





# Marine CSEM synthetic study to assess the detection of CO<sub>2</sub> escape and saturation changes within a submarine chimney connected to a CO<sub>2</sub> storage site

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## SUMMARY

Carbon capture and storage (CCS) within sealed geological formations is an essential strategy to reduce global greenhouse gas emissions, the primary goal of the 2015 United Nations Paris Agreement. Large-scale commercial development of geological CO<sub>2</sub> storage requires high-resolution remote sensing methods to monitor CO<sub>2</sub> migration during/after injection. A geological formation containing a CO<sub>2</sub> phase in its pore space commonly exhibits higher electrical resistivity than brine-saturated (background) sediments. Here, we explore the added value of the marine controlled-source electromagnetic (CSEM) method as an additional and relevant geophysical tool to monitor moderate to significant changes in CO<sub>2</sub> saturation within a fluid conduit breaking through the seal of a CCS injection reservoir, using a suite of synthetic studies. Our 2-D CSEM synthetic models simulate various geological scenarios incorporating the main structural features and stratigraphy of two North Sea sites, the Scanner Pockmark and the Sleipner CCS site. Our results show significant differentiation of leakage through the seal with CO<sub>2</sub> saturation ( $S_{CO_2}$ ) ranging between 20 and 50 per cent, while our rock physics model predicts that detection below 20 per cent would be challenging for CSEM alone. However, we are able to detect with our 2-D inversion models the effects of saturation with 10 and 20 per cent CO<sub>2</sub> within a chimney with 10 per cent porosity. We demonstrate that simultaneous inversion of  $E_y$  and  $E_z$  synthetic electric field data facilitates a sharper delineation of a CO<sub>2</sub> saturated chimney structure within the seal, whereas  $E_z$  synthetic data present higher sensitivity than  $E_y$  to  $S_{CO_2}$  variation, demonstrating the importance of acquiring the full 3-D electric field. This study illustrates the value of incorporating CSEM into measurement, monitoring and verification strategies for optimal operation of marine CCS sites.

**Key words:** Controlled source electromagnetics (CSEM); Electrical resistivity; Marine electromagnetics; Numerical methods; Carbon capture and storage.

## 1 INTRODUCTION

The objective of the 2015 United Nations Paris Agreement is to limit global temperature rise to less than 2 °C above pre-industrial levels by reducing greenhouse gas emissions and therefore promoting cleaner energy (UN Paris Agreement 2015). The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IEA

2021) highlights that carbon capture and storage (CCS) is needed to compensate for CO<sub>2</sub> emissions from hard-to-abate industry sectors (e.g. agriculture, cement and aviation). Thus, CCS is necessary to curb global emissions to comply with the Paris Agreement targets. In Europe, private and public sectors are jointly developing CCS offshore projects. An example is the Northern Lights project, driven by three private companies and the Norwegian government (Furre

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*et al.* 2019). An extensive list of CCS projects, both onshore and offshore, at various stages of development, are detailed by Ringrose & Meckel (2019).

CO<sub>2</sub> can be sequestered into geological media (reservoirs) by: (i) injection into depleted oil and gas reservoirs; (ii) injection into saline aquifers; (iii) replacing methane in coal beds; (iv) storage in salt caverns (Bachu 2000) or (v) mineralization in mafic and ultramafic reservoirs (e.g. Goldberg *et al.* 2008). Depending on geothermal and pressure conditions, CO<sub>2</sub> can be stored as a gas, liquid or supercritical fluid (e.g. Goldberg *et al.* 2008; Hoteit *et al.* 2019).

Depleted (sandstone) gas reservoirs or saline aquifers are ideal CCS sites because (i) they are superimposed by low-permeability cap rock, thus, providing a seal that prevents the upward migration of gas, (ii) they are typically near infrastructure once used to extract oil/gas and (iii) they do not chemically react with CO<sub>2</sub>. Offshore CO<sub>2</sub> storage in sandstone reservoirs has been successfully demonstrated in the North Sea, particularly in the Sleipner field, the world's first commercial CO<sub>2</sub> storage project (Baklid *et al.* 1996; Hansen *et al.* 2005). The CO<sub>2</sub> injected in the Sleipner reservoir, a saline aquifer at depths of around 800 m below the seafloor, is frequently monitored with seismic reflection methods (Chadwick *et al.* 2019).

Remote monitoring of CCS sites is key to understanding CO<sub>2</sub> containment during and after injection. CO<sub>2</sub> leakage from the injection reservoir to shallower depths or in the water column is a significant concern for CCS. Detecting and understanding CO<sub>2</sub> flow outside the storage reservoir at an early seepage stage is important in preventing unexpected CO<sub>2</sub> from causing acidification of bottom water, thus affecting marine life (Vielstädte *et al.* 2019), contaminating any freshwater reservoirs and for risk and liability management (Gasperikova *et al.* 2022).

Failure in the seal can create pathways for the migration of subsurface fluids to shallower depths. CO<sub>2</sub> injection may cause migration of fluids through pressure-induced fractures (Rutqvist *et al.* 2016), or by pressure changes within pre-existing fractures and subvertical conduits (also referred to as chimneys/pipes), which serve as leakage pathways (e.g. Robinson *et al.* 2021; Davies 2003). These chimneys exist in the North Sea (Karstens & Berndt 2015) and globally (Cartwright & Santamarina 2015). We use the term chimney for subvertical fluid conduits or fluid escape features that are generally observed in seismic reflection data as seismic blanking zones (Karstens & Berndt 2015). In Sleipner, it has been shown that the CO<sub>2</sub> migrates vertically upwards from the reservoir injection point and intrareservoir barriers (mudstones) through several relatively high-permeability chimneys. One particular chimney serves as the primary pathway for CO<sub>2</sub> upward migration (Chadwick *et al.* 2004, 2019; Williams & Chadwick 2021).

Seismic *P*-wave velocity ( $V_p$ ) is a good indicator of fluid changes in the pore space of rocks.  $V_p$  in rocks with a high water saturation is particularly sensitive to gas (e.g. CO<sub>2</sub>) present within the pore space; a small amount of gas (e.g. <5 per cent) would result in a significant decrease in the *P*-wave velocity because the effective bulk modulus of the pore fluid is then much smaller than the bulk modulus of water (Lee 2004). Therefore,  $V_p$  normally remains insensitive to high gas saturations but this depends on the gas distribution within the pore space (Brie *et al.* 1995; Lee 2004) but generally  $V_p$  is very sensitive to low gas saturations (Domenico 1976). Electrical resistivity is very sensitive to changes in the fluid within the pore space because brine or saline water is very conductive (low resistivity) while gas has a high resistivity. Electrical resistivity is sensitive to porosity and the amount of brine present in the pore space. However, electrical resistivity is not sensitive to the disconnected gas

that may be present in low saturations. Thus, measurements of  $V_p$  and electrical resistivity can be used in conjunction to quantify the non-aqueous fluid saturations.

### 1.1 Marine CSEM—a viable technique to monitor CCS sites

This study uses a marine CSEM system consisting of a deep-towed transmitter and seafloor receivers. The transmitter generates an electromagnetic (EM) field that diffuses through the seawater and seafloor. If the EM field propagates through a more resistive unit within the shallow seafloor, the electric field amplitude is less attenuated, which is measurable by towed or seafloor receivers. Previous studies have demonstrated that the CSEM method can pinpoint subsurface vertical migration of resistive fluid phases (gases; e.g. Goswami *et al.* 2016; Attias *et al.* 2016). Since CO<sub>2</sub> is electrically resistive, it can be detected by CSEM (Ramirez & Friedmann 2008; Schmidt-Hattenberger *et al.* 2012; Park *et al.* 2017). Onshore, electrical resistivity methods have been used to monitor CO<sub>2</sub> storage sites (Schmidt-Hattenberger *et al.* 2011; Streich *et al.* 2010). The use of CSEM monitoring has been modelled for oil and gas and geothermal applications onshore (e.g. Wirianto *et al.* 2010; Streich *et al.* 2010; Börner *et al.* 2015) and offshore (e.g. Orange *et al.* 2009). CSEM monitoring has been successfully implemented in onshore CCS sites (e.g. Girard *et al.* 2011), hydrocarbon production fields (e.g. Tietze *et al.* 2019) and geothermal fields (Bretaudou *et al.* 2021).

Park *et al.* (2017) present results of a marine CSEM survey acquired after the start of CO<sub>2</sub> injection at the Sleipner field and discusses the benefits of monitoring CCS using time-lapse marine CSEM.

Seismic reflection survey repeats are commonly used to monitor CO<sub>2</sub> storage sites, also referred to as 4-D or 'time-lapse' seismic surveys. Time-lapse seismic surveys are critical to monitoring the CO<sub>2</sub> plume migration at the Sleipner field in the North Sea (Chadwick *et al.* 2004, 2005, 2014, 2019). CSEM can complement the seismic reflection methods with information regarding the nature of the pore fluid and helps distinguish between fluid substitution, lithology, and mechanical effects. Therefore CSEM should be considered for reservoir integrity monitoring. The synthetic CSEM/seismic monitoring studies by Fawad & Mondol (2021) and Dupuy *et al.* (2021) show that both methods are required to monitor CO<sub>2</sub> storage adequately. Nearly all published studies on time-lapse CSEM conclude that monitoring the subsurface with CSEM is feasible (e.g. Girard *et al.* 2011; Tietze *et al.* 2019; Bretaudou *et al.* 2021). CSEM studies using both synthetic data (Fawad & Mondol 2021; Gasperikova *et al.* 2022; Gehrmann *et al.* 2021a) and real data (Schmidt-Hattenberger *et al.* 2011) infer that CSEM methods can monitor CO<sub>2</sub> storage sites. Fawad & Mondol (2021) present a CSEM synthetic study in the Norwegian North Sea, combining time-lapse marine CSEM and reflection seismic while Gasperikova *et al.* (2022) discusses the sensitivities of gravity, EM and seismic to detect CO<sub>2</sub> migration outside of the reservoir (secondary plumes) for onshore CCS sites. Schmidt-Hattenberger *et al.* (2011) discuss the benefits of using time-lapse CSEM to monitor the Ketzin (Germany) onshore CCS site. Dean & Tucker (2017) suggested that changes in resistivity associated with CO<sub>2</sub> injection sites are close to or below the detection limits for time-lapse CSEM, but no supporting model or data are presented.

The sensitivity of the CSEM method to various resistivity contrasts due to CO<sub>2</sub> leakage within known background geology can be

derived from synthetic studies. In this work, we conduct a suite of synthetic studies to determine the marine CSEM method sensitivity to various CO<sub>2</sub> leakage scenarios through a chimney structure connected to a CO<sub>2</sub> storage reservoir. We combine two sites, both associated with seismic chimneys, in a synthetic model study: the Scanner pockmark in the North Sea, representative of the seal breached by a chimney connected to a pockmark vent system; and the Sleipner CO<sub>2</sub> injection site, used as a saline aquifer analogue for CO<sub>2</sub> injection. To our knowledge, this is the first study to examine CSEM's capability to monitor CO<sub>2</sub> leakage via a fluid conduit within a clay-rich overburden. Gasperikova *et al.* (2022) analyse CO<sub>2</sub> plumes outside of the reservoir and we expand this work by considering rock physics of a clay-rich overburden and a fluid conduit. The importance of reservoir flow models in CCS and their integration with geophysical monitoring has been discussed in Commer *et al.* (2022), who used a simplified approach to constrain EM inversions applying the fluid saturation predicted from the flow modelling. We used a similar approach to interpret our CSEM modelling results in the context of CSEM monitoring. We applied realistic saturation scenarios modelled with guidance from the multiphase fluid flow modelling and saturation distribution, considering the escape of CO<sub>2</sub> via a chimney at Scanner pockmark site (Marín-Moreno *et al.* 2019).

## 2 GEOLOGICAL SETTING

The Scanner pockmark is an active gas vent complex in the south of UK's license block 15/25 located at 58°16'54.0"N, 0°58'14.6"E (Fig. 1) in ~155 m of water (Gafeira & Long 2015). A chimney structure interpreted below the Scanner pockmark is known to function as a fluid conduit that reaches the seabed (Karstens & Berndt 2015; Robinson *et al.* 2021; Böttner *et al.* 2019). In the case of the Scanner pockmark, the migrating fluid is methane and not CO<sub>2</sub>, but the structure and shallow clay-rich stratigraphy serves as an analogue to study leakage pathway structures within the modelled seal connecting a CO<sub>2</sub> reservoir with the seafloor. Li *et al.* (2020) calculated the current methane flux from the Scanner Pockmark into the water column to be between  $1.6 \times 10^6$  kg yr<sup>-1</sup> and  $2.7 \times 10^6$  kg yr<sup>-1</sup> (272–456 l min<sup>-1</sup>), from active acoustic inversion imaging. Callow *et al.* (2021) provides an overview of geophysical surveys performed in this site.

The Sleipner CO<sub>2</sub> injection site, located in the Norwegian North Sea, has a seal characterized by thin layers of clay, as indicated by high gamma-ray intensity (Chadwick *et al.* 2005, Fig. 2). We also examine the Sleipner site as an analogue for our model. We use the Sleipner injection reservoir, a saline aquifer where CO<sub>2</sub> is sequestered, and the deep seal stratigraphy immediately above it to complement our Scanner pockmark seal model, which covers the shallower seal. Both the Scanner and Sleipner sites have similar Neogene to Quaternary stratigraphy (Figs 1b and 2). The Scanner and Sleipner Quaternary sediments (~400 m thick) are composed of fine-grained material (silt and clay) as described by Stoker *et al.* (2011). This Quaternary succession is underlain by the ~600 m thick Nordland Group (NG), a sequence of Neogene age claystone interbedded with limestone and the Utsira sandstone (Judd *et al.* 1994), referred as the Utsira reservoir in this paper. At Sleipner, the Utsira reservoir is ~800–1000 m deep and ~200–300 m thick. The clay-rich seal above the Utsira reservoir is several hundred metres thick, divided into three units (Zweigel *et al.* 2004, Fig. 2) that are referred to as the geological seal throughout the paper. The lowest part of the seal, also known as the 'Shale Drape', forms a clay-rich

basin-restricted unit within the Utsira formation itself (Chadwick *et al.* 2002). Above this resides the thick Pliocene succession, the Nordland Group, also called the 'middle seal' (Chadwick *et al.* 2002). The 'middle seal' is comprised mainly of prograding units, dominantly clay in the basin centre and coarsening into sandier facies both upwards and towards the basin margins (Stoker *et al.* 2011). The uppermost section, the 'upper seal', is comprised of the Quaternary clay-rich glaciomarine and glacial tills sequence from the Aberdeen Ground (AG), Coal Pit (CP) and Witch Ground formations (WG; Chadwick *et al.* 2002).

## 3 METHODS

### 3.1 Rock physics

Rock physics models are used to estimate the expected resistivity for a given CO<sub>2</sub> saturation for the seal properties of the Scanner pockmark and the CO<sub>2</sub> injection reservoir at Sleipner. Our model scenarios assume that CO<sub>2</sub> is injected at a saline aquifer with the same properties as the Utsira formation, reaching  $S_{\text{CO}_2} = 50$  per cent and escapes through a chimney within a clay-rich seal with various CO<sub>2</sub> saturations. For comparison following (Constable 2010), we also estimate *P*-wave velocity for a 'patchy gas model' from Lee (2004), using a confining pressure of 2.59–18.21 MPa from top to base seal, calculated using the geological thickness and rock properties from the hybrid Sleipner/Scanner geological model. We calculate temperatures of 17.8 °C for the seal and 37 °C for the reservoir using a North Sea geothermal gradient of 30 °C km<sup>-1</sup> (Shell-UK-limited 2014).

The electrical resistivity for the sandstone reservoir is estimated using Archie's Law (Archie 1942), while the resistivity for the seal composed of clay-rich silty sediments is derived from Waxman–Smits–Juhász shale-sand model (Juhász 1981; Appendix A). Appendix A discusses Archie's and Waxman–Smits equations, derivations, parameters, and their implementation to calculate the resistivity and partial water saturation of clay-rich sands from well-logs. The empirical relationship proposed by Archie (1942) relates the bulk electrical resistivity of a geological formation in the subsurface ( $\rho_0$ ; saturated with any fluid) with its porosity ( $\phi$ ), pore fluid resistivity ( $\rho_w$ ) and fluid saturation ( $S_w$ ), as follows:

$$\rho_0 = a \rho_w \phi^{-m} S_w^{-n}, \quad (1)$$

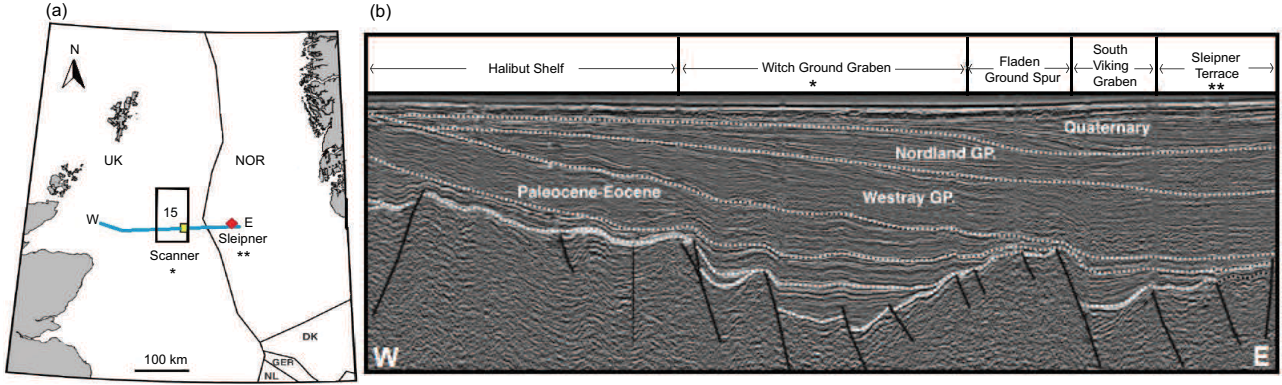
where  $a$  is the tortuosity coefficient,  $m$  is the cementation exponent and  $n$  is the saturation exponent.

Archie's equation is not adequate for sediment, where conductive clay minerals are present (Wyllie & Gregory 1953). In clay-rich sands, an excess of ions around clay particles generate additional conduction pathways along the clay surface, and the electrical resistivity of the clay surface depends on the brine conductivity in a non-linear manner (Mavko *et al.* 2009). This conduction occurs in addition to the diffusion of natural ions through the bulk pore fluid. As a result, the resistivity of clay-rich sand for partially brine-saturated formation ( $\rho_t$ ) is lower than that of clean sand with the same porosity and water saturation (Juhász 1981). The resistivity equation considering the clay effect by Waxman & Smits (1968) is shown below:

$$\rho_t = \left[ \frac{a \rho_w}{\phi^m S_w^n (1 + \frac{\rho_w}{B} Q_v S_w)} \right], \quad (2)$$

where  $B$  is the equivalent cation conductance, which is dependent on temperature and salinity (eq. A7, Appendix A) and  $Q_v$  is the cation exchange capacity (CEC) per unit volume (eq. A6, Appendix A).





**Figure 1.** Regional geological setting and stratigraphy of the Witch Ground Basin in the North Sea. (a) The Scanner study area (yellow box inside license block 15/25) is highlighted as well as the Sleipner field (red diamond) and position of the regional seismic line (blue line) shown in (b) modified from Callow (2021). (b) A regional seismic cross-section, trending west to east across the Central North Sea and the Witch Ground Graben, after Callow (2021) and Copestake *et al.* (2003). Six stratigraphic intervals are highlighted. The Scanner pockmark area is in the seismic section under the ‘Witch Ground Graben’ (one star) while Sleipner is under the ‘Sleipner Terrace’ label (two stars).

To obtain  $Q_v$ , the total pore volume and CEC must be known from core measurements (Appendix A, eq. A6). The normalized Waxman–Smits–Juhász equation (Juhász 1981) removes the need to measure the CEC from cores as it uses  $V_{SH}$  (volume of shale) derived from well-logs, such as the gamma-ray or density-neutron logs. This is given below, after isolating  $\rho_t$  from eq. (A14) in Appendix A:

$$\rho_t = \frac{aS_w^{-n}\phi^{-m}}{\left[\frac{1}{\rho_w} + \frac{V_{SH}\phi_{SH}}{\phi} \left(\frac{a}{\rho_{SH}\phi_{SH}^m - 1}\right) S_w^{-1}\right]}, \quad (3)$$

where  $\phi_{SH}$  is the total shale porosity and  $\rho_{SH}$  the resistivity of the formation with 100 per cent volume of shale ( $V_{SH}$ ); while  $m$  and  $a$  are the cementation and tortuosity exponents for the clay-rich formation. See eq. (A6) to eq. (A14) in Appendix A for more details.

We estimated  $V_{SH}$  from the gamma-ray log data for well 15/09/13 at Sleipner (Park *et al.* 2011, Fig. 2b) by linearly interpolating ( $GR_{log}$ ) between the minimum ( $GR_{min}$ ) and maximum ( $GR_{max}$ ) values, as follows:

$$V_{SH} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}. \quad (4)$$

The gamma-ray log responds to the number of radioactive minerals (e.g. potassium, uranium and thorium) contained within the rocks adjacent to the borehole (Brannon & Osoba 1956). This log is used as an indicator for the presence of clay because formations rich in clay show a high radioactive count, while sands are characterized by low radioactive content and a low gamma-ray count (Brannon & Osoba 1956).

We used the range 11–103 gAPI to estimate  $V_{SH}$ , based on the clean rock at 2500 mbsf ( $GR_{min}$ ) and the shale formation at 2910 mbsf ( $GR_{max}$ ), respectively (Fig. 2b). The resistivity corresponding to 2910 mbsf depth (Fig. 2d) was used as the resistivity of the ‘clay-rich’ formation ( $\rho_{SH} = 4 \Omega m$ ).

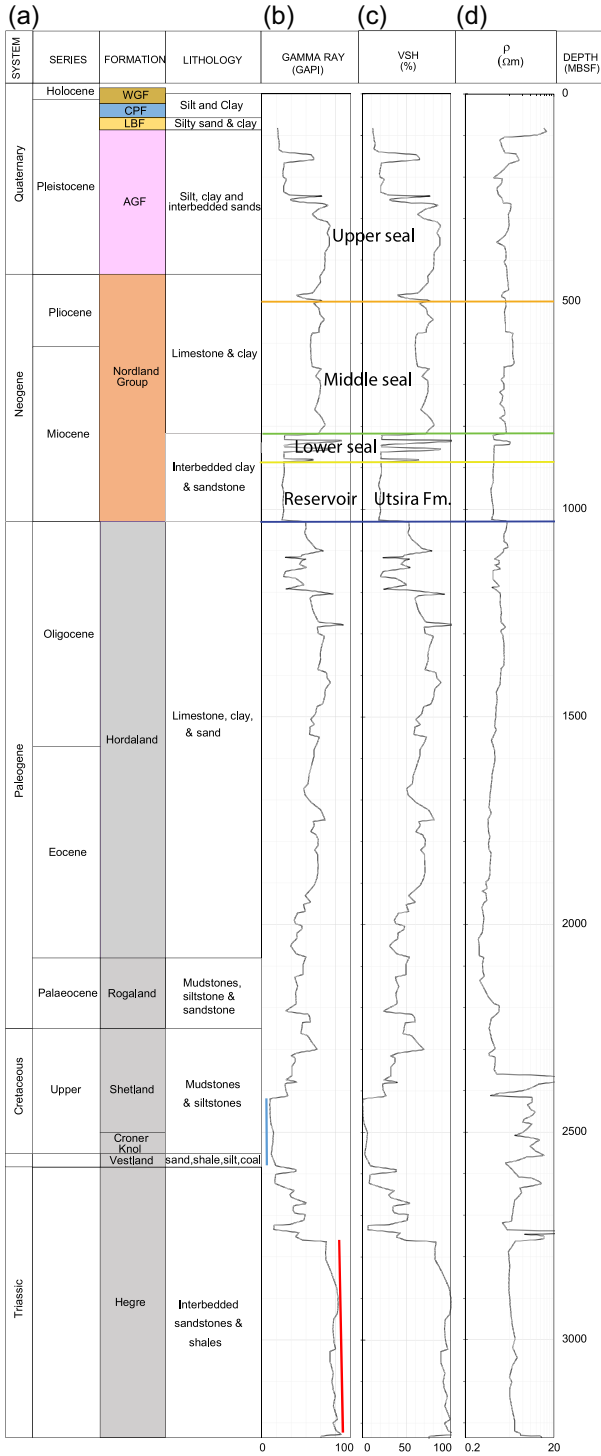
Finally, Arp’s Law (eq. B1, Appendix B) is used to determine the pore water resistivity ( $\rho_w$ ) within the Scanner pockmark (Tables 1). Arp’s Law extrapolates the pore water resistivity from a known pore water resistivity ( $\rho_w$ ) and temperature at a depth using the geothermal gradient of the area of interest (Arps 1953).

### 3.2 Model scenarios

In order to understand the effect of a chimney isolated from any fluid changes in  $CO_2$  saturations we modelled a simplified layered model using the rock physics properties of the Scanner pockmark for the seal and the properties of Sleipner field for a saline aquifer reservoir underneath it and a chimney that cross-cuts the seal. We considered synthetic modelling scenarios before the  $CO_2$  injection starts (Fig. 3a) and after injection (Figs 3b–e and 4). We considered the reservoir saturation with brine only before injection (i.e. a saline aquifer) and a reservoir partially saturated with  $CO_2$  after injection. The effect of fractures within the chimney was modelled by giving a 10 per cent higher porosity to each layer within the chimney bounds (Fig. 3a).

For all our scenarios, the resistivity for the Utsira formation (target site) before injection ( $S_w = 1$ ) and after injection ( $S_{CO_2} = 0.5$ ) was determined with Archie’s empirical relationships (Section 3.1, Appendix A), using the properties from Table 1. The Utsira sand Archie’s parameters:  $m = 1.6$ ,  $a = 1.1$  and  $n = 1.8$  are selected based on Mavko *et al.* (2009) and confirmed by laboratory studies performed on  $CO_2$  saturated Utsira sand samples (Alemu *et al.* 2013; Falcon-Suarez *et al.* 2018). For the sealing formation, the resistivity within and outside the chimney for the different saturation scenarios, before and after the injection started, was determined using the Waxman–Smits–Juhász shaley-sand model (Section 3.1, Appendix A) using the properties listed for each formation on Table 1. The seal Archie parameters used were  $m = 1.8$ ,  $a = 0.9$  and  $n = 2$  (Table 1), consistent with observations of clay-rich shallow marine sediments (Riedel *et al.* 2006; Mavko *et al.* 2009).

In order to understand the resistivity changes in the chimney within the seal and the detectability of potential leaks through it we considered a chimney fully saturated with brine that cross-cuts the seal and is connected to a  $CO_2$  reservoir saturated with 50 per cent  $CO_2$  (Fig. 3b). Then we consider three scenarios where a leak through the chimney has occurred and this results in a chimney saturated bottom to top with (i) 10 per cent  $CO_2$  (Fig. 3c), (ii) 20 per cent  $CO_2$  (Fig. 3d) and (iii) 50 per cent  $CO_2$  (Fig. 3e). All these scenarios consider injection that has occurred in a saline aquifer for some time, and the reservoir has reached a saturation of 50 per cent  $CO_2$ . We also analysed the changes in  $CO_2$  saturation within the chimney due to the evolution of a leak through time. Two scenarios were considered with saturation variation within the



**Figure 2.** (a) Regional chronostratigraphy of the model area, the Witch Ground Basin and Sleipner Terrace in the North Sea, as discussed in Section 2. WGF stands for Witch Ground Formation, CPF for Coal Pit Formation and AGF for Aberdeen Ground Formation. Well-logs for 15/9-13 (Sleipner) from Park *et al.* (2017). (a) Measured gamma-ray intensity, the blue line centred at 2500 m depth marks the  $GR_{min}$  and the red line centre at 3000 m depth marks the  $GR_{max}$  used to calculate the volume of shale or clay ( $V_{SH}$ ). (b) Calculated  $V_{SH}$  from GR and (c) resistivity log. The three seal intervals as described in Section 2 are indicated in (b), (c) and (d); the orange line corresponds to the base of the upper seal, the green line is the base of the middle seal and the yellow line is the base of the lower seal. The base of the Utsira reservoir is indicated with a navy blue line.

chimney that correspond to 5 and 25 yr after injection (Figs 4b and c), according to the flow modelling results of Marin-Moreno *et al.* (2019) for the Scanner pockmark area (analogue for the seal). The flow model assumes that the CO<sub>2</sub> in the reservoir is connected to the chimney and migrates upwards primarily through connected microfractures within the chimney. The volume of such microfractures within the chimney is likely to be a small proportion of the total pore volume of the chimney. Hence, even if the microfractures become fully saturated with CO<sub>2</sub>, the CO<sub>2</sub> saturation averaged over the total pore volume of the chimney is likely smaller than that in the reservoir. We implement realistic saturation changes and fluid distribution through time by using the same overburden layer thickness, porosities and rates of CO<sub>2</sub> propagation within the chimney as Marin-Moreno *et al.* (2019).

### 3.3 Marine CSEM system and 2-D synthetic models

In CSEM synthetic studies, the true resistivity model of the subsurface is assumed to be known. By varying either the electrical resistivity, due to geological properties, or the survey line parameters (e.g. transmitter–receiver geometry, frequency), we can examine the feasibility of using specific CSEM setups to resolve variations of the electrical resistivity in the seafloor.

This study uses a marine CSEM system comprising a deep-towed horizontal electric dipole (HED) transmitter and ocean-bottom electric field (OBE) receivers. The model study is based on the transmitter and receiver geometry from profile 2 (Fig. 5b) of the Scanner pockmark (Fig. 5a; Gehrmann *et al.* 2021b). Therefore, while the modelling considers realistic acquisition parameters designed to investigate a realistic geological scenario, our study is limited to what this particular survey geometry is capable of detecting, in regards to CO<sub>2</sub> saturation within the modelled chimney. A suite of synthetic forward models were generated with added Gaussian noise, and multiple inversions were run to simulate various fluid saturations within a chimney structure. We inferred changes in fluid saturation across the chimney, from the resulting resistivity inversion model, using two rock physics models (Archie 1942; Juhasz 1981) as described in Sections 3.1.

During the survey along profile 2, the transmitter was towed 20–40 m above the seabed and transmitted a 1 Hz, 100 Am<sup>-2</sup> square wave (Gehrmann *et al.* 2021b). The transmitter passed six OBE receivers spaced 500 m apart along the 7-km-long profile, resulting in 213 unique transmitter–receiver geometries (Fig. 5). We modelled CSEM data with 1 Hz fundamental frequency and the higher amplitude harmonics 3, 5, 7, 9 and 11 Hz observed in the CSEM data (Appendix C). Both the horizontal (inline—aligned with towline direction,  $E_y$ ) and vertical ( $E_z$ ) electric field components were modelled for all frequencies and transmitter–receiver geometries.

The synthetic data for the CSEM system and navigation parameters as described above were generated using MARE2DEM (Key 2016), a parallel adaptive finite element code for 2-D forward and inverse modelling of EM data. The data were contaminated with 4 per cent random Gaussian noise. The 4 per cent value is based on the data quality of the CSEM survey at Scanner. Similarly, the noise floor (inferred from the Scanner CSEM survey) was set to 10<sup>-13</sup> V Am<sup>-2</sup> for both vertical and inline components. Our 2-D model includes an insulating air layer, a stratified seawater layer with a variable resistivity profile, and a seabed layer. The interface between the seafloor and water layer (seafloor bathymetry) is generated by using the measured transmitter depth and altitude

**Table 1.** Archie's and Waxman–Smits input parameters for WG, Witch Ground Formation; CP, Coal Pit Formation; LB, Ling Bank Formation; AG, Aberdeen Ground Formation; NG, Nordland Group seal; UF, Utsira Formation (injection reservoir). Table modified from Marin-Moreno *et al.* (2019)

Layer	Thickness <sup>ad</sup>	$\phi$ <sup>bc</sup>	$T$ <sup>e</sup>	$\rho_w$ <sup>f</sup>	$a$ <sup>hi</sup>	$m$ <sup>gh</sup>	$BQ_v$ <sup>j</sup>	CEC <sup>h</sup>	$n$ <sup>k</sup>
Seabed	–	–	7 °C	0.2777 $\Omega$ m	–	–	–	–	–
WGF	23 m	0.44	7.69 °C	0.2733 $\Omega$ m	0.9	1.8	0.0748	0.05	–
CPF	37 m	0.34	8.8 °C	0.2665 $\Omega$ m	0.9	1.8	0.1757	0.05	–
AGF	300 m	0.2	17.8 °C	0.2218 $\Omega$ m	0.9	1.8	4.5	–	2
NG	440 m	0.18	31 °C	0.1995 $\Omega$ m	0.9	1.8	4.5	–	2
UF	200 m	0.35	37 °C	0.1781 $\Omega$ m	1.1	1.6	–	–	1.8

<sup>a</sup> Judd *et al.* (1994) for WG, CP and AG.

<sup>b</sup> Paul & Jobson (1991) for WG and CP.

<sup>c</sup> Audigane *et al.* (2007). <sup>d</sup>Chadwick *et al.* (2004) for AG, NG and UF.

<sup>e</sup>Temperature at seabed Shell-UK-limited (2014) and 30 °C km<sup>-1</sup> Harper (1971).

<sup>f</sup> Calculated pore water resistivity (Arps 1953) using North Sea (STEMM-CCS) CSEM transmitter CTD data from Gehrmann *et al.* (2021b).

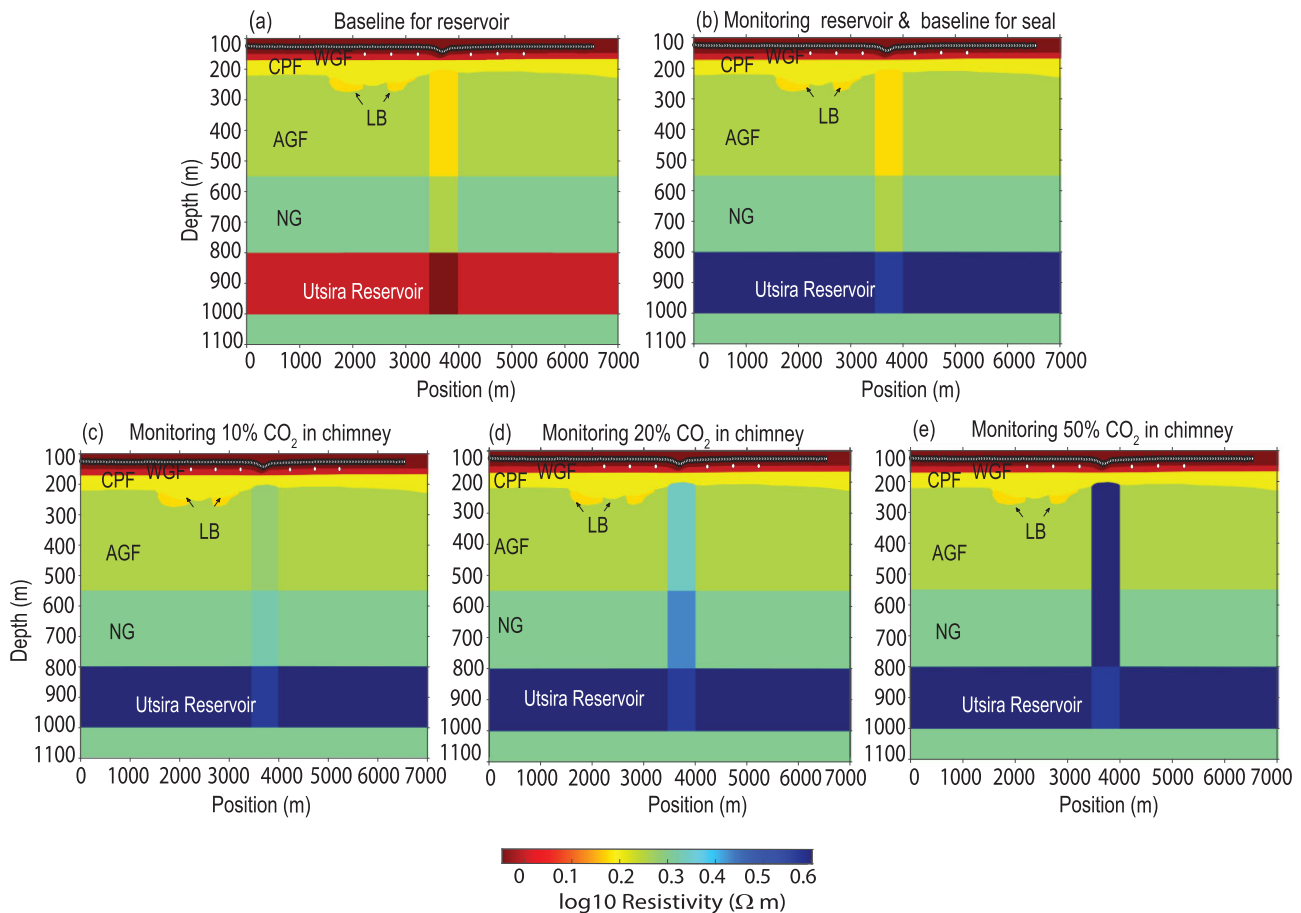
<sup>g</sup> For WGF, CPF and AGF Riedel *et al.* (2006) and Falcon-Suarez *et al.* (2021).

<sup>h</sup> For NG seal and UF Falcon-Suarez *et al.* (2018).

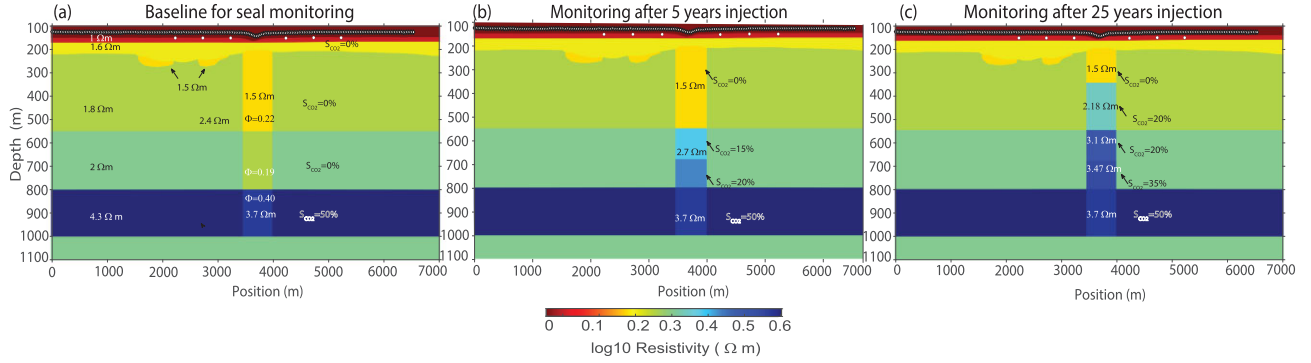
<sup>i</sup> For WG, CP, AG and NG Mavko *et al.* (2009).

<sup>j</sup> Calculated from eq. (A14) with  $\phi_{sh} = 0.1$  (Audigane *et al.* 2007) and  $V_{SH} = 0.8$  (Chadwick *et al.* 2002).

<sup>k</sup> Alemu *et al.* (2013).



**Figure 3.** True 2-D resistivity model scenarios considered to analyse the detectability of a CO<sub>2</sub> leak through a chimney. The Utsira Reservoir is a saline aquifer and we model it without CO<sub>2</sub> in (a) and with injected CO<sub>2</sub> reaching 50 per cent CO<sub>2</sub> saturation within the reservoir in (b) to (e). We model scenarios (b) without CO<sub>2</sub> escaping into the chimney, (c) CO<sub>2</sub> saturating the chimney by 10 per cent, (d) 20 per cent and (e) 50 per cent. The baseline models (a, b) contain a chimney (or fractures) with a porosity that is 10 per cent higher than the surrounding sediments. The baseline models serve as the reference points to analyse CO<sub>2</sub> changes within the reservoir and the seal. As we model CO<sub>2</sub> leaking through the chimney we focus on the second baseline model (b). No leakage has occurred through the chimney ( $S_{CO_2} = 0$ ) in model (b). The models after leakage through the chimney in (c) are the same as (b) but with  $S_{CO_2} = 10$  per cent within the chimney; (d) same as b with  $S_{CO_2} = 20$  per cent within the chimney and (e) same as (b) with  $S_{CO_2} = 50$  per cent within the chimney. The porosity and resistivity values for each formation, indicated in this figure can be found in Tables 1 and Table 2.



**Figure 4.** True 2-D resistivity model scenarios considering the detectability of a CO<sub>2</sub> leak through a chimney with variable saturations representing different times after CO<sub>2</sub> injection has started, as per dynamic modelling from Marín-Moreno *et al.* (2019). (a) True model after injection, including 50 per cent CO<sub>2</sub> saturation within the Utsira formation (saline aquifer). No leakage has occurred through the chimney ( $S_{CO_2} = 0$ ). (b) True model with leakage through the chimney after 5 yr of CO<sub>2</sub> injection and (c) True model with leakage through the chimney after 25 yr of CO<sub>2</sub> injection.

data (Gehrmann *et al.* 2021b) for the survey profile 2 (Fig. 5). An air resistivity of  $10^8 \Omega m$  was used while the seawater resistivity was derived from the CTD (conductivity, temperature and depth) sensor-operated during the STEM-CCS survey, a CSEM experiment at Scanner (Robinson *et al.* 2021) and ranges from 0.2756 to 0.2779  $\Omega m$  at 20–160 m water depth. At this location, the changes in seawater resistivity with depth are insignificant. However, previous studies have demonstrated that an accurate seawater resistivity profile has a significant effect in recovering geologically plausible subsurface resistivity (e.g. Key 2009; Attias *et al.* 2020). The resistivity of the seafloor model was calculated as described in Section 3.1 using the input parameters from Table 1. The seafloor model consisted of six layers based on the stratigraphy described in Section 2 (Fig. 2). Thicknesses as reported by Judd *et al.* (1994) were used for the Witch Ground and Aberdeen Ground formations (Table 1). Depth converted seismic reflection data from the Chimney experiment (Bull *et al.* 2018) were used to estimate the thickness for the Coal Pit and Ling Bank formations (Callow 2021). The Nordland group seal and the Utsira sandstone thicknesses are from Chadwick *et al.* (2004). A 500 m wide chimney was modelled, which cuts the stratigraphy from the top of the Aberdeen Ground formation at 400 m below seafloor (mbsf) to the Utsira formation at 1000 mbsf, using the Chimney’s position/width observed in seismic reflection section (Fig. 1b).

### 3.4 Inverse model parametrization

The CSEM inversion starting model used a 1  $\Omega m$  half-space resistivity for the sub-surface. The inversion allowed subsurface resistivity to vary, whereas the air and stratified seawater resistivity structures were fixed parameters. A quadrilateral mesh was constructed within the survey area (Key 2016), starting at the seafloor (minimum mesh is 10 m thick by 50 m wide) and up to 2000 m depth with a height growth ratio of 1.05, which corresponds to a thickness of 500 m at 2000 m depth, and a horizontal to the vertical smoothing ratio of 3. We used a triangular mesh outside the discretized quadrilateral mesh, with cell size increasing with distance from the survey area. The inversion starting model mesh had  $\sim 12000$  free parameters.

First, a series of unconstrained inversions are run from a 1  $\Omega m$  half-space starting model using synthetic electric field data (contaminated with noise) generated from 2-D forward models of the reservoir before and after CO<sub>2</sub> injection, with a homogeneous chimney saturation. Second, constrained inversions were generated with 2-D

synthetic data for scenarios after injection with variable CO<sub>2</sub> saturations within the chimney. This was achieved by placing penalty cuts at the top and base of the injection reservoir with a weight of 0.1. Penalty cuts allow for ‘rough’ changes in resistivity, eliminating the inversion algorithm’s preference to smooth interfaces. MacGregor & Sinha (2000) present real CSEM data examples where seismic and geological data are incorporated to constrain the depths of structural boundaries. A priori information (e.g. seismic horizons or geological information) help guide the inversion toward yielding resistivity models that are consistent with other data sets and knowledge from the area of interest. In CCS projects, where the boundaries of the injection reservoir are known from seismic reflection data, constraining the reservoir can improve CSEM inversions.

## 4 RESULTS

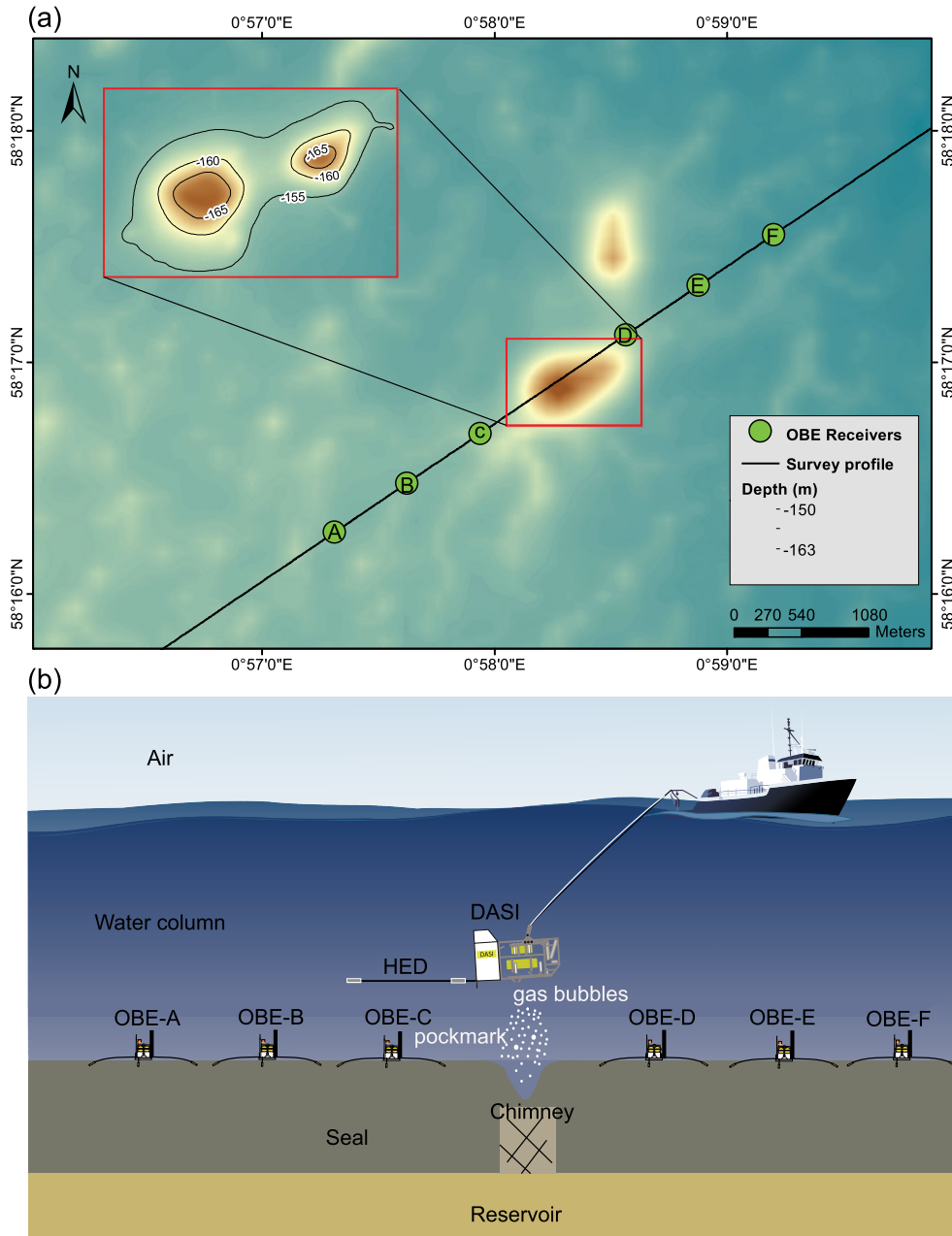
### 4.1 Rock physics results

Since our objective is to investigate the detectability of a CO<sub>2</sub> leak or plume outside of the injection reservoir, two rock physics relationships (Archie’s and Waxman–Smits–Juhász’s) are compared to construct a resistivity model of the clay-rich formations that we are modelling as the seal. Both Archie’s and Waxman–Smits–Juhász’s relationships predict similar saturations for a given resistivity in the Witch Ground and Coal Pit clay-rich formations (Fig. 6). These two formations have a higher porosity than the deepest clay-rich formations, the Aberdeen Ground and Nordland Group (Table 1). The saturations predicted by Waxman–Smits–Juhász for the deepest clay-rich formations (Aberdeen Ground and Nordland Group) are 1.5–2.5 times higher than those predicted with Archie’s law, given the same bulk resistivity value.

A comparison of the seal and reservoir CO<sub>2</sub> saturations shows that the same resistivity value in the seal and reservoir results in a different CO<sub>2</sub> saturation due to different rock physics relationships used to represent the reservoir and the seal. Apart from different rock physics models, we considered the geology, clay content, and porosity of each formation. The discrepancy observed between each layer/formation is driven primarily by differences in clay content and porosity. The differences between Archie’s and Waxman–Smits–Juhász models per formation (Fig. 6) show the importance of using a rock physics model for a clay-rich seal that considers the additional surface conduction pathways around the clay particles.

In Fig. 7 we compare the  $P$ -wave velocity and resistivity against gas saturation, using a similar approach to Constable (2010) and





**Figure 5.** (a) Survey layout on a 10 m bathymetry grid from Bull *et al.* (2018) of the Scanner pockmark (red square). On the top left, a more detailed (2.5 m) bathymetry map of the Scanner pockmark (red square) in (a). (b) Schematic of the CSEM method (not drawn to scale): the deep-towed active source instrument, DASI (Sinha *et al.* 1990) is towed across the Scanner pockmark (black line in (a)) with six OBE receivers spaced 500 m apart and deployed on either side of the pockmark and associated seismic chimney. Sketch in (b) modified from Weitemeyer *et al.* (2011).

references within. The largest change in acoustic  $P$ -wave velocity occurs for the first few percent of  $\text{CO}_2$  saturation and, as the saturation increases, the velocity response changes very little. In contrast, there is little change to the electrical resistivity for the  $\text{CO}_2$  saturation below 20 per cent but a rapid increase of electrical resistivity is observed at  $\text{CO}_2$  saturations higher than 20 per cent.

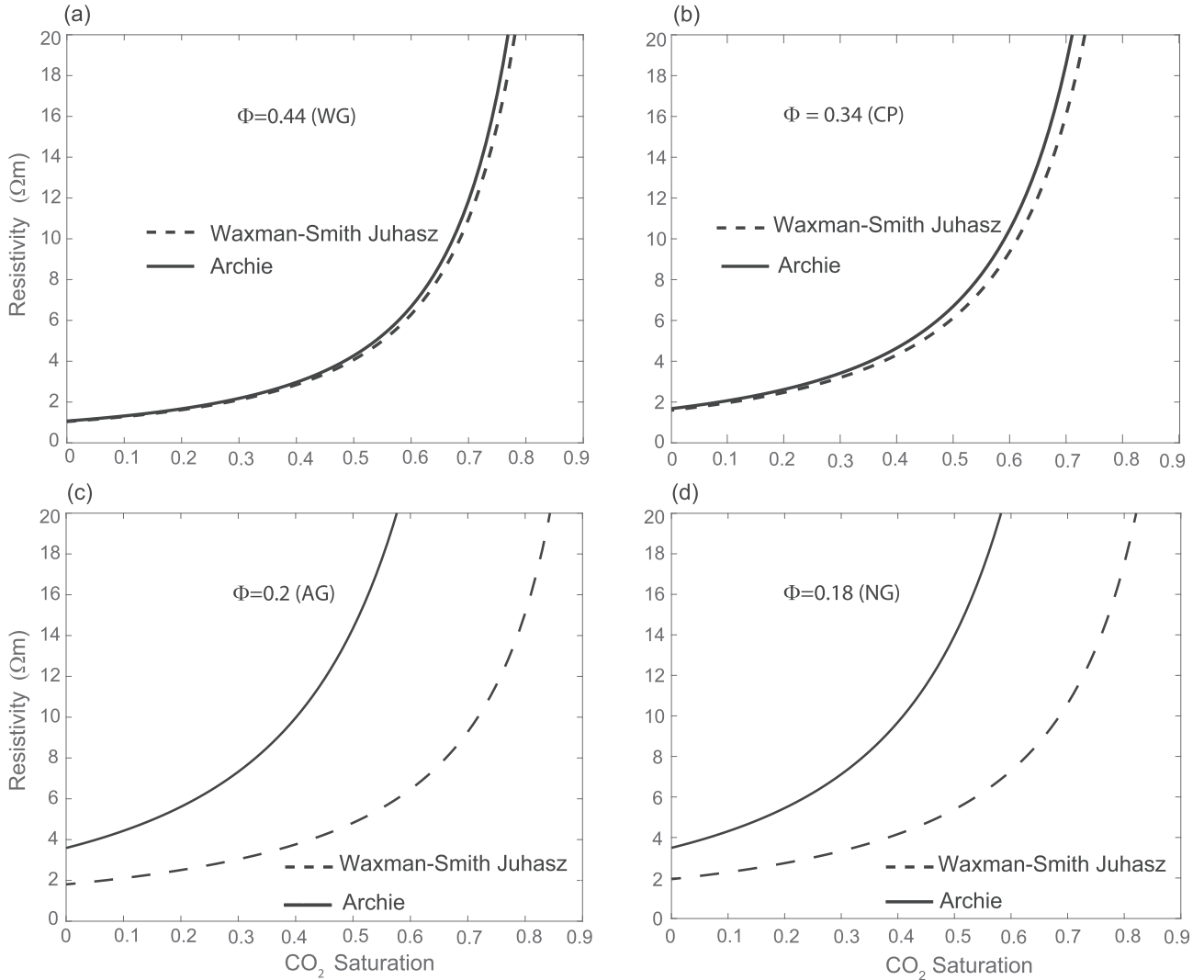
#### 4.2 Detectability of $\text{CO}_2$ saturation changes on 2-D CSEM synthetic data

The anomaly due to  $\text{CO}_2$  escaping through the chimney was computed using the amplitude percentage difference for two models

with a chimney connected to the  $\text{CO}_2$  reservoir saturated with 50 per cent  $\text{CO}_2$  and: (i) a chimney saturated with 10 per cent  $\text{CO}_2$  (Fig. 3c) and (ii) a chimney saturated with 20 per cent  $\text{CO}_2$  (Fig. 3d). The percentage difference is obtained by calculating the difference with a model of a chimney with no  $\text{CO}_2$  ( $S_{\text{CO}_2} = 0$  per cent) and the reservoir saturated with 50 per cent  $\text{CO}_2$  (Fig. 3b).

Considering a noise floor of  $10^{-13}$   $\text{V Am}^{-2}$ , as observed in the STEMM-CCS data, the  $E_z$  anomaly for a 20 per cent saturation ranges between 20 and 60 per cent amplitude percentage difference while the  $E_y$  anomaly ranges between 10 and 30 per cent amplitude percentage difference, with the highest response at 9–11 Hz. The anomaly for  $E_y$  and  $E_z$  for the two  $\text{CO}_2$  saturated models with





**Figure 6.** Resistivity versus CO<sub>2</sub> saturation for modelled seal geological units, all which are clay-rich (a) the Witch Ground formation (WG), (b) the Coal Pit formation (CP), (c) the clay rich Aberdeen Ground formation (AG) and (d) Nordland Group (NG). Archie’s saturation versus electrical resistivity relationship (solid line) is compared with the Waxman–Smidt–Juhasz relationship (dashed line). Both relationships are computed for each geological unit with the porosities,  $\phi$ , reported in the literature as per Table 1.

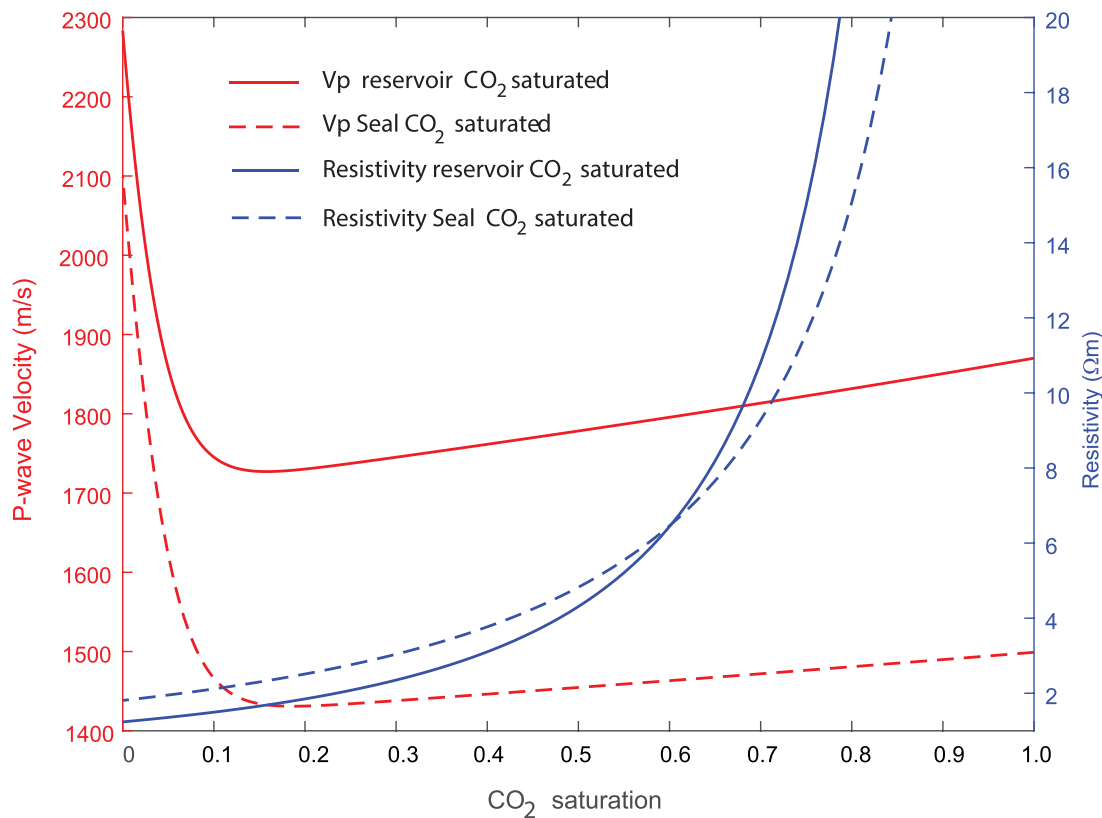
20 per cent CO<sub>2</sub> (Fig. 8) and 10 per cent CO<sub>2</sub> (Fig. A2, Appendix D) is higher in percentage difference than the random noise modelled (4 per cent) and above the instrument noise floor, meaning that both are detectable.

For the  $E_z$  model with  $S_{CO_2} = 20$  per cent the amplitude anomaly for one receiver (receiver OBE-D) exists at a narrower range of offsets for the higher frequencies (5–11 Hz). This anomaly occurs at shorter source–receiver offset ranges, only (700–1500 m). For 1–3 Hz frequencies, the anomaly occurs at higher source–receiver offsets (2000–3000 m, Fig. 8a). For one of the OBE receivers (OBE-D), the  $E_y$  amplitude anomaly at frequencies of 5–11 Hz occurs at a source–receiver offset of 700–1500 m, while for 3–5 Hz the anomaly is at 1200–1700 m. At frequencies of 1–3 Hz, the anomaly is much broader and extends from 1200 to 3900 m offset (Figs 8a and b). For the frequencies inverted in this study (1–11 Hz), the electric field amplitude anomaly of a CO<sub>2</sub> plume with 20 per cent saturation is more prominent as frequency increases in both the  $E_z$  and  $E_y$  components (Fig. 8). However, the anomaly in  $E_z$  is of higher amplitude than in  $E_y$ .

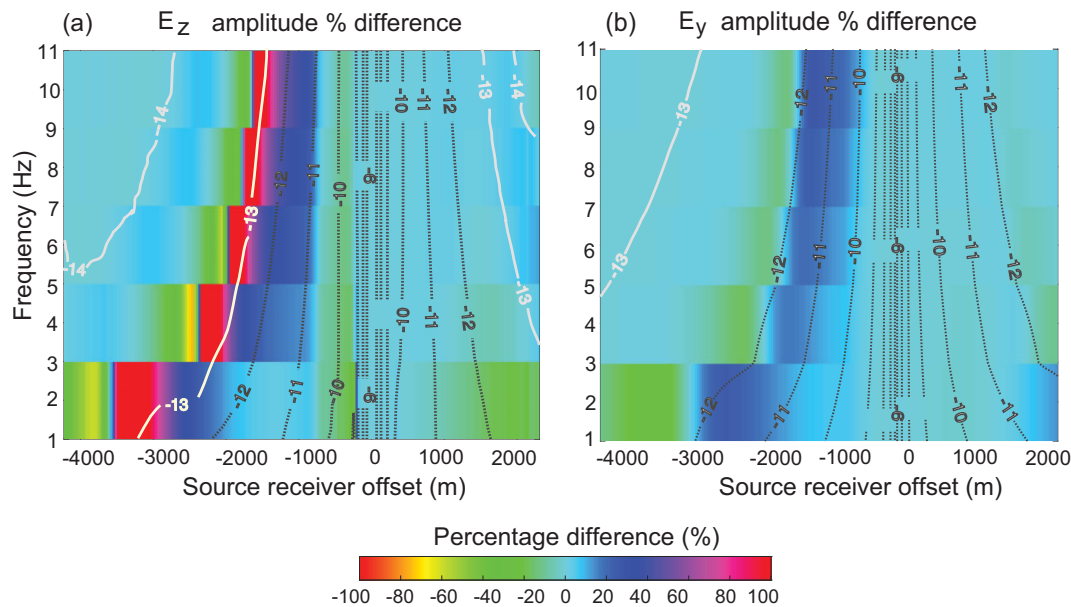
### 4.3 Synthetic inversion results of the chimney structure

Our suite of synthetic inversions with 4 per cent data error, converged to an RMS misfit of  $\sim 1.0$ . Normalized residuals for our inverted values are within 4 per cent for the amplitude and phase of the  $E_y$  (inline) and  $E_z$  (vertical) electric field ( $E$ -field) components. Fig. A4 (Appendix F) shows an example of  $E_y$  and  $E_z$  electric field data for an ocean bottom instrument (OBE) at a fundamental frequency of 1 Hz.

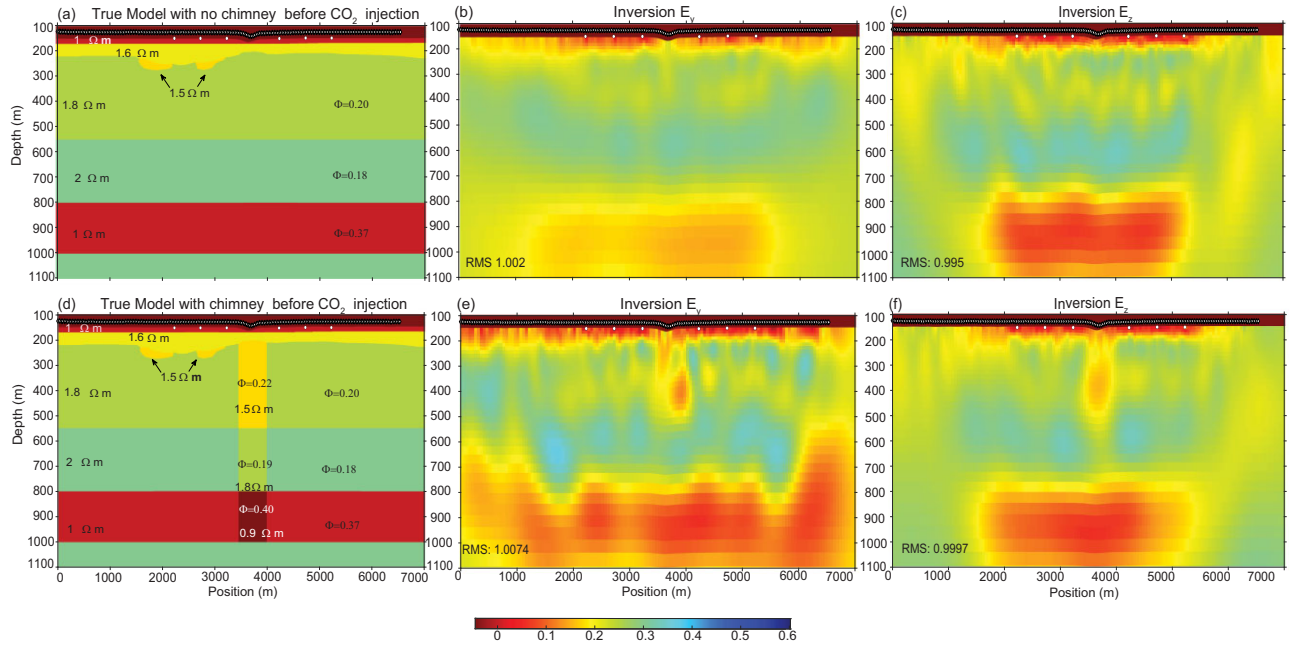
Our synthetic modelling considered a 10 per cent more porous chimney (Fig. 9d), due to connected fractures, compared to the background geology (Fig. 9a). The model of Fig. 9(d) represents a stage before CO<sub>2</sub> injection has started. This model would generally be called the ‘baseline’ survey of a monitoring CCS project, which provides a reference point to analyse CO<sub>2</sub> changes within the reservoir and overburden through the life of a CCS project. In the following sections, we analyse the detectability of a CO<sub>2</sub> leak through a chimney with CSEM and not the changes in saturation within the reservoir. Hence, we do not compare our CO<sub>2</sub> saturated models with this ‘baseline’ model but rather with the model with



**Figure 7.** Calculated resistivity for the seal using Juhasz (1981) (dashed blue line) and the reservoir using Archie (1942) (solid blue line) against  $\text{CO}_2$  saturation. Resistivity and velocity were calculated for the reservoir (Utsira formation) and seal (from the Witch Ground formation to the Nordland group), using rock physics parameters from our model area in the North Sea (see Table 1).  $P$ -wave velocities for the seal (red dashed line) and the reservoir (red solid line) versus  $\text{CO}_2$  saturation calculated using a patchy gas saturation distribution (Lee 2004). We use a confining pressure of 2.6 MPa for the seal and 18.2 MPa for the reservoir and Brie *et al.* (1995)'s calibration constant  $e = 30$ , which provides a nearly uniform gas distribution, inline with experimental results from Lee (2004) for marine unconsolidated sediments.



**Figure 8.** Amplitude percentage difference between chimney saturated with 20 per cent  $\text{CO}_2$  (model in Fig. 3d) and a chimney saturated with brine or  $S_{\text{CO}_2} = 0$  (model in Fig. 3b) for  $E_z$  (a) and  $E_y$  (b). This amplitude anomaly in percentage difference for the 2-D model with  $S_{\text{CO}_2} = 20$  per cent is calculated for a receiver 1000 m away from the chimney (OBE-D). Dashed black contours correspond to the  $\log_{10}$  electric field amplitude of the model saturated with 20 per cent  $\text{CO}_2$ . STEMM-CCS survey instrument noise floor at  $10^{-13}$   $\text{V Am}^{-2}$ , contours below noise floor marked with a continuous white line. Colour represents the percentage difference.



**Figure 9.** 2-D Synthetic resistivity model and resistivity inversion results for the host sediments and for a brine chimney within the host sediments utilizing the geometry, data range and properties of STEMM-CCS survey line 2. (a) True model with no chimney. (b) Inversion model of the synthetic data with no chimney for  $E_y$  and (c)  $E_z$ . (d) True model with chimney representing a 10 per cent porosity increase and (e) inversion model with chimney for  $E_y$  and (f)  $E_z$ . The white circles in the sections represent OBE sites and the white triangles are the transmitter positions. The reservoir layer in these models is 100 per cent saturated with brine (saline aquifer) and, hence a conductive target for CSEM. We use the same colour bar for all our resistivity inversion figures, following the academic convention of hot colours for conductive anomalies and cold colours for the resistive anomalies.

0 per cent saturation within the chimney and 50 per cent within the reservoir (Fig. 3b).

Even when the model of the chimney in Fig. 9(d) is not strictly the baseline for our study of the seal, we consider it relevant to understand the resistivity structure and the expected CSEM anomaly related to the chimney only. CO<sub>2</sub> injection time-lapse analysis of resistivity models requires a thorough investigation of the resolution and model characteristics at different stages and understanding of the underlying geology. Analysing the signal related to a chimney only (before CO<sub>2</sub> injection) is essential for detecting and monitoring a leak through a chimney and interpreting resistivity inversion results related to this.

The  $E_y$  and  $E_z$  inversions of the model in Fig. 9(d) show a visible response to a 10 per cent porosity perturbation inside a chimney cutting through a stratified subsurface (Figs 9d–f), which resulted in a conductive anomaly contrasting from the background sediments (Figs 9a–c). The synthetic inversion model results using the inline and the vertical electric field data adequately delineate the conductive chimney structure (Figs 9d–f).

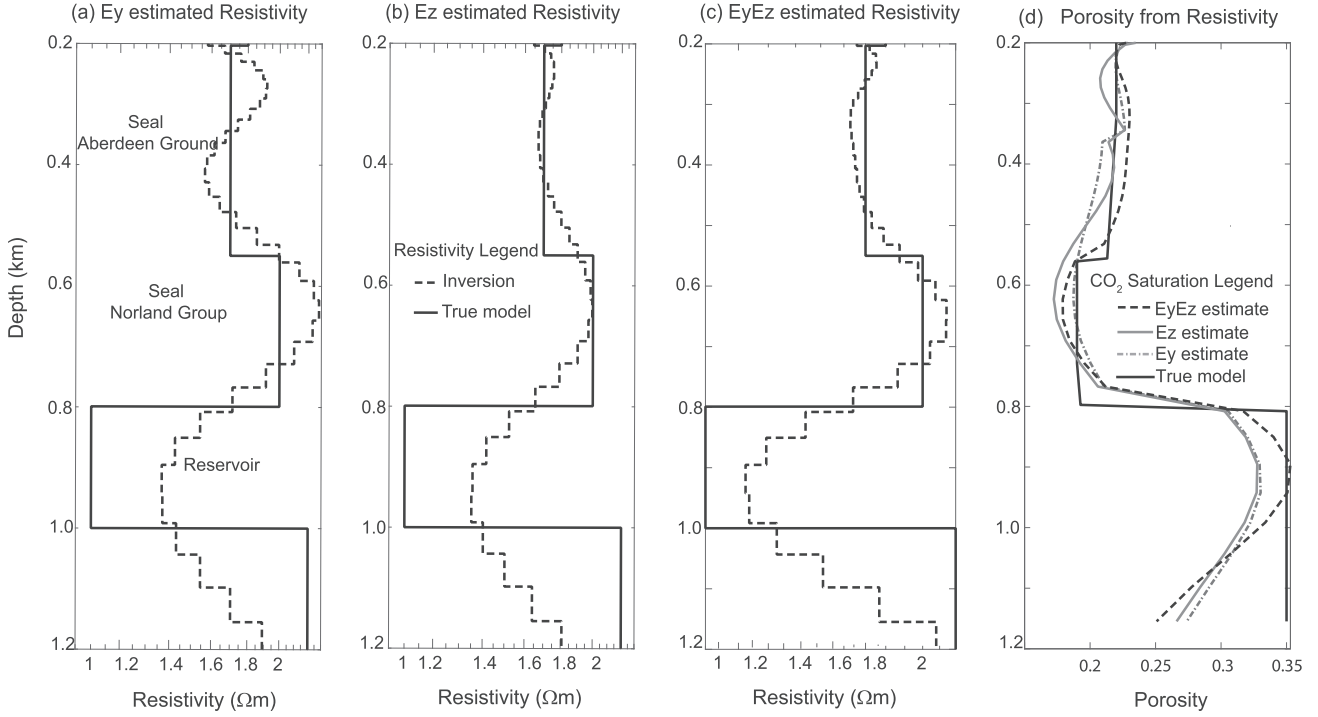
We analyse the electrical resistivity inversion of the conductive chimney also by looking at resistivity profiles extracted from our 2-D inversion at a model distance of 3.8 km. The resistivity profile for the  $E_z$  2-D inversion detects the chimney’s resistivity range of 1.6–1.9  $\Omega\text{m}$  for the Aberdeen Ground formation and 1.9–2.1  $\Omega\text{m}$  in the Nordland Group (Fig. 10b). The inversion using  $E_y$  data presents a similar resistivity range for these formations (Fig. 10a). We derived the porosity from the inverted resistivity profile to analyse the sensitivity of our inversion models (Fig. 10d). For the the clay-rich interval, we derived the porosity profile for the inverted resistivity for  $E_y$ ,  $E_z$  and  $E_y E_z$ , using the Waxmann–Smits–Juhász approach (eq. 3). For the reservoir we derived the porosity profile using

Archie’s equation (eq. 1). The porosity of the Aberdeen Ground formation (Table 1,  $\phi = 0.22$ ), composed mainly of clay, can be derived from the resistivity of the  $E_z$  and  $E_y$  components separately, producing porosity values of 0.19–0.25 from both components when inverted separately (Fig. 10d). The simultaneous  $E_y E_z$  inversion of the chimney produces a sharper resistivity and porosity model than the inversion of individual  $E$ -field components. For example, the porosity of the Aberdeen Ground formation ranges from 0.2 to 0.21 when  $E_y$  and  $E_z$  are inverted jointly (Figs 10d).

#### 4.3.1 $S_{\text{CO}_2}$ scenarios—unconstrained inversions

We explored the potential of marine CSEM to differentiate between three scenarios of CO<sub>2</sub> reservoir leakage via the electrical resistivity response. The models considered assume different CO<sub>2</sub> leakage scenarios through a chimney in the overburden connected to a CO<sub>2</sub> reservoir. A constant saturation of 50 per cent CO<sub>2</sub> was modelled within the reservoir while saturation changes were modelled within the chimney. Three saturations from bottom to top of the chimney are considered in our sensitivity analysis: 10, 20 and 50 per cent of CO<sub>2</sub>.

Our models show that both the  $E_y$  and  $E_z$  electric field components are sensitive to such CO<sub>2</sub> saturations (Fig. 11). However, in all scenarios, the  $E_z$  component resolves the true model features with better resolution than  $E_y$ . At  $S_{\text{CO}_2} = 10$  per cent, the  $E_y$  and  $E_z$  inversions indicate a small resistivity change at the chimney location that requires knowledge of the true model to interpret it as a saturation change (Figs 11a–c). At  $S_{\text{CO}_2} = 20$  per cent,  $E_y$  and  $E_z$  inversions (Figs 11b–d) detect the chimney structure, with 50–100 m deviations from the true model (Figs 11d–f). When  $S_{\text{CO}_2} = 50$  per cent, both  $E_y$  and  $E_z$  sharply resolve the overall chimney



**Figure 10.** Resistivity and porosity profiles at the chimney (2-D model distance = 3.8 km). Resistivity true model (solid line) and inverted (dashed line) resistivity derived from  $E_y$  (a)  $E_z$  (b) and  $E_y E_z$  (c) at the chimney with 10 per cent porosity increase. (d) Porosity estimated from  $E_y$  (grey dashed line),  $E_z$  (grey solid line) and joint  $E_y E_z$  (black dashed line) while the true model porosity is the (solid black line) using the rock physics model of Waxman–Smits–Juhász for the clay-rich formation and Archie for the reservoir (Section 3.1).

structure (Figs 11g, h and i). At the chimney edges, the resistivity anomaly from the  $E_y$  inversion is lower than in the true model ( $\sim 2.8 \Omega\text{m}$  versus  $5 \Omega\text{m}$ ), 50 m wider at the top, and 150 m thinner at depth near the reservoir (Fig. 11h). In comparison, the  $E_z$  inversion presents sharper chimney edges, with a resistivity of  $\sim 3.5\text{--}4 \Omega\text{m}$  at the edges, consistent with a width of  $\sim 505$  m and the chimney is marginally wider when closer to the reservoir ( $\sim 510$  m; Fig. 11i).

$E_y E_z$  inversion of the 10 per cent saturation scenario did not resolve the chimney location and width (Fig. 12b), similar to when the components were inverted individually. The resistivity at the chimney for the AG formation was predicted to be around  $2 \Omega\text{m}$  versus  $1.9 \Omega\text{m}$  in the true model, corresponding to saturations between 0 and 10 per cent (Figs 13c and d) using the Waxman–Smits–Juhász relationship (eq. A10). For the 20 per cent saturation case, when inverting  $E_y$  and  $E_z$  jointly, the width of the chimney is 450 m, which is more accurate than when these components are inverted individually. The chimney’s width is taken at an intermediate depth, halfway from its base. Note, the true width of the chimney is 500 m. The resistivity at the top of the chimney for the Aberdeen Ground formation is predicted to be  $2.4 \Omega\text{m}$  versus  $2.18 \Omega\text{m}$  true model, corresponding with  $\text{CO}_2$  saturations from 10 to 20 per cent (Figs 13f and g).

For the 50 per cent  $\text{CO}_2$  saturation model, the simultaneous inversion using both  $E_y$  and  $E_z$  data accurately recovers the lateral extent of the top 300 m of the chimney while the bottom 500 m is less well resolved. The resistivity in the chimney for the Aberdeen Ground formation recovered by this inversion varies from 2.5 to  $5.4 \Omega\text{m}$  compared with  $4.8 \Omega\text{m}$  in the true model, corresponding to 35–50 per cent  $\text{CO}_2$  saturation (Figs 13j and k) calculated using eq. (A10).

#### 4.4 Inverted resistivity and predicted $\text{CO}_2$ saturations

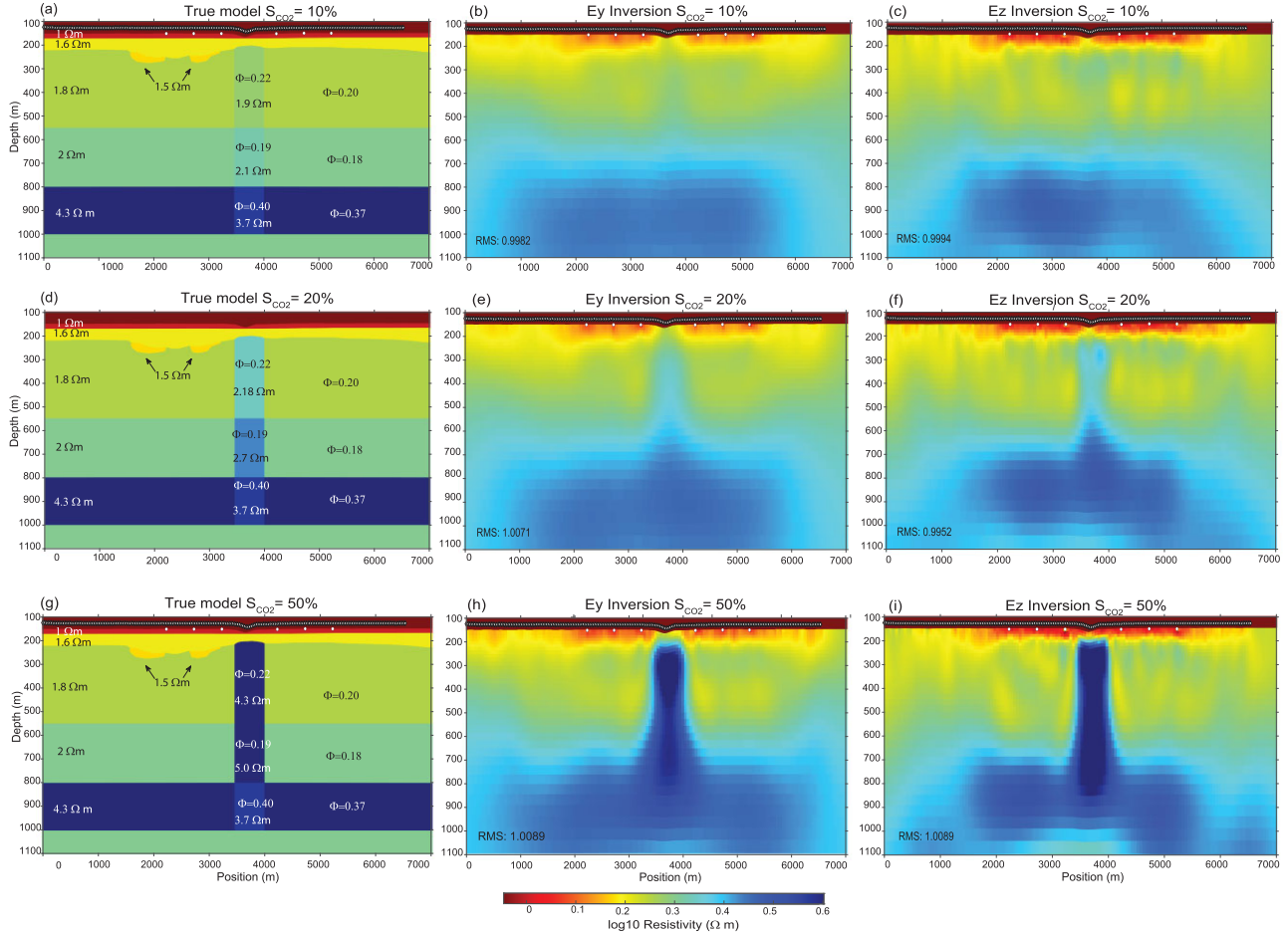
We compared the predicted resistivity from an inversion with the true model for the various model scenarios by extracting resistivity profiles at the chimney centre. We also calculate the corresponding  $\text{CO}_2$  saturation ( $S_{\text{CO}_2}$ ) of the various chimney seals for each extracted resistivity profile. For this calculation we used eq. A10, the normalized Waxman and Smits’s equation (Juhász 1981), and the parameters in Table 1.

For the model with 10 per cent  $S_{\text{CO}_2}$ , a vertical profile extracted from the chimney centre in the  $E_y$  inversion has resistivity of  $\sim 1.6\text{--}2.1 \Omega\text{m}$ , which corresponds to an Aberdeen Ground formation  $S_{\text{CO}_2}$  of 0–15 per cent (Fig. 13a). The  $E_z$  inversion has a sharper vertical resistivity profile for the Aberdeen Ground formation, ranging between  $\sim 1.7$  and  $2 \Omega\text{m}$ , corresponding to  $S_{\text{CO}_2}$  of 0–10 per cent (Fig. 13b).

When the chimney is at an  $S_{\text{CO}_2} = 20$  per cent, the seal resistivity profile from the  $E_y$  inversion is smoother than the one from the  $E_z$  inversion (Figs 13d and e).  $E_y$  predicts a resistivity range of  $\sim 1.8\text{--}2.4 \Omega\text{m}$  as opposed to the  $2.18 \Omega\text{m}$  (Table 2) for the Aberdeen Ground formation, corresponding to 10–20 per cent  $\text{CO}_2$  saturation.  $E_z$  inversions suggest that the Aberdeen Ground formation resistivity varies from  $\sim 1.8$  to  $2.2 \Omega\text{m}$ , which corresponds to 10–20 per cent calculated saturation  $S_{\text{CO}_2}$  for this resistivity.

At  $S_{\text{CO}_2} = 50$  per cent, the resistivity from the  $E_y$  inversion is smoother (Fig. 13h) though less sensitive to the chimney structure in comparison to the resistivity from the  $E_z$  inversion (Fig. 13i). In the Aberdeen Ground formation, the  $E_y$  inversion has a resistivity of  $\sim 2\text{--}5 \Omega\text{m}$  (30–50 per cent  $S_{\text{CO}_2}$ ) instead of  $4.3 \Omega\text{m}$ ; comparable to the  $E_z$  inversion ( $\sim 2.5\text{--}5 \Omega\text{m}$ ,  $\sim 25\text{--}50$  per cent  $\text{CO}_2$ ).





**Figure 11.** Synthetic (true) models and inversion results for three different scenarios of CO<sub>2</sub> leakage from the reservoir into the chimney, using the geometry, data range, and properties of STEM-CCS survey line 2. In the left column, the true models are shown. (a) True model with the chimney saturated with 10 per cent CO<sub>2</sub>, (d) True model with the chimney saturated with 20 per cent CO<sub>2</sub> and (g) True model with the chimney saturated with 50 per cent CO<sub>2</sub>. In the second column are the inverted resistivity sections using only  $E_y$  data for (b) 10 per cent CO<sub>2</sub>, (e) 20 per cent CO<sub>2</sub> and (h) 50 per cent CO<sub>2</sub>. In the third column the inverted resistivity sections using only  $E_z$  data are shown for (c) 10 per cent CO<sub>2</sub>, (f) 20 per cent CO<sub>2</sub>, and (i) 50 per cent CO<sub>2</sub>. The circles on inverted models represent OBE sites while the white triangles are the transmitter positions.

#### 4.4.1 A $S_{CO_2}$ gradient within the chimney—constrained inversions

CO<sub>2</sub> leakage through the chimney was modelled at two different times, 5 and 25 yr after the CO<sub>2</sub> reaches the base of the chimney. Here, the primary focus is on the detectability of CSEM to CO<sub>2</sub> and porosity-induced resistivity changes within the chimney. Therefore, a constant CO<sub>2</sub> saturation of 50 per cent was assumed in the reservoir. Although the CO<sub>2</sub> saturation in the reservoir will vary in space and time, during and after CO<sub>2</sub> injection operations, it remains fixed for this study, thus focusing on the seal leakage and not the reservoir. The porosity distribution and the vertical changes in CO<sub>2</sub> saturation in the chimney are guided by Marin-Moreno *et al.* (2019) multi-phase reactive transport simulation of CO<sub>2</sub> leakage at the Scanner Pockmark.

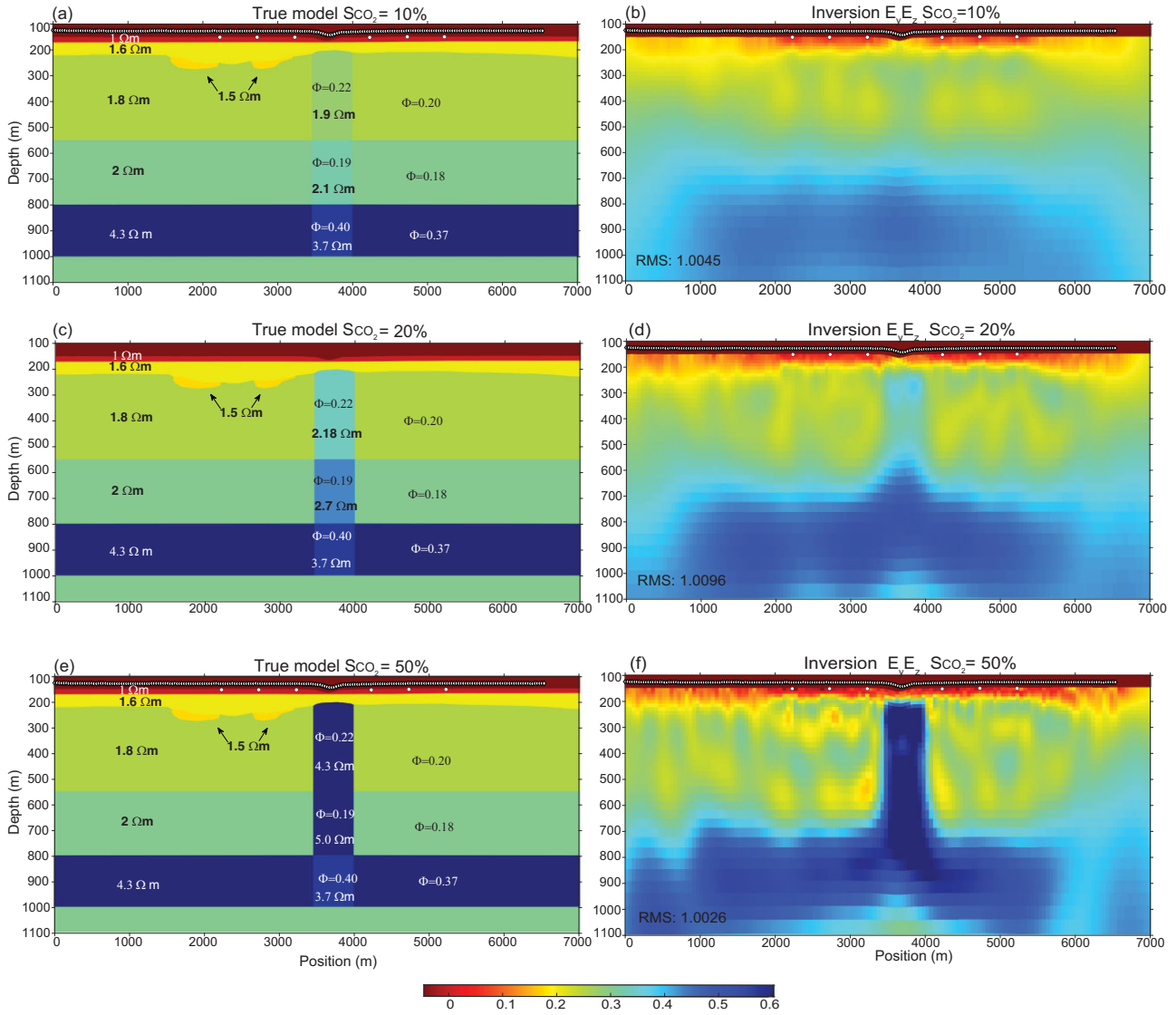
At 5 yr (Fig. 4b), the first 100 m from the bottom of the chimney (~800–700 mbsl) has 20 per cent CO<sub>2</sub> saturation followed by a 150 m section with 15 per cent CO<sub>2</sub> (up to ~550 mbsl) and the rest saturated with brine. In this model, we allow a resistivity discontinuity across the reservoir boundaries (constrained inversion), which enhances the differentiation between resistive (CO<sub>2</sub> saturated

– deep chimney) and conductive (brine saturated – shallow chimney) regions. The variable saturation can be differentiated in the inversion (Figs 14b and c).

At 25 yr (Fig. 4c), the first 100 m from the bottom of the chimney (~800–700 mbsl) are saturated with 35 per cent CO<sub>2</sub> followed by a 150 m section with 25 per cent CO<sub>2</sub> saturation (~550 mbsl), a 200 m section with 20 per cent CO<sub>2</sub> saturation (up to ~350 mbsl), and the rest saturated with brine.

The  $E_y$  component resolved the chimney’s CO<sub>2</sub> saturated layers (true model features) with better lateral and vertical resolution than  $E_y E_z$  combined. We constrained these inversions by enforcing penalty cuts of 0.1 (Key 2016) to the base and top of the reservoir layer at 800 and 1000 m depth. Constraining the reservoir enhanced the  $E_y$  response. The inversion model for  $E_y E_z$  at 25 yr (Fig. 14f) captures well the upward migration of CO<sub>2</sub> through the chimney so that the resistor that emerges from the reservoir is more elongated compared to the model at 5 yr (Fig. 14c).

The constrained inversions at 5 and 25 yr show distinctive (time-dependent) detectable differences in the chimney’s height and resistivity. In both scenarios, the chimney’s brine-saturated ( $S_{CO_2} =$



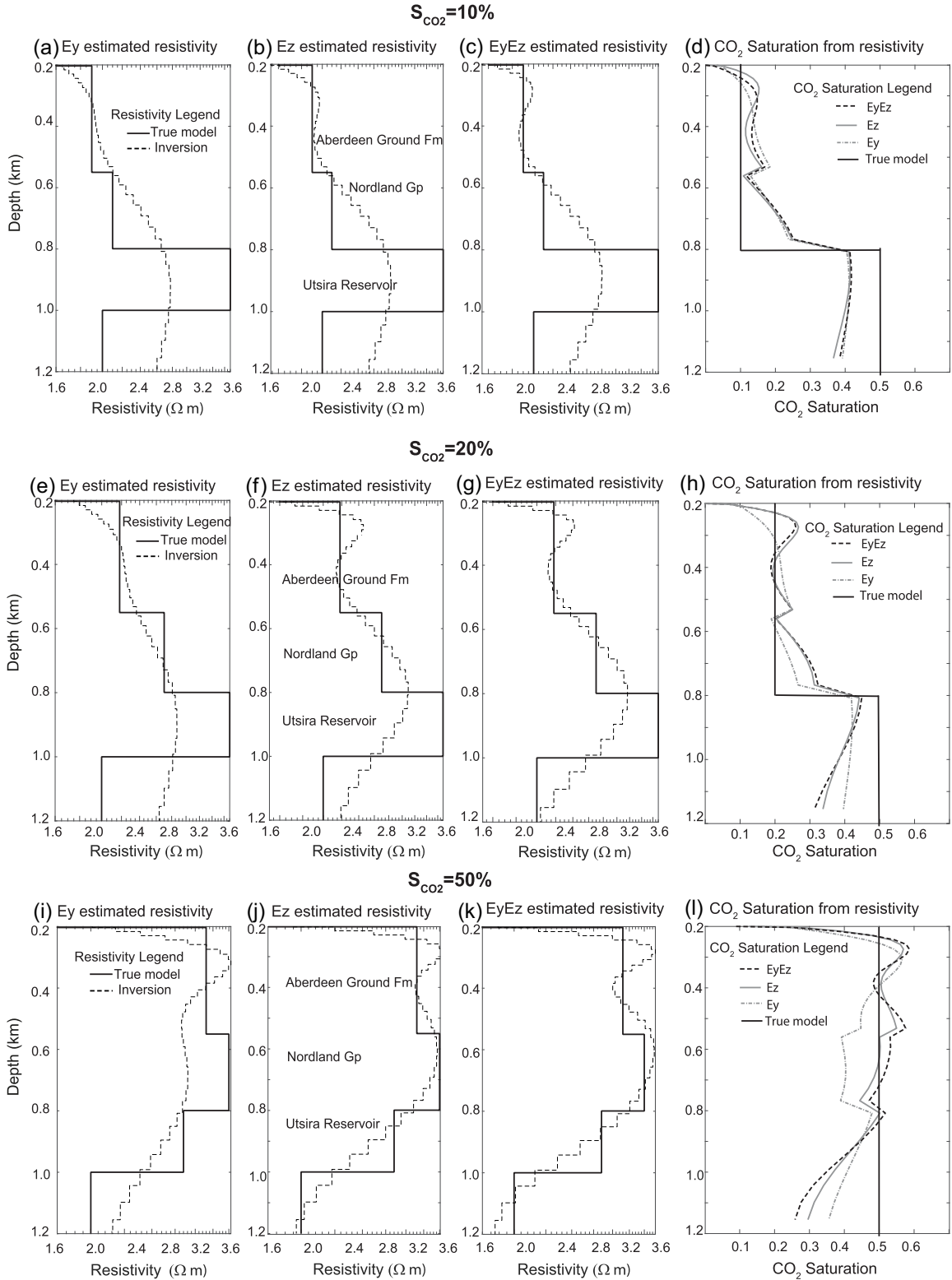
**Figure 12.** True synthetic resistivity models and resulting resistivity sections from inversion using both  $E_y$  and  $E_z$  data. Three different scenarios of  $CO_2$  leakage from the reservoir into the chimney are the true model with the chimney saturated with 10 per cent  $CO_2$ , (c) the true model with the chimney saturated with 20 per cent  $CO_2$  and (e) the true model with chimney saturated with 50 per cent  $CO_2$ . In the second columns (b), (d) and (f) is the resulting resistivity sections from a simultaneous  $E_y$  and  $E_z$  component inversion for the three scenarios (10, 20 and 50 per cent  $CO_2$  leakage in the chimney).

0 per cent) upper regions are well-resolved by our constrained synthetic inversions (Fig. 14).

## 5 DISCUSSION

We have explored the added value of using marine CSEM to detect upward  $CO_2$  migration through subvertical fluid escape/chimney structures. Comparing the  $P$ -wave velocity and resistivity of our model area as a function of gas saturation (Fig. 7), similar to Constable (2010), the benefit of coupling CSEM and seismic methods for monitoring  $CO_2$  leakage becomes evident. Combining CSEM and seismic methods allows one to distinguish clearly if a leak is significant because CSEM will present a significant signal when saturations exceed 20 per cent while seismic velocities may remain almost constant at this stage of saturation. Seismic velocities are highly sensitive to saturations below 10 per cent, whereas resistivity shows only a gradual response to saturation increases between 10 and 20 per cent.

Our results show that there is a distinct difference between inversion models with 0 and 10 per cent  $CO_2$  saturation and 10 and 20 per cent  $CO_2$  saturation within the modelled chimney. However a chimney with 10 per cent saturation is not clearly detectable in the regularised 2-D inversions (Figs 11b, c and 12b) when comparing its response with that of the background sediments. However, the inversion of a chimney with 20 per cent saturation is clearly detectable (Figs 11e, f and 12d). When comparing 2-D CSEM synthetic data for a model with a chimney saturated with 10 per cent  $CO_2$  ( $S_{CO_2} = 10$  per cent) with the background sediments ( $S_{CO_2} = 0$  per cent) the resistivity contrast is too small to be detected with CSEM (Fig. A3, Appendix D). However, when we compare 2-D synthetic data between a model with a chimney after injection and before a leak with a chimney with 10 per cent  $CO_2$  we observe an amplitude percentage difference of 10–20 per cent in  $E_y$  and 25–40 per cent in  $E_z$  in the synthetic data (Fig. A2, Appendix D). This signal seems large enough in  $E_z$  data for one receiver but is not detectable in the inversion results. We believe that using the survey



**Figure 13.** Resistivity profiles and CO<sub>2</sub> saturation at the chimney (2-D model distance = 3.8 km) for separate  $E_y$ ,  $E_z$  and simultaneous  $E_y$  and  $E_z$  inverted resistivity results (black dashed line) against the true resistivity model (solid black line) for the three CO<sub>2</sub> leakage scenarios (10, 20 and 50 per cent).  $E_y$  only inverted resistivity profiles are in the first column with the chimney saturated with (a) 10 per cent CO<sub>2</sub>, with (e) 20 per cent CO<sub>2</sub> and with (i) 50 per cent CO<sub>2</sub>. The second column are the  $E_z$  only inverted resistivity profiles for the same three scenarios: (b)  $S_{CO_2} = 10 =$  per cent, (f)  $S_{CO_2} = 20$  per cent and (j)  $S_{CO_2} = 50$  per cent. In the third column are the simultaneous  $E_y E_z$  inverted resistivity profiles for the same three scenarios: (c)  $S_{CO_2} = 10$  per cent, (g)  $S_{CO_2} = 20$  per cent and (k)  $S_{CO_2} = 50$  per cent. Finally, the fourth column is the predicted CO<sub>2</sub> saturations derived from the inverted resistivity models and rock physics relationships (see Section 3.1). The true CO<sub>2</sub> saturations (black solid line) are plotted along with predictions from the three data types:  $E_y$  (grey dotted line),  $E_z$  (grey solid) and joint  $E_y$  and  $E_z$  (black dashed line) for (d)  $S_{CO_2} = 10$  per cent, (h)  $S_{CO_2} = 20$  per cent and (l)  $S_{CO_2} = 50$  per cent.

**Table 2.** Resistivity of the partially brine saturated formations (Gas models) within the chimney: WGF, Witch Ground Formation; CPF, Coal Pit Formation; LBF, Ling Bank Formation; AGF, Aberdeen Ground Formation; NGS, Nordland Group seal and UF, Utsira Formation (Reservoir).

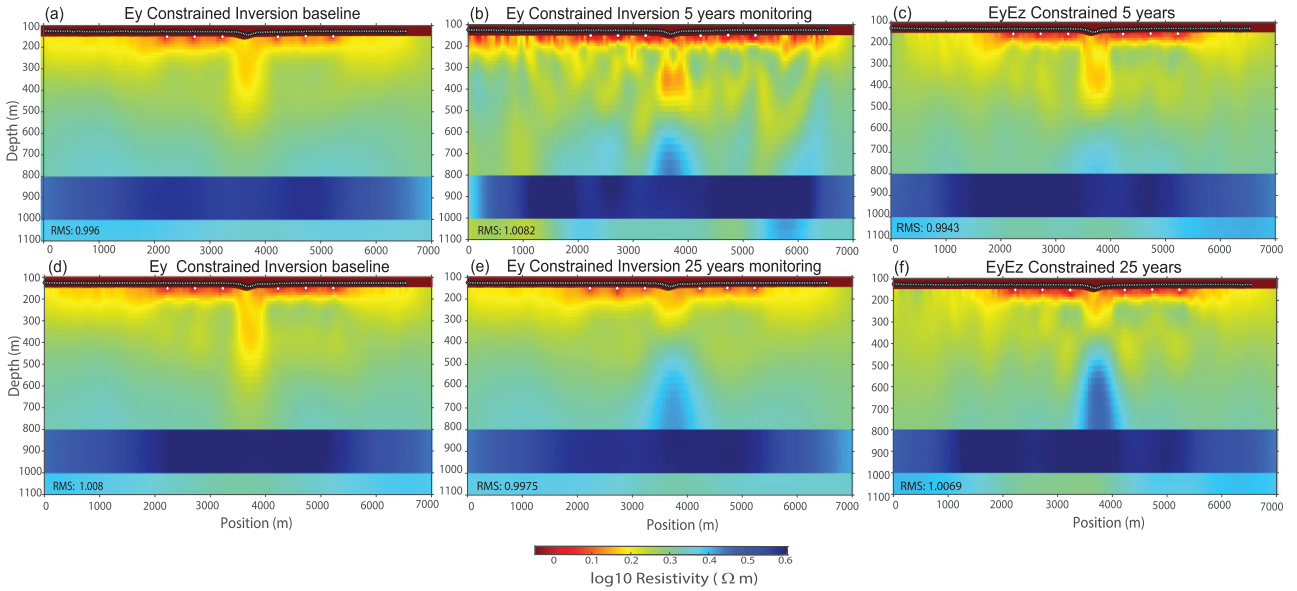
Layer	$\phi$	Outside chimney			Within chimney				
		$\rho_0^{(1)}$	$\rho_0^{(2)}$	$\phi_c$	$\rho_t^{(1)}$	$\rho_t^{(2)}$	$\rho_t$	$\rho_t$	$\rho_t$
		$S_w = 1$	$S_w = 1$		$S_w = 1$	$S_w = 1$	$S_{CO_2} = 0.1$	$S_{CO_2} = 0.2$	$S_{CO_2} = 0.5$
WGF*	0.44	1 $\Omega\text{m}$	1 $\Omega\text{m}$	—	—	—	—	—	—
CPF*	0.34	1.6 $\Omega\text{m}$	1.6 $\Omega\text{m}$	—	—	—	—	—	—
AGF	0.2	1.8 $\Omega\text{m}$	1.8 $\Omega\text{m}$	0.22	1.5 $\Omega\text{m}$	1.5 $\Omega\text{m}$	1.81 $\Omega\text{m}$	2.18 $\Omega\text{m}$	4.3 $\Omega\text{m}$
NGS	0.18	2 $\Omega\text{m}$	2 $\Omega\text{m}$	0.19	1.8 $\Omega\text{m}$	1.8 $\Omega\text{m}$	2.1 $\Omega\text{m}$	2.7 $\Omega\text{m}$	5.0 $\Omega\text{m}$
UF	0.37	1 $\Omega\text{m}$	4.0 $\Omega\text{m}$	0.40	0.9 $\Omega\text{m}$	3.7 $\Omega\text{m}^{(3)}$	3.7 $\Omega\text{m}^{(3)}$	3.7 $\Omega\text{m}^{(3)}$	3.7 $\Omega\text{m}$

\*Formations with no fractures as the chimney does not extend up to these layers. A porosity 10 per cent lower is assumed at the chimney from the AG up to the Utsira formation.

<sup>(1)</sup>Background model, 100 per cent saturated with brine before CO<sub>2</sub> injection.

<sup>(2)</sup>Background model, 100 per cent saturated with brine in the seal after injection.

<sup>(3)</sup>Utsira formation 50 per cent saturated with CO<sub>2</sub>.



**Figure 14.** Resistivity inversion for the baseline and the two scenarios with gradational CO<sub>2</sub> saturation in the chimney representing different times after CO<sub>2</sub> injection, corresponding to Fig. 4. The same geometry, data range, and properties of the STEM-CCS survey line 2 are used in modelling. In the top row the resistivity inversions, constrained by the reservoir top and base using  $E_y$  for the baseline model (Fig. 4a) in (a);  $E_y$  for the model with leakage through the chimney after 5 yr of CO<sub>2</sub> injection (Fig. 4b) in (b);  $E_y E_z$  for the model with leakage through the chimney after 5 yr of CO<sub>2</sub> injection in (c). In the second row there are the inverted resistivity sections, constrained by the reservoir top and base using:  $E_y E_z$  for the baseline model (Fig. 4a) in (d); using  $E_y$  for the model with leakage through the chimney after 25 yr of injection (Fig. 4c) in (e) and  $E_y E_z$  for the model with leakage through the chimney after 25 yr of CO<sub>2</sub> injection (Fig. 4c) in (f).

geometry and rock physics applied here we are able to detect with confidence a CO<sub>2</sub> leak with a saturation below 20 per cent and the detection limits with our inversion modelling are somewhere between 10 and 20 per cent saturation. These results may also imply that if a chimney or conduit has a smaller porosity than what we modelled a saturation of 10 per cent may not be detectable in CSEM data. Consequently, similar to Gasperikova *et al.* (2022), we consider our detection threshold potentially valid for an analogue area in the North Sea, with comparable boundary conditions (i.e. water depth, injection depth), geology and rock physics properties, concurring with Gasperikova *et al.* (2022) notion that the detection limits of CSEM for CO<sub>2</sub> leaks are site-specific.

Seismic velocities are extremely sensitive to low CO<sub>2</sub> saturations (e.g. below 10 per cent), which makes seismic methods a powerful tool to detect any type of seepage at an early stage. However, as the seismic velocities normally have little sensitivity to changes above

a 10 per cent saturation they fail to quantify the degree of saturation for values above this saturation. Therefore, the seismic method will be limited in certain CO<sub>2</sub> injection scenarios especially monitoring the CO<sub>2</sub> plume in a depleted gas reservoir. CSEM methods determine saturation changes above the seismic-based limits of around 10 per cent saturation. Hence, CSEM complements the seismic methods in the quantification of CO<sub>2</sub> saturation and in assessing the amount of CO<sub>2</sub> that has travelled within and from the reservoir. The value of this quantification depends on what CO<sub>2</sub> saturation limits within the seal regulators will allow for and the required level of quantification. If a zero-tolerance approach is taken, a change of 1 per cent gas saturation within the seal would require sequestration to stop and the information provided by seismic  $P$ -wave velocity suffices. However, if some leakage from the reservoir is tolerated or regulators would be interested to know if a leak occurs how big this is, and how it evolves over time and space, then CSEM is required.



Independent of the regulations, which may vary worldwide and with time, it is clear that quantifying a leak into shallower depths or up to the seabed is important.

Geology and porous media are complex, and given the non-uniqueness of the deterministic inversion, using complementary geophysical data sets is vital. Park *et al.* (2017) and Gasperikova *et al.* (2022) discuss the merits of integrating CSEM with seismic and gravity data for post-injection monitoring of CCS reservoirs.

Dean & Tucker (2017)'s risk-based framework for measurement, monitoring, and verification (MMV) of the Golden-eye storage complex in the United Kingdom, at similar water depth (120 m) and in close proximity to scanner, concludes that CSEM is not a recommended method as the contrast expected in electric resistivity would not be detectable and notes issues with CSEM in shallow water. There are no CSEM models or data presented in their publication to justify this conclusion. Similarly, unsupported by data analysis, the 2015 IEAGHG report (IEAGHG 2015) infers that CSEM does not enhance MMV strategies. Our suite of synthetic modelling demonstrates unequivocally that the CSEM method adds value in monitoring CCS sites.

Our inversion models consider several scenarios, indicating that a leak via a chimney of homogeneous and varying CO<sub>2</sub> saturations can be imaged by CSEM (Figs 11, 12, 14 and 8). We demonstrate that monitoring CO<sub>2</sub> leakage scenarios through a chimney 500 m wide and fully connected to the reservoir, using marine CSEM, is achievable and aided by: (i) adding a vertical  $E$ -field component, (ii) inverting multiple frequencies, (iii) applying seismic constraints to the injection reservoir, (iv) using an ultra-fine (few metres) starting mesh (adaptive refined) and (v) site-specific inversion parametrization.

We note that fluid saturations can be underestimated if the subsurface clay content is unaccounted for when using Archie's law for clean sands. Therefore, Archie's equation requires modification for rock physics property analysis or inversion modelling of a CCS site (Juhasz 1981). Realistic rock physics and dynamic modelling (Commer *et al.* 2022) are key in assessing the feasibility and interpreting geophysical data with the purpose of CCS monitoring. A change in porosity of 10 per cent in the chimney, composed of clay and silt fully saturated with brine, extending from 200 to 1000 mbsf, is detectable as a conductive anomaly in both  $E_y$  and  $E_z$  electric field components when inverting multiple frequencies consisting of the 1 Hz fundamental frequency and the odd harmonics up to 11 Hz. Alterations in chimney porosity may imply increased permeability, which manifests as variations in electrical resistivity, detectable by constrained CSEM modelling (Figs 12 and 14).

A marine CSEM study by Attias *et al.* (2016) delineated a similar chimney structure (saturated with gas hydrate) using seismically constrained 2-D CSEM inversion of the  $E_y$  component. In comparison, our unconstrained 2-D CSEM inversion of the  $E_z$  component for a chimney containing homogeneous  $S_{CO_2}$  of 20 and 50 per cent produced satisfactory lateral resolution (Figs 11 and 12). However, inversion of a chimney saturated homogeneously by CO<sub>2</sub> less than 20 per cent requires seismic constraints to resolve the true model (Figs 11b and c). In the synthetic models discussed above,  $E_z$  is more sensitive to alterations in the chimney's  $S_{CO_2}$  than  $E_y$ .  $E_z$  inversion provides a more satisfactory lateral resolution to CO<sub>2</sub> saturated chimney. Combined  $E_z$  and  $E_y$  inversions predict the true resistivity model better.

We assume CO<sub>2</sub> vertical upward migration via the chimney at a rate of 0.1 m d<sup>-1</sup> (Marín-Moreno *et al.* 2019), which has been used to determine the saturation distribution of a leak via the chimney after 5 and 25 yr of injection. According to the modelling presented

in Fig. 14, a leak after 5 yr of injection and for the specific boundary conditions and geology modelled could be detected. This observation could have implications as to how early CSEM monitoring should start and also highlights the importance of making this decision in conjunction with predictions from an area-specific flow model. In accordance with Marín-Moreno *et al.* (2019) the CO<sub>2</sub> migrates 365 m vertically through the modelled chimney (~600 m length) in 10 yr. This implies that, in case of a CO<sub>2</sub> leak, CSEM monitoring needs to be conducted before 10 yr of injection, as recommended for cases where no chimney is present (Fawad & Mondol 2021).

## 5.1 Study limitations

Our study simulates and analyses CO<sub>2</sub> leaking through a fluid pathway in the seal above a CCS reservoir with a specific geometry and specific rock physics parameters (Table 1, Figs 3 and 4). The models are a proxy for an existing fluid escape feature in the North Sea (Scanner Pockmark). However, the North Sea has many fluid pathways with similar characteristics (Karstens & Berndt 2015) so our work provides a basis for studying such fluid escape features. Our modelling is based on a realistic and relevant geological worst-case leakage scenario in an area where CCS projects are considered. The synthetic models were constructed using realistic survey geometry; however, perturbation analysis to assess navigational uncertainties was not performed. Porosity and temperature affect resistivity. Generally, porosity decreases with depth due to compaction of the sediment above, which may increase the resistivity (Athy 1930a), and temperature increases with depth due to the geothermal gradient, which may cause the pore water to warm and decrease resistivity (Arps 1953). Depending on the rock matrix and the pore fluid filling the pore space, these two effects may counteract each other. Therefore, adequate modelling of deeper reservoirs and seal formations requires consideration of porosity and temperature effects on the formation's resistivity. In addition, studies on geophysical monitoring of CCS can benefit from appropriate and project-specific dynamic modelling, since generalizations are not always valid (Gasperikova *et al.* 2022).

Our deterministic inversion results have the uncertainties of a smooth regularized inversion. Quantifying uncertainties on a deterministic CSEM inversion is not typically addressed and sensitivity analyses alone are not enough to equate to the resolution of modelled features. There are three approaches in recent work to estimate CSEM uncertainties: (i) Through fully non-linear and Bayesian approach (Ray 2021), (ii) smooth optimization-based stochastic posterior approximation (Blatter *et al.* 2022) and (iii) using 3-D seismic and geology knowledge (scenario base inversion) as constraints to determine uncertainties with statistical inversion techniques (Causse 2023). Ideally, depending on the project risk profile and computer power available, one or more of these approaches could be used in future work.

Our study does not model CSEM survey repeatability as we do not consider it relevant when looking at resistivity inversions. Orange *et al.* (2009), Andréis & MacGregor (2011) and Tietze *et al.* (2019) discussed the limitations of survey repeatability (raw data-driven analysis) to monitor CCS sites. However, Shantsev *et al.* (2020) demonstrates that the limitations associated with marine CSEM navigation repeatability are insignificant when CSEM data is processed rigorously and coupled with a well-parametrized inversion scheme.

We acknowledge the limitations of a 2-D analysis to describe a pipe-like structure that is a 3-D feature; however, a 3-D analysis requires substantial computing resources and it is beyond the scope of this paper.

## 6 CONCLUSIONS

This study analyses the capability of the marine CSEM technique to detect leakage from a CO<sub>2</sub> storage site through vertical fluid conduits above the reservoir. For this purpose, we generated a suite of unconstrained and constrained synthetic CSEM inversion models and we infer the following:

(1) CSEM inverse modelling detects gas leakage through a chimney. We have demonstrated that CSEM is sensitive to a 10 per cent porosity increase within a 500 m wide chimney (Fig. 9) and variations in CO<sub>2</sub> saturation within the chimney (Figs 9, 8 and A2 in Appendix D). The resistivity contrast due to the modelled porosity increase is moderate (0.2–0.3 Ωm; 10–20 percentage difference). However, for surveys and data sets with navigation errors or noise larger than assumed here, the signal of a similar conductive chimney may not be detected. Our modelling shows that CO<sub>2</sub> saturation differences with more than 20 per cent amplitude percentage differences are likely to be detected.

(2) The vertical component of the electric field has higher sensitivity to changes in the chimney's electrical resistivity than the inline horizontal component, as a result of the modelled vertical chimney geometry. Thus, it is essential to use both *E*-field components to optimize carbon storage sites monitoring using marine CSEM to gain higher sensitivity to vertical leakage pathways saturated with CO<sub>2</sub>.

(3) At 1 Hz fundamental frequency, receivers at distances greater than 1000 m from the target chimney are more sensitive to the chimney's electrical resistivity than those at closer ranges. However, as frequency increases, nearby receivers gradually become more sensitive. Thus, performing pre-survey CSEM synthetic studies can help to determine the ideal receiver positions for mapping regions of interest that are vertically structured.

(4) For upward migration velocities of 0.1 m d<sup>-1</sup> through the modelled chimney, monitoring with CSEM should start as early as 5 yr after injection.

(5) An integrated approach that combines CSEM and seismic data will help to constrain better the full range of possible saturations (0–100 per cent). Thus, time-lapse CSEM surveys can potentially enhance the current CCS measurement, monitoring and validation (MMV) strategy, by identifying significant leaks that seismic data alone could not identify. Reducing carbon emissions by 85–95 per cent until 2050 to meet UNFCCC Paris Agreement (2015) requires regulatory monitoring of global CCS operations. Based on the above, we conclude that time-lapse marine CSEM can enhance CO<sub>2</sub> monitoring capabilities.

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## DATA AVAILABILITY

The inversion and modelling package MARE2DEM is open source and can be obtained from the official MARE2DEM website <https://mare2dem.bitbucket.io/master/download.html>. Model files to recreate the synthetic data may be obtained on reasonable request from the first author.

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## APPENDIX A: ELECTRICAL RESISTIVITY MODELLING FOR SAND AND CLAY-RICH SEDIMENTS

The empirical relationship proposed by Archie (1942) relates physical rock and fluid properties to the bulk (matrix+fluid) electrical resistivity for clean sand through two empirical relationships (eqs A1 and A2)

$$F = \rho_0 / \rho_w = a \phi^{-m} \quad (\text{A1})$$

$$\frac{\rho_t}{\rho_0} = \left( \frac{\phi^m \rho_t}{a \rho_w} \right) = S_w^{-n} \quad (\text{A2})$$

From which:

$$S_w = \left( \frac{a \rho_w}{\phi^m \rho_t} \right)^{1/n} \quad (\text{A3})$$

$F$  is known as the formation factor, given by the resistivity ratio of the bulk fully saturated formation ( $\rho_0$ ) and pore water resistivity ( $\rho_w$ ). The second relationship relates the electrical resistivity of a partially saturated formation  $\rho_t$  with water saturation  $S_w$ , porosity  $\phi$ , tortuosity factor  $a$  saturation exponent,  $n$  and cementation factor  $m$ .

The tortuosity factor  $a$  is an empirical constant close to 1 (Mavko *et al.* 2009). The saturation exponent  $n$  depends on the type of fluids, with values close to 2 for gas–water systems (Mavko *et al.* 2009). For unconsolidated sand,  $m$  varies depending on the shape of the sediments and increases from 1.3 to 1.9 with decreasing grain size and sphericity (Falcon-Suarez *et al.* 2021).

In order to correct the effect of clay on the formation resistivity, the original Archie's equation is commonly modified by adding a conductivity term  $X$  to account for the excess conductivity (Mavko *et al.* 2009):

$$\frac{1}{\rho_t} = \frac{S_w^n}{F \rho_w} + X \quad (\text{A4})$$

In the Waxman & Smits (1968) modification the term  $X$  is defined in the following equation:

$$\frac{1}{\rho_t} = \frac{S_w^n}{F \rho_w} + \frac{S_w^{n-1} B Q_v}{F} = \frac{S_w^n \phi^m}{a \rho_w} + \frac{S_w^{n-1} B Q_v \phi^m}{a} \quad (\text{A5})$$

depending on  $Q_v$ , the cation exchange capacity per unit pore volume (meq m<sup>-3</sup>) and  $B$  is the equivalent conductance of the clay (Na<sup>+</sup>) exchange cations.

$$Q_v = \frac{\text{CEC}(1 - \phi) D_0}{\phi} \quad (\text{A6})$$

where CEC is the cation exchange capacity and  $D_0$  is the mineral grain density of the shale.

There have been several expressions developed for  $B$  since the original paper from Waxman & Smits (1968). Juhasz (1981) gives the following expressions for  $B$ , with  $T$  as the temperature in °C:

$$B = \frac{-1.28 + 0.225T - 4.059 \times 10^{-4} T^{1.23}}{1 - \rho_w} \quad (0.045T - 0.27) \quad (\text{A7})$$

Isolating the resistivity  $\rho_t$  for partially brine saturated formation:

$$\rho_t = \left[ \frac{a \rho_w}{\phi^m S_w^n (1 + \frac{\rho_w}{B} Q_v)} S_w \right] \quad (\text{A8})$$

The brine saturation  $S_w$  can be obtained from these models by solving (Bilodeaux 1997):

$$S_w = \left[ \frac{a \rho_w}{\rho_t} \phi^m (1 + \rho_w B Q_v / S_w^{n-1}) \right]^{1/n} \quad (\text{A9})$$

For  $n = 2$  the explicit solution (ignoring the negative root) is:

$$S_w = \sqrt{\frac{a \rho_w}{\rho_t} \phi^m (1 + \rho_w B Q_v / S_w^{n-1})} \quad (\text{A10})$$

The normalized Waxman–Smits equation from Juhasz (1981) removes the need for CEC being measured from cores as it uses  $V_{SH}$  (volume of shale) derived from well-logs (e.g. gamma ray or density-neutron) to estimate  $Q_v$ , obtained as follows:

$$Q_{vn} = \frac{Q_v}{Q_{vsh}} = \frac{V_{SH} \phi_{sh}}{\phi} \quad (\text{A11})$$

where  $\phi_{sh}$  is the total shale porosity and  $Q_{vn}$  is the normalized  $Q_v$ , which is in fact the shale-water saturation expressed in terms of the fraction total pore space, ranging from 0 in clean sand to 1 in clay.

$\rho_{wsh}$  is the shale water resistivity for 100 per cent brine-saturated ‘shaly’ or ‘clay-rich’ formation identified with the aid of the gamma-ray or  $V_{SH}$  log. This value is chosen from the resistivity well log. Similarly,  $BQ_v$  is normalized with the shale response and written in terms of  $Q_{vn}$  and since  $BQ_{vsh}$  is the difference between apparent shale water conductivity ( $1/\rho_{wsh}$ ) and formation water conductivity ( $1/\rho_w$ ).  $BQ_v$  can be written in terms of formation water resistivity ( $\rho_w$ ) and shale resistivity ( $\rho_{sh}$ ) as follows:

$$\begin{aligned} B Q_v &= Q_{vn} B Q_{vsh} = Q_{vn} \left( \frac{1}{\rho_{wsh}} - \frac{1}{\rho_w} \right) \\ &= \frac{V_{SH} \phi_{sh}}{\phi} \left( \frac{F_{sh}}{\rho_{sh}} - \frac{1}{\rho_w} \right) \end{aligned} \quad (\text{A12})$$

The normalized Waxman–Smits–Juhasz equation of Juhasz (1981) is obtained from substituting eq. (A12) in the eq. (A5), resulting in:

$$\frac{1}{\rho_t} = \frac{S_w^n}{F \rho_w} + \frac{V_{SH} \phi_{sh}}{\phi} \left( \frac{F_{sh}}{\rho_{sh}} - \frac{1}{\rho_w} \right) \frac{S_w^{n-1}}{F} \quad (\text{A13})$$

and simplifying,

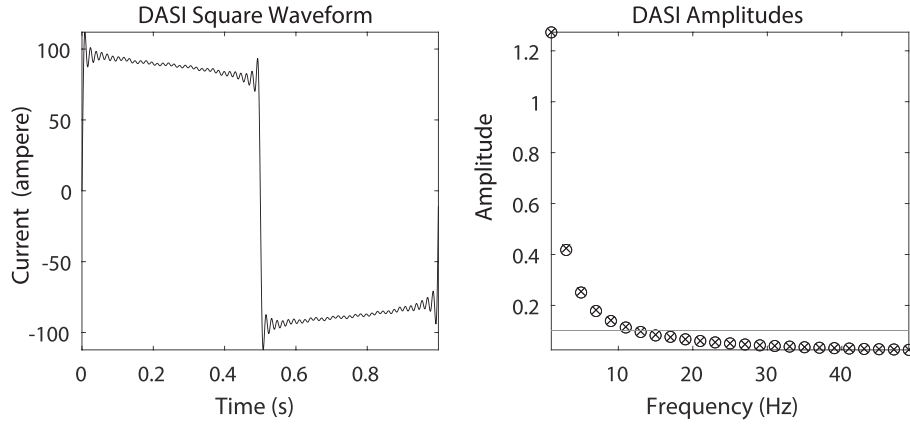
$$\frac{1}{\rho_t} = \frac{S_w^n \phi^m}{a} \left[ \frac{1}{\rho_w} + \frac{V_{SH} \phi_{sh}}{\phi} \left( \frac{a}{\rho_{sh}} \phi_{sh}^m - \frac{1}{\rho_w} \right) S_w^{n-1} \right] \quad (\text{A14})$$

## APPENDIX B: ARP'S LAW

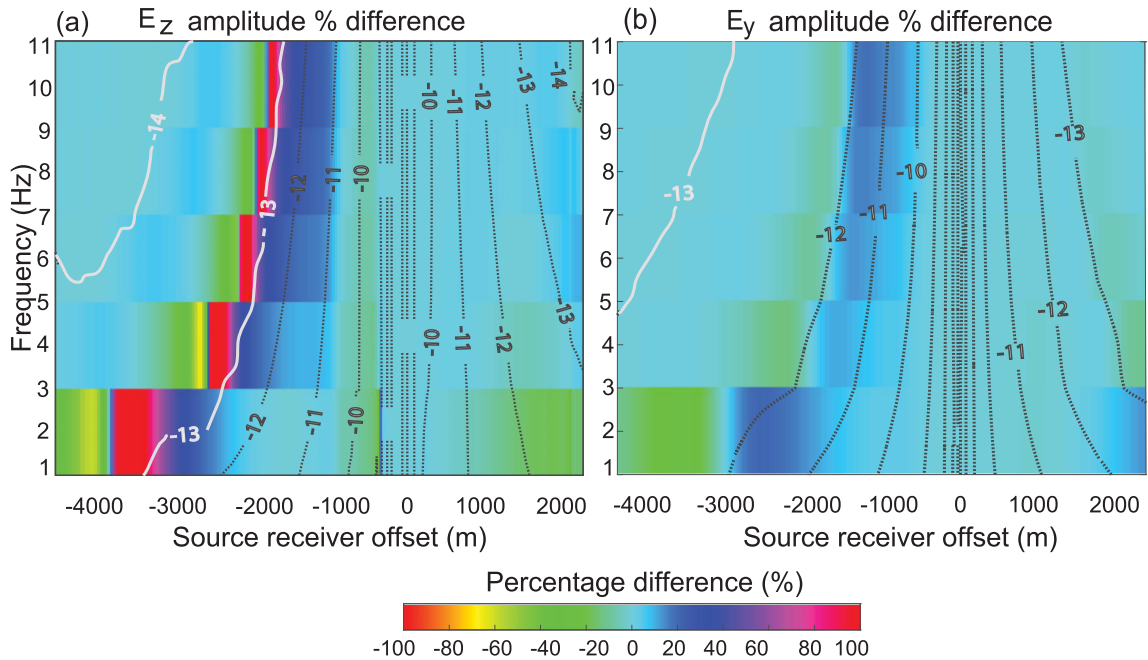
The pore water resistivity  $\rho_w$  within the sediments is calculated using Arp's empirical relationship Arps (1953). Arp's Law extrapolates the pore water resistivity from a known pore water resistivity and temperature to any given depth using the geothermal gradient (Arps 1953; Collett & Ladd 2000).

$$\rho_w^{T_2} = \rho_w^{T_1} \frac{T_1 + 21.5}{T_2 + 21.5} \quad (\text{B1})$$

where  $\rho_w$  is the brine solution resistivity,  $T_1$  and  $T_2$  is the corresponding temperature at top and bottom layers. The pore water resistivity per layer was computed iteratively down the model per layer starting with the water resistivity at the seabed of 0.2777 Ωm measured from the CTD and the North Sea seabed annual average temperature of 7 °C from Shell-UK-limited (2014). This is consistent with the temperature measured by the CTD at 20–40 m above



**Figure A1.** A 100 A square waveform with 1 Hz fundamental frequency was transmitted by DASI during the Scanner pockmark survey (left-hand panel). The normalized waveform time series is Fourier transformed to get the amplitude for the fundamental and harmonic frequencies (filled circles) compared with an ideal 1 Hz square wave (x). Frequencies whose amplitudes are below 0.1 of peak current (below horizontal line) have low signal strength.



**Figure A2.** Amplitude percentage difference between two models: a chimney with  $S_{CO_2} = 0$  per cent and a chimney with  $S_{CO_2} = 10$  per cent for  $E_z$  (a) and  $E_y$  (b). This amplitude anomaly (percentage difference) for the 2-D model with  $S_{CO_2} = 10$  per cent is calculated for a receiver 1000 m away from chimney (OBE-D). Dotted black contours correspond to the  $\log_{10}$  electric field amplitude (model with a chimney). The STEMM-CCS instrument noise floor at  $10^{-13}$  V Am $^{-2}$ , contours below noise floor marked with a continuous white line. Colour represents the percentage difference.

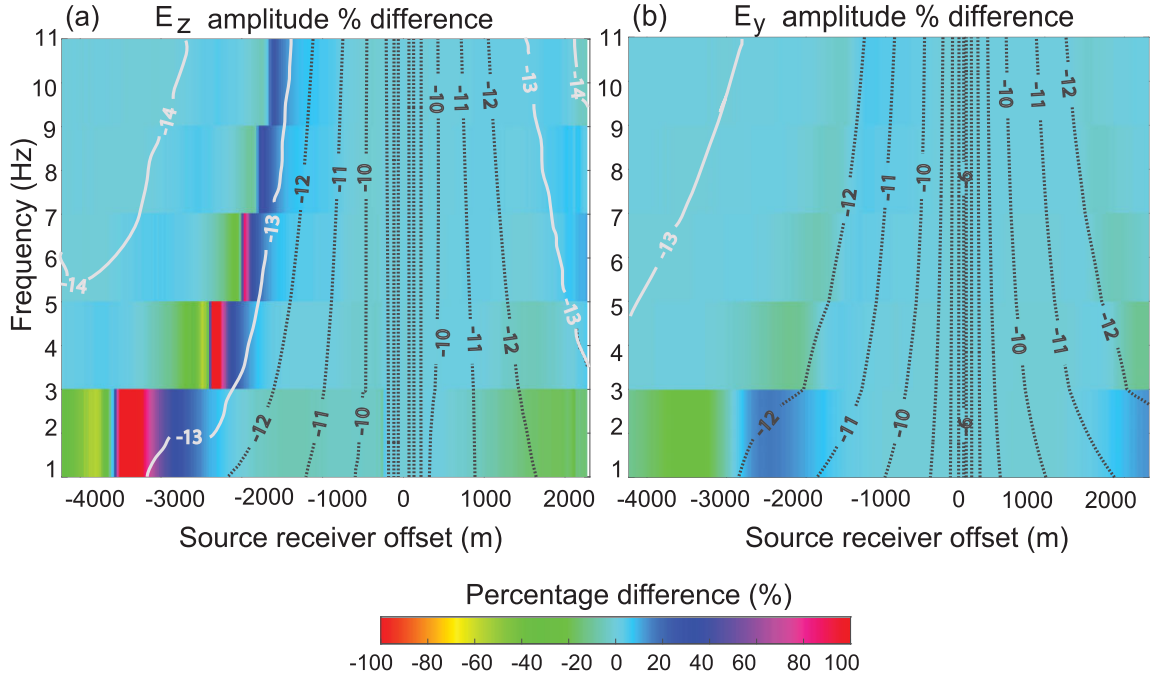
the seabed of 7.7 °C. The Temperature of each layer was determined using these starting parameters, Arrp's Law, and the North Sea geothermal gradient of 30 °C km $^{-1}$  Harper (1971). All input values are presented in Table 1.

### APPENDIX C: FREQUENCY SELECTION

The Frequency selection was guided by analysing the square wave transmitted during this survey (Fig. A1). Frequencies above 11 Hz (from 13 to 60 Hz) were disregarded for the 2-D modelling by looking at the amplitude attenuation at each harmonic frequency and selecting 0.1 as the amplitude (peak current) cut-off, as shown in Fig. A1.

### APPENDIX D: ANOMALY OF A CHIMNEY SATURATED WITH 10 PER CENT CO $_2$

We calculate the anomaly of a chimney saturated with 10 per cent CO $_2$  in comparison with the scenario of a chimney with no CO $_2$ , in order to analyse the detectability of a chimney with 10 per cent CO $_2$  after injection. Fig. A2 shows the amplitude percentage difference plot between the model with a chimney saturated with brine from base to top (Fig. 3b) and a model saturated with 10 per cent CO $_2$  (Fig. 3c), for receiver OBE-D and the 6 frequencies modelled (1–11 Hz). For both  $E_z$  and  $E_y$ , the anomaly for the chimney at the fundamental frequency (1 Hz) is very narrow, only present at the higher source-receiver offset between 2000 and 3000 m. For the



**Figure A3.** Amplitude percentage difference between two background models: the chimney with  $S_{\text{CO}_2} = 10$  per cent and the model with no chimney for  $E_z$  (a) and  $E_y$  (b). This amplitude anomaly (percentage difference) for the 2-D model with  $S_{\text{CO}_2} = 10$  per cent is calculated for a receiver 1000 m from the chimney (OBE-D). Dotted black contours correspond to the  $\log_{10}$  electric field amplitude of the model with a chimney. The STEMM-CCS instrument noise floor at  $10^{-13} \text{ V Am}^{-2}$ , contours below noise floor marked with a continuous white line. Colour represents the percentage difference.

higher frequencies (3–11 Hz) the  $E_z$  anomaly is of higher percentage difference (25–40 per cent) than the anomaly in  $E_y$  (10–20 per cent). The error modelled was 4 per cent and similar to what was observed in the STEMM-CCS CSEM data from the North Sea.

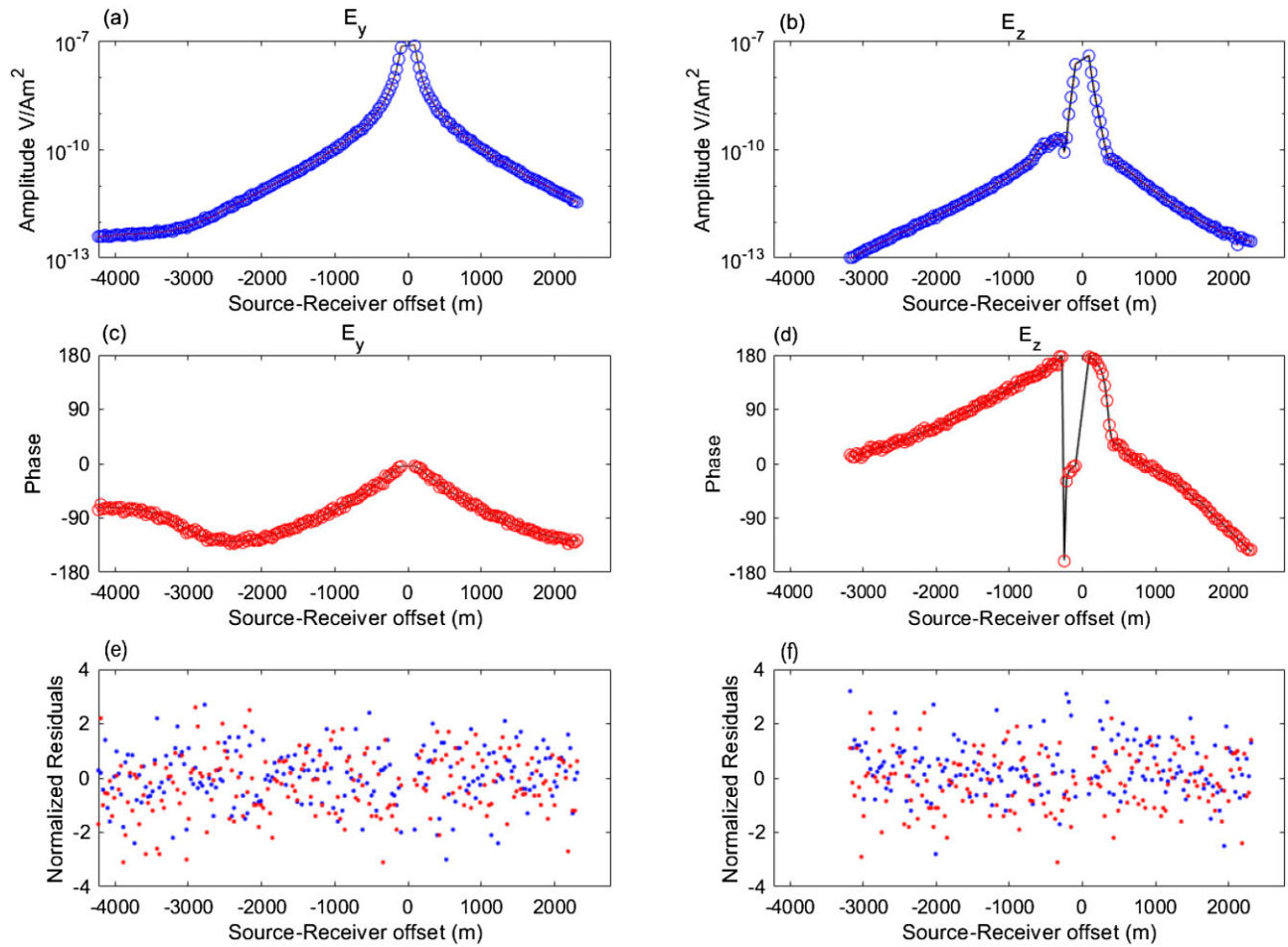
#### APPENDIX E: ANOMALY OF A SEAL WITH NO CHIMNEY AND A CHIMNEY SATURATED WITH 10 PER CENT CO<sub>2</sub>

With the purpose of analysing the anomaly of a 10 per cent saturation chimney in comparison with the background sediments Fig. A3 shows the amplitude percentage difference between the model with no chimney (Fig. 9a), where only the host geology is modelled, and a model with a chimney saturated with 10 per cent CO<sub>2</sub> (Fig. 3c), for receiver OBE-D and the 6 frequencies modelled (1–11 Hz). For both  $E_z$  and  $E_y$  there is a minor amplitude anomaly above the noise floor for the whole frequency band (1–11 Hz). There is a very narrow

anomaly in  $E_y$  at 1–3 Hz. The  $E_z$  and  $E_y$  anomaly are in the range of 0–10 per cent percentage difference. In this study, we believe this scenario is not detectable, as we have modelled data with 4 per cent Gaussian error.

#### APPENDIX F: SYNTHETIC DATA AND INVERSION EXAMPLE

Fig. A4 below shows an example of electric field data for an ocean bottom instrument (OBE) at a fundamental frequency of 1 Hz. The air-wave affects the  $E_y$  component and is observed from  $\sim 3100$  m source–receiver (Tx–Rx) offset and beyond. This is recognized due to the phase flattening and a more gradual amplitude decay. It is expected that for this offset, sensitivity to the resistivity structure of the seabed will be reduced (Constable 2010). However, for our study, the chimney signal is expected at offsets  $< 3100$  m, as can be seen in Fig. 8.



**Figure A4.** The 1 Hz amplitude response [top (a) and (b)], phase [middle (c) and (d)] response and normalized residuals [bottom (e) and (f)] of a 2-D model before injection (no chimney) is shown for the synthetic forward modelled data (circles) and the resulting inverted data (solid black line) for  $E_y$  [left (a), (c) and (e)] and  $E_z$  [right (b), (d) and (f)] versus source–receiver offset at OBE-D.