Importance of igneous intrusions for CCS in the Southern North Sea

Introduction

The geology of the Southern North Sea basin and its proximity to major onshore industrial sources of CO_2 makes it an ideal site for the storage of this greenhouse gas on a national and local scale. The basin contains numerous gas fields that have been in production since the 1960s due to a convenient overlap of a Carboniferous gas-prone source rock, a lower Permian reservoir, and an upper Permian evaporite seal (i.e. the Zechstein Supergroup). The Zechstein overburden was affected by Cenozoic salt tectonics (e.g. Stewart and Coward, 1995), leading to the formation of significant structural closures in the largely water-bearing Triassic sandstones (e.g. the Bunter sandstone) that underlie mudstone and evaporite sealing intervals. In this context, depleted gas fields and the supra-salt regional aquifer represent the main targets for CO_2 storage. However, in the Southern North Sea basin, igneous intrusions are present (Figure 1). For example, a NW-trending Paleocene dyke swarm, associated with the Mull igneous centre, is documented onshore, extending from NW Scotland to the Southern North Sea coast (e.g. MacDonald et al., 2010, 2015). Based on borehole, magnetic and seismic reflection data, the dyke swarm extends for >400 km offshore, reaching the Dutch sector of the Southern North Sea (e.g. Kirton and Donato, 1985; Brown et al., 1994; Underhill, 2009; Wall et al, 2010; Carver et al., 2023). Overlying the offshore dykes and affecting the top Chalk, a complex series of aligned craters, which form >200 km long, curvilinear chains, are imaged in seismic data (e.g. Brown et al., 1994; Wall et al., 2010). The craters could have resulted from explosive interactions between magma and a shallow chalk/ooze country rock (Wall et al., 2010).

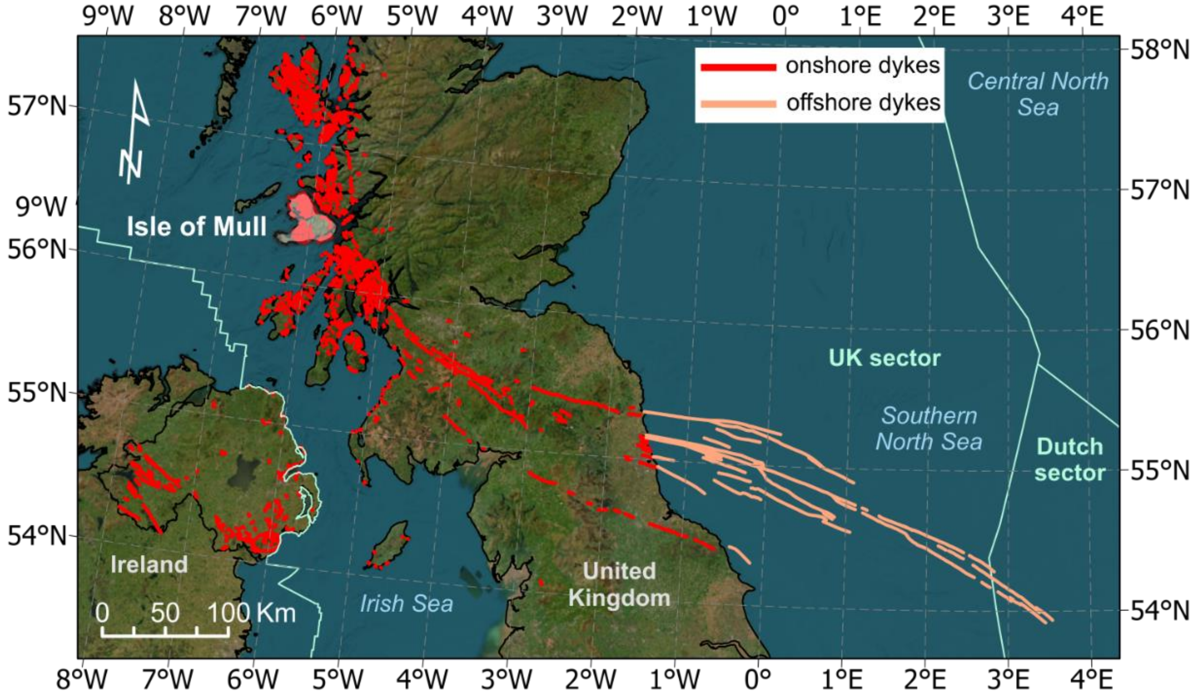

Figure 1 *The full extent of the mapped dykes originating from the Mull igneous centre based on past studies (e.g. Kirton and Donato, 1985; Brown et al., 1994; Underhill, 2009; MacDonald et al., 2010; Wall et al., 2010; MacDonald et al., 2015; Carver et al., 2023).*

The selection of potential carbon storage sites in the Southern North Sea basin should account for the presence of these igneous dykes, since the latter are presumed to cross-cut Paleozoic-Mesozoic strata, including sub- and supra-salt reservoirs and their top seals, possibly compromising their retention capacity. To identify high-risk areas for CO_2 storage, an improved understanding on the extent and dimensions of sub-vertical igneous bodies present in the Southern North Sea, as well as their potential impact on the petrophysical characteristics of their sedimentary host rocks, might be needed. We aim to contribute to the overall understanding of CCS integrity in the Southern North Sea by using 2D and

3D reflection seismic and borehole data to reassess the seismic expression of dykes, the development of intrusion-related structures (e.g. craters, faults and small sills) affecting the country rocks, and the interactions between salt and magma.

Data and Methods

This study is based on publicly available 2D and 3D seismic and borehole data covering the UK and Dutch sectors of the Southern North Sea. The seismic data are zero-phased, time-migrated, and displayed with SEG reverse standard polarity (i.e. European polarity), which means that an increase in acoustic impedance is signalled by a negative reflection event (blue peak). The borehole data include completion logs/reports, checkshots, and wireline logs (i.e. gamma ray, resistivity, density, and sonic logs).

Synthetic seismograms were created using sonic and density logs to tie the wells to the seismic data, which allowed the matching of stratigraphic tops to corresponding reflection events. Across the 3D seismic surveys, four key reflections were mapped: the top Chalk, base Chalk, top Triassic, and top Zechstein Supergroup (ZSG). An additional four horizons within the Cenozoic interval overlying the chalk were mapped: two within the Paleocene (T2 and T3), one in the earliest Eocene (top Balder/Dongen tuff), and one defining the top Ypresian (T4).

Results and Discussion

The seismic interpretation of the top Chalk horizon and corresponding time-structure map reveal three, c. 120-200 km-long, segmented crater chains (Figure 2). Individual craters are c. 100-200 ms TWT (c. 120-240 m) deep and c. 0.1-2 km wide. Thickness variations of the crater fill and overlying Cenozoic packages are reflected by TWT-thickness maps, which constrain the timing of crater development (and presumably magma intrusion) to the early Paleocene. The crater chains are underlain by zones of seismic disturbance (Figure 2).

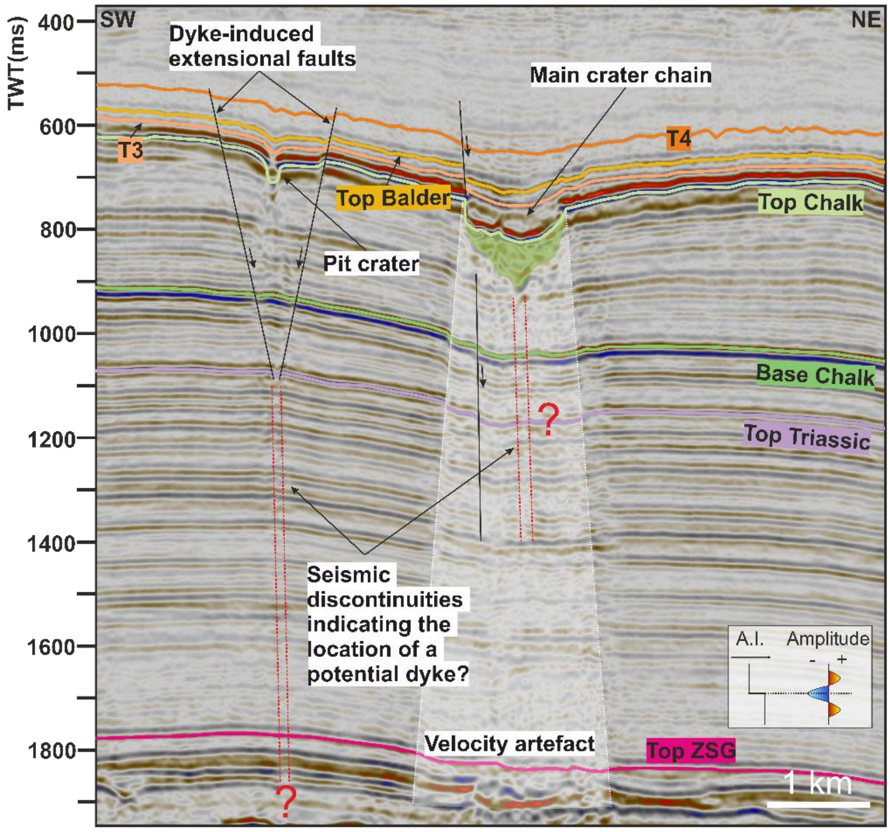

Figure 2 *Cross-section through one of the three crater chains associated with the offshore dykes.*

Within these zones, seismic reflections are deflected downward and tend to decrease in amplitude, whereas their geometry varies from parallel-continuous to chaotic. The zones of seismic disturbance mainly affect the stratigraphic interval between the top Chalk and top Zechstein Supergroup. The width of these disturbance zones match those of the overlying craters at top Chalk level, increasing downwards towards the salt. Where craters are absent or poorly developed within the chains, the zones of disturbance are typically limited to a thin (c. 50-300 m), sub-vertical seismic discontinuity (Figure 2). These discontinuities are usually associated with pairs of conjugate faults that form linear grabens, offsetting the stratigraphic interval between the top Chalk and the upper tips of the discontinuities, where the faults seem to terminate. Deviating from the crater chains, similar structures (i.e. faults and sub-vertical discontinuities) and discrete craters were highlighted by a variance extraction along the top Chalk time-structure map. Additional faults were interpreted within portions of the chains where trough-like segments are visibly wider (c. 2 km). The faults bound groups of narrow (c. 150-200 m), linear blocks that are parallel to and tilted towards the trough margins.

The crater-associated zones of seismic disturbance, including the thin, sub-vertical discontinuities, are mainly restricted to the Mesozoic salt overburden, leaving the Zechstein interval largely undisturbed. Nevertheless, intra-Zechstein seismic anomalies were identified below the crater chains in the form of concordant, sub-horizontal, high-amplitude reflections that occasionally seem to display a polarity reversal.

In previous studies, the origin of craters affecting the Chalk in the Southern North Sea basin has been attributed to processes linked to dyke emplacement (e.g. Brown et al., 1994; Underhill, 2009; Wall et al, 2010; Carver et al., 2023). The presence of magma within a high-porosity (c. 50-70%; Wall et al., 2010), water-filled chalk led to explosive excavations of cone-shaped cavities (e.g. Lorenz, 1986). The craters represent the expression of these cavities at the contemporaneous sea floor. However, subsidiary processes contributing to crater development (e.g. chalk removal through dissolution) are also plausible, based on thickness patterns shown by the Cenozoic thickness maps. We interpret the zones of seismic disturbance underlying the craters as geophysical artefacts (i.e. velocity push-downs) and dykes, respectively. The artefacts are the result of velocity contrasts between the clastic crater fill (c. 2 km/s) and the surrounding chalk (c. 4 km/s) (e.g. Brown et al., 1994). Disturbance zones represented by thin, sub-vertical discontinuities could be the seismic expression of dykes (e.g. Magee and Jackson, 2020). Identifying dykes within the wider zones of disturbance caused by the chalk-crater fill velocity contrast proves difficult, and only possible in the areas where the overlying craters are absent or poorly developed, i.e. where the zone of disturbance is not dominated by geophysical artefacts. The conjugate faults terminating at the dyke tips formed in response to intrusion-induced extension (e.g. Rubin and Pollard, 1988; Magee and Jackson, 2021). We infer the same formation mechanism in the case of the faults deviating from the crater chains, which, together with the small, discrete craters associated with them, may be linked to additional, as-yet undocumented dykes. The faults bounding groups of narrow, linear blocks within the craters could be the result of submarine landsliding that contributed to crater widening. The anomalous tabular reflections identified within the Zechstein Supergroup could indicate the presence of igneous rock encased within lower density and lower velocity evaporites (i.e. dyke-fed sills; e.g. Gauer et al., 2004; Underhill, 2009; Wall et al., 2010; Schofield et al., 2014). Alternatively, the reflections may image high-velocity evaporite (i.e. anhydrite) or non-evaporite (e.g. carbonate) lithologies.

Conclusions

Our project has begun to shed light on the impact of igneous intrusions in sedimentary basins. We have begun to further refine the key criteria required to identify sub-vertical dykes in seismic reflection data, and how to extract the geometrical properties of these dykes (e.g. thickness) from their seismic expression. We will continue to investigate how intruded rocks are affected by processes involved in the formation of dyke-induced structures (e.g. craters and faults) and, conversely, assess the control of host rocks on magma emplacement mechanics (i.e. vertical vs. lateral magma emplacement). These findings allow for an improved analysis of the geological risk to CCS in the Southern North Sea, in addition to other, comparable sedimentary basins. The mapping of dykes, the estimative extent of intrusion damage zones as a function of dyke dimensions, and our knowledge of magma-host rock interactions should determine the selection of potential CCS sites in the Southern North Sea. For instance, dykes may compartmentalise target aquifers, acting as barriers for fluid flow, or, if fractured and/or leached, dykes and adjacent host rocks may allow CO_2 leakage.

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