14th International Conference on Greenhouse Gas Control Technologies, GHGT-14

21st -25th October 2018, Melbourne, Australia

Constraining the physical properties of chimney/pipe structures within sedimentary basins

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Abstract

Evaluation of seismic reflection data has revealed structures cross-cutting the overburden within many sedimentary basins worldwide, including those in the North Sea and Norwegian Sea. These seismically-imaged pipes and chimneys are considered to be possible pathways for fluid flow. Natural fluids from deeper strata have migrated through these structures at some point in geological time. We test the hypothesis that many chimney and pipe structures imaged on seismic reflection profiles worldwide are the consequence of (1) a fracture network that has been reactivated by pore fluid pressure which facilitates the migration of fluids upwards; and (2) shallow sub-seafloor lateral migration of fluids along stratigraphic interfaces and near-surface fractures. An experimental approach to determine the physical properties of these structures beneath the sub-seafloor is described, with particular reference to an investigation of the Scanner Pockmark complex in the North Sea. The study is relevant to storage operators, policy-makers and those keen to demonstrate that it is possible to constrain and fully understand the physical properties and possible fluid flow pathways in the sedimentary overburden above sub-seafloor CO_2 storage reservoirs
Keywords: seismic chimney; pipe; fluid flow; fracture network

1. Introduction

Numerous geological structures within sedimentary basins can breach sealing sequences and facilitate the movement of fluids sub-vertically [1,2,3]. Seismic reflection data within sedimentary basins have been used to image the subsurface, allowing interpretation of potential migration pathways, and also to identify vertical fluid conduits, gas accumulations, and sediment mobilization (pockmarks etc.). There is agreement that there is ubiquitous evidence for focused fluid flow through low permeability sedimentary units.

Seismic chimneys and pipes (vertical seismic anomalies) are common in basins and they are interpreted as focused fluid flow structures which hydraulically connect deeper stratigraphic layers with the sediment overburden

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(4,3]. The activity of vertical fluid conduits can be limited to blowout-like events, e.g. resulting in pipe structures offshore Norway [5], or fluid flow may be continuous and long-lasting, e.g. the chimney structures above the leaking hydrocarbon reservoir Tommeliten [6]. Understanding of these shallow fluid flow systems is critical for assessing the integrity of sub-seafloor CCS sites.

One of the most comprehensive analysis of a fluid migration features in the North Sea [3] analysed large 3D seismic reflection volumes within the South Viking Graben and found 46 large-scale chimney structures within the shallowest 1000 m of the overburden, most of which terminate at or close to the seabed. The most prominent features imaged had large-scale (500 – 800 m long, 100 to 1000 m wide) seismic anomalies, whose pipe or chimney-like seismic signatures were similar to those interpreted world-wide as being due to vertical fluid flow. Vertical seismic anomalies interpreted as being due to fluid flow are found throughout the North Sea [e.g. 7,3,2,6], and globally [e.g. 1,8].

Karstens and Berndt [3] describe three types of North Sea chimney structures. Type C anomalies are elongate and meandering in plan view, and are possibly seismic artefacts or related to underlying tunnel valleys, and are considered less important in vertical migration of fluids and seal bypass, and we do not consider further. Type A “columnar” anomalies, or pipe structures and type B more “chaotic” anomalies are interpreted as the seismic image of fluid conduits that have by-passed the sealing formation (Nordland Shales), with the presence of bright spots clearly indicating the presence of gas within the structures. Most authors attribute the formation of chimneys or pipes as being due to hydro fracturing of an impermeable cap rock [1,2,3] with breaching of the cap rock caused by either capillary or fracture failure. Localization of fluid flow is a common feature of fracture networks [9]. Both these mechanisms for cap rock breaching require high pore over pressure.

Field core from the North Sea overburden has revealed the Cenozoic section to be pervasively faulted and fractured, with extensive regions of well-connected polygonal faulting occurring immediately below the Utsira Formation [10]. The Utsira sand is a major reservoir (used at Sleipner), with high porosity (>30%) and permeability (>1000 mD or 10-12 m2). The overlying Nordland Shales provide a series of seals to this reservoir and has <<1mD matrix permeability and >2 MPa capillary pressure. The dynamics of the CO2 plume in the Sleipner well suggest high horizontal permeabilities of >2000mD and, more significantly, high vertical permeability (~400 mD) or capillary pressures of >2000 kPa and 50 kPa, respectively. Vertical permeability in the Nordland suggests either lateral discontinuity of the shales (unlikely as some are several metres thick) or the presence of fractures (most likely). At Sleipner, there are no gas chimneys and the fracturing is attributed to microfracturing, possibly in response to the sudden removal of grounded ice [11].

2. Scanner Pockmark

This paper describes results from two geophysical cruises to the Scanner pockmark complexes in the North Sea. The Scanner pockmark complex is located in UK License Block 15/25 (Figure 1), around 190 km east of Scotland within the Witch Ground Basin close to a number of oil and gas condensate fields. The closest field to Scanner is the decommissioned Blenheim Oil Field, which is a heavily faulted Palaeocene sandstone play on the flank of the Fladen Ground Spur (Figure 1). Within the Blenheim field, structure maps of the Late Palaeocene Top Mey Sandstone [12] show a dominant NW-SE normal fault set.

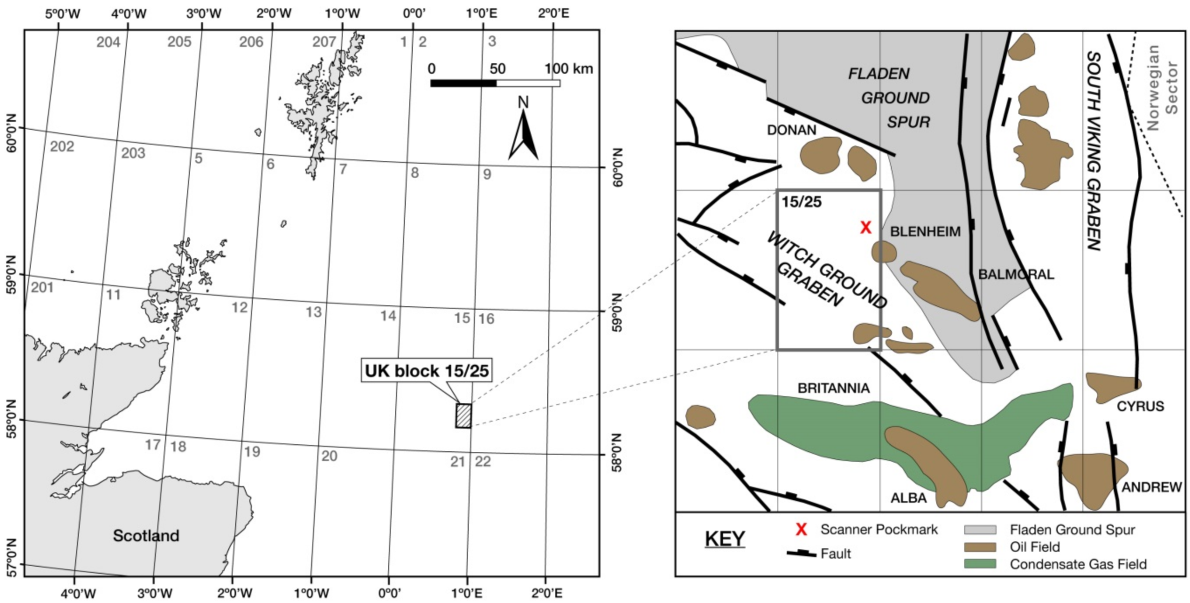

Fig. 1. Position of the Scanner Pockmark within the North Sea. The Scanner pockmark complex is within the Witch Ground Graben.

The Witch Ground Basin was the locus of rapid fine-grained sediment deposition between 15 and 13 ka after the end of the last glacial period. The soft muds of this formation are affected by large numbers of pockmarks [13]. Following the stabilisation of sea level after the last glaciation, the Witch Ground has been little affected by erosion or sedimentation, and hence pockmarks at the current seabed show the effects of gas escape over at least the last 6000 years. Although most pockmarks are small, less than 2 – 3 m, several studies have identified the presence of large pockmarks within Block 15/25 with very active methane venting [14,15].

The Scanner pockmarks are known to be the locations of vigorous and persistent methane venting, are associated with bright spots at shallow depth, and have chimney structures imaged on seismic reflection data to depths of several hundred metres. The Scanner pockmark is a composite feature involving two overlapping seabed pockmarks, each a few hundred metres in diameter, lying in c. 155 m water depth. Within the pockmarks samples of methane-derived authigenic carbonate (MDAC) have been recovered [16]. These MDAC deposits are formed by the anaerobic oxidation of escaping methane, cementing sediment grains just beneath the sea-bed, which with the process of continued gas movement across the seabed, become a hard ground.

In this paper we describe an experimental methodology to determine the physical properties and geometry of a representative chimney structure within the North Sea (Scanner Pockmark, Figure 1). The main aim of this study is to understand the physical properties of seismic chimney structures, develop appropriate methodologies which are widely applicable in the North Sea and elsewhere, and to model gas flux for realistic scenarios. The structure of the chimney may contribute to the understanding of causes of breaching, but this is not a primary aim of this paper.

3. Evidence for small scale seismic chimney formation - QICS

Although on a much smaller scale, some analogies can be made with the chimney structures induced during the QICS experiment. A shallow controlled sub-seabed CO2 release to replicate small-scale, but realistic, leakage that has migrated into the near-seabed environment was completed on the west coast of Scotland [17]. A borehole was drilled from shore, to a depth of 11 m beneath the sea floor, in 12 m of water and 350 m offshore. A total of 4.2 tonnes of CO2 was injected into the overlying sediments, over a 37-day period, during which flow was increased from 10 to 210 kg d^{-1}. Repeated seismic reflection imaging [18] demonstrated the formation of chimneys as gas migrated upwards by fracture propagation and reactivation of pre-existing fractures, and subsequent spreading of gas along the shallow stratigraphy.

4. Models of Seismic Chimneys

Our hypothesis (Figure 2), based on previous literature, and the QICS experiment, is that seal breaching occurs due to reduced effective stress and leads to either reactivation of pre-existing fractures, or opening of new fractures and the generation of a localized connected fracture system. Gas-rich pore fluids then exploit these locations, with buoyancy causing vertical migration through the linked fracture system. It is this combination of localized vertical migration and lateral flow that is imaged from 4-D seismic (as in the plumes at Sleipner) as chimney structures. Thus the chimneys resolvable from seismic reflection data provide a first order prediction of potential areas of leakage, but the overlying sediment beds may disperse such vertical flow, making direct detection at the surface more difficult.

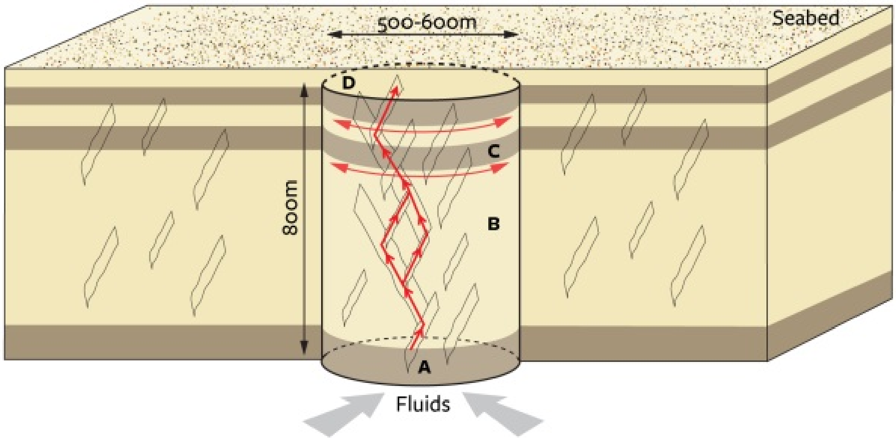

Fig. 2. Conceptual model for a seismic chimney structure which extends close to the seabed. The diagram shows that the overburden sediments are pervasively faulted. Where seal rupture occurs (A) pore fluids drive fracture propagation and linkage (B) allowing fluids to rise due to buoyancy and elevated fluid pressure. In the near surface fluids will migrate along impermeable stratigraphic interfaces (C). In rare situations fractures may propagate to the very near-surface (D) or even rupture the seabed.

5. Experimental Approach

Our experimental design uses multiple seismic sources with different frequency bandwidths to collect seismic reflection data on surface streamers and wide-angle data recorded on ocean bottom seismometers to characterize the fracture system within and around the Scanner pockmark gas chimney in the North Sea. We collected an innovative broadband multicomponent seismic dataset, and are performing a state-of-the-art anisotropy analysis to characterize the fracture system. The wide frequency-band (10 Hz – 6 kHz) in our data set will allow us to apply techniques based on the frequency-dependence of seismic anisotropy, allowing a more detailed picture of the fracture system to be developed than through conventional methods.

Our hypothesis on the formation of gas chimneys suggests that there should be a different fracture geometry outside the chimney compared to inside, with the chimney being associated with connected fracture sets, with possible concentric fracture distributions. To test this hypothesis requires state-of-the-art seismic techniques.

It is well established that the most accurate and reliable seismic fracture detection requires multicomponent data [19]. The measurement of seismic anisotropy, particularly using shear-wave splitting, has been established as a key technique to infer orientation and density of fracture networks [20]. Techniques such as estimation of the coherency of stacked seismic images [21] are able to image larger fractures, but it is only through consideration of anisotropy that we can obtain information on the key features which are at sub-seismic resolution.

Theoretical work [22,23,24] predicts that properties such as fracture scale length and fluid saturation can be inferred from the frequency-dependence of anisotropic attributes. Recent work in Southampton and Edinburgh has established key relationships between fracture parameters, rock properties, fluid saturation and seismic anisotropy. The theoretically predicted relationship between shear-wave splitting and fracture density has been verified [25] through laboratory measurements on synthetic rock with controlled fracture geometry, and with fluid viscosity effects [26]. More recently, the impact of partial saturation on anisotropy and attenuation in fractured materials has been studied [27,28,29]. This latter work develops models that can link laboratory and field datasets

The excess permeability associated with a fracture system is likely to be strongly dependent on the degree of connectivity. This in turn is typically related to the range of fracture orientations, since fracture sets in multiple orientations may have more connections than a single aligned set. The greatest anisotropy is often associated with perfectly aligned fractures, and the most permeable zones show the least anisotropy in reservoir formations. Our hypothesis has unconnected vertical fractures outside the chimney that are preferentially aligned with the regional stress field, with connected and possibly concentric fracture systems within the chimney. If this is so, we would expect to see significant differences in anisotropy outside and inside the chimney. Such differences would include not only the strength of the anisotropy but also the symmetry system, with aligned fractures giving rise to azimuthal anisotropy, described by transverse isotropy with a horizontal symmetry axis, and concentric fractures showing little azimuthal anisotropy, with the response being described by transverse isotropy with a vertical symmetry axis. Our analysis will test our hypothesis by differentiating between these symmetry systems.

Our surveys used ocean bottom seismometers (OBS) to measure the converted waves which are known to be essential for characterizing fracture systems. A key component of our approach is to use three seismic sources with different frequencies, in the range 10 Hz to 6 kHz (low frequency airguns, GI guns, sparker systems). This approach will provide a unique opportunity to study the frequency-dependence of anisotropy over a much wider frequency range than has been used in previous studies. To our knowledge, this will be the first survey of its kind, and successful completion would likely lead to significant impact in the wider geophysical industry.

Our experimental design builds on that developed for a chimney structure in deeper water [30]. We deployed a grid of OBSs, centred on the chimney structure, with spacings increasing radially from c. 200 m to c. 400 m, with two OBS positioned 20 m apart in the main pockmark. In addition a smaller asymmetrical grid of OBS was positioned away from the pockmark to determine the background anisotropy (Fig. 3). These instruments recorded every shot from our range of seismic sources, using a hydrophone and three orthogonal geophones and a sample interval of 0.25 ms. We fired our seismic sources separately repeating grids of lines, with line spacing as close as 25 m.

6. Geophysical Experiment at Scanner Pockmark

RRS James Cook 152 (funded by NERC, CHIMNEY) successfully completed two anisotropy experiments over the Scanner and Challenger pock marks by shooting various seismic sources into a grid of 25 and 7 ocean bottom seismometers respectively (Figure 3). Five different seismic sources (Bolt airguns, GI guns, Squid surface sparker, Duraspark surface sparker, and Deep Tow Sparker) were recorded by the ocean bottom seismometers (Figures 4), and an acoustic recorder deployed c. 25 m above the seabed. Multichannel seismic reflection profiles were collected with GI guns (Figure 5) and both surface sparker sources, and single channel seismic reflection profiles were collected with the Deep Tow Sparker source. In addition data collected by Maria S. Merian (funded by STEMM-CCS) collected seismic reflection data using GI guns, and these sources were recorded on 18 Ocean bottom seismometers (OBS) around the Scanner pockmark. The results from the two cruises will be integrated together to test the chimney model hypothesis.

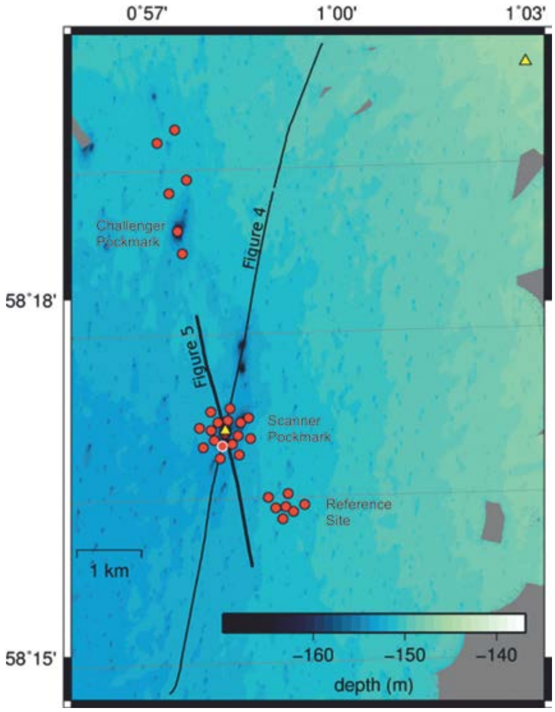

Fig. 3. Location of all instruments deployed during JC152 superimposed on the seabed bathymetry. The red circles show the position of the 25 ocean bottom seismometers (OBS) deployed at the Scanner pock mark and a reference site during the first part of the cruise, and the position of a further 7 OBS deployed around and north of the Challenger pock mark. The yellow triangles show the position of acoustic recorder deployments to record source signatures. The position of the OBS record illustrated in Figure 4 and seismic reflection profile shown in Figure 5 are shown.

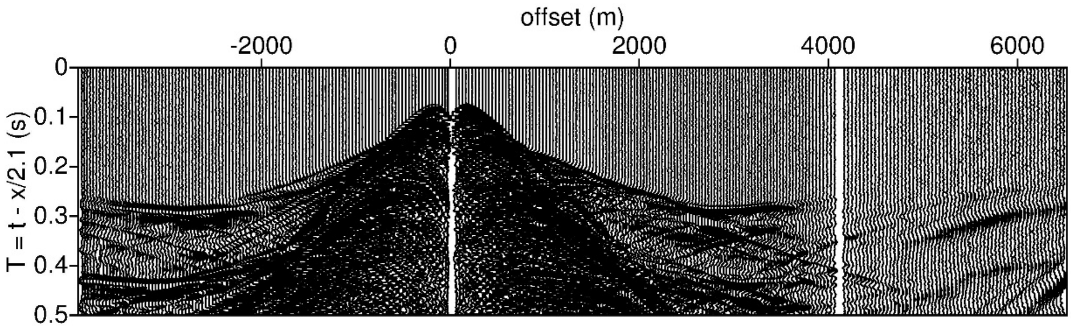

Fig. 4. Example Ocean Bottom Seismometer data collected close to Scanner Pockmark (position shown in Figure 3). This example is an in-line GI-gun profile from OBS8 of the Chimney OBS Network. A velocity reduction of 2.1 km/s has been applied.

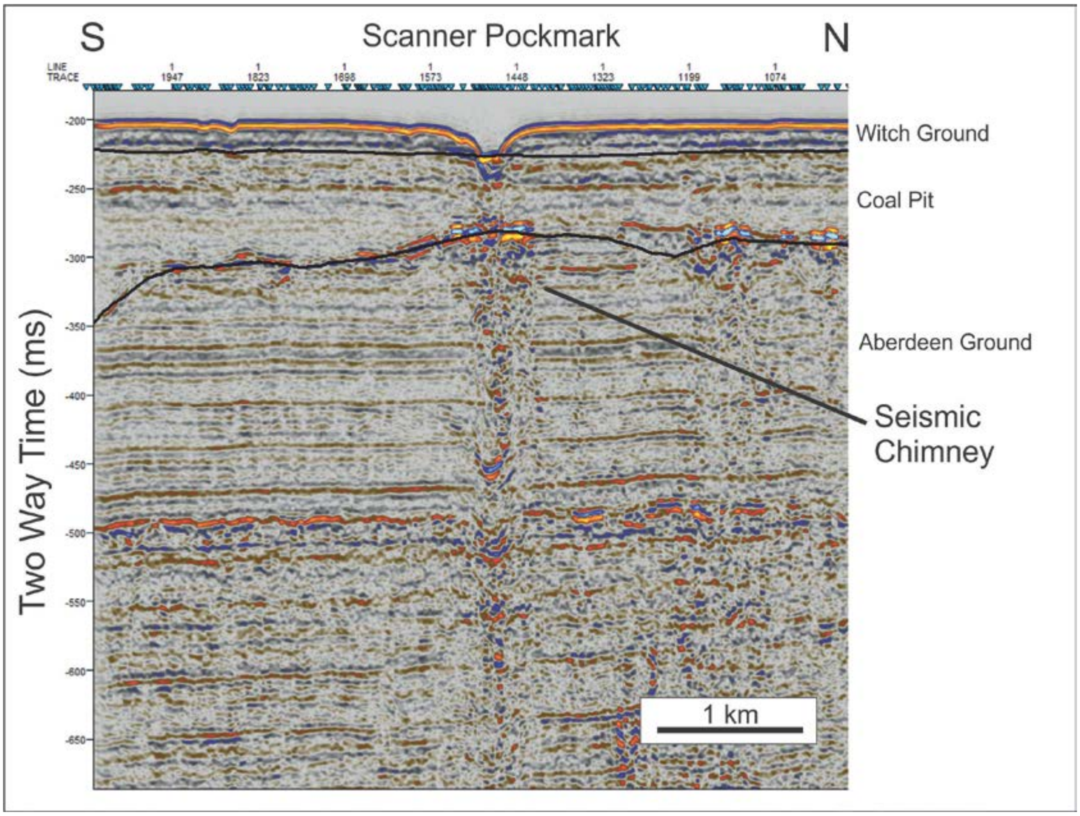

Fig. 5. Pre-stack depth migrated seismic reflection profile collected with a GI-gun source across the Scanner Pockmark during JC152 (position of profile shown in Figure 3). Note the position of the bright amplitude anomalies beneath the pockmark and a seismic chimney structure. The presence of gas in the sub-surface, and the chimney structure will be further tested by tomographic and anisotropic analyses.

7. Analysis and conclusions

Preliminary analysis of 2D seismic reflection profiles shows the overall shape of the sedimentary succession in the Scanner pockmark region. Between the seafloor and the well-stratified sediments of the Nordland formation (200-350 ms TWT) clear indications for several stages of deposition and erosion are visible. A characteristic tunnel valley with steep flanks and several phases of deposition and erosion is located SW of the Scanner pockmark. This new high resolution seismic reflection data acquired with the various seismic sources is of high quality, and indicates the presence of gas at several different levels and complex areas of gas blanking. The new data reveal a complex fluid migration system in the sub-surface which comprises fluids that rise from > 500 m depth as well as gas produced within the shallowest post-glacial sediments resulting in a variety of fluid pathways and seep sites at the seabed. Seismic anisotropy analysis using the broad band data collected by the ocean bottom seismometer data is on-going.

Acknowledgements

This work has received funding from the Natural Environment Research Council (CHIMNEY; NERC Highlight Topic; NE/N016130/1) and European Union’s Horizon 2020 research and innovation programme under grant agreement No.654462 (STEMM-CCS).

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