# Turning exploration risk into a carbon storage opportunity in the UK Southern North Sea

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**ABSTRACT:** Interpretation of a large, well-calibrated 3D seismic data volume in the UK Southern North Sea (SNS) suggests that the occurrence of two little known and hitherto poorly documented carbon dioxide ($CO_2$)-rich gas discoveries is strongly controlled by the style and timing of deformation and the presence of a regional Upper Permian (Zechstein Supergroup) evaporite super-seal. It can now be shown that the $CO_2$-rich accumulations are limited to Rotliegend Group, Leman Sandstone Formation (LSF) reservoirs located on the western edge of a major, extensional fault block, the Fizzy Horst, that lies on the eastern flank of a through-going NNW-striking, partially-inverted depocentre, termed the Brown Graben. Significantly, unlike other structures, which experienced Cenozoic compressional reactivation, the traps containing the $CO_2$ are located adjacent to deep-seated faults upon which contractional reactivation occurred *only* during the Late Cretaceous suggesting a spatial and temporal control on its occurrence. The structural results provide a robust, unifying and testable structural model through which to assess the inherent exploration risk of drilling unwanted, $CO_2$-prone traps in this part of the prospective basin. Conversely, the fact that $CO_2$ was evidently sealed over geological time-scales shows the significance and long-lived (*c.* 50 Ma) effectiveness of the Zechstein Supergroup evaporite canopy in retaining $CO_2$, as well as larger and less mobile methane ($CH_4$) molecules. The results thus highlight the potential that traps containing LSF reservoirs have as future sites for $CO_2$ storage (carbon sequestration) in the SNS.

**KEYWORDS:** *Southern North Sea, carbon sequestration, carbon capture and storage, dawsonite, Leman Sandstone Formation, basin inversion, exploration risk, Rotliegend Group reservoir play fairway, igneous dykes, carbon dioxide*

## INTRODUCTION AND RATIONALE

The discovery of significant carbon dioxide ($CO_2$) and nitrogen ($N_2$) gas volumes in the Southern North Sea (SNS) in 1995 by the 50/26b–6 exploration well was a major surprise and led to it being christened the 'Fizzy' Discovery. In an instant, the hitherto-held view that the main Permian, Rotliegend Group, Leman Sandstone Formation (LSF) reservoir play fairway in the SNS (Fig. 1) was an exclusive methane ($CH_4$) province needed reappraising. The subsequent discovery of more $CO_2$ (and $N_2$) gas in the neighbouring Dutch blocks P1 and P2 and by exploration well 54/1b-6 (termed the Oak Discovery) eleven years later only served to further underline the exploration risk of finding $CO_2$ rather than $CH_4$.

The unexpected occurrence of $CO_2$ in the discoveries clearly demands an explanation if pre-drill risk is to be assessed accurately and minimized in the area. The primary objectives of this study are, therefore, to examine why the $CO_2$ (and $N_2$) was found where it was, namely, in the heart of the prolific LSF $CH_4$ gas play fairway (Fig. 1), and to investigate whether the local geology might help predict its possible occurrence prior to drilling. This paper attempts to address these issues primarily by assessing the nature and timing of tectonic structures in and around Fizzy and Oak through the interpretation of a large, well-calibrated 3D seismic data volume (Fig. 2). However, it is very evident that a more complete understanding of the likely origins, longevity and possible mechanism for $CO_2$ gas entrapment in the LSF has a far greater significance in highlighting the importance that these discoveries have in demonstrating the major carbon storage opportunity that exists at this stratigraphic level in the SNS.

## BASIN DEVELOPMENT AND THE PETROLEUM SYSTEM

After more than four decades of exploration activity and the discovery of gas in Carboniferous, Permian, Triassic and Cretaceous reservoirs, the main components of the stratigraphy, structure and petroleum system of the UK and Dutch sectors of

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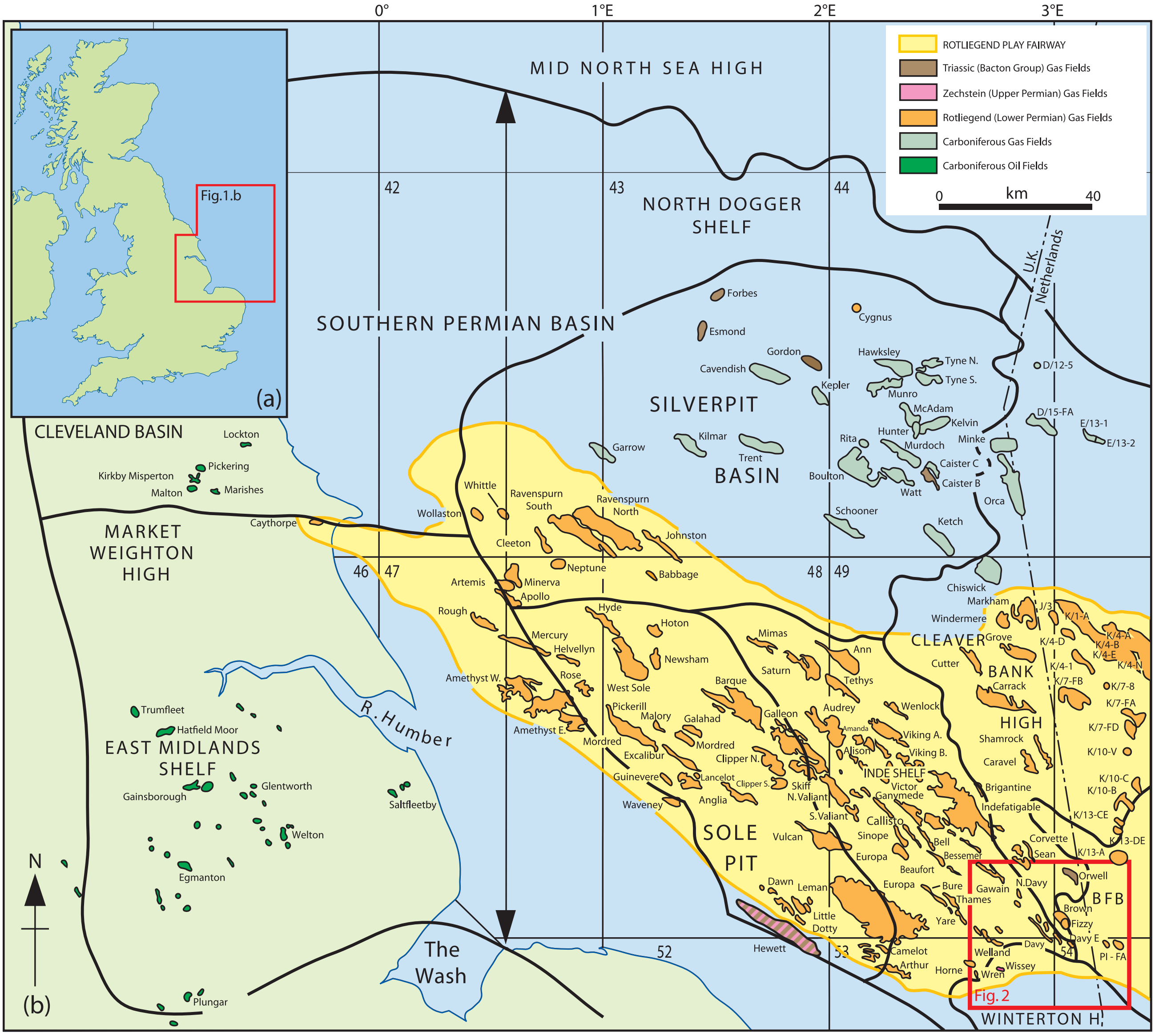


**Fig. 1.** Regional map of the Southern North Sea showing the location of the main fields (colour coded by reservoir age) and the main structural elements in the Southern Permian Basin. The limits of the Rotliegend play fairway (highlighted in yellow) are effectively defined by the northerly facies change to the Silverpit Claystone Formation and the southerly extent of the Zechstein Supergroup evaporite seal (modified after Underhill 2003). The study area containing the Fizzy and Oak $CO_2$ discoveries lies in the SE corner of the basin adjacent to the UK–NL international border at the intersection between four UKCS Quadrants (Q49, 50, 53 & 54), in a position close to where the Broad Fourteens Basin (BFB), Inde Shelf, Winterton High and Cleaver Bank High meet.

the SNS are well known (Fig. 1; Underhill 2003). The gas province is considered to lie within the confines of the Southern Permian Basin (SPB; Fig. 1), a major E–W-striking sedimentary basin that formed above folded and tilted Carboniferous and older sediments, deformed in the immediate foreland to the Variscan fold-and-thrust belt (Ziegler 1990; Cameron *et al.* 1992; Glennie 1998; Glennie & Underhill 1998; Underhill 2003).

The main (predominantly gas-prone) source rock underlies the SPB and consists of coals mainly (but not exclusively) belonging to the Upper Carboniferous (Westphalian), Coal Measures Group (Fig. 3). These sediments were originally deposited in a foreland basin formed adjacent to, and ahead of, the Variscan mountain chain (Glennie & Underhill 1998). Subsequent fault reactivation, folding, tilting and erosion led to the Carboniferous units being truncated and variably subcropping the Base Permian Unconformity (BPU; Corfield *et al.* 1996; Besly 1998).

Permian syn-sedimentary rifting largely determined the spatial extent of its tectonic sub-components, including the Sole Pit Basin, Inde Shelf, Cleaver Bank High, Broad Fourteens Basin, Silverpit Basin and Winterton High (Van Hoorn 1987; Alberts & Underhill 1991; Fig. 1). Whilst differential subsidence and growth faulting also controlled the regional and local depositional thicknesses (Arthur *et al.* 1985; George & Berry 1997), the predominant influence on the petroleum system at this time was its tropical (desert) palaeolatitude, with the resultant admixture of aeolian wadi and sabkha depositional environments (Glennie 1998) since that controls the extent of the Rotliegend Group clastic play fairway (Fig. 1). Further north, beneath the Silverpit Basin, contemporaneous deposition of desert lake (salina) mudstones led to the Rotliegend, Silverpit Claystone Formation acting as a seal for Carboniferous clastic reservoirs truncated by the BPU (Bailey *et al.* 1993; Besly 1998; Glennie 1998).

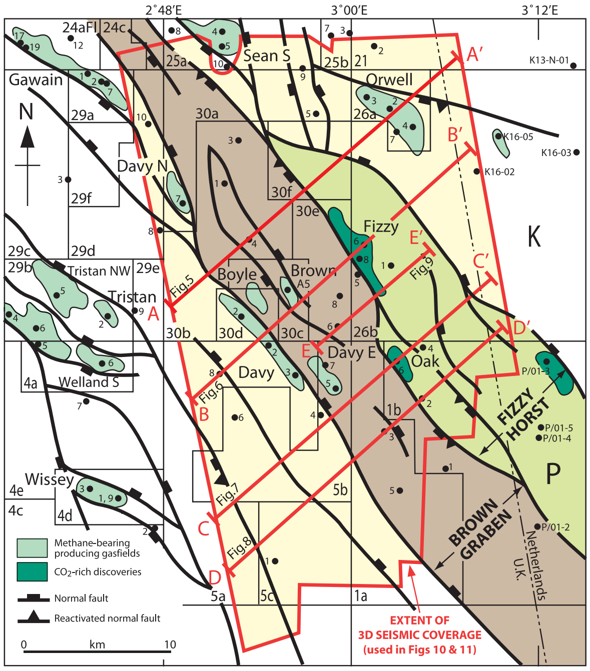


**Fig. 2.** Location map showing the extent of 3D seismic data coverage used in this study and the relative position of the main $CO_2$ and $CH_4$ gas accumulations (fields and undeveloped discoveries), exploration wells, seismic lines and other figures used in this paper. The seismic data were acquired by WesternGeco and provided to the project by Tullow Oil. The locations of the five seismic lines used to demonstrate the prevailing structural styles in Figures 5–9 are highlighted.

As active extension diminished and subsidence rates declined during the post-rift (Geluk 1999, 2005), Late Permian marine recharge and evaporation occurred producing a mixed and cyclic carbonate–evaporite (margin-basin) deposystem ascribed to the Zechstein Supergroup (Tucker 1991), the anhydritic and halitic parts of which largely form the super-seal for the underlying LSF gas play (Taylor 1998).

A return to continental conditions during the Triassic led to clastic red-bed deposition ascribed to the Bacton and Haisborough groups (Johnson *et al.* 1994). Coarse-grained fluvial sediments belonging to the Hewett and Bunter Sandstone formations have proven reservoir potential where they are sealed by the Bunter Shale Formation and Röt Halite Member, respectively (Fisher & Mudge 1998). For the most part, the Triassic reservoirs are contained within anticlinal closures formed by subsequent fault reactivation (e.g. in the Orwell and Hewett gas fields) or created by the mobility (halokinesis) of the Zechstein Supergroup evaporites (e.g. in the Silverpit sub-basin; Underhill 2004, 2009). In some locations, salt mobility appears to have been triggered by Cenozoic dyke intrusion (Underhill 2009), a process which also led to higher than normal $CO_2$ and $N_2$ gas concentrations in the Triassic, Bacton Group reservoirs of nearby gas fields such as in the Forbes, Esmond and Gordon fields of the Silverpit area (Fig. 1; Bifani 1986; Ketter 1991).

Despite being punctuated by the phase of Late Jurassic (Cimmerian) regional uplift that removes much and, in some places, all of the Jurassic section to create the Base Cretaceous Unconformity (BCU; Badley *et al.* 1989), apatite fission track analysis, vitrinite reflectance studies and well-based burial curve plots have suggested that Mesozoic subsidence and deposition of the Cromer Knoll and Chalk Groups resulted in Carboniferous source rocks reaching their maximum maturity in the

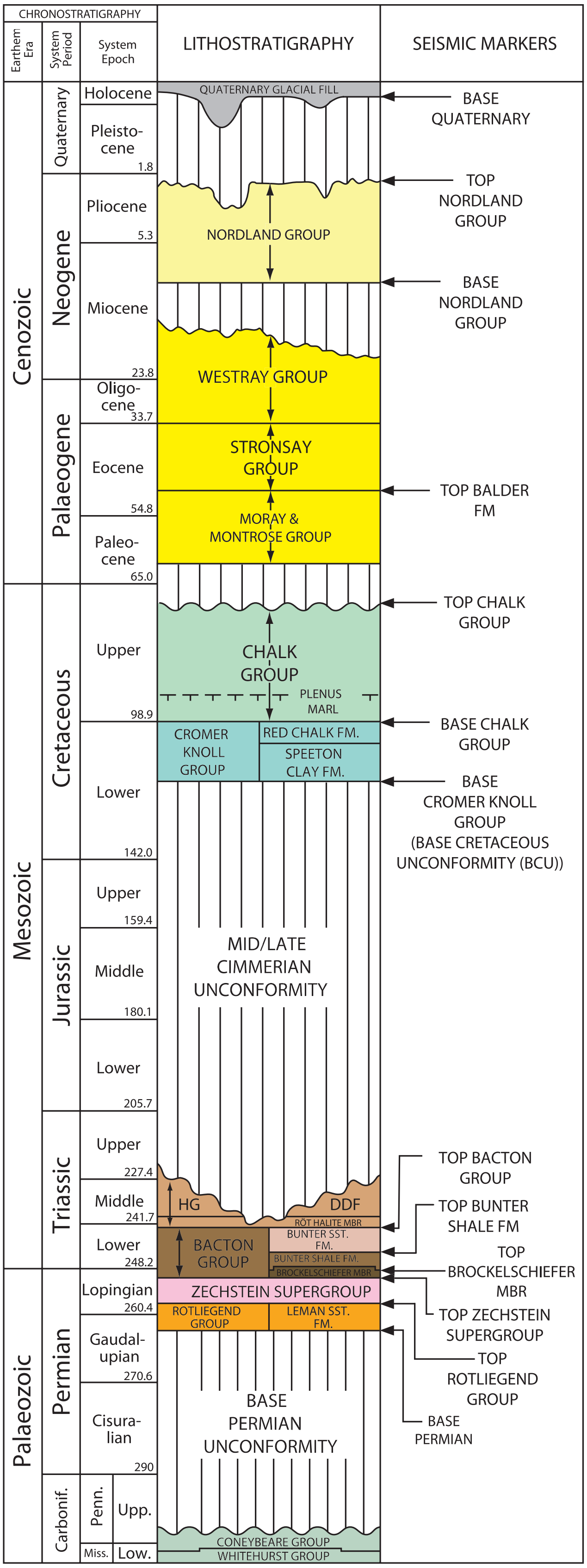


**Fig. 3.** General stratigraphy derived from wells in the immediate study area showing the main lithostratigraphic elements and main seismic markers used in the interpretation. The colour code used is the same as that displayed on the seismic lines and structural restoration used in the paper. HG, Haisborough Group; DDF, Dowsing Dolomite Formation.

early part of the Late Cretaceous (Glennie & Boegner 1981; Van Hoorn 1987; Alberts & Underhill 1991). Gas generation from the kitchen areas is thought to have subsequently been arrested by later Cretaceous and, more especially, Cenozoic regional uplift and basin inversion that also affected large parts of NW Europe (Ziegler 1990; Hillis 1995). These substantive uplift episodes also led directly to the formation of numerous prospective structural traps (Glennie & Boegner 1981). The paradoxical mis-timing between charge and trap formation in what is evidently a highly successful gas province, implies that the Zechstein Supergroup evaporites have acted as a highly effective super-seal that formed a canopy under which $CH_4$ could re-migrate during later deformation events without being lost to the system (Alberts & Underhill 1991).

## EXPLORATION ACTIVITY

The study area straddles the four-cornered intersection of United Kingdom Continental Shelf (UKCS) Quadrants 49, 50, 53 and 54 (Figs 1, 2). Until the drilling of Fizzy and Oak, it had proved to be highly prospective, with $CH_4$ production being achieved from LSF reservoirs in thirteen fields and discoveries: Boyle, Brown, Davy, Davy E, Davy N, Gawain, Horne, Sean S, Tristan, Tristan NW, Welland S, Welland NW and Wren (Fig. 2). $CH_4$ has also been discovered in, and produced from, the Triassic Bunter Sandstone Formation in the Orwell Field and Zechstein Supergroup (Z3) Plattendolomit Formation carbonates in the Wissey Field (formerly Scram: Clark 1986) in the study area (Figs 1, 2).

After such excellent exploration success and the recognition of further drillable, low-risk prospects, it came as a major surprise when exploration well 50/26b–6 discovered an anomalously high (*c.* 50%) and previously inexplicable amount of $CO_2$ and $N_2$ (9%) in a 100.6 m (330 ft) thick, dawsonite-bearing, yet otherwise good quality (18% porosity; 260 mD permeability), LSF reservoir with 60% gas saturation (Fig. 4). Although the original exploration well was not tested, the Fizzy accumulation was appraised two years after discovery by a highly deviated well, 50/26b–8, that included a 1559 m (5116 ft) horizontal section and which had an even higher (90%) gas saturation. This time a production test was run and total gas flow was at a rate of $40 \times 10^6$ SCF/day ($1.133 \times 10^6$ SCM/day). Despite encouraging appraisal data and a calculated gas sales volume of $CH_4$ of *c.* $120 \times 10^9$ SCF, the discovery has yet to be produced commercially, primarily because of its significant $CO_2$ content.

The other $CO_2$ discovery in the UK sector of this part of the SNS, Oak, was drilled by Serica's exploration well 54/1b-6 in 2006 to test a separate, well-defined fault-bounded terrace structure situated approximately 10 km along-strike to the SSE. Like Fizzy, it was also found to contain thick, good-quality LSF host reservoir with a 34.44 m (113 ft) gross gas column, the upper 24.38 m (80 ft) of which produced at a rate of $10 \times 10^6$ SCF/day ($0.284 \times 10^6$ SCM/day) on a 44/64″ choke. Ordinarily this would have been heralded as a success and led to field development, something that because of its high $CO_2$ content now appears increasingly unlikely.

## SUBSURFACE DATABASE

The 3D seismic data used in this study consist of pre-stack time migration (PSTM) data acquired in 1995 by WesternGeco as part of a larger, speculative seismic survey, called Q49–53. As well as covering the immediate area in which $CO_2$ has been discovered, the seismic volume used extends over *c.* 450 km$^2$ and covers part or all of nine UKCS licence blocks and a narrow western strip of three licences situated in the Dutch Sector (Fig. 2). The two (Fizzy and Oak) $CO_2$ accumulations and seven neighbouring $CH_4$-producing fields (Boyle, Brown, Davy, Davy E, Davy N, Orwell and Sean S) also lie within its boundaries (Fig. 2). Use has been made of checkshots, velocity logs and synthetic seismograms from 33 exploration wells to constrain the seismic interpretation in the area, all but one of which are located in the UK sector (Fig. 2). As a result of the stratigraphic constraints made possible through the dense seismic and well coverage in the local area, fault geometries can be determined and the tectonic evolution deduced with confidence.

Given the fidelity and coverage of the dataset that has become available in recent years, it is somewhat surprising that little published information exists regarding the detailed tectonic and stratigraphic evolution of the area. The only detailed descriptions in the immediate area focus upon the development of the Brown and Davy gas fields (McCrone 2003), the Sean gas fields to the north (Hillier 2003), the Thames, Yare and Bure gas fields to the west (Werngren 1991) the Gawain gas field to the north-west (Osbon *et al.* 2003) and the presence of Werrahalit pods in the Tristan area (Underhill & Hunter 2008). No detailed account of the Fizzy and Oak accumulations exists in the literature.

## SEISMIC INTERPRETATION AND STRUCTURAL SYNTHESIS

Whilst the whole 3D seismic volume was interpreted, use is made herein of four, representative, well-constrained *c.* 30 km long, dip sections (Figs 5–8) and one more local *c.* 10 km long dip section (Fig. 9) to illustrate the main fault geometries and timing of structural development that characterize the area around the Fizzy and Oak discoveries. It is the observations of, and interpretations drawn from, the seismic data that permit top time-structure maps (Fig. 10) and isochron maps (Fig. 11) to be produced for each of the key stratigraphic horizons and the intervals they bound, respectively. A schematic structural restoration was also constructed through the Fizzy discovery to illustrate the development and evolution of structural styles in the area (Fig. 12). It is these maps and the structural restoration that provide the basis for demonstrating a temporal and spatial structural control on the $CO_2$ occurrence.

The seismic data demonstrate that the area is characterized primarily by numerous NNW-, NW- and WNW-striking, steep, variably ENE-, WSW-, NE-, SW-, NNE- and SSE-dipping normal faults in the deeper (pre-Zechstein) parts of the sections (Figs 5–11). The opposed dip-direction displayed by prominent normal faults located west of the Fizzy discovery defines a pronounced graben structure (Figs 2, 5–11), named the Brown Graben herein after the Brown gas field located in a small horst running along its axis (Figs 2, 6; McCrone 2003).

Flattening of the BCU not only demonstrates the characteristic block-and-basin tectonic system (Fig. 12a), but also allows normal faults with the largest displacements to be readily identified, including those that border the Brown Graben. As well as preserving the greatest thickness of Triassic sediments within the region, a two-, to three-fold increase in LSF thickness in the Brown Graben has been documented (McCrone 2003). This observation demonstrates that the graben represents a long-lived feature controlled by syn-sedimentary normal faulting during the Permian and Triassic. Evidence for pronounced Bouguer gravity anomalies on the margins of the Brown Graben (Fig. 13), suggests that the long-lived structural high may be underlain by a significant granite body.

Elsewhere in the basin, extensional tectonism is known to continue through until Late Jurassic times. It is not possible to demonstrate this here due to the absence of any preserved

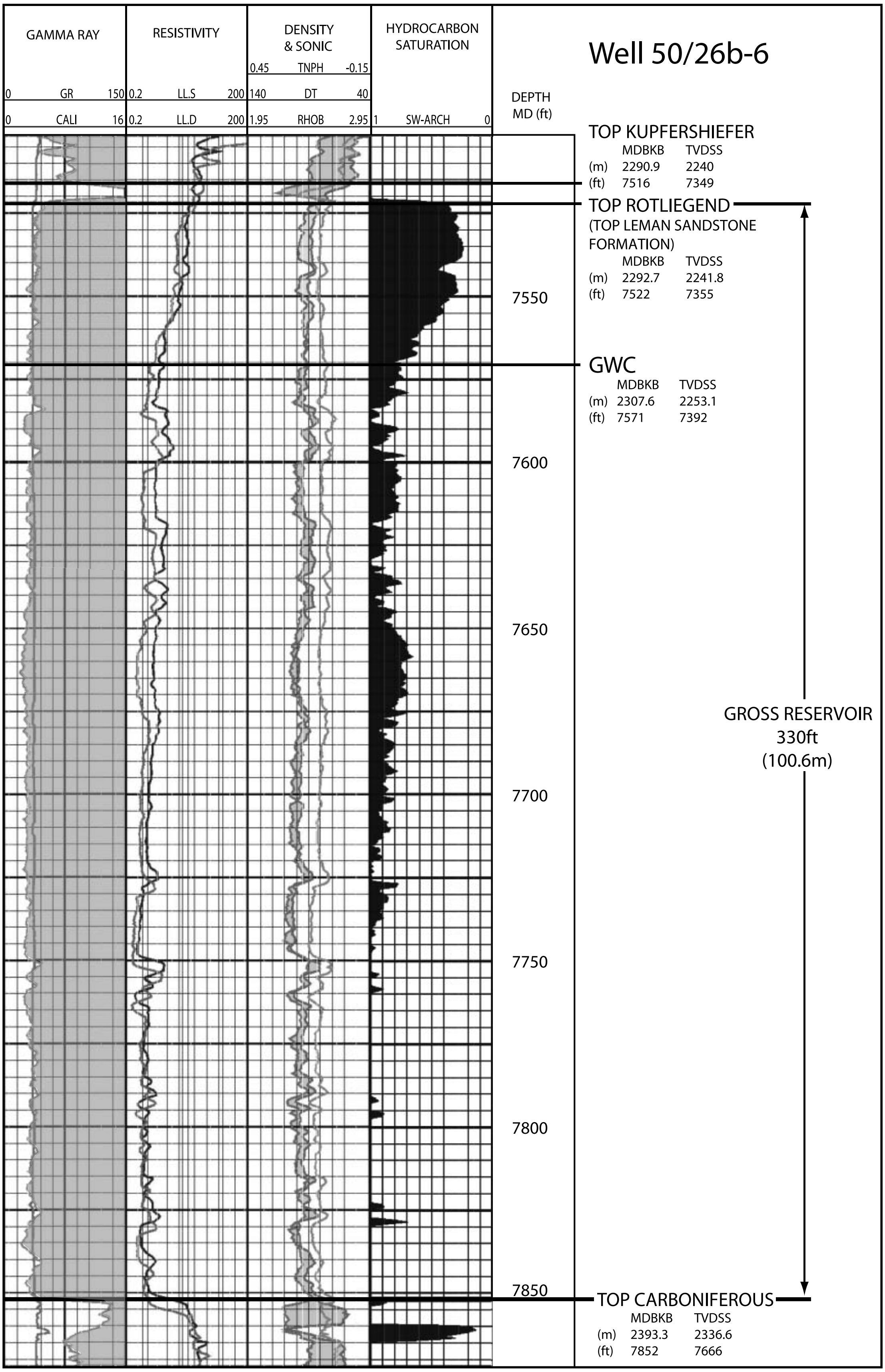


**Fig. 4.** Electrical well-log signatures of the Rotliegend Group, Leman Sandstone Formation (LSF) reservoir penetrated by the 50/26b–6 Fizzy discovery well. The figure highlights the thickness and good quality of the LSF reservoir in the well, despite it being partially cemented by dawsonite, a mineral associated with reactions between CO$_2$ and host reservoirs (Hellevang *et al.* 2005; Kaszuba *et al.* 2006) usually derived from a magmatic source (Baker *et al.* 1995; Li *et al.* 2007).

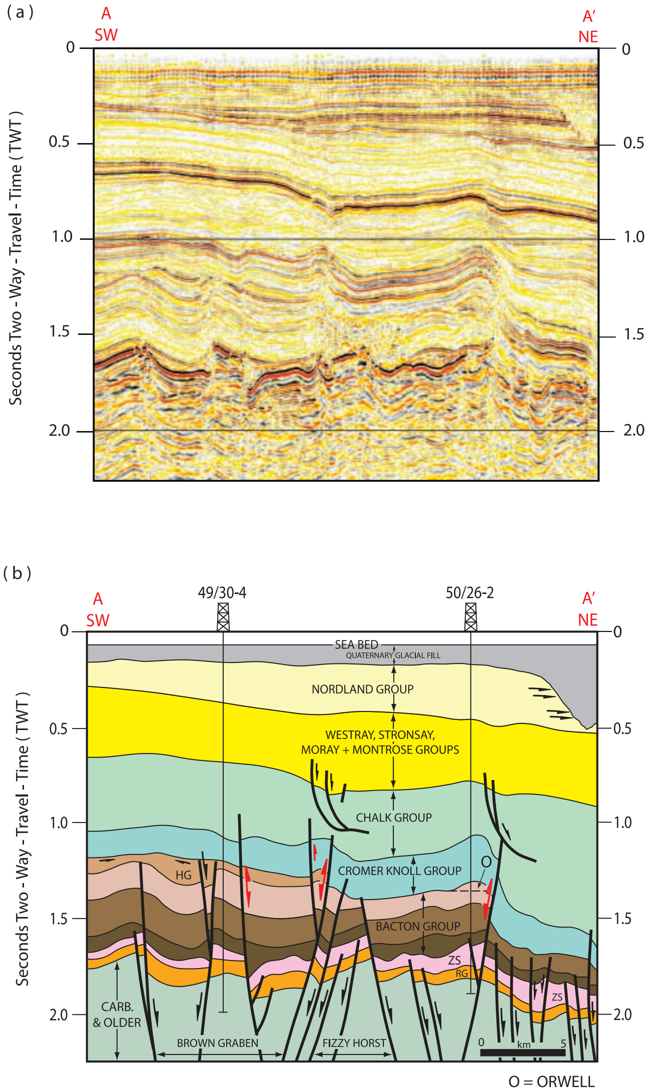


**Fig. 5.** Uninterpreted and interpreted SW–NE-striking seismic dip-line through exploration wells 49/30b-4 and 50/26–2 (Orwell Field) illustrating the stratigraphy for the area and the dominant structural style of normal faulting and structural inversion that sets up the main trap types in this part of the basin. The line highlights the occurrence of a major syn-sedimentary graben (the Brown Graben) in which Rotliegend Group sediments are more than twice as thick as on its flanks. The northeastern boundary normal fault of the Brown Graben and the Orwell fault are both marked by significant contractional reactivation. In both cases, thinning of, and listric faulting within, the Chalk Group above the reactivated normal faults demonstrates that positive inversion took place during the Late Cretaceous. The position of the seismic section is shown on Figure 2. RG, Rotliegend; HG, Haisborough Group; ZS, Zechstein Supergroup. The seismic line is shown courtesy of WesternGeco.

section as a result of Late Jurassic (Cimmerian) uplift and erosion that led to the removal of any original Jurassic section and the creation of the BCU (Badley *et al.* 1989).

Tracing the extensional structures to shallower levels shows that some of the deep-seated faults have clearly undergone compressional reactivation to cause reverse offset of the BCU and top Cromer Knoll Group seismic markers as well as the formation of monoclinal folds that affect lower parts of the Chalk Group (Figs 5–8).

The most prominent reactivated normal faults that experienced reversal of throw are those that mark the boundary faults to the Brown Graben (Fig. 12c). Reactivation has led to the local development of footwall shortcut reverse faults (*sensu* Cooper *et al.* 1989) on the western edge the Fizzy Horst (Fig. 9). The structural observations suggest that the two margins of the Brown Graben acted as significant footwall buttresses along which displacement localized during contractional reactivation, something that might be expected if its

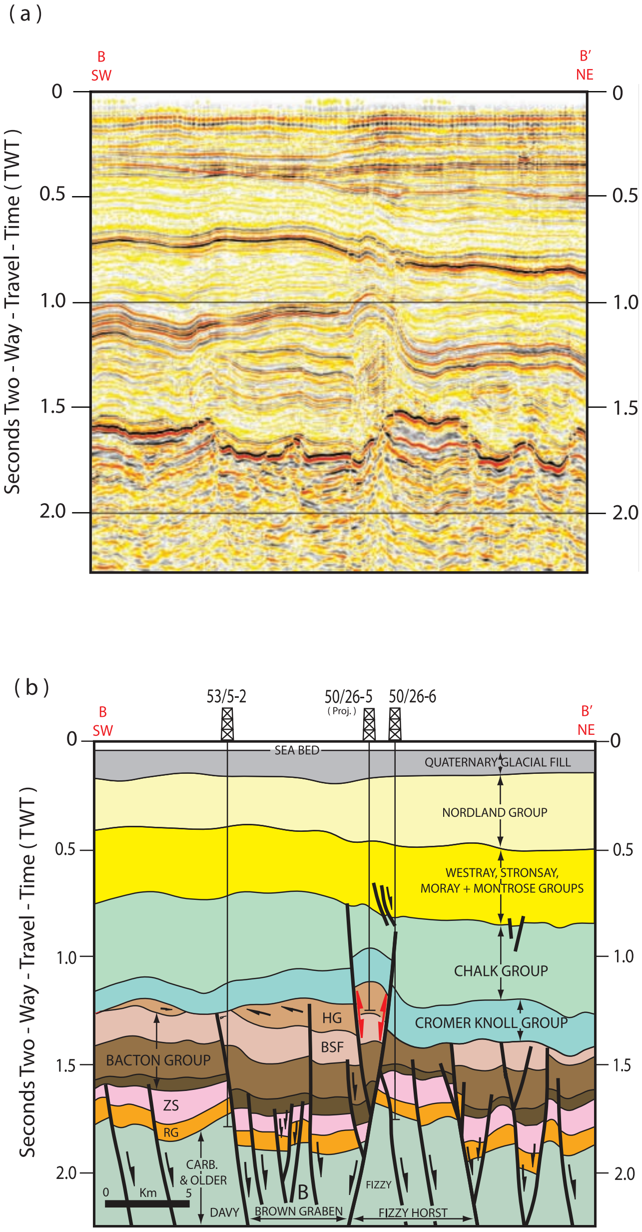


**Fig. 6.** Uninterpreted and interpreted SW–NE-striking seismic dip-line through exploration wells 53/5–2 (Davy Field), the Brown Field (B), 50/26b–5 and 50/26b–6 (Fizzy $CO_2$ discovery) illustrating the occurrence of a major palaeohorst block containing the Fizzy Field in the immediate footwall to the structurally inverted northeastern boundary normal fault of the Brown Graben. As in Figure 5, thinning of, and listric faulting within, the Chalk Group above the reactivated normal fault and a prominent linked antithetic demonstrates that positive inversion took place during the Late Cretaceous. Whilst the 50/26b–5 well was probably intended to be a test of the Bunter Sandstone Formation (BSF) contained within the structurally inverted pop-up defined by reactivated conjugate normal faults, work undertaken during this study has shown that it only drilled into the Upper Triassic, Haisborough Group section and hence, the BSF play appears to remain untested. The position of the seismic section is shown on Figure 2. See Figure 5 for abbreviations. The seismic line is shown courtesy of WesternGeco.

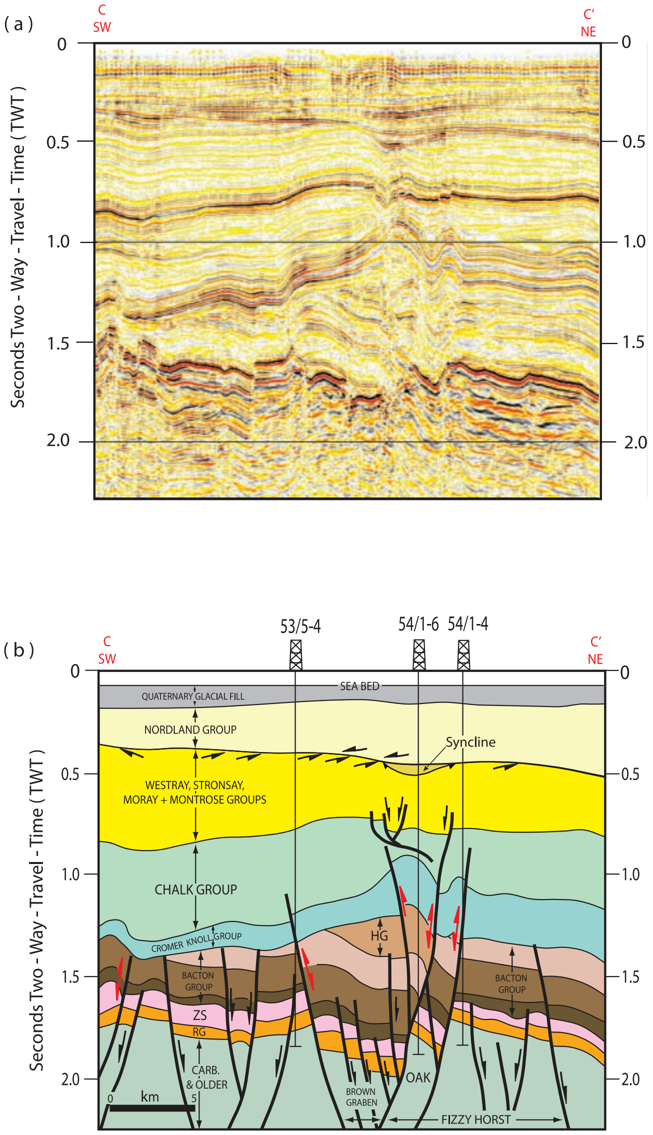


**Fig. 7.** Uninterpreted and interpreted SW–NE-striking seismic dip-line through exploration wells 53/5–4, 54/1b–6 (Oak $CO_2$ discovery) and 54/1–4 illustrating the complexity of structural deformation that characterizes the buttressed hanging wall to the structurally inverted northeastern boundary normal fault of the Brown Graben. As with the Fizzy $CO_2$ discovery, the Oak discovery is situated in a structurally inverted terrace, lying in the immediate footwall to the Brown Graben. Thinning of, and listric faulting within, the Chalk Group above the reactivated normal fault and a prominent linked antithetic fault splay again demonstrate that positive inversion took place during the Late Cretaceous. The position of the seismic section is shown on Figure 2. See Figure 5 for abbreviations. The seismic line is shown courtesy of WesternGeco.

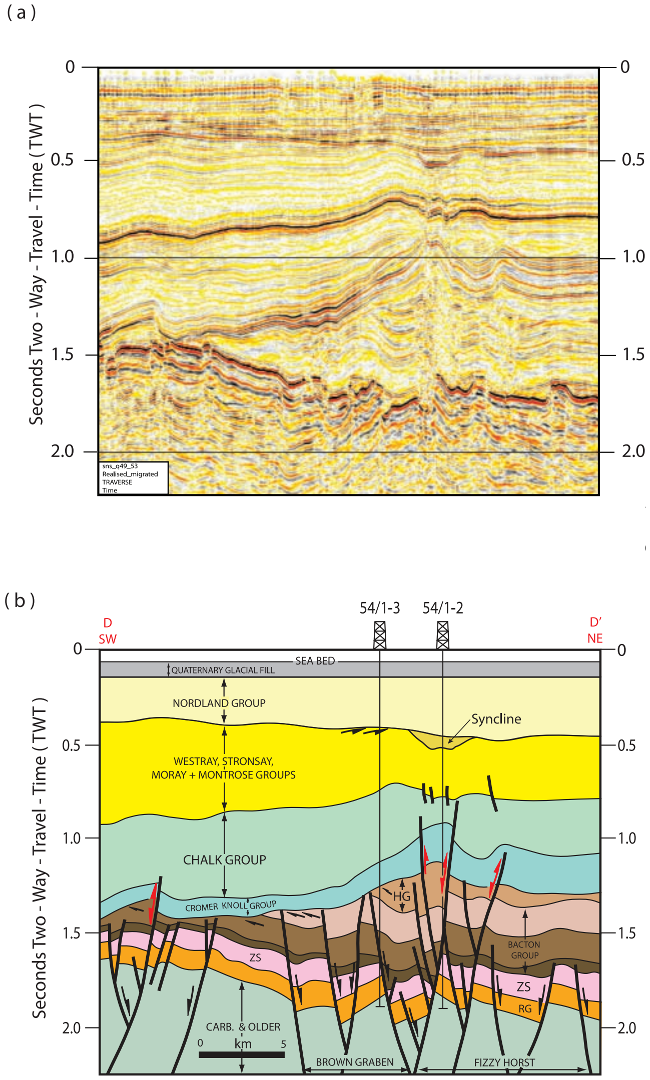


**Fig. 8.** Uninterpreted and interpreted SW–NE-striking seismic dip-line through exploration wells 54/1–3 and 54/1–2 highlighting hanging-wall and footwall deformation associated with the structurally inverted northeastern boundary normal fault of the Brown Graben. As before, thinning of, and listric faulting within, the Chalk Group above the reactivated normal fault and a prominent linked antithetic demonstrates that positive inversion took place during the Late Cretaceous. The position of the seismic section is shown on Figure 2. See Figure 5 for abbreviations. The seismic line is shown courtesy of WesternGeco.

margins were defined by a deeply buried granitic intrusion, or rigid basement body as implied by gravity data (Fig. 13).

Thinning, stratal rotation and erosional truncation that characterize upper parts of the Chalk Group (Figs 5–9) clearly demonstrate that the contractional deformation took place during the Late Cretaceous after a period of renewed subsidence in the Early Cretaceous (Figs 12b, c). More detailed analysis of the reflector terminations illustrates that at least three unconformities occur within upper parts of the Chalk Group (Fig. 9) thus attesting to the importance of progressive, punctuated and localized fault reactivation along its bounding faults during the Upper Cretaceous episode of deformation.

The structural geometries displayed are consistent with those that typify basin inversion in neighbouring areas of southern England (e.g. Wessex Basin; Williams *et al.* 1989; Underhill & Paterson 1998; Underhill & Stoneley 1998) and the SNS (Badley *et al.* 1989). In the case of the Orwell structure (discovered by well 50/26–2; Figs 2, 5), reversal of movement on the precursor normal fault has set up a hanging-wall closure at Bunter Sandstone Formation level (Fig. 5). The significant fault throw at Permian levels there appears to have caused a breach of the Zechstein Supergroup evaporite seal and the means by which $CH_4$ gas could escape up the main field-bounding fault from the Lower Palaeozoic to create the only known Triassic reservoir discovery in the immediate area (Figs 1, 5).

The Late Cretaceous timing of tectonic inversion is consistent with deformation displayed by some Chalk Group sections in NW Europe (e.g. in the Norwegian Central Graben: Ziegler

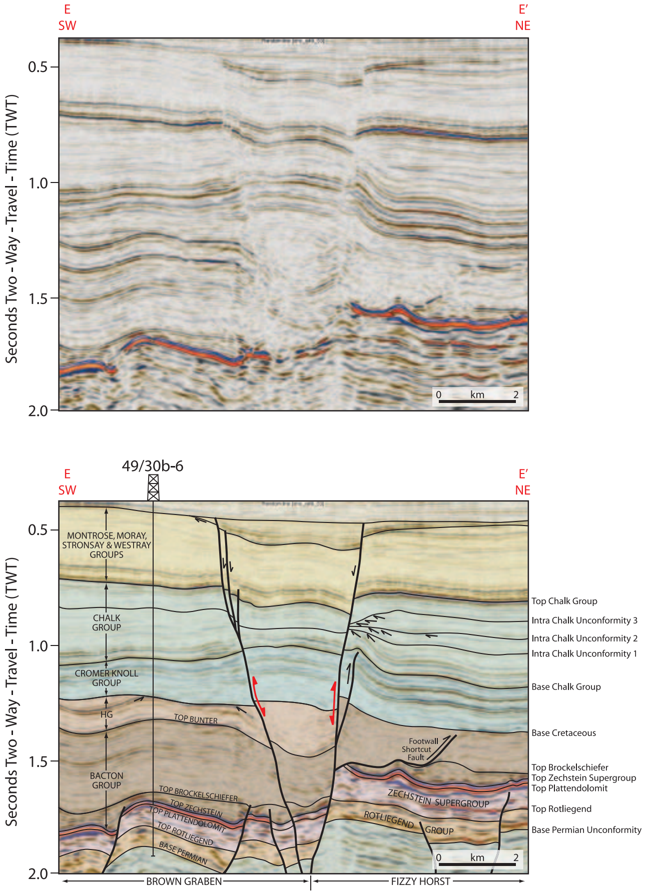


**Fig. 9.** Detail of a seismic section through the inversion structure generated against the Fizzy Horst, highlighting the presence of a prominent footwall short-cut fault transecting its footwall buttress. The presence of three prominent erosional unconformities in the Chalk Group provides the evidence for intra-Chalk structural reactivation of the buried and structurally inverted normal fault. The fault system reactivated again in extension during the Cenozoic. The location of the seismic line is shown on Figure 2. Seismic line shown courtesy of WesternGeco.

1990; Etretat in France and Portsdown: Gale 1980). With the North Atlantic Ocean yet to open between Britain and Greenland (that occurred *c.* 55 Ma ago), and the Alpine mountain belt in its infancy, the main driver for intraplate contraction at this time is likely to have been NE–SW-directed compressional plate margin forces related to opening of the Bay of Biscay and propagation of the Labrador Sea, west of Greenland (Ziegler 1990).

Other than being gently folded, the top Chalk shows little effect of the underlying zones of disturbance and is devoid of contractional faulting (Figs 5–9). Instead, it is marked by small extensional offsets along faults that appear to sole-out along bedding planes within the underlying Chalk Group itself (e.g. Figs 5, 7) and probably resulted from gravity collapse due to gradients induced by structural relief and compaction above the uplifted strata in the buried hanging wall of the structurally inverted fault below.

Regional doming related to the development of the Proto-Iceland hotspot led to the development of a major disconformity between the Chalk and the Early Cenozoic, which led to Late Paleocene or Early Eocene strata of the Montrose or Moray groups resting directly (and disconformably) upon pre-Maastrichtian chalk (Fig. 3). Igneous and volcanic activity during the Early Cenozoic led to the development of the British Palaeogene Igneous Province, west of Britain, the effects of which extended across northern Britain and into the SNS where it is expressed by the presence of WNW-striking, linear dykes (Brown *et al.* 1994; Underhill 2009) and a zone of devolatized coals that extends across the SNS into the Dutch sector (Eames 1975; Bell 1976; Kirton & Donato 1985; Fig. 14). The most southerly onshore example, the Cleveland Dyke, may be traced across the basin and appears to lie immediately north of the study area (Fig. 14).

Observations in higher parts of the Cenozoic section demonstrate that renewed subsidence during the Palaeogene was accompanied by minor and spatially localized extensional faulting that offsets the top Chalk Group immediately above the axes of intra-Upper Cretaceous structural inversion (Figs 7–9, 12d). Taken together with the evidence for subsequent erosional truncation and sub-crop of a well-defined elongate syncline located in upper parts of the Westray Group (Figs 7–9), the seismic interpretation implies that compaction above the deep-seated faults continued to exert an influence on sedimentation long after they became dormant, but before regional bevelling during the Oligo-Miocene uplift episode (Fig. 12e). The top parts of subsequent Neogene deposition are eroded by a prominent base Quaternary unconformity, the deeply incised parts of which were formed by major, incised Quaternary and Holocene tunnel valleys (e.g. Fig. 5; Praeg 2003).

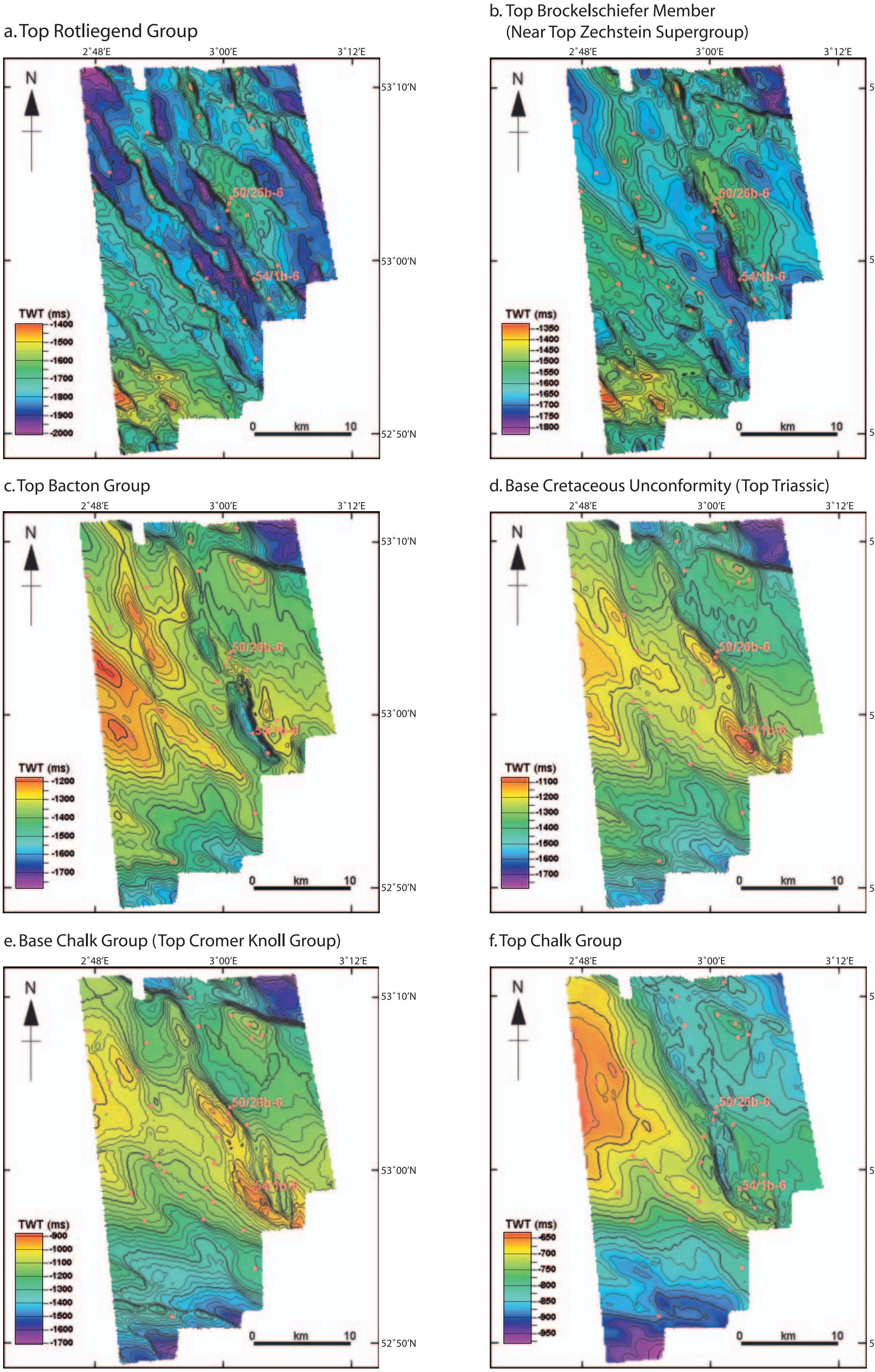
## DISCUSSION

### Implications for exploration risk and prospectivity

It is clear from the seismic interpretation and structural restorations that the Fizzy and Oak $CO_2$-rich accumulations lie in a western terrace of, and in the immediate footwall to, the prominent Fizzy Horst extensional fault block, respectively (Fig. 2). Both structures are bounded by long-lived, deep-seated and through-going normal faults, which only experienced significant contractional reactivation during the Late Cretaceous (Fig. 12). Given the Oligo-Miocene timing of $CH_4$ (re)migration implied by other well results, a post-Cretaceous, pre-Neogene $CO_2$ (and $N_2$) charge appears likely in Oak and Fizzy. Gas ingress was probably driven by high heat flow and ingress along the deep-seated tectonically inverted fault system during the Palaeogene with preservation of the accumulations over the past 50 Ma or so.

Whilst direct evidence for an igneous source is lacking in the immediate area, the magnetic data suggest that contemporaneous Palaeogene igneous dyke intrusion crosses the region (Fig. 14), with consequent high heat flow and coal devolatization seen in neighbouring parts of the SNS (e.g. in the Silverpit Basin and Dutch sectors; Eames 1975; Bell 1976; Kirton & Donato 1985; Brown *et al.* 1994; Underhill 2009). Such a source is not unusual and fault-related $CO_2$ charge has often been found to be associated with deep-seated inorganic charge from a magmatic source or devolatization of $CO_2$ released from minerals following metamorphism or metasomatism (Wopfner & Hocker 1987; Wycherley *et al.* 1999; Li *et al.* 2007). It is also conceivable that alteration of deeply buried Carboniferous (Dinantian) limestones may also contribute some of the $CO_2$.

The reported presence of traces of the sodium aluminium carbonate hydroxide mineral, dawsonite ($NaAlCO_3(OH)_2$), within the LSF reservoir in Fizzy, albeit amounting to less that 1% solid volume, may also be relevant here. Whilst rare in nature, thermodynamic and reactive transport calculations predict that dawsonite precipitates during diagenesis or hydrothermal activity associated with the dissolution of aluminium-bearing minerals in the presence of sodium-bearing brine (Wopfner & Hocker 1987; Duan *et al.* 2005; Hellevang *et al.*



a. Top Rotliegend Group

b. Top Brockelschiefer Member (Near Top Zechstein Supergroup)

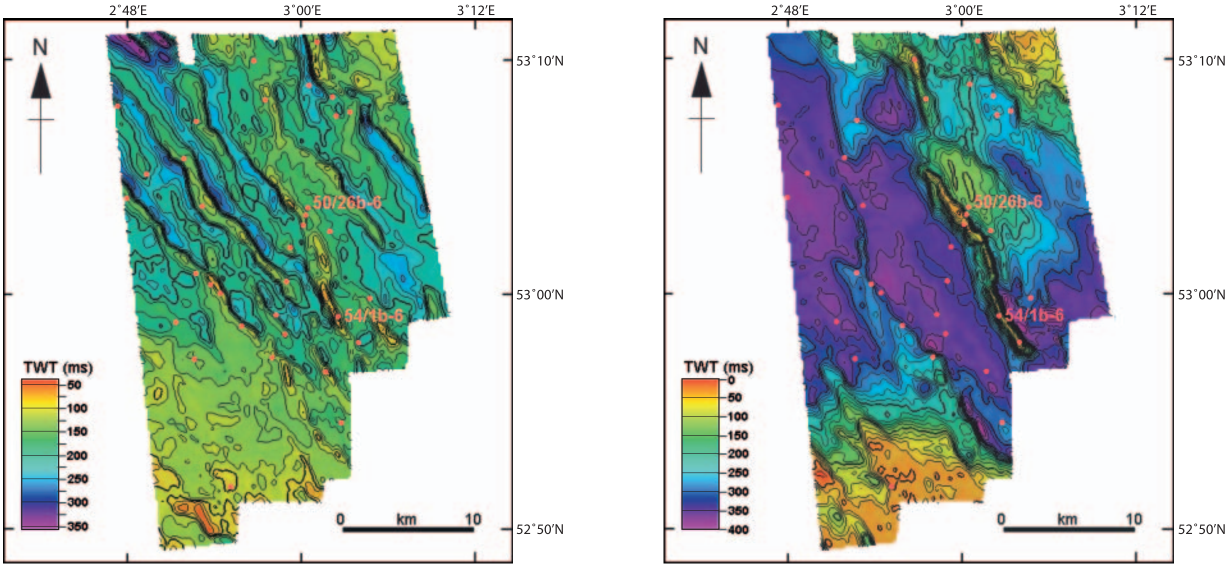
c. Top Bacton Group

d. Base Cretaceous Unconformity (Top Triassic)

e. Base Chalk Group (Top Cromer Knoll Group)

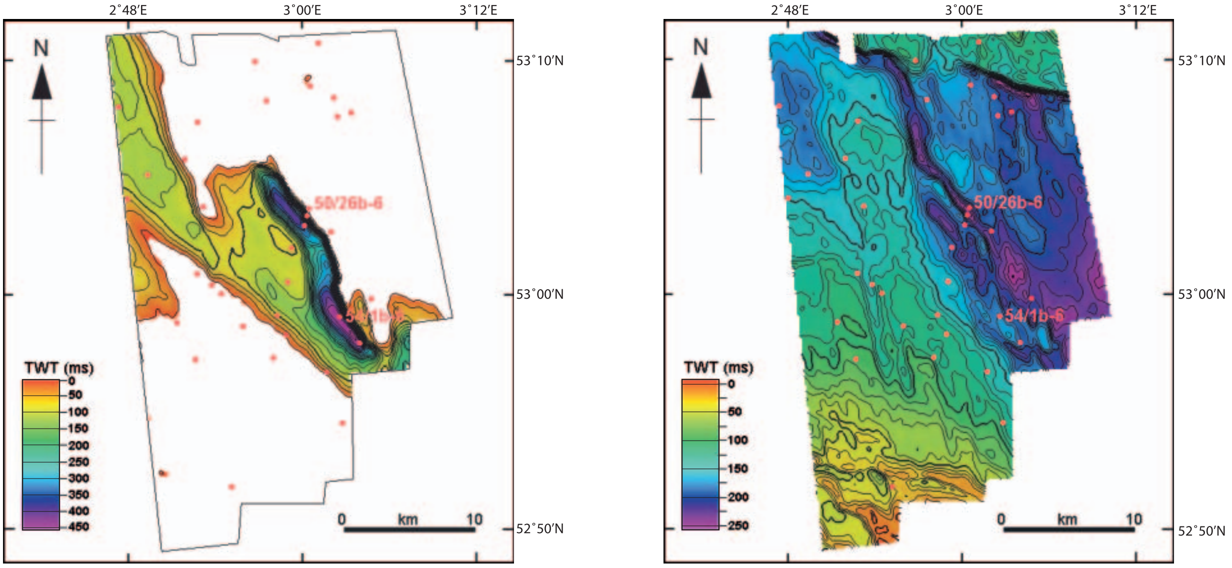
f. Top Chalk Group

**Fig. 10.** Top structure maps (in ms two-way travel time; TWT) for the following six key stratigraphic horizons: (**a**) top Rotliegend (Leman Sandstone Formation); (**b**) top Brockelschiefer (near top Zechstein Supergroup); (**c**) top Bacton Group; (**d**) Base Cretaceous (base Cromer Knoll Group/top Triassic Haisborough Group); (**e**) base Chalk Group (top Cromer Knoll Group); (**f**) top Chalk Group.



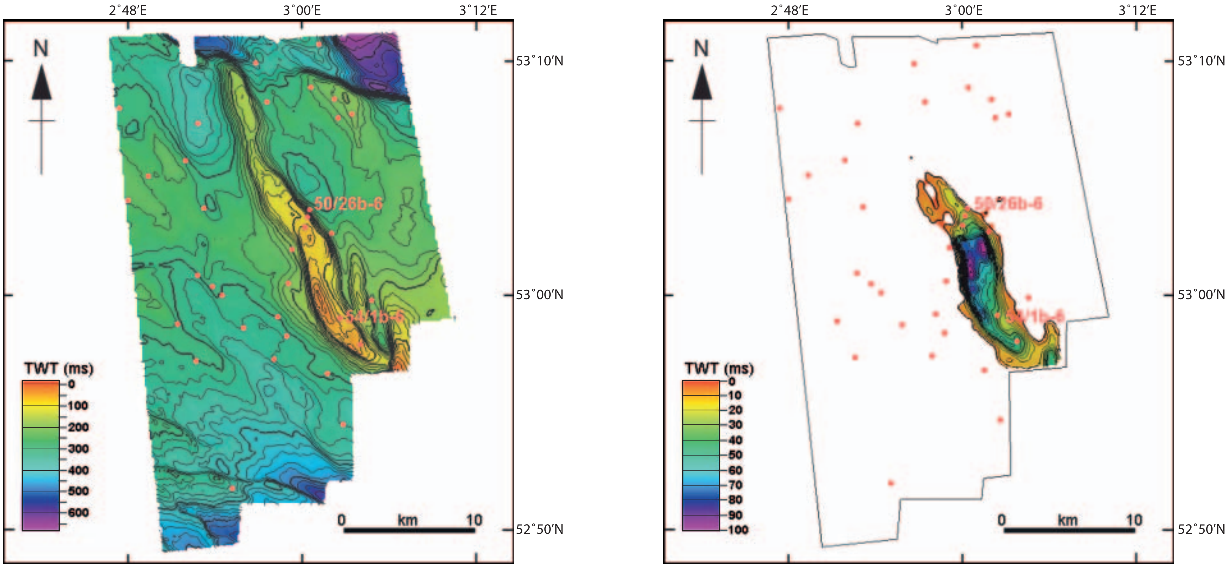
a. Zechstein Supergroup Isochron

b. Bacton Group Isochron



c. Haisborough Group Isochron

d. Cromer Knoll Group Isochron



e. Chalk Group Isochron

f. Westray Group Syncline Isochron

2005; Kaszuba *et al.* 2006). For example, it is readily synthesized from kaolinite in concentrated sodium bicarbonate ($NaHCO_3$) if there is a sodium source present. In the case of the Rotliegend LSF reservoir, that sodium source may conceivably be from a deep metasomatic source, as demonstrated in other sedimentary basins (Baker *et al.* 1995; Wycherley *et al.* 1999), hydrothermal reactions with the K-plagioclase feldspar, albite (Hangx & Spiers 2009) or from the overlying evaporites belonging to the Zechstein Supergroup.

Whatever its exact derivation, the occurrence of dawsonite in the Fizzy discovery's LSF reservoir suggests that at least some of the $CO_2$ was fixed in a solid form. In this instance, however, core and electrical well-log analyses of the Fizzy wells suggest that mineral growth has not caused any major deterioration in reservoir quality through porosity and/or permeability reduction, values for which remain high (Fig. 4). It is presumed that the lack of suitable mineralogies in the quartz arenitic LSF reservoir lithology reduced the chances of dawsonite precipitation through chemical reaction. The additional important consequence thereof is that $CO_2$ sequestration through mineral growth and solid precipitation is not likely to be significant in the LSF and its ultimate $CO_2$ storage success in reservoirs of that age would instead be reliant upon physical capture of the gas.

Given the close temporal and spatial association of $CO_2$-bearing discoveries, the clear implication is that a higher pre-drill risk of $CO_2$ occurrence should be placed on structures reactivated in, and traps created by, Late Cretaceous fault movement. In particular, any undrilled prospects that lie along the eastern flank of the Brown Graben or within the Fizzy Horst itself are considered to have a high likelihood of being $CO_2$-filled. Caution and the appropriate risking should also be considered for any other prospects in the SNS, both in the UK sector and in Dutch waters, where deep-seated normal fault reactivation (structural inversion) was confined to the Upper Cretaceous (i.e. prior to igneous intrusion) and not reactivated thereafter.

### Turning drilling disappointment into a carbon storage opportunity

There has been significant and growing international concern in recent years about the possible long-term environmental impact of releasing vast amounts of $CO_2$ into the atmosphere from the combustion of oil, coal and natural gas (fossil fuels). It is generally thought that, unless action is taken, future $CO_2$ emissions will dwarf those to date, leading to further global warming and increased acidification of the ocean (IPCC 2005). However, with fossil fuels accounting for >80% of the world's energy needs and renewable (wind, tidal etc.) and nuclear sources increasing only at slow, albeit steady rates, the challenge is to balance global demand for energy supply and societal need, whilst trying to manage and reduce greenhouse gas emissions that drive global warming. One effective way of maintaining fossil fuel use, whilst at the same time reducing damage to the environment through atmospheric change, is to prevent greenhouse gases like $CO_2$ from reaching the atmosphere by capturing and storing it (carbon sequestration). Of the various storage options, one of the simplest is to consider pumping the $CO_2$ into depleted subsurface reservoirs, like the Rotliegend Group LSF. While this has an obvious potential to reduce $CO_2$ emission levels and, in so doing, make a contribution towards stabilizing or reducing its effects on global climate change, the secure storage of $CO_2$ presupposes that it can be trapped on geological time-scales and not escape up faults (Shipton *et al.* 2004) or along boreholes.

The current lack of understanding about the general integrity of sealing formations of $CO_2$, which is after all, a smaller (0.28 nm), more mobile molecule than both $N_2$ (0.30 nm) and $CH_4$ (0.38 nm), prohibits confident prediction of $CO_2$ entrapment over geological time-scales in most instances. This is where the Fizzy and Oak gas accumulations may have a major significance for carbon sequestration studies, since the existence of $CO_2$ in these traps *already demonstrates* the sealing integrity of the Zechstein Supergroup evaporite seal. Importantly, it also shows the carbon storage capability of LSF reservoirs in a location where it has evidently worked. The more general significance of this fact is that it confirms that the Zechstein Supergroup evaporites clearly act as a very effective regional super-seal, not only for methane, as previously recognized, but also for $CO_2$ elsewhere in the SNS. Hence, other traps containing Rotliegend Group LSF $CH_4$-bearing reservoirs that lie beneath the extensive Zechstien Supergroup salt canopy are likely to be excellent sites for carbon storage.

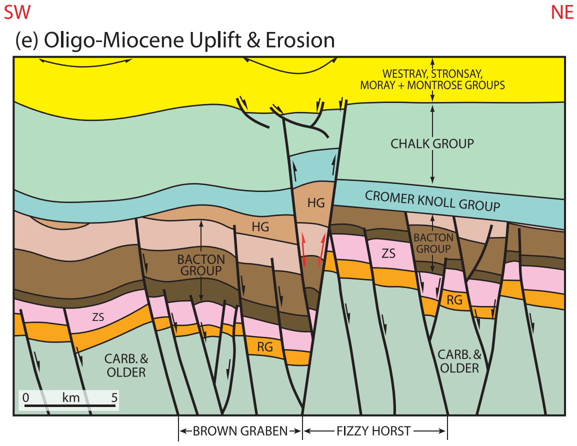
## CONCLUSIONS

The results of a new seismic interpretation in the SE part of the SNS (UKCS Quadrants 49, 50, 53 and 54) demonstrate that the enigmatic occurrence of $CO_2$ (and $N_2$) gas within what is otherwise a dry $CH_4$ gas play fairway is associated with through-going, deep-seated, normal faults that were structurally inverted during the Late Cretaceous. The resultant creation of the Fizzy and Oak traps prior to gas charge allowed significant quantities of $CO_2$, perhaps generated by Palaeogene volcanic/igneous activity, to migrate into the extant structures. In contrast, subsequent Cenozoic structural inversion events led to the creation of numerous other structures into which $CH_4$ appears to have been able to re-migrate. Recognition of deep-seated, reactivated normal faults and exclusively Late Cretaceous inversion structures affords the opportunity to assess $CO_2$ risk prior to drilling.

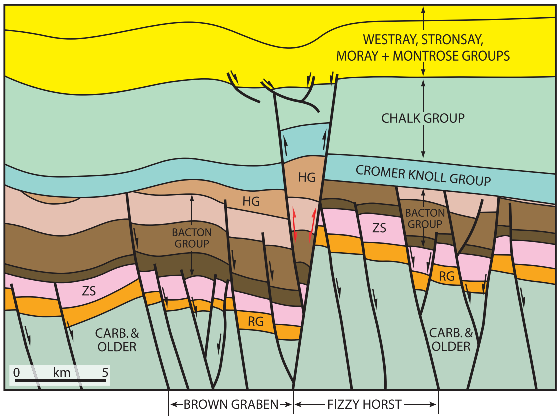
Whilst the results of this study may help reduce pre-drill exploration risk, they also demonstrate that long-lived, natural, geological entrapment of $CO_2$ occurs in Rotliegend Group LSF reservoirs, thus showing the integrity of the Zechstein Supergroup evaporite super-seal over geological time-scales (*c.* 50 Ma or more) despite the basin's long-lived fault reactivation history. The implication is that whatever the exact source of the $CO_2$ in Fizzy and Oak, its very occurrence in traps that lie within the Rotliegend LSF play fairway demonstrates that the numerous depleted gas fields could house and retain $CO_2$ over geological time-scales, a prerequisite for carbon sequestration. As such, the SNS has the potential to become a significant player in greenhouse gas storage in the future.

**Fig. 11.** Isochron maps depicting the major variations in sedimentary thicknesses in the study area (in ms TWT). (**a**) Zechstein Supergroup and Brockelschiefer Formation; (**b**) Bacton Group; (**c**) Haisborough Group highlighting the presence of the Brown Graben and illustrating the main extensional sub-basin trends therein; (**d**) Cromer Knoll Group showing both the general SW–NE thickening trend and the more localized thickening that characterizes the Orwell area demonstrate its continued syn-sedimentary extensional activity during the Lower Cretaceous; (**e**) Chalk Group, which illustrates the severe thinning and narrow thrust-bound zone of deformation that results from intra-Late Cretaceous structural inversion along the eastern flank and above the hanging wall to the Brown Graben, something that is unique to the carbon dioxide occurrence in the area; (**f**) syncline at the top of the Westray Group, the coincidence of which strongly suggests a causal link with the underlying axis of inversion.

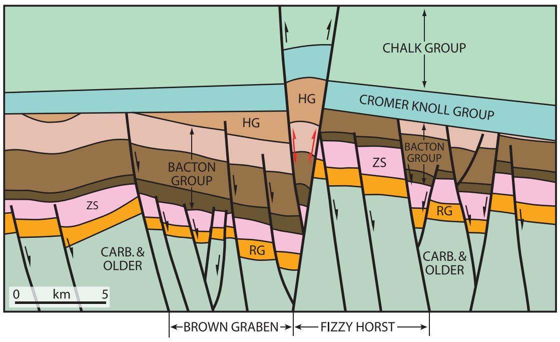
(e) Oligo-Miocene Uplift & Erosion



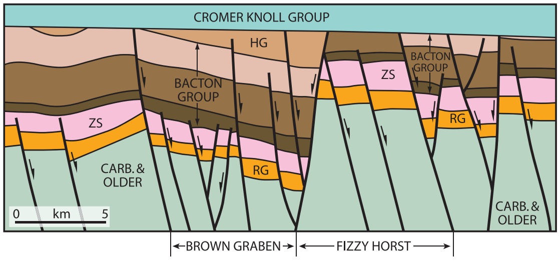
(d) Early Cenozoic Deposition



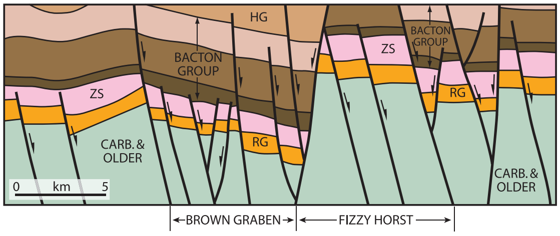
(c) Late Cretaceous Inversion



(b) Early Cretaceous Subsidence



(a) Base Cretaceous Unconformity



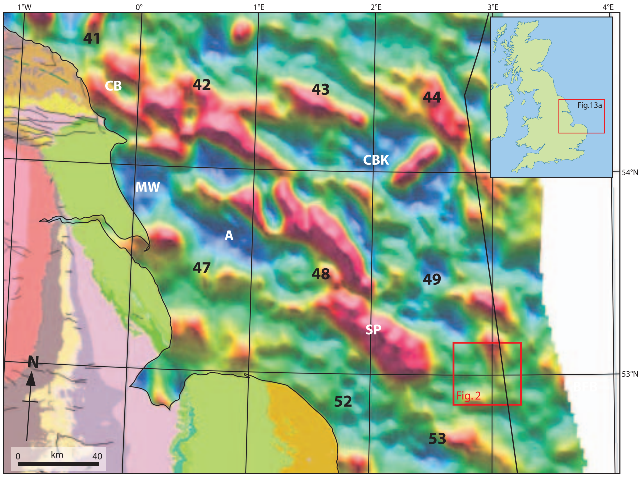


**Fig. 13.** Regional and local maps depicting the 150 km depth-residual Bouguer anomaly gravity for the study area in the SNS. The map provides a basis for identifying the main axes of basin inversion in the UK (Sole Pit (SP) and the Cleveland Basin (CB)), as well as the main buried granitic bodies that occur on their margins (e.g. Market Weighton (MW), Amethyst (A) and Cleaver Bank (CBK); see Donato & Megson (1990) and Donato (1993) for details). The presence of large negative anomalies close to the Fizzy Horst may imply that buried basement granites played a role in the location of the structural high itself and provided a rigid buttress that helped focus the effects of structural inversion along the eastern margin of the Brown Graben. The gravity data are shown courtesy of ArkeX.

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**Fig. 12.** Schematic structural restoration showing the temporal and spatial development and evolution of structural styles in the Fizzy and Oak area. The schematic cartoon shows how the intra-Late Cretaceous inversion focused along the eastern margin of the Brown Graben to form a local pop-up defined on its western side by a steeply dipping antithetic hanging-wall reverse fault and reactivation of the graben's master extensional fault that presumably occurred as a result of compressional stress build-up against its rigid buttress defined here as the Fizzy Horst. The unique association between their enigmatic $CO_2$ and $N_2$ gas fill, unique structural position, the Late Cretaceous timing of reactivation and the intensity of structural inversion leads to the suggestion that the accumulations resulted from Early Cenozoic gas charge along the Brown Graben's deep-seated NE-boundary fault. Whilst the source of the carbon dioxide charge remains uncertain, evidence of high heat flow and $CO_2$ charge from Tertiary igneous dyke intrusion (Kirton & Donato 1985; Brown *et al.* 1994; Underhill 2009) suggests that this process might also have some role to play in this area. See Figure 5 for abbreviations.

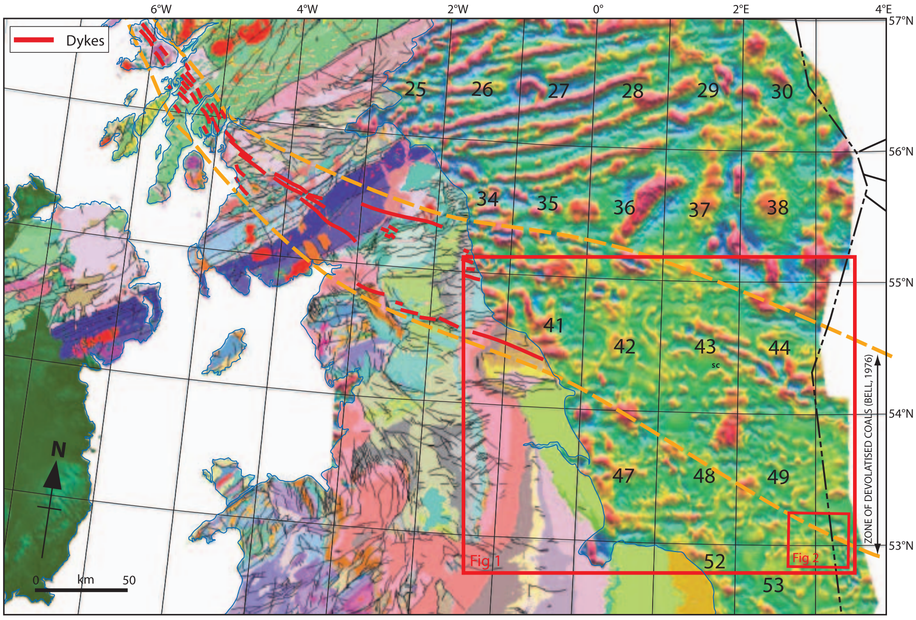

**Fig. 14.** Map showing the magnetic anomalies in the SNS. The prominent WNW–ESE-striking strongly negative linear anomalies mark the offshore trace of Palaeogene dykes and zone of volatized Carboniferous coals (Eames 1975; Bell 1976; Kirton & Donato 1985). The map provides evidence for the southernmost of the igneous intrusions, the Cleveland Dyke, which passes in the vicinity of the study area, thus lending some support to the notion that Palaeogene igneous intrusion was the cause of the high $CO_2$ and $N_2$ gas content in the immediate area. The magnetic data are shown courtesy of ArkeX.

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## REFERENCES

Alberts, M.A. & Underhill, J.R. 1991. The effect of Tertiary structuration on Permian gas prospectivity, Cleaver Bank area, southern North Sea, UK. *In:* Spencer, A.M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons*. Special Publication of the European Association of Petroleum Geoscientists Memoir, **1**, 161–173.

Arthur, T.J., Pilling, D., Bush, D. & Macchi, L. 1985. The Leman Sandstone Formation in U.K. Block 49/28: Sedimentation, diagenesis and burial history. *In:* Brooks, J., Goff, J.C. & Van Hoorn, B. (eds) *Habitat of Palaeozoic Gas in NW Europe*. Geological Society, London, Special Publications, **23**, 251–266.

Badley, M.E., Price, J.D. & Backshall, L.C. 1989. Inversion, reactivated faults and related structures: seismic examples from the southern North Sea. *In:* Cooper, M.A. & Williams, G.D. (eds) *Inversion Tectonics*. Geological Society, London, Special Publications, **44**, 201–219.

Bailey, J.B., Arbin, P., Daffinoti, O., Gibson, P. & Ritchie, J.S. 1993. Permo-Carboniferous plays of the Silverpit Basin. *In:* Parker, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, 707–715.

Baker, J.C., Bai, G.P., Hamilton, P.J., Golding, S.D. & Keene, J.B. 1995. Continental-scale magmatic carbon dioxide seepage recorded by Dawsonite in the Bowen Gunnedah-Sydney basin system, Eastern Australia. *Journal of Sedimentary Research*, **A65**, 522–530.

Bell, J.D. 1976. The Tertiary intrusive complex on the Isle of Skye. *Proceedings of the Geologists' Association*, **87**, 247–271.

Besly, B. 1998. Carboniferous. *In:* Glennie, K.W. (ed.) *Petroleum Geology of the North Sea Basin: Basic concepts and recent advances*. Blackwell Science, Oxford, 104–136.

Bifani, 1986. Esmond Gas Complex. *In:* Brooks, J., Goff, J.C. & Van Hoorn, B. (eds) *Habitat of Paleozoic Gas in N.W. Europe*. Geological Society, London, Special Publications, **23**, 209–221.

Brown, G., Platt, N.H. & McGrandle, A. 1994. The geophysical expression of Tertiary dykes in the southern North Sea. *First Break*, **12**, 137–146.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, G.K., Bulat, J. & Harrison, D.J. 1992. *The Geology of the southern North Sea*. United Kingdom Offshore Regional Report. British Geological Survey and HMSO, London.

Clark, D.N. 1986. The distribution of porosity in Zechstein carbonates. *In:* Brooks, J., Goff, J.C. & Van Hoorn, B. (eds) *Habitat of Palaeozoic Gas in N.W. Europe*. Geological Society, London, Special Publications, **23**, 121–149.

Cooper, M.A., Williams, G.D. & de Graciansky, P.C. *et al.* 1989. Inversion tectonics – a discussion. *In:* Cooper, M.A. & Williams, G.D. (eds) *Inversion Tectonics*. Geological Society, London, Special Publications, **44**, 335–347.

Corfield, S.M., Gawthorpe, R.L., Gage, M., Fraser, A.J. & Besly, B.M. 1996. Inversion tectonics of the Variscan foreland of the British Isles. *Journal of the Geological Society, London*, **153**, 17–32.

Donato, J.A. 1993. A buried granite batholith and the origin of the Sole Pit Basin, UK Southern North Sea. *Journal of the Geological Society, London*, **150**, 255–258.

Donato, J.A. & Megson, J.B. 1990. A buried granite batholith beneath the East Midland Shelf of the Southern North Sea. *Journal of the Geological Society, London*, **147**, 133–140.

Duan, R., Carey, J.W. & Kaszuba, J.P. 2005. *Mineral chemistry and precipitation kinetics of dawsonite in the geological sequestration of $CO_2$*. Abstract GC13A-1210, presented at the American Geophysical Union, Fall Meeting.

Eames, T.D. 1975. Coal rank and gas source relationships – Rotliegend reservoirs. *In:* Woodland, A.W. (ed.) *Petroleum and the Continental Shelf of North-west Europe*. Applied Science Publishers, Barking, 191–201.

Fisher, M.J. & Mudge, D.C. 1998. Triassic. *In:* Glennie, K.W. (ed.) *Introduction to the Petroleum Geology of the North Sea* (2nd edn). Blackwell Scientific, Oxford, 212–244.

Gale, A.S. 1980. Penecontemporaneous folding, sedimentation and erosion in Campanian Chalk near Portsmouth, England. *Sedimentology*, **27**, 137–151.

Geluk, M. 1999. Late Permian (Zechstein) rifting in the Netherlands: models and implications for petroleum geology. *Petroleum Geoscience*, **5**, 189–199.

Geluk, M.C. 2005. *Stratigraphy and tectonics of Permo-Triassic basins in the Netherlands and surrounding areas*. PhD thesis, Utrecht University.

George, G.T. & Berry, J.K. 1997. Permian (Upper Rotliegend) synsedimentary tectonics, basin development and palaeogeography of the southern North Sea. *In:* Ziegler, K., Turner, P. & Daines, S.R. (eds) *Petroleum Geology of the Southern North Sea; Future Potential*. Geological Society, London, Special Publications, **123**, 31–61.

Glennie, K.W. 1998. Lower Permian–Rotliegend. *In:* Glennie, K.W. (ed.) *Petroleum Geology of the North Sea: Basic concepts and recent advances*. Blackwell Science, Oxford, 137–173.

Glennie, K.W. & Boegner, P. 1981. Sole Pit inversion tectonics. *In:* Illing, L.V. & Hobson, D.G. (eds) *The Petroleum Geology of the Continental Shelf of N.W. Europe*. Heyden, London, 110–120.

Glennie, K.W. & Underhill, J.R. 1998. The development and evolution of structural styles in the North Sea. *In:* Glennie, K.W. (ed.) *Petroleum Geology of the North Sea Basin: Basic concepts and recent advances*. Blackwell Science, Oxford, 42–84.

Hangx, S.J.T. & Spiers, J. 2009. Reaction of plagioclase feldspars with $CO_2$ under hydrothermal conditions. *Chemical Geology*, doi:10.1016/jchemgeo.2008.12.005.

Hellevang, H., Aagaard, P., Oelkers, E.H. & Kvamme, B. 2005. Can dawsonite permanently trap $CO_2$. *Environmental Science & Technology*, **39**, 8281–8287.

Hillier, A.P. 2003. The Sean North, Sean South and Sean East Fields, Block 49/25a, UK North Sea. *In:* Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoir, **20**, 825–833.

Hillis, R.R. 1995. Quantification of Tertiary exhumation in the United Kingdom Southern North Sea using sonic velocity data. *American Association of Petroleum Geologists Bulletin*, **79**, 130–152.

IPCC. 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage*. Working Group III of the Intergovernmental Panel on Climate Change (Metz, B., Davidson, O., de Coninck, H.C., Loos, M. & Meyer, L.A. (eds)). Cambridge University Press, Cambridge.

Johnson, H., Warrington, G. & Stoker, S.J. 1994. Permian and Triassic of the southern North Sea, v. 6. *In:* Knox, R.W.O'B. & Cordey, W.G. (eds) *Lithostratigraphic Nomenclature of the UK North Sea*. British Geological Survey, Nottingham.

Kaszuba, J.P., Viswanathan, H.S., Carey, B., Carpenter, T.M., Counce, D. & Duan, R. 2006. *On the reactivity of dawsonite in geologic carbon sequestration*. Abstract #V53D-1779, presented at the American Geophysical Union, Fall Meeting.

Ketter, F.J. 1991. The Esmond, Forbes and Gordon Fields, Blocks 43/8a, 43/13a, 43/15a, 43/20a, UK North Sea. *In:* Abbotts, I.L. (ed.) *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume*. Geological Society, London, Memoir, **14**, 425–432.

Kirton, S.R. & Donato, J.A. 1985. Some buried Tertiary dykes of Britain and surrounding waters deduced by magnetic modelling and seismic reflection methods. *Journal of the Geological Society, London*, **142**, 1047–1057.

Li, M., Wang, T., Liu, J., Lu, H., Wu, W. & Gao, L. 2007. Occurrence and origin of carbon dioxide in the Fushan Depression, Beibuwan Basin, South China Sea. *Marine and Petroleum Geology*, **25**, 500–513.

McCrone, C.W. 2003. The Davy, Bessemer, Beaufort and Brown Fields, Blocks 49/23, 49/30a, 49/30c, 53/5a, UK North Sea. *In:* Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 705–712.

Osbon, R.A., Werngren, D.C., Kyei, A., Manley, D. & Six, J. 2003. The Gawain Field, Blocks 49/24, 49/29a, UK North Sea. *In:* Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 713–722.

Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin – high resolution from low frequencies. *Journal of Applied Geophysics*, **53**, 273–298.

Shipton, Z.K., Evans, J.P., Kirschner, D., Kolesar, P.T., Williams, A.P. & Heath, J. 2004. Analysis of $CO_2$ leakage through 'low permeability' faults from natural reservoirs in the Colorado Plateau, Utah. *In:* Baines, S.J. & Worden, R.H. (eds) *Geological Storage of Carbon Dioxide*. Geological Society, London, Special Publications, **233**, 43–58.

Taylor, J.C.M. 1998. Upper Permian–Zechstein. *In:* Glennie, K.W. (ed.) *Petroleum Geology of the North Sea: Basic concepts and recent advances*, Blackwell Science, Oxford, 174–211.

Tucker, M.E. 1991. Sequence stratigraphy of carbonate–evaporite basins: models and application to the Upper Permian (Zechstein) of northeast England and adjoining North Sea. *Journal of the Geological Society, London*, **148**, 1019–1036.

Underhill, J.R. 2003. The tectonic and stratigraphic framework of the United Kingdom's oil and gas fields. *In:* Gluyas, J.G. & Hichens, H.M. (eds) *United Kingdom Oil and Gas Fields, Commemorative Millennium Volume*. Geological Society, London, Memoirs, **20**, 17–59.

Underhill, J.R. 2004. An alternative origin for the 'Silverpit Crater'. *Nature*, doi:10.1038/nature/02476.

Underhill, J.R. 2009. Role of intrusion-induced salt mobility in controlling the formation of the enigmatic 'Silverpit Crater', UK Southern North Sea. *Petroleum Geoscience*, **15**, 197–216.

Underhill, J.R. & Hunter, K.L. 2008. Effect of Zechstein Supergroup (Z1 Cycle) Werrahalit pods on prospectivity in the Southern North Sea. *American Association of Petroleum Geologists Bulletin*, **92**, 827–851.

Underhill, J.R. & Paterson, S. 1998. Genesis of tectonic inversion structures: seismic evidence for the development of key structures along the Purbeck–Isle of Wight Disturbance. *Journal of the Geological Society, London*, **155**, 975–992.

Underhill, J.R. & Stoneley, R. 1998. Introduction to the development, evolution and petroleum geology of the Wessex Basin. *In:* Underhill, J.R. (ed.) *Development, Evolution and Petroleum Geology of the Wessex Basin*. Geological Society, London, Special Publications, **133**, 1–18.

Van Hoorn, B. 1987. Structural evolution, timing and tectonic style of the Sole Pit Inversion. *Tectonophysics*, **137**, 239–284.

Werngren, O.C. 1991. The Thames, Yare and Bure Fields, Block 49/28, UK North Sea. *In:* Abbotts, I.L. (ed.) *United Kingdom Oil and Gas Fields, 25 Years Commemorative Volume*. Geological Society, London, Memoirs, **14**, 491–496.

Williams, G.D., Powell, C.M. & Cooper, M.A. 1989. Geometry and kinematics of inversion tectonics. *In:* Cooper, M.A. & Williams, G.D. (eds) *Inversion Tectonics*. Geological Society, London, Special Publications, **44**, 3–15.

Wopfner, H. & Hocker, C.F.W. 1987. The Permian Groedan Sandstone between Bozen and Meran (northern Italy), a habit of dawsonite and nordstrandite. *Neus Jahrbuch fur Palaontologie Monatshefte*, **3**, 161–176.

Wycherley, H., Fleet, A. & Shaw, H. 1999. Some observations on the origins of large volumes of carbon dioxide accumulations in sedimentary basins. *Marine and Petroleum Geology*, **16**, 489–494.

Ziegler, P.A. 1990. *Geological Atlas of Western and Central Europe* (2nd edn). Shell Internationale Petroleum Maatschappij, The Hague.

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