spooner[2], Lazar Staykov[1], Sam Telfer[2,] David Woodward[2,10], and Max Coleman[11]

[1] Department of Earth Sciences, Durham University, DH1 3LE, UK
[2] Department of Physics, University of Sheffield, S3 7RH, UK
[3] Department of Physics, Durham University, DH1 3LE, UK
[4] Department of Electronic and Electrical Engineering, University of Bath, Claverton Down, Bath, BA2 7AY, UK
[5] STEM Team, University of Highlands and Islands, 1 Inverness Campus, Inverness, IV2 5NA, UK
[6] Nesta, 58 Victoria Embankment, London EC4Y 0DS, UK
[7] Atkins, Chadwick House, Birchwood Park, Warrington, WA3 6AE, UK
[8] Imperial College, London, UK
[9] Boulby Underground Laboratory, Boulby Mine, Loftus, Saltburn-by-the-Sea, Cleveland, TS13 4UZ
[10] Penn State University, Physics Department, University Park, PA 16802, USA
[11] NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

Abstract

Carbon capture and storage is a transition technology from a past and present fueled by coal, oil and gas and a planned future dominated by renewable energy sources. The technology involves the capture of carbon dioxide emissions from fossil fuel power stations and other point sources, compression of the CO_2 into a fluid, transporting it and injecting it deep beneath the Earth's surface into depleted petroleum reservoirs and other porous formations.

Once injected, the CO_2 must be monitored to ensure that it is emplaced and assimilated as planned and that none leaks back to surface. A variety of methods have been deployed to monitor the CO_2 storage site and many such methods have been adapted from oilfield practice. However, such methods are commonly indirect, episodic, require active signal generation and remain expensive throughout the monitoring period that may last for hundreds of years.

A modelling framework was developed to concurrently simulate CO_2 geostorage conditions and background cosmic-ray muon tomography, in which the potential was assessed for using variations in muon attenuation, due to changes in CO_2 abundance, as a means of CO_2 detection. From this we developed a passive, continuous monitoring method for CO_2 storage sites using muon tomography, the tools for which can be deployed during the active drilling phase (development) of the storage site. To do this it was necessary to develop a muon detector that could be used in the hostile environment (saline, high temperature) of the well bore. A prototype detector has been built and tested at the 1.1 km deep Boulby potash mine on the NE coast of England, supported the existing STFC Boulby Underground Laboratory on the site. The detector is now ready to be commercialised.

Introduction

In 2015 the Earth's atmosphere reached a milestone that many people hoped it would not. Carbon dioxide levels of 400 ppm were measured, up approximately 50% from pre-industrial levels (Scripps, 2018) and a direct result of humans' obsession with burning fossil fuels as the primary energy source for almost every developed nation on Earth. The impact of CO_2 on the atmosphere is well understood. As a greenhouse gas it traps more of the sun's heat within the atmosphere as its concentration rises and so drives climate change. The interaction between atmosphere and hydrosphere with increased levels of CO_2 has also led to harmful ocean acidification. The increased acidity leads to a reduction in the viability of corals and other marine species with carbonate skeletons. Some would argue that the impact of increased CO_2 levels on the oceans will be more devastating than that on the atmosphere (Anthony et al., 2008; Doney et al., 2009).

The potential threat of increased levels of CO_2 to the stability of the atmosphere was recognised over 30 years ago and together the World Meteorological Organisation and the United Nations Environment Programme founded the Intergovernmental Panel on Climate Change (IPCC). Its aim was to provide regulators and policy makers with advice on the scientific assessments of climate change, the associated risks and impacts as well as potential mitigation strategies.

The IPCC has been hugely influential and most governments now accept that human activity in the form of fossil fuel usage is driving climate change. As a direct result of IPCC activities, billions of dollars have been invested in countless research programmes collectively aimed at reducing humankind's emissions and if not emissions then the impact of such emissions. Humankind now has a panoply of technologies which could be applied to the problem but rollout is patchy, slow and often inconsistent. Fossil fuel use continues to rise and so too atmospheric CO_2 concentration. Only the global economic slowdown of 2008 reduced consumption of gas, oil and coal, albeit temporarily.

Ultimately the problem is one of chemistry. Oxidation of the elemental carbon in coal and the hydrocarbons in oil and gas releases huge amounts of energy per mass consumed, much more so than burning biomass, lithium batteries, solar panels, wind turbines and other renewable sources. Basically, fossil fuels are cheap and hugely versatile, whole economies are built upon their use. Changing habits is difficult, particularly when much of the world's population is in fuel poverty, especially when doing so would put one’s nation at an economic disadvantage to other nations. Indeed, often governments typically last a handful of years, a short enough time that climate change may seem too distant compared with more immediate concerns.

Climate change is without any doubt the biggest threat to humanity (Chomsky, 2017). Here we examine a small part of one technology which could have a significant impact in terms of reducing greenhouse gas emissions without compromising the fossil fuel based global economies. Carbon Capture and Storage (CCS) involves the capture of CO_2 from power plants and other industries, compression of the CO_2 and injection of that CO_2 deep below the Earth's surface into depleted oil and gas fields or similar geological formations (Gluyas and Mathias, 2014). It is tried and tested on relatively small scales, it works. Indeed, CCS is but an incremental technological development of routine oil production in which water and/or gases (sometimes CO_2) are pumped into the ground to win more oil production. Currently about 5 million tonnes of CO_2 are stored annually using this technology compared with about 33 billion tonnes released to the atmosphere (Storrow, 2018). Nonetheless, Pacala and Socolow (2004) estimated that approximately one seventh of global emissions could be treated in such a way.

Background to instrument development

Although the technology for CCS is tried and tested, it is not optimal. There are many areas for improvement in capture, compression, transportation and storage. Financially, the biggest gains are to be made in capture technology which is by far the most expensive component part. This is because the retrofit of capture technology to decades-old power stations and industrial plants is difficult. Flue gases containing CO_2 are typically low pressure and dilute with respect to CO_2. New power stations and industrial plants can be constructed in such a way that CO_2 capture is an integral part of their design and subsequent process. However, the component of CCS which is the least well developed is in the monitoring of carbon dioxide once stored deep underground. That CO_2 which is injected into the Earth needs to be in the expected part of the reservoir for optimal filling and storage and essentially must stay there and not escape back to the surface. Were it to do so, then the long-term impact would be the same as if it had never been stored, furthermore, at the point of escape there may be more significant impacts. Natural, volcanically induced, eruptions of CO_2-rich gases have caused suffocation of humans and other animals (Baxter et al., 1989) and whilst CO_2 would not be stored in the same high-risk environments as exploited by nature, it is clear that the CO_2 storage sites need comprehensive monitoring for decades and quite possibly centuries.

Monitoring technologies do exist and most are borrowed from the petroleum exploration and production industries. The most widely used of the petroleum industry technologies is 4D (time lapse) seismic reflection monitoring. The method is suitable given that the acoustic properties of a rock change when the fluid content of the rock changes. In petroleum production, as oil and/or gas is extracted, water flows into the depressurised region created, either naturally or by pumping, to maintain reservoir pressure. In carbon storage, dense state CO_2 is the newly introduced, injected component. Storage sites are at least 1 km beneath the Earth's surface, and even at this depth and greater, the acoustic changes associated with CO_2 injection can be monitored and the development of the growing CO_2 plume mapped. Good though it is, 4D seismic monitoring has some significant drawbacks. Seismic monitoring is episodic, requiring generation of a signal in the first place. For example, the Sleipner CO_2 storage project operated by Statoil in the Norwegian sector of the North Sea has had an annual seismic acquisition project (Arts et al, 2002). The acquired data is then processed and interpreted. Effectively the data is a snapshot for one day in 365. Moreover, because the data needs to be processed, the interpretation lags behind the acquisition by several months at best. In addition, seismic surveys on sea and particularly on land are very expensive, running to millions of dollars per survey. Finally, the seismic surveys measure changes in acoustic properties of the subsurface. They do not directly measure CO_2 distribution.

It is against this backdrop that we explored a different monitoring technology, one which is continuous, passive, directly measures the properties of CO_2 and is potentially far less expensive than seismic monitoring; muon tomography. In muon tomography the properties of naturally occurring, high energy, sub-atomic particles are exploited. Muons are created in the Earth's upper atmosphere following collisions between cosmic rays, themselves generated in various astrophysical sources, and atoms of nitrogen and oxygen. Muons are leptons with mass about 200 times that of an electron. They are charged and extremely penetrating, passing through the atmosphere and shallow parts of the Earth's crust. Attenuation occurs as a function of both the density and thickness of the matter through which the muons pass. The muon flux at the Earth's surface is relatively high (De Pascale et al, 1993),an area of approximately one square centimetre is penetrated every minute by a muon. However, at 1 km beneath the Earth's surface the flux is lower and a detector of 1 m x 1 m would expect to record a muon, on average, every 20 minutes.

Muon flux modelling

To understand if this technology would be feasible in terms of cost, scale and sensitivity, robust simulations were performed. Realistic three-dimensional and stratified models of the geology of the overburden of test sites were produced, and sophisticated models of CO_2 injection were generated. Both the geological and CO_2 density models were then used as inputs for a simulation of muon attenuation, with a muon detector situated at a nominal location within the geological model. The simulation of the muon flux at the Earth’s surface was generated according the Gaisser Parameterisation (Gaisser, 1990) corrected for the curvature of Earth. With this formulation, it was possible to forecast the muon flux before, during and after CO_2 injection.

Detailed geological models of two sites were built. The first site modelled was that of the Boulby Mine (Figure 1). Seismic and well data were used to recreate the stratigraphy of the Triassic Sherwood sandstone (the target storage horizon) and the overburden within a three-dimensional computer simulation. Each stratigraphic layer was assigned a bulk density (rock and pore fluids) based upon measurements made during the original exploration, appraisal and development of the mine. Although Boulby is not intended to be a storage site for CO_2, it was nonetheless a singularly important part of the muon tomography project because, with the support of the existing STFC Boulby Underground Laboratory at the site (Henton de Angelis. 2017) and the assistance of the mine operators ICL-UK, we could easily place muon detectors in the mine in short boreholes drilled into the walls of the mine galleries. This could be done with ease and at low cost and detectors could be recovered. CO_2 disposal wells drilled into the North Sea will cost several tens of millions of dollars each. The chances of the project team being able to persuade an operator of testing such novel equipment in a real well was vanishingly small and so Boulby with its geology matching that of planned storage sites in the North Sea was critical. A second model was built for the Hewett complex of depleted gas fields (Figure 2, Clarke, 2014). This area has high storage capacity and at the time of the muon tomography project one of the power utility companies operating in the UK favoured its development for CO_2 storage.

Different detector configurations were tested, the effect of which is to reduce the total 'acceptance' for muons to be detected, compared with the proportion rejected as background noise; that is to say the accepted detections are from those muons that have interacted with two or more of the scintillation bars. The detectors were simulated as borehole containers containing several scintillator bars (described in Section "Muon detector development"). In the very worst case, an acceptance of 5% of muons over a total surface area of 1000 m^2 was used (Kudryavsev et al, 2012). Even with this seemingly low acceptance, the muon flux modelling (after muon attenuation through the strata) indicated that the plume of CO_2 could be detected within 49 days (Klinger et al, 2015). Such model outputs could then be compared with measured data acquired at the test sites.

The simulation was computationally intensive so a significant proportion of the work was attributed to reducing such overheads, by employing multithreading, batch computing, and optimal choices of meshes to represent the geological strata. Memory optimisations were achieved by performing the simulation in stages (strata by strata).

This procedure was the first detailed simulation of muon radiography which simultaneously incorporated geological data to describe a subsurface CO_2 storage site, with a simplified but nevertheless realistic modelling of CO_2 plume evolution and non-trivial muon detector configurations. This is particularly important since non-ideal behaviour in real situations (for example from geological heterogeneity) mean that detailed simulations will be the only method for understanding the required detector topology for effective imaging, as well as providing a basis for comparison with real detector data.

Muon detector development

The muon tomography project aimed to deliver a new passive and continuous monitoring system for tracking a subsurface plume of CO_2 generated as the gas is injected into a depleted petroleum reservoir or deep saline aquifer. Naturally occurring muons which pass through the overburden and then the CO_2 disposal interval would be detected by an array of detectors deployed in short radius sidetrack well beneath the injection site. Detectors were required which could be deployed in well bores of $9^5/_8$ inch diameter and withstand temperatures of up to about 70 degrees centigrade and pressures of 2000 psi and operate for period of years or tens of years without maintenance.

In designing the detectors, the initial challenge to address was that of providing a system capable of tracking the muon's passage whilst operating in the constraints of a borehole geometry. Bars of plastic scintillator were chosen and the borehole detector was assembled from typically a dozen such bars. A plastic scintillator comprises a material such as polystyrene called the base impregnated with special compounds called fluors that react to the interaction of an incoming particle (such as a muon) to emit a flash of light. A combination of plastic scintillators and small, fast light sensors is therefore capable of reconstructing the muon's path through the borehole detector.

The detector assembly is housed inside a sealed, dust and light protected steel tube, designed to be inserted in a typical $9^5/_8$ inch borehole of the type used in the petroleum industry. Ancillary supports for the mechanical arrangements within the steel tube were made using a 3D printer. Robust designs were also made using the 3D printer to hold the scintillator arrays and the photo sensors (Figure 3).

Plastic scintillator rods of different types were procured from Eljen Technology (Texas) and compared by measuring the time resolution of each rod. Time resolution is the crucial factor in this experiment as it is used to localise the muon interaction point along the scintillator bar. Better accuracy in time measurement (in the order of ns (10^{-9} seconds) to ps (10^{-12} seconds)) minimises the error in localising the muon interaction point and thus improves cosmic muons tracking.

A total of 3 types were compared, EJ200, EJ204 and EJ208, where EJ200 performed slightly better than the others. The sigma of the Gaussian fitting of the time distributions from the different types of scintillator appeared as follows:

EJ200: (0.87 ± 0.06) ns
EJ204: (0.92 ± 0.04) ns
EJ208: (1.02 ± 0.06) ns

During this experimental study, an optical guide was used in between the scintillator and the photo sensor. The optical guide was made by solidifying sylgard optical gel. The refractive index of the optical gel matches well with the scintillator and the photo sensors, but the transparency becomes poorer when it becomes solid. Later, photo sensors were directly coupled to the scintillator rods using optical coupling gel and with the photo sensor is 1 mm away from the rod. A better time resolution of (0.5 ± 0.05) ns has been achieved in this way in the EJ200 type scintillator rod (Figure 4).

Detector deployment and testing

The main reason for wishing to access a deep borehole was to be able to test the muon detector at what would be expected to be ambient conditions at a sub-sea CO_2 storage site. Major concerns at the start of the project were that the likely temperature in storage sites of 50-70°C would be too high for the detectors then available and that the environment would also be too chemically hostile. Thus, access to a borehole with subsequent detector testing was seen as an important milestone ahead of persuading a company to place a detector in a multi-million pound offshore well.

Following the difficulty in accessing an onshore borehole from surface a contingency was developed whereby we could test the detector in a borehole drilled in the wall of the Boulby Mine at approximately 1 km beneath the Earth's surface. This was done as indicated in Figure 5. The borehole was allowed to reach the rock temperature of 35ºC (unlike the working galleries in the mine which are cooled to allow for comfortably working conditions in the mine) and the detector inserted and run in full test mode for 2 months. Muons were detected on average every 20 minutes, in line with the expectations from our model. Neither the elevated temperature nor the hostile chemical environment of the borehole affected the instrument.

Detector commercialisation

Despite the huge successes of the project, work came to an abrupt end in December 2015 without having commercialised the detector system. The causes were two-fold and both came from outside the project. The first was falling petroleum prices. The second was the UK government's cancellation of the CCS demonstration project in November 2015. Falling energy prices forced the major petroleum service sector to cut costs and with that the research and development funds within companies with which we had been working. In addition, and within weeks of an award being made by the UK government to a consortium of companies able and willing to develop the nation's first offshore storage site, £1 billion of funding was axed; a hidden item in the November 2015 Comprehensive Spending Review. The government claimed costs were too high but the likely truth is that CCS was an easy target, even if in years to come the UK fails to meet its legally binding emissions reduction targets and suffers even greater fines. The effects combined mean that CCS is not likely to be deployed in the UK in the foreseeable future and the muon tomography project is looking elsewhere for commercial development.

Conclusions

We set out to develop a continuous, passive methodology for monitoring dense phase carbon dioxide, stored deep below the Earth's surface in porous reservoir rocks as part of the technology known as carbon capture and storage. The project was successful insofar as solid-state detectors were developed that could be deployed in deep, high-temperature, saline conditions at depths in excess of 1 km beneath the surface of the Earth. The detectors were developed and deployed for 2 months in a borehole drilled in the side of a gallery within the Boulby Mine in northern England. Muons were detected at a rate in line with expectation from modeling studies of the same. The muon detectors developed for the CCS project have yet to be commercialized.

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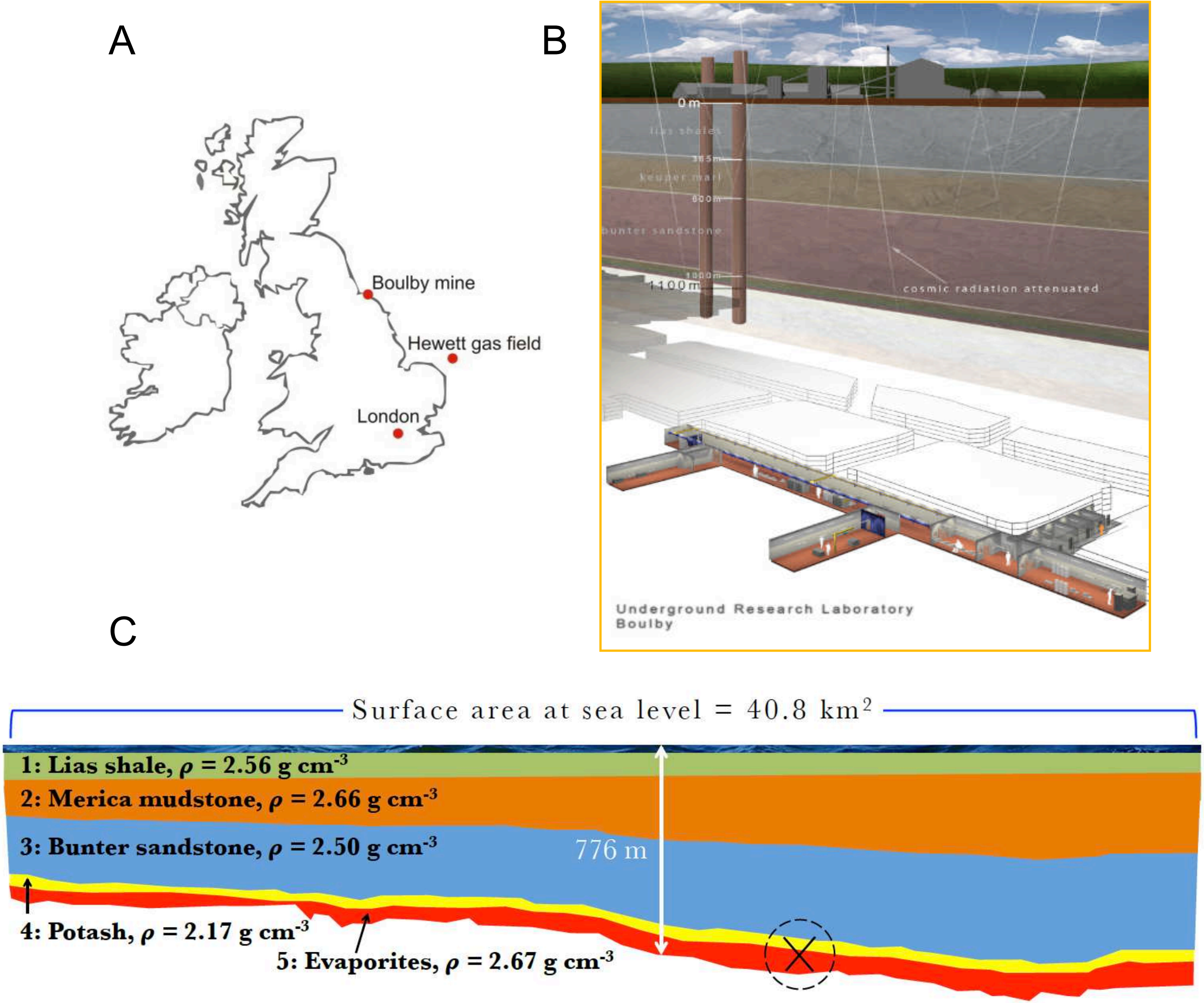
Figure 1 A location of Boulby Mine and Hewett Gas Field, B Sketch of the underground research laboratory at Boulby. The test boreholes were drilled into the gallery walls adjacent to the laboratory, C. A diagram of geological stratigraphy for the Boulby area and used in the simulations. The layer number, simplified composition and bulk density is indicated. There is an additional layer of sea water above Layer 1 with a depth of 32 m. Layer 3 is the saline aquifer formation suitable for CO_2 storage. The approximate location of the potential detector is shown by X. In the simulations CO_2 was injected vertically above the detector site (from Klinger et al, 2015).

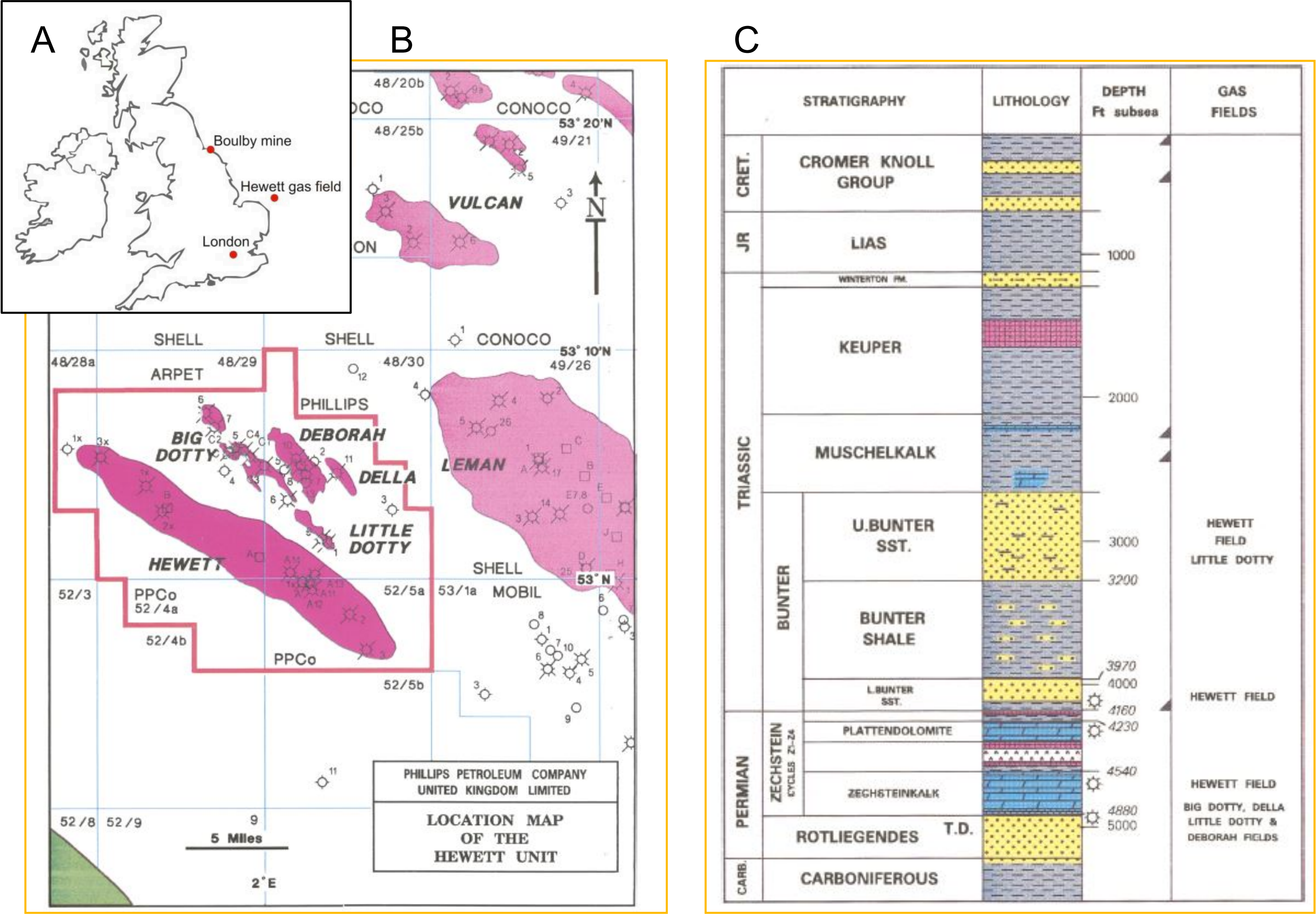
Figure 2 A location of Boulby Mine and Hewett Gas Field, B Hewett Field location map (from Cooke-Yarborough & Smith, 2003), C Hewett Field stratigraphy (from Cooke-Yarborough & Smith, 2003).

Figure 3 A stainless steel tube outer housing for the muon detector. The tube was designed to be compatible with use in an industry standard 9⅝ inch borehole. B internal configuration of borehole muon detector. The black plates support scintillation rods. C 3D printed support plate for scintillation rods. D 3D printed housing for photomultiplier.

Figure 4 A EJ200 type scintillation rods, B. Diagram showing array of scintillation rods within muon detector and typical muon trajectory. The muon would interact with several rods, creating photons, the arrival times of which at the ends of the rod are measured allowing the moun trajectory to be reconstructed.

Figure 5 Muon detector about to be borehole deployed, Boulby Mine, October 2014.


A
Boulby mine
Hewett gas field
London
B
0 m
lias shales
385m
keuper marl
600m
bunter sandstone
1000m
1100m
cosmic radiation attenuated
Underground Research Laboratory
Boulby
C
Surface area at sea level = 40.8 km²
1: Lias shale, ρ = 2.56 g cm⁻³
2: Merica mudstone, ρ = 2.66 g cm⁻³
3: Bunter sandstone, ρ = 2.50 g cm⁻³
776 m
4: Potash, ρ = 2.17 g cm⁻³
5: Evaporites, ρ = 2.67 g cm⁻³


A
Boulby mine
Hewett gas field
London
B
48/20b
CONOCO
53° 20'N
48/25b
49/21
VULCAN
N
SHELL
CONOCO
53° 10'N
48/28a
48/29
48/30
49/26
ARPET
PHILLIPS
BIG DOTTY
DEBORAH
DELLA
LEMAN
LITTLE DOTTY
HEWETT
53° N
52/3
PPCo
52/4a
52/5a
53/1a
MOBIL
52/4b
PPCo
52/5b
52/8
52/9
9
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2° E
PHILLIPS PETROLEUM COMPANY
UNITED KINGDOM LIMITED
LOCATION MAP OF THE HEWETT UNIT
C
STRATIGRAPHY
LITHOLOGY
DEPTH Ft subsea
GAS FIELDS
CRET.
CROMER KNOLL GROUP
JR
LIAS
WINTERTON FM.
TRIASSIC
KEUPER
MUSCHELKALK
BUNTER
U.BUNTER SST.
BUNTER SHALE
L.BUNTER SST.
PERMIAN
ZECHSTEIN CYCLES Z1–Z4
PLATTENDOLOMITE
ZECHSTEINKALK
ROTLIEGENDES
T.D.
CARB.
CARBONIFEROUS
1000
2000
3000
3200
3970
4000
4160
4230
4540
4880
5000
HEWETT FIELD
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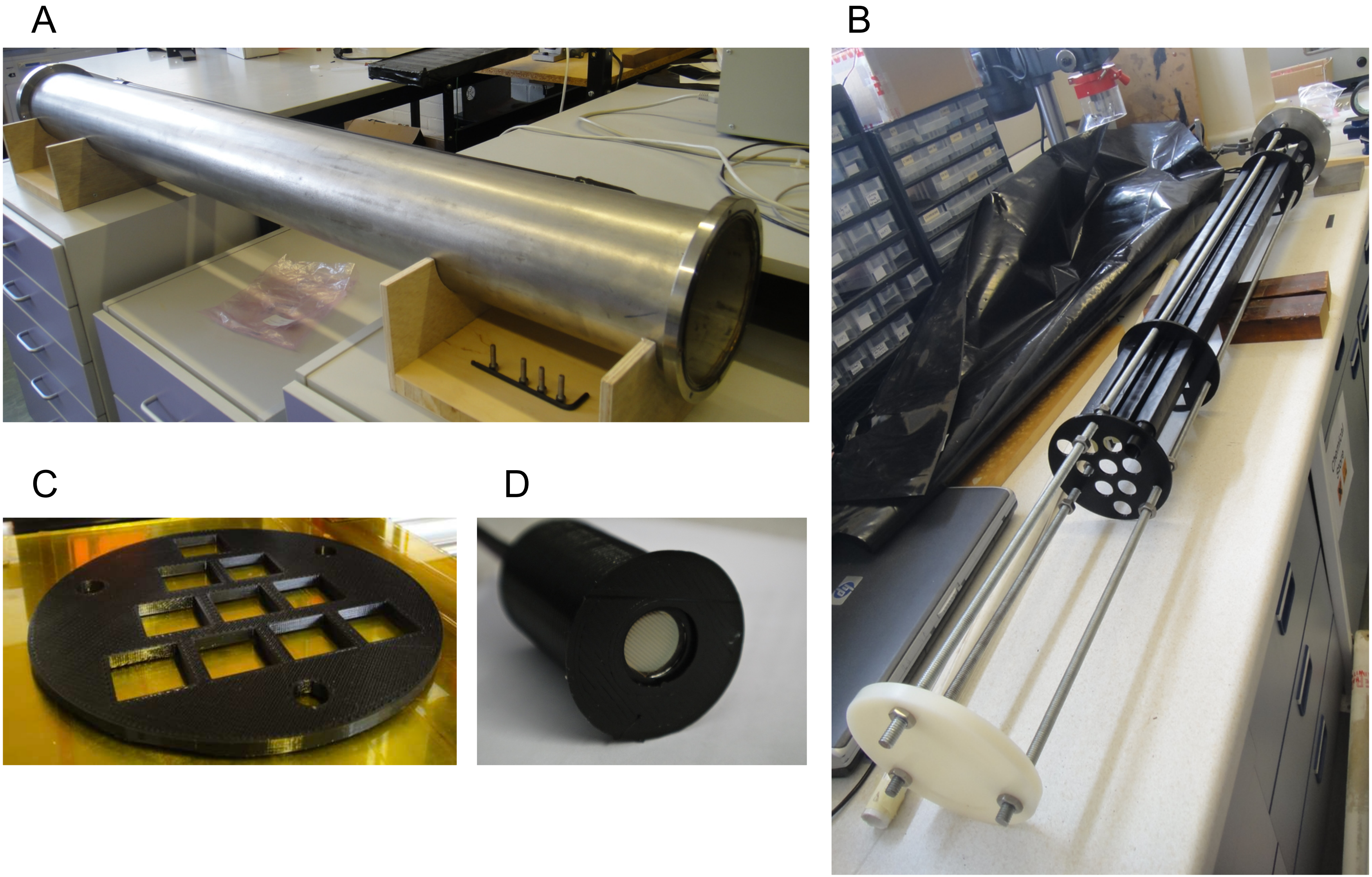
HEWETT FIELD
BIG DOTTY, DELLA
LITTLE DOTTY &
DEBORAH FIELDS


A
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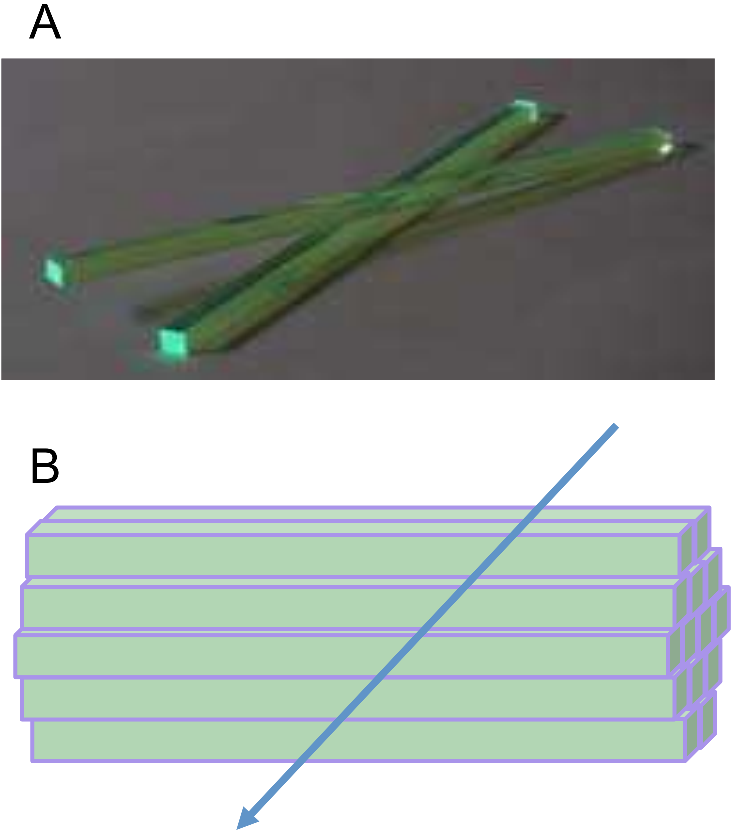
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