Structural evolution of the Breagh area: implications for carboniferous prospectivity of the Mid North Sea High, Southern North Sea

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Abstract: Exploration success at Breagh demonstrates that western parts of the Mid North Sea High area are prospective despite the absence of an Upper Permian (Rotliegend Group) Leman Sandstone Formation reservoir and source rocks belonging to the Upper Carboniferous Westphalian Coal Measures Group. Detailed seismic and well interpretation shows that the Breagh trap was a long-lived footwall high, the prospectivity of which was enhanced by Variscan folding and uplift, leading to the truncation (subcrop) of Lower Carboniferous reservoirs beneath the Base Permian Unconformity. Its drape (supra-crop) by Upper Permian (Zechstein Super Group) evaporites creates the seal. The complexity of its overburden means that an accurate picture of the Breagh structure only emerges after accurate depth-conversion that takes the effects of the Mesozoic graben into account. Pronounced easterly tilting during the Cenozoic affected the area and controlled gas migration into the structure from palaesostructures lying to the east. However, evidence that Breagh is not filled to spill point (underfill) suggests that charge limitation remained an issue. The study demonstrates that a poorly-documented and under-explored Lower Carboniferous play exists in Southern North Sea, which relies upon careful structural mapping and basin modelling to be undertaken for the play to be understood and its further potential to be realized.

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Up until the late 1990s, the prevailing view was that Lower Carboniferous (Dinantian) reservoir plays were restricted to small fields in onshore areas like the Midland Valley of Scotland (Fig. 1)(e.g. Coulsward, Midlothian and Milton of Balgonie: Hallett et al. 1985; Underhill et al. 2008). Gas has long been known to exist within the Lower Carboniferous in the area of and surrounding the Mid North Sea High (MNSH). A number of discoveries that record tight gas in Lower Carboniferous sandstones have remained fallow since as early as the 1960s. One notable example was the gas discovered in the Yoredale Formation of the Farne Group by exploration well 42/13-2 in 1997. The appraisal and development of that discovery led to the appraisal and development of the Breagh gas field, enabled by the advent of hydraulic fracturing, which produced first gas in 2013. Production from the field has challenged the long-held view that there was a lack of prospectivity in the MNSH area. While the stratigraphic interval remains under-explored across the area, Breagh demonstrates that the Dinantian reservoirs have potential and provides encouragement for Lower Carboniferous clastic prospectivity in the area. The success has reignited exploration interest in the MNSH by both government and industry with the acquisition of a new regional 2D survey and applications in the 32nd United Kingdom (UK) offshore Licensing Round.

The aim of this paper is to present the results of a seismic interpretation and depth conversion of the area in and around Breagh (UK Quadrants 41, 42 and 43). The outcomes of the study provide the basis for a new understanding of the structural evolution and its controls on the nature and timing of trap formation, source-rock maturation and petroleum migration. Unravelling the post-depositional subsidence history, particularly the impact of Cenozoic uplift and tilt, Mesozoic rifting, and the important role played by Zechstein evaporites through both halokinesis and as a detachment for structures in the overburden, help to identify prospective areas outwith the main Carboniferous play fairway (Fig. 2). The results complement descriptions of the reservoirs that make up the Lower Carboniferous play fairway (Booth et al. 2020) and the learnings from a recent regional structural–stratigraphic analysis of the MNSH region (Brackenridge et al. 2020).

Geological setting

The definition of the MNSH in literature has remained loose. Here, we define the MNSH as a palaeotopographical basement high that was created during Permian rifting and, hence, delineated by the pinchout of Permian (Rotliegend) clastic sediments on its flanks. It separates the west–east–striking Southern Permian Basin (SPB) from its Northern Permian Basin (NPB) counterpart (Fig. 1) (Cameron et al. 1992; Brackenridge et al. 2020). As such, the MNSH has historically formed the northern limit to the prospectivity of the UK Southern North Sea (SNS), a prolific gas basin for decades with reserves encountered in reservoirs of Triassic, Permian and Carboniferous age (Fig. 2) (Underhill 2003; Kombrink et al. 2010).

The MNSH and the surrounding flanks have remained largely under-explored and historically viewed as unprospective due to the lack of well penetrations of the prolific Permian reservoirs and
Mesozoic source-rock intervals of the North Sea. The area instead includes a number of Devonian and Carboniferous basins (Fig. 1) (Arsenikos et al. 2015, 2018; Vincent 2015) formed during the Variscan plate cycle. Many workers have detailed the geological evolution of the SNS (e.g. see compilations by Glennie and Underhill 1998; Pharaoh et al. 2010 and references therein) such that there is a relatively good understanding of the tectonostratigraphic evolution of the area and its hydrocarbon potential (Maynard and Dunay 1999; Collinson et al. 1993; Cameron et al. 2005; Collinson 2005; Glennie 2005; Kombrink et al. 2010; Milton-Worrall et al. 2010; Rodriguez et al. 2014; Monaghan et al. 2017). The tectonostratigraphic evolution of the study area on the southern flank of the MNSH is less well understood and will be discussed in detail later in this paper. Accordingly, a short framing summary follows below to introduce the regional setting (Fig. 3).

Fig. 1. Southern North Sea structural map. Summary structural overview of the Early Carboniferous configuration of basins in the Southern and Central North Sea, Mid North Sea High, and onshore eastern England. The map shows the major basin-bounding faults and inferred granites across the area, including the postulated Breagh Granite proposed in this study. The map was compiled from various sources including Arsenikos et al. (2018) for the Central North Sea and Mid North Sea High, Corfield et al. (1996) and Smit et al. (2018), and authors therein. The locations of granites are after Rollin (1982), Donato et al. (1983), Leeder and Hardman (1990), George and Berry (1997) and Arsenikos et al. (2018). The location and area of Figure 1 and of the Breagh area (Figs 4, 12 and 18) are depicted by the red solid and stippled outline, respectively.
which were infilled with fluvio-deltaic sediments sourced from the Caledonian mountain range to the north (Collinson 2005). The Upper Carboniferous post-rift transition to a foreland basin setting led to the deposition of widespread delta-top facies and thick, laterally continuous, coal deposits (Tucker et al. 2003). These coals later formed the principal source rock for the SNS prolific play fairways (Bailey et al. 1993). Uplift, folding and erosion associated with the closure of the Rheic Ocean and Variscan Orogeny at the end of the Carboniferous resulted in the formation of a major unconformity and variable subcrop, the Base Permian Unconformity (BPU), also referred to as the Saalian Unconformity (Heeremans et al. 2004).

Early Permian synsedimentary extension, related to post-orogenic collapse, resulted in the formation of the major unconformity and variable subcrop, the Base Permian Unconformity (BPU), also referred to as the Saalian Unconformity (Heeremans et al. 2004).

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Early Permian synsedimentary extension, related to post-orogenic collapse, resulted in the formation of the SPB in the Variscan foreland and determined the tectonic framework for the various subdomains to the SNS along NW–SE (Tornquist) trends (e.g. Broad Fourteens Basin, Cleaver Bank High, Inde Shelf, Silverpit Basin, Sole Pit Basin and Winterton High: Fig. 1) (van Hoorn 1987; Alberts and Underhill 1991; Geluk 1999; Woodcock and Strachan 2012). These trends were repeatedly, yet selectively, reactivated during the Mesozoic and Cenozoic, exerting a strong control on the overlying sedimentation and structuration (Oudemayer and de Jager 1993).

The MNHS remained an area of non-deposition for most of the Permian. To the south, fine-grained clastic sediments of the Silverpit Formation accumulated in a major desert lake (salina) (Alberts and Underhill 1991; Bailey et al. 1993; Johnson et al. 1994; Glennie 1998). A narrow belt of aeolian and alluvial sandstones of the highly prospective Rotliegend Group Leman Sandstone Formation (LSF) formed around the playa-lake’s northern margins (Glennie 1990; George and Berry 1997; Glennie 1998; Geluk 2005; Gast et al. 2010; Taggart 2015; Catto et al. 2017). These form the main reservoirs to many of the discoveries in the SNS on the playa-lake’s southern margin.

In the latest Permian, the SPB, now some 200–300 m below sea level, experienced rapid flooding from the north along Proto-Atlantic and North Sea fracture systems: the Zechstein Transgression (Smith 1970a, b, 1979; Ziegler 1990; Glennie 1998). Climatic and glacio-eustatic sea-level fluctuations in the latest Permian, combined with restriction of the newly marine SPB and passive subsidence, led to cyclic evaporation and recharge of the basin and the development of a carbonate–evaporite (margin-basin) depositional system, the Zechstein Supergroup, that extended across parts of the MNHS (Smith 1980; Paul 1987; van der Baan 1990; Tucker 1991; Kiersnowski et al. 1995; Taylor 1998; Geluk 2007; Peryt et al. 2010; Jackson and Stewart 2017; Mulholland et al. 2018).

By the end of the Permian, the SPB returned to being an arid continental basin as the marine gateways that periodically filled the Zechstein basin were cut off (Glennie 1997a). Continental clastic red beds (the Bacton Group) accumulated in playa-lake, floodplain and fluvial environments during the Lower Triassic (Lorenz and Nicholls 1984; Fisher 1986; Johnson et al. 1994; Fisher and Mudge 1998; Bachmann and Kozur 2004). The Bacton Group is
overlain by the Haisborough and Penarth groups, ascribed to the Middle–Upper and uppermost (Rhaetian) Triassic, respectively, and comprise fine-grained clastics and evaporites with marked cyclicity due to short-lived, widespread Tethyan marine incursions (e.g. Röt Halite Member). By the latest Triassic, a more consistent marine connection between NW Europe and the Tethyan realm was established, such that fully marine conditions existed across the region during the Jurassic and Early Cretaceous (Ziegler 1990; Cameron et al. 1992; Fisher and Mudge 1998; Lott et al. 2010).

Halokinesis strongly affected depositional patterns from the end of the Triassic (Stewart and Coward 1995). The presence of highly mobile evaporites in the SNS led to decoupling of sub- and supra-salt structures, preventing thick-skinned basement overprint in the Mesozoic and younger sediments (van Hoorn 1987; Arthur 1993; Oudmayer and de Jager 1993; Stewart and Coward 1995; Grant et al. 2019b). Rifting ceased in the Middle Cretaceous and progressive global sea-level rise curtailed clastic deposition. Widespread pelagic carbonate sedimentation commenced by the end of the Albian and a thick sequence of chalk accumulated across the region (Crittenden 1987; Oakman and Partington 1998; Vejbæk et al. 2010).

Widespread inversion and uplift, in response to Alpine–Atlantic plate-margin events, affected the NW European and SNS–MNSH

The pervasive NW–SE structural grain in the SNS and the thick Zechstein evaporites continued to affect structural styles during the inversion, serving to decouple sub- and supra-Zechstein fault systems (van Hoorn 1987; Oudmayer and de Jager 1993). In the sub-salt section, reactivation via contraction and/or transpression took place selectively along existing pre-Zechstein faults (Glennie and Boegner 1981; van Hoorn 1987; Alberts and Underhill 1991; Vejbæk et al. 2010). In the supra-salt section, updip towards the basin margins, extension due to gravity spreading was accommodated by extensional faulting and an amplification of NW–SE-trending salt-cored anticlines in the centre of the basin (Stewart and Coward 1995).

Regional uplift and easterly tilting also affected Britain during the Paleogene and Neogene, and resulted in a variable Cenozoic–Mesozoic present-day subcrop to the seabed across the SNS (Guariguata-Rojas and Underhill 2017; Brackenridge et al. 2020).

Study area, database and methods
Approximately 1073 km² of pre-stack time migration (PSTM) 3D seismic data formed the primary database for this study (Fig. 4). This seismic database comprises a subset of the 2015 PGS SNS MegaSurvey multiclient dataset, located over the Breagh Field (named here the Breagh 3D survey). Additional coverage to the south is provided by the 2012 Lochran 3D survey, a proprietary survey owned by INEOS made available by public release, and regional 2D time-migrated seismic lines including lines from the Oil and Gas Authority’s 2015 Frontier Basins MNSH seismic acquisition; and nearby proprietary 3D seismic surveys were also inspected to help with regional observations and tie wells, and to calibrate the seismic stratigraphy.

Data from nine exploration and appraisal wells within the 3D seismic outline, along with a number of nearby wells, helped to constrain the seismic interpretation and depth conversion (Table 1). Well coverage is more concentrated in the more northerly Breagh 3D survey as a consequence of the discovery of the Breagh Field. Only three wells have been drilled in the Lochran survey area to the south and all are located towards the west of this survey.

Well-calibrated 3D seismic interpretation was completed down to the BPU within the seismic survey coverage. Discrepancies in seismic quality between the two surveys added complications to interpretation. The Breagh 3D seismic survey, acquired in 1995 and later reprocessed as part of the PGS MegaSurvey, is of poorer quality than the newer Lochran survey. Interpretation across the area was, hence, driven from the Lochran survey with the learnings taken into the Breagh seismic.

Four seismic horizons were confidently interpreted: base Zechstein (BPU–Rotliegend composite); top Zechstein; top Bacton Group; and base Chalk (Fig. 3; Table 2). Additional surfaces were picked locally and/or interpreted from cross-sections to illustrate other key tectonostratigraphic markers (e.g. top Triassic, top Lias Group, top Corallian Formation and base Cromer Knoll Group (BCU)).
Interpretation beneath the Zechstein is well known to be hampered by a number of problems (see the discussion in Besly 2018). Overburden complexity from extensive mobilization of the Zechstein salt, leading to ray-path bending and imaging difficulties, forms the greatest issue. Mapping the BPU is complicated by: (i) stratigraphic variation beneath the unconformity causing marked changes in acoustic impedance (see the discussion in Cooper et al. 2005); and (ii) the thinning and pinchout of Rotliegend sediments beneath the Zechstein, resulting in seismic tuning effects. The true thickness of the Rotliegend beneath the Zechstein, resulting in seismic tuning effects. The true 2005); and (ii) the thinning and pinchout of Rotliegend sediments converted surface are such that the thickness of the Rotliegend beneath the Zechstein surface is therefore only mappable where Rotliegend Group in this area falls within the depth error margins expected, and therefore the base Zechstein closure can serve as a proxy for the base Zechstein. The uncertainties in resolution to the depth-converted BPU surface is therefore only mappable where Rotliegend Group is present.

<table>
<thead>
<tr>
<th>Well</th>
<th>Spud year</th>
<th>Operator</th>
<th>Well type</th>
<th>Target/objective</th>
<th>Completion status</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>42/13-1</td>
<td>1968</td>
<td>BP</td>
<td>Exploration</td>
<td>Primary: Carboniferous Group; Secondary: Bunter and Rotliegend sandstones (not encountered)</td>
<td>Plugged and abandoned, dry hole</td>
<td>–</td>
</tr>
<tr>
<td>42/13-2</td>
<td>1997</td>
<td>Mobil North</td>
<td>Exploration</td>
<td>Lower Carboniferous sandstones in a large pericinal base Zechstein closure</td>
<td>Plugged and abandoned, gas discovery</td>
<td>Breagh</td>
</tr>
<tr>
<td>42/13-3</td>
<td>2007</td>
<td>Sterling</td>
<td>Appraisal</td>
<td>Prove commercial gas rates from the Carboniferous, Screamerton Formation reservoir of the Breagh accumulation (15 MMscf minimum)</td>
<td>Suspected, gas well</td>
<td>Breagh</td>
</tr>
<tr>
<td>42/13-4</td>
<td>2008</td>
<td>RWE Dea</td>
<td>Exploration/appraisal</td>
<td>Test the presence of gas-bearing Carboniferous sandstones in a mapped base Zechstein high in the eastern part of the Breagh accumulation</td>
<td>Suspected, gas well</td>
<td>Breagh</td>
</tr>
<tr>
<td>42/13-5</td>
<td>2008</td>
<td>RWE Dea</td>
<td>Appraisal/development</td>
<td>Pilot: target reservoir sands 500 m SE of 42/13-3 to help locate the horizontal section of 5Z side-track for optimal sand penetration</td>
<td>Pilot: plugged and abandoned, gas shows</td>
<td>Breagh</td>
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<tr>
<td>42/13a-6</td>
<td>2011</td>
<td>LASMO North</td>
<td>Appraisal</td>
<td>Encounter reservoir sands within the Visean, Yoredale Formation Middle Limestone ’Zone 1’, and apprise Lower Limestone Formation ’Zone 3’ sands</td>
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<td>Breagh</td>
</tr>
<tr>
<td>42/18-1</td>
<td>1991</td>
<td>Burmah North Sea</td>
<td>Exploration</td>
<td>Bunter Sandstone Formation</td>
<td>Plugged and abandoned, dry hole</td>
<td>–</td>
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<tr>
<td>42/18-2</td>
<td>1993</td>
<td>Burmah North Sea</td>
<td>Exploration</td>
<td>Middle–Upper Namurian sandstones in an east–west-trending faulted anticline</td>
<td>Plugged and abandoned, dry hole</td>
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</tr>
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<td>42/23-1</td>
<td>1966</td>
<td>Exploration</td>
<td>Exploration</td>
<td>Primary: Rotliegend sandstones Secondary: Zechstein carbonates, and Triassic Bunter and Jurassic reservoirs</td>
<td>Plugged and abandoned, Carboniferous gas shows. Non-commercial flow from Zechstein carbonate</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 1. Well database used for structural–stratigraphic analysis, and the calibration and depth conversion of the mapped horizons in the PGS MegaSurvey Lochran 3D seismic area**

**Structural evolution of the Breagh area**

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**Structural–stratigraphic observations**

Well correlations, seismic sections, and depth–structure and isopach maps reveal the nature of the structural–stratigraphic relationships in the Breagh area (Figs 5–11). Particularly the complex fault patterns, and the variable thicknesses between and within stratigraphic units. They also highlight the variable Carboniferous subcrop pattern at the BPU, and the Mesozoic subcrop at the BCU and the seabed (Fig. 12).

**Carboniferous**

Seismic imaging of the Carboniferous at Breagh is hampered in areas beneath the graben in the Mesozoic overburden where the effects of faulting and halokinesis have affected data resolution. Lower Carboniferous sediments truncate at the BPU, and are likely to continue below well penetration depths and rest upon Upper Devonian Upper Old Red Group (UORG) sediments, encountered nearby to the NE in well 42/10b-2. The UORG lie unconformably on Middle Devonian Kyle Group limestones, as suggested by other regional seismic lines south of the MNSH.

The Yoredale Formation sits unconformably beneath the BPU at Breagh, and comprises a c. 200 m-thick sequence of sandstones interbedded with thin intercalated mudstones, siltstones, sandstones and distinctive limestones. The major sandstones are up to 12 m thick and comprise fine- to medium-grained, well-sorted quartz arenite, with planar to trough cross-stratification. These form the main reservoirs for the Breagh Field, with porosities of c. 12% and average permeabilities of c. 1–10 mD (with ranges from 0.1 to 100 mD; Hickens and Hughes 1998; McRae et al. 2009).
<table>
<thead>
<tr>
<th>Interpreted seismic horizon</th>
<th>Reflection type</th>
<th>Reflection character</th>
<th>Internal character</th>
<th>Horizon-bounded seismic-stratigraphic unit (velocity interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seabed</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Water column Cenozoic (Paleogene)</td>
</tr>
<tr>
<td>Top Chalk</td>
<td>Peak</td>
<td>Present in the north and NE of the area. High-amplitude, continuous reflection</td>
<td>Low- to moderate-amplitude, parallel, continuous reflections. Reflectors about 100 ms above the base of the unit broken into short &lt;500 m packages in northern areas associated with volcanic tuff-bearing mudstones of the Balder Formation</td>
<td>Chalk Group</td>
</tr>
<tr>
<td>Top Cromer Knoll Group (base Chalk Group)</td>
<td>Trough</td>
<td>High-amplitude reflection, often masked in the upper 100 ms by seismic noise associated with the shallow, high-seabed reflection</td>
<td>Unit is generally less than 200 ms thick. Moderate- to high-frequency, parallel, continuous reflections. Seismic amplitudes increase towards the base from low to moderate</td>
<td>Cromer Knoll Group</td>
</tr>
<tr>
<td>Base Cretaceous Unconformity (BCU) (top Humber Group)</td>
<td>Peak</td>
<td>Variable amplitude character and continuity. Semi- continuous. Where well defined, appears as a moderate-amplitude reflection</td>
<td>Moderate- to high-amplitude and frequency, continuous and parallel reflections</td>
<td>Humber Group</td>
</tr>
<tr>
<td>Top Corallian Formation</td>
<td>Peak</td>
<td>Very-high-amplitude continuous reflection</td>
<td>Moderate-amplitude, parallel, continuous reflections</td>
<td>West Sole Group</td>
</tr>
<tr>
<td>Top Lias Group</td>
<td>Trough</td>
<td>High-amplitude reflection</td>
<td>Low- to moderate-amplitude, semi-continuous, wavy, reflections. More transparent in upper parts</td>
<td>Lias Group</td>
</tr>
<tr>
<td>Top Haisborough Group</td>
<td>Peak</td>
<td>Moderate- to high-amplitude, continuous reflection</td>
<td>Moderate-amplitude and frequency, parallel, continuous reflections</td>
<td>Haisborough Group (including the Penarth Group)</td>
</tr>
<tr>
<td>Top Bacton Group (Röt Halite Member)</td>
<td>Trough</td>
<td>Low- to moderate-amplitude, partially continuous reflection</td>
<td>Transparent to low-amplitude reflection; chaotic to discontinuous</td>
<td>Bacton Group</td>
</tr>
<tr>
<td>Top Zechstein (top Brückelschiefer)</td>
<td>Trough</td>
<td>Moderate-amplitude, partially continuous reflection</td>
<td>Low- to moderate-amplitude, wavy, discontinuous reflections in the lower part (Leine Halite Formation (Z3)). High-amplitude, parallel continuous reflections in upper 100 ms (Z4)</td>
<td>Upper Zechstein (Z3–Z4)</td>
</tr>
<tr>
<td>Top Plattendolomit Formation (Z3)</td>
<td>Peak</td>
<td>Very-high-amplitude continuous reflection. Generally rafed into 0.5–3 km-long sinuous packages in the Silverpit Basin. More continuous in the offshore Cleveland Basin and Dogger Shelf</td>
<td>Unit thinness and high-amplitude nature of the reflection typically masks the internal character. Subtle amplitude changes are observable along dip and strike</td>
<td>Plattendolomit Formation</td>
</tr>
<tr>
<td>Top Stassfurt Halite Formation (Z2)</td>
<td>Trough</td>
<td>High-amplitude, continuous reflection (but often masked by Plattendolomit side-lobe. Difficult to interpret where Plattendolomit is rafed.)</td>
<td>Shelf/isolated platforms: typically too thin to discern any recognizable character. Where thicker, comprises moderate-amplitude, relatively continuous, wavy reflections</td>
<td>Stassfurt Halite Formation</td>
</tr>
<tr>
<td>Top Basalanhydrit Formation (Z2)</td>
<td>Peak</td>
<td>Shelf/isolated platforms: low- to moderate-amplitude, largely continuous reflection; occasionally transparent or wavy</td>
<td>Basal: moderately to high-amplitude, chaotic, wavy discontinuous reflections</td>
<td>Lower Zechstein</td>
</tr>
<tr>
<td>Top Rotliegend Group (base Zechstein)</td>
<td>Trough</td>
<td>Moderate- to high-amplitude, partially continuous reflection. Absent from areas north of the Breagh Field</td>
<td>Low-amplitude, chaotic; wavy discontinuous character where thick enough to be discernible</td>
<td>Rotliegend Group</td>
</tr>
<tr>
<td>Base Permian Unconformity (top Carboniferous)</td>
<td>Peak</td>
<td>Variable amplitude character and continuity depending on the Carboniferous subcrop</td>
<td>Variable depending on seismic survey. Low-amplitude and frequency, chaotic to discontinuous reflection on older surveys. Moderate-amplitude, low- to moderate-frequency, relatively continuous and parallel reflections on newer surveys. Often truncated by the Base Permian Unconformity (BPU)</td>
<td>Carboniferous –</td>
</tr>
</tbody>
</table>

The table lists the main seismic horizons interpreted and corresponding horizon-bounded seismic–stratigraphic units, which defined the velocity intervals (1–5) used in the depth conversion (Table 3). The table highlights the reflection type for ‘SEG normal’ polarity, where a positive seismic amplitude (peak) corresponds to a downward increase in acoustic impedance (‘hard kicks’) and negative amplitudes (troughs) correspond to a downward decrease in acoustic impedance (‘soft kicks’), the reflection character and the internal character of the horizon-bounded seismic–stratigraphic unit. See Figure 3 for the chrono- and tectonostratigraphic location of the seismic horizons. Whilst the top Plattendolomit Formation is listed, in practice the reflection is initiated at the top of the thin anhydrite (Hauptanhydrit Formation immediately above: see Taylor 1998).
## Table 3. Velocity model

<table>
<thead>
<tr>
<th>Velocity interval</th>
<th>Lithology</th>
<th>Thickness distribution</th>
<th>Typical velocities (m s⁻¹)</th>
<th>Velocity model*</th>
<th>V₀ (m s⁻¹)</th>
<th>K</th>
<th>Average % residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water column</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>V₀ = constant</td>
<td>1494</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2. Chalk Group</td>
<td>Chalk</td>
<td>Absent across most of the southwestern portion of the Breagh–Lochran area. NW–SE-striking seabed subcrop immediately south of Breagh. Thickens towards the north</td>
<td>Average c. 2815 m s⁻¹</td>
<td>V₀ + K (T–T₀)</td>
<td>3177.4</td>
<td>–0.8646</td>
<td>4.25</td>
</tr>
<tr>
<td>3. Base Chalk–top Bacton Group</td>
<td>Outside the graben</td>
<td>Argillaceous, fine-grained clastics with intercalated evaporites and dolomites</td>
<td>Generally thickens towards the south (1156 m, well 42/23-1; 900 m, well 42/13a-6). However, the unit is truncated by the seabed in the south.</td>
<td>Average c. 3285 m s⁻¹</td>
<td>V₀ + K (Z)</td>
<td>2266.5</td>
<td>–1.478 6.78</td>
</tr>
<tr>
<td>4. Bacton Group</td>
<td>Sandstone in the upper part, argillaceous with thin siltstones, sandstones and occasional beds of ferruginous ooliths in the lower part</td>
<td>Relatively uniform (average c. 500 m outwith the graben). Absent from the centre of the northern graben (LTSZ) (e.g. 42/13-2). Present, but thin in the southern graben. Thins in the footwall into the graben-bounding faults</td>
<td>Average c. 4241 m s⁻¹</td>
<td>V₀ = constant</td>
<td>4241</td>
<td>–</td>
<td>3.92</td>
</tr>
<tr>
<td>5. Zechstein Super Group</td>
<td>Predominantly halite, with subordinate anhydrite, dolomite, limestones and K/Mg salts. Anhydrite and dolomite mostly present at the base of the unit</td>
<td>Variable but typically around 600–900 m outside graben areas. Locally reaches over 1000 m (1084 m, well 42/13-1). Thin within the graben (339 m, well 42/13-4)</td>
<td>Average c. 4731 m s⁻¹</td>
<td>V₀ + K (T–T₀)</td>
<td>4209.3</td>
<td>0.7534</td>
<td>1</td>
</tr>
</tbody>
</table>

Velocity intervals used in the depth conversion of the Breagh–Lochran 3D seismic area. The table includes descriptions of the dominant lithology, thickness distribution and typical velocities for each interval. Velocity models for each interval are listed, along with the corresponding coefficients used to depth convert each interval. The average resultant percentage residual between the depth-converted surface and well tops from the listed velocity function prior to calibration is also included. The base Chalk–top Bacton Group interval was divided into two sub-intervals for areas outside and inside the graben in the Mesozoic overburden to reflect the differences in velocity distribution across the graben bounding faults.

*V₀ – T₀ denotes two-way travel-time thickness (TWT).
†Estimated from the UNESCO international standard algorithm for the water column using average salinity and temperature data from the western Southern North Sea.
‡Average velocity for the wells at Breagh that penetrate the graben hanging wall.
Fig. 5. Well correlation. (a) WNW–ESE (A–A’) and (b) SSW–NNE (B–B’), true vertical depth subsea (TVDSS) well correlation panels across the Breagh area in Quadrants 41–43. The line of section (a) intersects wells 41/15-1, 42/13-4 (Breagh), 42/13a-6 (Breagh), 42/15b-1 and 43/16-2. The line of section (b) intersects wells 42/22-1, 42/15-1, 43/13-2 (Breagh), 43/13-3 (Breagh) and 42/09-1. The line of section (b) has been extended c. 20 km to the north to include the presence of the lower Zechstein Z1–Z2 platform evident from seismic sections in the area. The locations of sections are shown in Figure 4. Well spacing is proportional and the section is displayed with an approximate vertical exaggeration of ×7. Well tracks show lithology, gamma-ray (GR) and sonic (DT) logs where available. See the text for the discussion.
Fig. 6. Seismic section A–A’. WNW–ESE-orientated uninterpreted (above) and interpreted (below) seismic two-way travel time (TWTT) dip section across the western part of Quadrant 41, the centre of Quadrant 42 and the western part of Quadrant 43. See Figure 4 for the location. The line passes through the offshore Cleveland Basin into the northwestern part of the Silverpit Basin and transects the Central Fracture Zone/North Dogger Fault Zone in the Mesozoic section. The line of the section is orientated to intersect wells (gas fields) 41/15-1, 42/13-2 and 42/13a-4, and wells (Breagh) 42/13a-6, 42/15b-1 and 43/16-2, and is the equivalent transect to that shown in the correlation panel A–A’ (Fig. 5a). Seismic data are courtesy of the OGA, PGS and Spirit Energy.
Fig. 7. Seismic section B–B’. SSW–NNE-orientated uninterpreted (above) and interpreted (below) seismic two-way travel time (TWTT) section across Quadrant 42. See Figure 4 for the location. The line passes from the Cleveland Basin onto the Dogger Shelf, transecting the Breagh Field and the Central Fracture Zone/North Dogger Fault Zone in the Mesozoic section. The section is orientated to intersect wells (gas fields) 41/22-1, 42/18-1 and 42/13-2, and wells (Breagh) 42/13-3 and 42/09-1, and is the equivalent transect to that shown in the correlation panel B–B’ (Fig. 5b). Seismic data are courtesy of ExxonMobil, INEOS, PGS and Total.
sandstones are interbedded with highly variable facies including thin siltstones, mudstones and limestones, with occasional coals and palaeosols. The lowermost Dun Limestone Member marks the boundary with the underlying Scremerston Formation.

Whilst the Yoredale Formation is truncated beneath the BPU at Breagh, a complete section totalling 826 m is seen in 41/15-1 to the west. Correlation between the limestones suggests an expansion of over three times the thickness of the lower part of the Yoredale Formation between the Oxford and Dun limestones (e.g. 446 m in 41/15-1 and 130 m in 42/13-2) to the west. Seismic evidence places Breagh in the footwall of a series of NW–SE-striking normal faults that downstep to the south and west with significant present-day relief at the BPU level. Structuration at the BPU appears to diminish further west of this fault zone, and the Carboniferous slopes gently into the hanging wall.

Upper Carboniferous sediments are not preserved beneath the BPU at the Breagh Field and Millstone Grit or older strata occur (e.g. at the base of well 42/18-2, some 10 km SE of Breagh, where <10 m-thick, grey, sharp-based sandstone packages are seen. East of Breagh, well 43/16-2 records over 340 m (base not seen) of Millstone Grit Formation; and west of Breagh, 220 m occur in well 41/15-1. North of Breagh, the Yoredale Formation subcrops the BPU (e.g. 42/09-1). From seismic and well data, the Millstone Grit Formation slopes gently SE towards the Silverpit Basin defining a

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Fig. 8. Seismic section C–C'. East–west-orientated (E–E') (a) uninterpreted and (b) interpreted seismic two-way travel time travel (TWTT) section across the Lochran 3D survey, south of the Breagh Field. See Figure 4 for the location. Seismic data are courtesy of INEOS.
Fig. 9. Structure maps. (a) Base Permian Unconformity/top Rotliegend (base Zechstein) two-way travel time (TWT) structure map (ms); (b) depth–structure map (m) showing the gas–water contact (GWC) for the Breagh Field (2337 m TVDSS; red); (c) top Bacton Group depth–structure map, which reveals the major graben system in the supra-Zechstein overburden; and (d) average velocities (m s\(^{-1}\)) at base Zechstein level. The depth map is the result of the depth conversion of the seismic dataset following seismic interpretation of key overlying seismic horizons, and calculation of velocity intervals determined from analysis of available well time–depth data. Importantly, the depth conversion incorporates: (i) the influence of the Mesozoic graben in the overburden; (ii) a variable subcrop of high-velocity sediments at the seafloor (i.e. Chalk); and (iii) the effect of late-stage regional tilting. See the text for the discussion. The orientation and locations of the well correlation and seismic sections A–A\(^\prime\) (Figs. 5a and 6) and B–B\(^\prime\) (Figs. 5b and 7), and seismic section C–C\(^\prime\) (Fig. 8) are indicated. The locations of the maps are indicated in Figure 4.
Fig. 10. Thickness maps. Isopach maps depicting the major variations in stratigraphic thickness of: (a) the Zechstein Supergroup; (b) the Bacton Group; (c) the Lower Cretaceous–base Haisborough Group interval; and (d) the Chalk Group within the Breagh–Lochran area. Fault patterns at the top and base of the interval are indicated, along with the outline of the Breagh Field (in red). The Zechstein is thinned within the graben areas. A pronounced salt diapir occurs at the intersection between the two graben in the centre of the map. The Bacton Group is relatively consistent in thickness across the area. However, it is absent from the northern graben and severely thinned in the southern graben. The Lower Cretaceous is relatively thin across the area and the majority of the interval depicted by (a) is composed of Jurassic (mainly Lias Group) and Haisborough Group sections. The interval is appreciably thick within the centre of the Mesozoic graben, particularly in the south, indicating synsedimentary fault growth. The Chalk Group (b) is absent across much of the southern part of the study area and thickens NNE of the seabed subcrop. The orientation and locations of the well correlation and seismic sections A–A’ (Figs. 5a and 6) and B–B’ (Figs. 5b and 7), and seismic section C–C’ (Fig. 8) are indicated. The locations of the maps are indicated in Figure 4.
broad anticlinal dome. Breagh sits in the core of this structure, slightly to the west of its axis.

**Base Permian Unconformity**

In general, the BPU dips to the SSE, towards the Sole Pit Basin, where it reaches depths of more than 3000 m. The surface displays as much as 1000 m of relief across the study area and is dissected by several fault trends. Structural styles vary between the two survey areas such that three general structural domains can be recognized (Fig. 11): two domains (east and west) in the Lochran area, and the third in the Breagh area to the north.

The northern domain is characterized by a broad domal structure (Breagh) bound by a terrace of NW–SE and NNW–SSE normal faults on its southwestern side (with up to 300 m of relief), and NE–SW faults on the northeastern side. This geometry gives a combined tilted fault block with dip closure configuration to the Breagh Field trap. The NW–SE structural grain is comparable to other SNS structures.

Faulting appears more extensive in the Lochran area, although this may be a consequence of the better data quality of the Lochran 3D survey thus revealing the BPU structure in more detail. In the eastern domain, numerous southwesterly-dipping NW–SE-striking faults define a series of c. 5 km-wide tilted fault blocks, which are occasionally cut by a series of NE–SW-striking faults of lesser significance. The western domain is characterized by a broad easterly-dipping slope dissected by several ENE–WSW faults that die out towards the west. The boundary between these two domains in the south is marked by a major north–south-striking curvilinear fault that dips towards the east. This fault system roughly coincides with a pronounced north–south-striking graben in the post-Zechstein overburden.

**Permian**

Rotliegend Group strata are absent at Breagh, and Zechstein carbonates and evaporites rest directly on the BPU. The Rotliegend Group is present in wells to the south, east and west (e.g. 42/18-2, 42/22-1 and 42/23-1), and appears to thicken away from the Breagh structure. Where present, the Rotliegend Group comprises a mudstone-dominated facies ascribed to the Silverpit Formation. Halite encountered in well 43/16-2 belongs to the Silverpit Halite Member. LSF sandstones occur in wells 42/22-1 (22 m) and 42/23-1 (17 m) in the south, and well 41/15-1 (4 m) to the west. The downstepping fault terrace to the west of Breagh is thought to control the northeastern limit of the Rotliegend Group, which is present in the wells to the south.

Zechstein deposits are omnipresent across the area and conformably overlie Rotliegend strata (where present), or Carboniferous sediments on the BPU at Breagh and towards the MNSH. The Zechstein is relatively uniform in thickness, gradually thickening towards the Silverpit Basin where salt pillows with wavelengths of c. 10 km are recognized. Across the study area, however, Zechstein thicknesses are highly variable, especially over Breagh. Variations are associated with halokinesis of the easily deformed halite of the Stassfurt Halite Formation (Na2) and formation of a major Mesozoic graben. Halokinesis has resulted in a series of elongate salt swells (salt rollers) in the footwalls at the base of the graben (Fig. 10). The thickest Zechstein sections occur in the immediate footwall to a major NW–SE-striking fault in the

![Fig. 11. Structural analysis. (a) Depth–structure map Base Permian Unconformity (BPU/top Rotliegend (base Zechstein)) composite surface showing the main faults identified (white). (b) Map showing the main Permo-Carboniferous trends at base Zechstein level classed and coloured by the general strike orientation. Four main fault trends can be recognized, NNW–SSE, NW–SE, east–west and NE–SW, which can be divided into three broad fault domains of consistent structural style. The outline of the Breagh Field, defined by the closing contour of the gas–water contact (GWC: 2337 m TVDSS) at BPU level, is indicated in grey. The locations of seismic lines A-A’, B-B’ and C-C’ are also shown. The locations of the maps are indicated in Figure 4.](http://pg.lyellcollection.org/Downloaded from)
Fig. 12. Maps of the subcrop to (a) the seabed, (b) the Base Cretaceous Unconformity (BCU: where present) and (c) the BPU in the Breagh area in Quadrants 41–43. Main structural elements also indicated. Data for (a) and (c) are sourced from the British Geological Survey (BGS) and (c) has been supplemented with the map from Kombrink et al. (2010, fig. 6.4) and well data. For (b) the map has been created using available well data supplemented by seismic observations. Beyond the limits of the erosional Cretaceous, where the BCU is truncated by the seabed, the subcrop to the seabed is shown in (b). Faults mapped using 3D seismic are indicated in red, and those from published literature, along with the main fold structures, in grey. The orientation and locations of the well correlation and seismic sections A–A’ (Figs 5a and 6) and B–B’ (Figs 5b and 7), and seismic section C–C’ (Fig. 8) are indicated in (a).
Mesozoic overburden that detaches onto the evaporites (e.g. 690 m of Na2 in 42/13-2: Figs 5a and 6). In the Lochran area, a pronounced diapir, with a height in excess of 1200 m, occurs in the centre of the mapped area at the intersection between the two graben in the overburden. Smaller Zechstein swells occur in the horst block between the two graben in the south (e.g. wells 42/18-1 and 42/23-1). The Zechstein in the graben hanging walls is severely thinned, often to less than 200 m (e.g. 37 m of Na2 are recorded in well 43/13-4). Outwith the graben, the Zechstein is typically between 600 and 1000 m in thickness. Here, variations in thickness result from the infilling by evaporites of a palaeotopography at the base of the unit giving a level palaeosurface.

The character of the high-amplitude intra-Zechstein Plattendolomit reflector varies across the study area. To the west of Breagh, the reflector is continuous over distances of >10 km. In contrast, to the east, the reflector is broken up into discontinuous ‘rafts’, typically several kilometres in width that display a range of commonly sinuous geometries and dips as a result of halokinesis. In areas of significant halokinisis, and pronounced Mesozoic structuration, the Plattendolomit reflection is more or less absent (i.e. in the areas immediate to Breagh). These observations demonstrate that the character of the Plattendolomit can be used as a proxy for halokinetic deformation of the Zechstein.

Mesozoic overburden

Away from areas of pronounced Zechstein halokinesis, the total thickness of preserved Mesozoic section is relatively uniform. Local (c. 10 km) or semi-regional (c. 50 km) variations occur in areas where the preserved section moulds to the fluctuating upper surface of the Zechstein. Across the Breagh area, the Mesozoic is structurally complex with significant thickness variations associated with the major Mesozoic graben system that strikes NNW–SSE directly above the Breagh Field. The graben system, originally named the Central Fracture Zone (CFZ) by Kirby and Swallow (1987), is considered the southwestern extension of the North Dogger Fault Zone (NDFZ) by Allen et al. (1994) and Stewart and Coward (1995).

The Bacton Group appears tabular and uniform. Undisturbed thicknesses are in the range of 400–600 m, thickening basinwards towards the Sole Pit Basin and thinning northwards towards the MNSH. Thickness changes within the underlying Zechstein appear to have little, if any, effect on the thickness of the overlying Bacton Group. Similarly, the overlying Haisborough Group displays relatively uniform thicknesses (c. 300–500 m). The Triassic sediments thin locally towards the graben at Breagh (e.g. 335 m, well 42/13a-6) and towards the MNSH (e.g. 339 m, well 42/09-1). The thickest sections are preserved in the west, towards the coastline (e.g. 546 m, well 41/15-1) and in the Silverpit Basin to the SE (e.g. 570 m, well 43/16-2). Thinning is most pronounced in the Bunter Sandstone Formation and the oolitic Rogenstein Member (uppermost Bunter Shale Formation) below in the Bacton Group. Moreover, analysing the main intercalated evaporite intervals, the more widespread lowermost Röt Halite (RHLT) thins towards Breagh, and the younger, less widespread evaporite members (Muschelkalk and Keuper Halite members, and Keuper Anhydrite Member) are absent towards the NE.

The Lower Jurassic Lias Group is truncated over a large part of the Breagh area either at the seabed in the west and south, or by the Chalk Group in the north. Complete sections are preserved in the Lochran area, and show thickening of the group west towards the Cleveland Basin and Flamborough Head areas and the UK coastline. The Middle and Upper Jurassic West Sole Group and Humber Group, respectively, are only present in the more southerly areas of Quadrants 41–43 a result of erosion at the base of the Chalk. Thicknesses are variable but follow a similar trend to the Lias.
Group. The West Sole succession in the graben areas and in the surrounding vicinity comprises shallow-marine sandstone facies, capped by a layer of oolitic limestone of the Corallian Formation at the base of the Humber Group. North of the study area, and in the northern part of the Silverpit Basin, the West Sole Group is absent (e.g. 43/16-2), and argillaceous Humber Group sediments lie directly on top of the Lia Group. The Humber Group generally thickens towards the south, where it conformably overlies the West Sole Group.

The Lower Cretaceous Cromer Knoll Group is only preserved in wells east of Breagh due to uplift and truncation at the seabed. The unit is thickest in the Breagh area but elsewhere is generally relatively thin, occasionally absent, and appears to pinch and swell, draping the underlying topography of the Jurassic. Into the north, the Cromer Knoll Group is absent (e.g. well 42/09-1) and 400–500 m of Chalk Group rest unconformably on Lia Group strata. The Chalk Group is truncated by the seabed in a NW–SE-striking band that encompasses the Breagh Field (Fig. 12a). West and south of Breagh, wells show progressively deeper subcrops of Humber (e.g. 42/18-1 and 42/23-1) and Lia (e.g. 41/15a-1 and 42/22-1) groups towards the UK coastline. Seismic sections display a general northeasterly dip of the Mesozoic section (see Figs 6 and 7). The lower part of the Chalk appears as a package of moderately bright, high-frequency parallel reflectors that drape the base Chalk horizon. The upper part of the succession appears transparent in comparison, with shorter more discontinuous reflections indicating stratal geometries that commonly appear to downlap onto the lower Chalk package. Northeast of Breagh, Palogene sediments conformably overlie the Chalk Group and reveal the full succession of Chalk, which, by estimation from 42/09-1, is c. 700 m thick in the northern areas and thickens basinwards.

Mesozoic extensional systems

Permo-Carboniferous fault patterns are absent from the top Zechstein surface, indicating a lack of upward fault propagation. The evaporites act as décollement horizons effectively decoupling sub- and supra-Zechstein structures. Numerous low-angle listric faults define major synsedimentary graben and half-graben. The Breagh area broadly comprises two graben systems that broadly strike NW–SSE, forming an en echelon geometry (Fig. 9c). The Zechstein section is thinned to locally welded (e.g. the western half-graben in Fig. 8) within the centre of the graben. In these areas, it is likely that Mesozoic strata rests directly above the immobile lower Zechstein.

The graben and half-graben are bound by a primary, major fault that detaches down onto the Zechstein, and a secondary fault that appears to first detach on the RHLT at the top of the Bacton Group, and then down onto the Zechstein at deeper levels. The primary fault defines the locus of synsedimentary growth packages in the Middle Triassic–Jurassic section. The Bacton Group is faulted-out in the graben centre by the low-angle listric faults that detach down on to the Zechstein, defining a c. 5 km-wide zone of complete separation of the Lower Triassic (Lower Triassic Separation Zone (LTSZ)). The thickness and geometry of the Haisborough Group and younger strata are variable within the graben but are generally thicker than undisturbed areas. The Mesozoic units typically thicken into the hanging wall of the primary graben fault, characteristic of synsedimentary growth, and may be folded into a rollover anticline. Faulting extends upwards to affect the lowermost Chalk Group, where it shows little evidence of synsedimentary growth.

A contrast in structural style of the graben occurs between the Breagh and Lochran areas. In the latter, two half-graben are evident (Fig. 8) separated by a broad salt-cored anticline forming a geometry that resembles a mock-turtle structure (Warren 2016, pp. 518–519) but with a residual salt core. The crest of this anticline comprises a smaller highly-faulted graben system that detaches onto the RHLT and extends upwards to disject the Upper Cretaceous Chalk Group. This smaller structure is similar to the Sole Pit High Collapse Zone observed further south on the Sole Pit High, where faulting and thick Zechstein diapirs are associated with inversion in the Cenozoic (Stewart and Coward 1995). The supraline fault geometry of these Mesozoic graben are comparable to the salt rollers observed offshore Angola, in the Lower Congo and Kwanza basins, Brazil, and the Gulf of Mexico (Duvall et al. 1992; Anderson et al. 2000; Rouby et al. 2002; Fiduk et al. 2004; Dutton and Trudgill 2009).

The easterly graben within the Lochran area is steeper and narrower, and extends north into the Breagh area, transecting the overburden directly above the Breagh Field, where it splits into two separate graben. Above the Breagh Field, a thickened salt diapir occurs beneath the westerly footwall, defined by multiple backstepping Zechstein detached faults. In the easterly footwall, a thickened zone of halite, encountered in wells 42/13-4 and 42/13-3 within the Haisborough Group, is shown to connect to the Zechstein forming a ‘salt wing’ that delaminates the underlying Bacton Group (Fig. 6).

Geophysical impact of the Mesozoic graben

The Mesozoic graben in the overburden are well known to impact seismic imaging and depth conversion of prospective sub-Zechstein structures that lie beneath (Fig. 13) (Werngren et al. 2003; Grant et al. 2019b); a consequence of the preservation of thick, low-velocity sediments within the graben centre, and ray-bending associated with complex faulting and large lateral velocity contrasts. These effects have demonstrable consequences when imaging and mapping the Breagh structure in two-way time (TWT). In TWT, Breagh appears as two separate closures, separated by a pronounced low which sits beneath and parallels the graben in the Mesozoic overburden (Fig. 9a and c). Equal gas–water contacts (GWC) and pressure gradients between these two apparent TWT highs suggest pressure communication and, perhaps, one single structure (Fig. 14). After depth conversion and compensating for the velocity ‘push-down’ effect caused by the graben (i.e. lower average velocities: see Fig. 9d) on PSTM seismic data, the Breagh structure is revealed as one large closure.

This stark contrast between the time and depth structure of Breagh exemplifies the uncertainties associated with TWT mapping. The effects have direct implications for prospectivity, such that structures could be missed entirely, underestimated or be non-existent. Depth conversion is therefore essential in graben areas in order to test the validity of time structures due to the overburden effects.

Petroleum system

Gas produced from Carboniferous and Permian clastic reservoirs of the SNS has long been thought to be derived from Carboniferous-aged coals. The source rock has typically been cited as Late Carboniferous (Westphalian A–C (Moscovian)) coal seams of the Conybeare Group sediments of the Caister Coal, Westoe Coal and Schooner formations (Bailey et al. 1993; Comford 1998; Glennie 1998; Lokhorst 1998; Gerling et al. 1999). In some areas, however, isotopic analyses suggest a mixed origin with input from both the Westphalian low-maturity terrestrial source and more mature Namurian (Millstone Grit Group, Bowland Shale Formation) and Dinantian age (Farne Group, Hodder Mudstone Formation (marine) and Scolemerston Formation (dominantly non-marine)) sources (Gerling et al. 1999). In a recent review, Besly (2018) has tested the veracity of Westphalian Coal Measures being the main source interval, and has argued that the deeper Namurian and Dinantian sediments, being more widespread, may in fact be the source intervals and provide the bulk of the gas contribution.
The timing of gas generation from Carboniferous coals varies considerably across the SPB. In the East Midlands Petroleum Province, generation ends by the end Jurassic (Pletsch et al. 2010), while in the Cleveland Basin area the end of generation is at the end Cretaceous (Pletsch et al. 2010). Over much of the North Sea and the northern part of The Netherlands, gas generation in the basin is thought to have been widespread until end Cretaceous, with a localized phase of renewed generation in the Neogene (Pletsch et al. 2010). Apatite fission-track analyses (AFTA), vitrinite reflection (VR) studies and burial curves suggest that the Upper Carboniferous source rocks reached maximum burial in many areas during the Late Cretaceous (Glennie and Boegner 1981; van Hoorn 1987; Alberts and Underhill 1991). Generation is thought to have ceased by the Paleogene and, perhaps, even earlier, at the end of the Cretaceous, due to widespread deformation associated with Alpine–Atlantic plate-margin-related tectonics that affected large parts of NW Europe (Ziegler 1990; Hillis 1995; Underhill and Paterson 1998; Underhill and Stoneley 1998; Rojas and Underhill 2017).

Rotliegend LSF sandstones form the main, highly prospective reservoir across much of the southern part of the SNS (Underhill 2003; Breunese et al. 2010; Taggart et al. 2015; Catto et al. 2017). In more central areas of the basin, the LSF is replaced by claystones of the Silverpit Formation (e.g. Silverpit Basin), which provides an effective seal for prospective Carboniferous fluvio-deltaic sandstones lying uncomfortably beneath (Besly 1998; Underhill 2003; Kombrink et al. 2010). These reservoirs host gas accumulations in a number of fields in UK Quadrants 43 and 44 (e.g. Ketch, Schooner, Boulton and Tyne) and in the adjacent blocks D, E and K in The Netherlands (Fig. 2). Dip and fault closures adjacent to the BPU form the major trap style, sealed by Permian strata immediately above (Fraser and Gawthorpe 2003; Cameron et al. 2005; Pletsch et al. 2010). A narrow strip of LSF exists along the southern margin of the MNSH (Catto et al. 2017; Brackenridge et al. 2020), to the north of which Zeichstein evaporites lie unconformably on truncated Carboniferous sediments to set up traps at the Breagh and Crosgan fields. The latter also demonstrates that a working petroleum system exists in Lower Carboniferous sandstone reservoirs in a hitherto under-explored area on the southern flank of the MNSH. This area was largely written off for exploration until recently since it is devoid of any Westphalian coal subcrop and lies some 30 km NW of any other Carboniferous gas field.

### Fig. 13.
Graben depth-conversion schematic diagram illustrating the effect that thick, low-velocity sediments preserved within the centre of the supra-salt (Zeichstein) Mesozoic graben have on seismic imaging and depth conversion. Reproduced after Grant et al. (2019b), (a) is in two-way time (TWT) and (b) is after depth conversion. In the case shown, a pronounced ‘push-down’ effect is observed beneath the graben when using a time section. Note the asymmetry to the ‘push down’ effect due to thickness differences within the graben. A significant ‘pull-up’ beneath the graben follows from accurate depth conversion taking into account thick packages of low-velocity Mesozoic sediments within the graben. The Zeichstein Z1–Z2 carbonate–anhydrite shelf and its consequent depth-conversion effect (after Grant et al. 2019a) is included for completeness. The Zeichstein Z1–Z2 shelf results in a ‘pull-up’ in time of the top Rotliegend surface in depth, due to the high velocities associated with the shelf (a) with respect to the basin (b).
that the field contains an estimated 14.6 Bcm (519 Bcf) of recoverable gas, with 0.32 MMSm³ (2 MMbbl) recoverable condensate (IHS Markit 2019), making it the 60th largest gas field in the UK, in terms of ultimate recoverable reserves. Breagh’s smaller cousin the Crosgan Field, located 25 km to the NE in Blocks 42/10 and 42/15a, was discovered by well 42/15a-2 in 1990 by Industrial Scotland Energy plc and contains an estimated 2.8 Bcm (100 Bcf) of P50 contingent recoverable resource. The fields are marked as ‘outliers’, and their discoveries have challenged long-held views concerning the prospectivity of the Lower Carboniferous and the MNSH region.

In the Breagh area, the coals within the Scremerston Formation have reached maturities low in the gas window. One-dimensional basin modelling of the 42/13a-06 well in the Breagh Field suggests that the bulk of charge occurred before the BPU (Fig. 15a). It would be unlikely that gases expelled locally from the Scremerston Formation prior to the BPU would be retained until the present day due to the inversion and trap modification that occurred later. Therefore, the charge into the structure is likely to have occurred later in geological history. A comparable burial graph and 1D basin model of a well in the Crosgan Field (well 42/10b-2: see Fig. 15b) shows that there is a later charge episode than that in the Breagh area, with some expulsion occurring in the late Cretaceous and Paleocene. Further to the east, it would be expected that there would be yet later charge due to the diminishing effect of the late Paleocene uplift. One mechanism to explain the charge in Breagh is that tilting and uplift of the region at the end Paleocene resulted in the remigration of existing gas accumulations and possible charge focus towards Breagh. The underfilling of Breagh suggests that the charge pathway is unlikely to continue updip from the field.

**Discussion**

**Tectonostratigraphic basin development**

The pre-Carboniferous evolution is difficult to determine in the Breagh area due to seismic imaging and resolution limitations beneath the Zechstein evaporites and the paucity of deep well penetrations. Devonian Old Red Sandstones penetrated at the base of 42/10a-1 indicate that the area formed part of the broad continental plain that existed across much of the UK and the North Sea after the mountain building Caledonian Orogeny. Early Carboniferous extension created a series of extensional basins throughout the eastern British Isles which are likely to have extended offshore, facilitating the thick Lower Carboniferous successions throughout the eastern British Isles which are likely to have extended offshore, facilitating the thick Lower Carboniferous successions recorded in wells in the offshore Cleveland Basin (Fig. 1).

Lower Carboniferous palaeogeographical reconstructions place Breagh at the southwestern margin of a major fluvial braid plain, part of a fluvio-deltaic environment that passed into deeper basinal environments towards the SW (Kombrink 2008; Kombrink et al. 2010; Symonds et al. 2015; Besly 2018; Kearsey et al. 2018; Booth et al. 2020). The Lower Carboniferous deposits at Breagh were deposited in a fluvial-dominated deltaic setting (Booth et al. 2020). The sandstones of the Yoredale Formation are interpreted as braided fluvial channel deposits and are age equivalent to analogous outcrops along the coast of Northumberland (e.g. Berwick upon

![Fig. 15. Basin-modelling study. Reconstructed burial/exhumation graph for (a) Breagh well 42/13a-6 and (b) Crosgan well 42/10b-2, and temperature, vitrinite reflectance and gas expelled rate history for a notional Lower Carboniferous coal section within the two wells.](http://pg.lyellcollection.org/)
Tweed, Spittal–Scremerston, Seahouses and Beadnell foreshore: Booth et al. 2020). Here the braided fluvial channels are shown to have lateral scales on the order of 1 km (Bristow and Best 1993).

The NW–SE Tornquist fault trend typically dominates the MNSH and SNS area. In the Breagh–Lochran area, both ENE–WSW (Caledonian) and NW–SE (Tornquist) fault trends are recognized (Fig. 11). Whilst the NW–SE strike takes dominance around the field itself, to the south the fault block structural configuration is defined along an ENE–WSW to east–west axis.

Northwest of Breagh, thick Lower Carboniferous deposits identified from seismic mapping (Arsenikos et al. 2018) appear preserved in a NE–SW-orientated sub-basin (Fig. 1), indicating the extension of the trend across the area immediately north of the Breagh Field.

Numerous workers have suggested that the Breagh area represents a Lower Carboniferous high (e.g. Leeder and Hardman 1990; Collinson et al. 1993; Corfield et al. 1996; Cameron and Ziegler 1997; Besty 1998; Maynard and Dunay 1999; Fraser and Gawthorpe 2003; Kombrinck 2008; Monaghan et al. 2017; Arsenikos et al. 2018; ter Borgh et al. 2018; see also fig. 23 of Besty 2018). The high is located at the intersection between the northern extension of the DFZ and the southwestern arm of the basement component of the NDFZ. The former comprises a major, long-lived zone of structural weakness associated with the boundaries to major crustal heterogeneities (Fig. 16), and probably exerted an influence on sedimentation and structuration even prior to the Carboniferous.

The Variscan subcrop pattern at the BPU shows an absence of Upper Carboniferous deposits at Breagh and in the areas to the NE. Whilst this absence may reflect either more uplift and erosion or simply non-deposition, Lower Carboniferous stratigraphic patterns suggest that the area was an active high. Significant expansion of the Yoredale Formation in well 41/15-1, west of Breagh across the NW–SE-striking major fault zone, and the presence of a correlatable, yet condensed, sequence in at Breagh suggest that synsedimentary growth took place to the west in the hanging wall, with limited sedimentation across the footwall (Fig. 17).

The absence of the Rotliegend above the BPU at Breagh and the southward-directed thickening of the unit (Fig. 17) indicate that an elevated structural feature existed, and influenced sedimentation after the Late Carboniferous–Early Permian sedimentary hiatus associated with the Variscan Orogeny. Rotliegend sediments appear to have passively infilled the surrounding accommodation of the dormant fault-bound high to form a clastic rim to the SPB (Brackenridge et al. 2020).

Whilst the Zechstein displays a more basinal character, the presence of an increased thickness of Werraanhydrit at the base of the Zechstein in well 42/13-3 and recognized on seismic (Figs 5b and 7) suggests that some residual topography remained, such that the area was the nucleus for carbonate–sulfate neritic platform growth (Fig. 17h). The feature is only poorly developed in comparison to the Werraanhydrit platforms (‘pinnacles’) at the Croggan discovery (well 42/10), further to the NE towards the Dogger Bank area described by Patruno et al. (2017), or those known from elsewhere in the Zechstein Basin (e.g. Germany: Strohmenger et al. 1996). The small Werraanhydrit platform at

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**Fig. 16.** Residual Bouguer (onshore) and free-air (offshore) gravity anomaly map for the Southern North Sea (SNS). The map provides a basis for identifying the main structural elements of the SNS, controlled by a pervasive NW–SE basement fabric which delineates the main axes of basin inversion (Sole Pit and Cleveland basins). Several pronounced gravity lows can be recognized, representing inferred buried granitic bodies (e.g. Market Weighton (MW), Amethyst (A), Cleaver Bank (CBK), Indefatigable (I), Newark (N), East Anglia Granite (EAG) and Teeside (T)) (see Alsop 1987; Donato and Megson 1990; Donato 1993; Leeder and Hardman 1990 for details). Data source (offshore) for free-air anomaly data: KMS20010 Global marine free-air gravity field (2-minute grid) (Andersen et al. 2005). Data sources (onshore) for Bouguer anomaly data: based on UK gravity database (British Geological Survey, 5 × 5 km grid).
Breagh may share a similar origin, atop antecedent topographical highs defined by Devonian-Carboniferous horst blocks or, like Crosgan, a Carboniferous inversion anticline. The small size and thick overlying package of halite at Breagh suggest that the palaeohigh did not retain its significance to enable the development of a similar-scale feature.

In Early Triassic times, Breagh and the area to the NE was subject to less subsidence than the surrounding areas of the south. Thickness patterns of the Bacton Group indicate that the Breagh palaeohigh exerted a minor influence on the deposition of the fluvial and floodplain sediments.

Synsedimentary hanging-wall growth began in the Jurassic, creating variable sedimentary thicknesses in the graben. Stratigraphic growth at Breagh, however, is less than in the Lochran graben and less than in the equivalent fault systems on the southwestern SNS margin (e.g. the DGS: see Grant et al. 2019b).

Fig. 17. Schematic cartoon reconstruction of the cross-section shown in Figure 6 depicting the tectonostratigraphic development of the Breagh area of the Southern North Sea from the Early Carboniferous to the present day.
Thinner strata at Breagh indicate less subsidence and accommodation creation. The localized diapirism observed at Breagh may also be a residual effect of a more elevated area with less overburden, acting as a focal point for surrounding salt due to lower overburden stress. This may explain why salt intrusion into the Triassic is limited to this part of the Breagh fault zone.

During the Middle Jurassic, deposition was generally limited to the graben areas. The thickest sections of the West Sole Group strata accumulated within the graben hanging walls, comprising distinct sandstone-rich facies of shallow-marine and estuarine origin capped by oolitic limestones of the Corallian Formation (Cameron et al. 1992; Lott and Knox 1994) that developed in local, tectonosedimentary palaeogeographical marine/coastal environments (e.g. Gawthorpe and Leeder 2000, fig. 7). The SSW dip of the Triassic-Jurassic section towards the Flamborough Head Fault Zone, evidenced by the section’s subcrop against the BCU (Fig. 12b), indicates a broadly NNE tilt to the pre-Cretaceous strata following uplift of the Central North Sea (CNS) during the Middle Cimmerian event.

The Cromer Knoll Group, which is thin (<50 m) or absent towards the north of Breagh, indicates that the area remained an
uptiled high on the shoulders of the NDFZ (Fig. 17). Subtle thickness variations in this generally thin succession appear to be controlled by the pinching and swelling of the Zechstein salt. Thicker Cromer Knoll sections occur within the graben at Breagh; however, considerably less compared to the DGS (locally over 900 m: Grant et al. 2019b), indicating less extension and accommodation creation.

The Chalk Group is only partially preserved at Breagh (Fig. 17). Unlike the DGS, the lower part of the Chalk Group is faulted in the Breagh graben. The stratigraphy is relatively uniform and tabular. Basal Chalk reflectors can be traced consistently across the Breagh High without any convincing reflector terminations or pronounced stratigraphic growth. This implies relatively passive pelagic or hemipelagic sedimentation at the beginning of the Late Cretaceous followed by later reactivation of existing faults. This is supported by locally disturbed sequences and possible mass transport complexes situated above graben fault tips. Disturbed Chalk sequences are seen in the areas of the Amethyst and Juliet fields in Quadrant 47 (Grant 2019; Grant et al. 2019b), and elsewhere in the North Sea (e.g. Norwegian Central Trough: Oakman and Partington 1998).

Cenozoic sediments are absent from the immediate area (Fig. 17) as a result of regional tilting events that affected the British Isles during Paleogene (Guariguata-Rojas and Underhill 2017) and Neogene times (Brackenridge et al. 2020).

**Origin of the Breagh High**

The Breagh area represents a long-lived antecedent high that has remained, for the most part, present throughout the development of the SNS basin. Comparable areas of the SNS are the Market Weighton–Amethyst High in Quadrant 47 or the Dogger High in Quadrants 37 and 38. In these areas there is unequivocal evidence from gravity data to suggest the presence of a buoyant basement granite (Donato and Megson 1990; Donato 1993). A granite beneath (or, at least, nearby) the Breagh Field has been postulated by some authors (e.g. Collinson 2005), and observed gravity (free-air anomaly) data from the Breagh area show hints of a possible low-density crustal anomaly (Kimbell and Williamson 2015). Gravity data do place the Breagh area along the NW–SE striking boundary between the lower-gravity anomaly (denser) crust of the Silverpit Basin and higher-anomaly (less dense) crust in the offshore Cleveland Basin (Fig. 16). This boundary may mask any gravity effect exerted by a small granitoid body in the area.

A recent residual gravity model (observed – calculated background anomalies: Kimbell and Williamson 2015) displays a NW–SE striking, ‘boot-shaped’ area of notably lower values beneath Blocks 42/13, 42/14 and 45/15 (Fig. 18a). This anomaly may represent a buried buoyant granite in the subsurface that would explain the existence and long-lived nature of the high beneath the area. Elevated bottom-hole temperatures and steeper geothermal gradients are consistently recorded in the pre-Zechstein strata from wells at Breagh and, to a slightly lesser degree, at Crogan relative to the surrounding area (Fig. 18b), suggesting an increased basal sediment heat flow and lending some support to the notion that the Breagh High is granite cored. In addition, the oil/wet gas mature Carboniferous strata are recorded from measured vitrinite reflectance data at Breagh and Crogan (c. 0.95% R, well 42/13-1; 0.78–1.88% R, well 42/10b-2: Vane et al. 2015) which are higher than those from wells to the south (e.g. 0.75% R, well 42/22-1: Barnard and Richards 1988). Basin-modelling studies suggest that a modest increase in the radiogenic heat production of the crust would match these elevated bottom-hole temperatures and the maturities estimated from VR data from wells at the field. Granites can cause elevated geothermal gradients and subsurface temperatures because of the heat generated during the decay of radioactive elements within its mineral structure (Allen and Allen 2013). Hence, it seems plausible that a more ‘granitic’ crust beneath Breagh due to an intrusion would explain the elevated geothermal gradients. These findings are supported by residual gravity observations that support the notion of a buried granite.

**New insights into the Lower Carboniferous petroleum system**

The long-lived elevation of the Breagh structure, perhaps due to being cored by a buoyant granite, has important consequences for the genesis of the trap and its gas fill. The Breagh area’s relative elevation, being situated in a basement foothill high during the episodes of rifting that affected the SNS in the Mesozoic, would have served as a focal point for any gas. The thin Upper Jurassic and Lower Cretaceous sequences preserved in the graben suggest that less pronounced rifting took place following the Middle Cimmerian event, and hence the trap formation may have predated this event. It follows that the regional tilting in response to uplift towards the north during the Middle Cimmerian event will have modified the earlier structuration. It is possible that some gas trapped in an earlier proto-Breagh structure may have been remobilized and leaked away, particularly considering the orientation of the main trap-forming structure on the southwestern side of the Breagh Field. Subsequent thermal relaxation and subsidence in the north, combined with Late Cimmerian rifting, may well have further modified the Breagh trap.

A plot of the repeat formation test (RFT) pressure data shows that the GWC in the Breagh is c. 2337 m TVDSS (Fig. 14). However, a mapped larger closing contour c. 100 m deeper (2440 m TVDSS) than the observed GWC in the Breagh Field (2337 m TVDSS) (Fig. 19) demonstrates the field to be significantly underfilled. This is contrary to (Carboniferous and Rotliegend) gas fields to the south that are generally filled down to their spill (leak) point (Gleennie 1998). The consequences of this finding are profound and leave two important questions: Is there a lack of charge and/or migration? Or has Breagh leaked? Certainly, it implies that present-day gas generation and migration from nearby gas-mature Lower Carboniferous source rocks in possible kitchen areas proposed by Monaghan et al. (2017) south of Breagh are insufficient to fill the structure.

The remigration of gas beneath the Zechstein evaporite ‘super’-seal following reorientation of the basin during inversion and basin tilting, modifying the base Zechstein structure, is a well-established premise across much of the SNS (Oele et al. 1981; Gleennie 1998; Gleennie and Underhill 1998; Johnson and Fisher 1998; Werngren et al. 2003). Hence, some workers envisage long-distance fill-and-spill migration to Breagh of remobilized gas from the Upper Carboniferous reservoirs of the Silverpit Basin (RWE Dea 2011; Rodriguez et al. 2014), akin to the Rotliegend play further south and SE (Gleennie 1998). Considering how prolific the main play fairway areas are and the effectiveness of the Zechstein seal, if long-distance migration is envisaged then it seems unlikely that Breagh remained underfilled during the Mesozoic charge.

The burial and thermal behaviour of the 42/13a-6 well is typical of much of the area, although some local variation exists across the Breagh Field, evident from variable stratigraphic thicknesses. Basin modelling and burial history reconstruction at 42/13a-6 indicates that while maximum burial may have occurred in the Early Paleogene (Fig. 15a), peak temperature and, consequently, the bulk of gas generation is likely to have occurred prior to the BPU, due to rapid deep pre-Variscan burial, with a possible minor charge pulse in the Paleocene.

Given that the bulk of the gas from the immediate area was expelled prior to seal deposition and structuration, the most likely source of charge for the Breagh structure would be from long-distance migration from Westphalian coals in deeper areas towards the east (Fig. 20). This could occur at any time after structuration; however, the end Paleocene deformation and more significant
Neogene tilting event would provide focus for migration pathways from gas kitchens to the east of the area or, alternatively, remobilize existing accumulations by tilt-related spillage or because of uplift-related decompression.

A possible cause of the underfill is that the trap, which formed during the Mesozoic, was modified during the later Cenozoic phases of uplift and regional tilting of the UK towards the WNW. The result was the (re-)configuration of the trap that, because of its western and northwestern fault-bound nature, created a present-day larger closure leaving the field underfilled. An alternative scenario, however, would suggest that the volume of charge available to the structure was limited during the end Paleocene event.

Remaining potential

Timing and charge history are the main risks to Carboniferous gas exploration in the SNS (Cameron et al. 2005) and formed the primary risk in the drilling of the Breagh discovery well (42/13-2) (Hickens and Hughes 1998). This is a consequence of the complex and punctuated subsidence and uplift histories, which are difficult to fully reconcile due to the widespread diachronous removal of large amounts of Mesozoic and Cenozoic strata coupled with halokinesis. Further risks to the exploration potential of the Breagh area result from predicting the nature of primary Lower Carboniferous reservoirs, whose fluvio-deltaic facies often form unconnected channels that make lateral correlation and reservoir quality prediction difficult without wells and core. The difficulty in correlation is exacerbated by the complex fault pattern within the Breagh Field which may compartmentalize the reservoir by either baffling fluid flow or by altering the juxtaposition of sandstone bodies from their original depositional configuration. Advances in 3D seismic imaging, processing and manipulation, with techniques such as spectral decomposition or root mean squared (RMS) extractions, provide a means of reducing reservoir presence.

Fig. 18. (a) Residual gravity map. Residual gravity anomalies in Quadrants 41–43 after subtracting a forward gravity calculation and background field from the observed gravity field. Modified after Kimbell and Williamson (2015). (b) Geothermal gradient map. Map showing the geothermal gradients (estimated) between the seabed and 2500 m TVDSS for selected wells with borehole temperature data, displayed alongside the thickness of the Zechstein Supergroup (in metres). Zechstein thickness map after Peryt et al. (2010).
Structural evolution of the Breagh area

Fig. 19. Breagh closure analysis. Depth–structure map of the Base Permian Unconformity (BPU/top Rotliegend (base Zechstein)) composite surface. The outline of the Breagh Field, defined by the closing contour of the gas–water contact (GWC: 2337 m TVDSS) at the BPU level is shown in red. The largest possible closing contour (dashed grey) is mapped at 2440 m TVDSS giving an area 63% larger than the Breagh Field, indicating that the structure is underfilled.

uncertainty in these settings (e.g. see examples in Chopra and Marfurt 2007).

The findings from this work have important implications for prospectivity in the area north of the Breagh Field and south of the MNSH. The underfilled nature of the field suggests that, following restructuration, the original closure remained intact and the structure did not leak. This reduces the potential for updip prospectivity from trapped gas leaked from Breagh. There remains the possibility for the remobilization of gas from other pre-inversion structures whose traps may not have remained intact. Hence, in the search for prospectivity, understanding the trap formation history both before and after the numerous phases of restructuration and regional tilting is important in assessing the charge potential for prospective structures. Whilst Breagh may not have leaked due to its persistent elevated presence during Mesozoic and Cenozoic times, surrounding areas may not have fared as well, perhaps explaining the field’s position as such an outlier some 30 km outside the main play fairly (Fig. 2). Therefore, harnessing further prospectivity from the area or in other comparable basins may best come from the search for similar long-lived antecedent highs, which would provide a more robust structural setting to the multiple phases of deformation that have affected the area. Investigating other gravity anomalies may be a good place to start.

In addition to the Lower Carboniferous play, penetration of the LSF in wells c. 10 km to the west and south of Breagh invites the possibility of a northern extension of the Rotliegend play. The thicknesses of sandstone encountered at the base of the Rotliegend in the southern wells (42/22-1 and 42/23-1) is comparable to those of known Rotliegend accumulations around the Market Weighton–Amethyst Granite in Quadrant 47 (Fig. 16), where the facies is typically thinner (e.g. 12–36 m in the Amethyst Field: Garland 1991). The terraced fault-block topography at the BPU during deposition of the Rotliegend Group may have worked to preserve pockets of thicker LSF within hanging-wall sequences. Updip pinchout of sandstone beneath the mudstones of the Silverpit Formation away from the footwall would present an opportunity for a structural–stratigraphic fault-trap play. Considering the difficulties in mapping the BPU and predicting Rotliegend thicknesses (see Cooper et al. 2005; Besly 2018), considerable risk should be accounted for when exploring for such targets, and structural closures at base Zechstein would present less uncertainty.

Zechstein Z2 carbonates of the isolated carbonate–sulfate platforms described at Crosgan, and further north by Patruno et al. (2017), offer additional exploration potential in the Breagh area, and regionally the Z2 carbonates form productive reservoirs (Karnin et al. 1992; Karnin et al. 1996; Peryt et al. 2010; Patruno et al. 2017). At Crosgan, the play has been proven by well 42/15a-2, which encountered a 52 m column of Hauptdolomit reservoir over the crest of the platform, with estimates of 13–42 Bcf gas initially in place (GIIP) and no definitive GWC in the well (Premier Oil 2007). Numerous gas shows have been detected in the tight Z2 basin bottomset carbonates across the area (Patruno et al. 2017), indicating the rather widespread potential for the play if additional isolated carbonate–sulfate platforms can be identified in the basin. Considering the rather sparse 3D seismic coverage in the area south of the MNSH, and the density of 2D coverage in respect to the potential scale of these features, it may be possible for additional platforms to exist in the areas between 2D lines. Or simply these platforms may not have been recognized or considered as potential exploration targets on existing legacy data.

The small (23 Bcf GIIP) Triassic discovery in the Bunter Sandstone Formation at 42/15b-1 about 15 km south of the Crosgan discovery (Premier Oil 2007) is located near the graben system and the isolated lower Zechstein platform of the Crosgan, which exhibits a reduced thickness of halite. The nearby Lower Carboniferous and Zechstein (Hauptdolomit Formation) carbonate discovery prove an effective Zechstein seal, and, like Breagh, there is a lack of through-going and inverted basement faults beneath the nearby Mesozoic graben. Moreover, whilst basement fault strands dissect the Zechstein platform, these faults are not hard-linked to the faults of the narrow Mesozoic graben above the platform. Hence, it seems unlikely that leaked gas from Crosgan charged the nearby small Triassic accumulation, which in fact hosts gas of slightly differing composition (more N-rich) (Premier Oil 2007). The gas in 42/15b-1 probably migrated from an inversion-related breached Zechstein salt weld further downdip. Nevertheless, the discovery demonstrates there is also some additional exploration potential in the Triassic and identifying areas of Zechstein seal breach by through-going inverted faults in areas of welded salt becomes a key success factor for Triassic plays.

Conclusions

The prospectivity of the Lower Carboniferous in the Southern North Sea has largely been ignored, mainly because of its depth of burial and a perceived lack of charge implicit from an absence of the Westphalian Coal Measures Group source rock. However, the discovery and development of Visean reservoirs in the Breagh Field demonstrate that there is potential at this stratigraphic level. The results of a new integrated evaluation of the 3D seismic data volumes with well data from the greater Breagh area of the Mid North Sea High emphasize the link between understanding the structure, trapping geometry and burial history, and the exploration and production success. Accurate depth conversion that accounts for the presence of a Mesozoic graben allows the extent of the
Breagh structure to be determined and its structural history to be revealed. Detailed analysis of its internal geometry shows that the trap structure consists of folded and truncated (subcropping) Visean reservoirs sealed by Upper Permian (Zechstein Super Group) evaporites. Basin-modelling studies suggest that charge from the Lower Carboniferous Scremerston Coal Group, which lies directly below the field, is likely to have occurred prior to Variscan uplift, implying that the field relies on a later lateral charge (long-distance migration). Hence, charge at Breagh resulted from spill and migration from gas-bearing palaeostructures and kitchens to the south and east following pronounced easterly tilt developed during the Cenozoic.

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