Controls on Lower Carboniferous (Dinantian) Prospectivity in the Mid North Sea High Region*

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Abstract

The discovery of, and subsequent production from, the Breagh gas field in Quadrant 42 of the Southern North Sea challenges long-held views concerning the limited prospectivity of the Mid North Sea High. The occurrence of the field attests to a petroleum system having been active in the area, something that lends encouragement to further exploration efforts in the basin. We have integrated seismic interpretation of two proprietary 3D pre-stack time migrated (PSTM) volumes, a regional grid of 2D data acquired as part of the Oil and Gas Authority (OGA) Frontier Basins research program, well, core and field-data from coastal exposures in Berwickshire and Northumberland to determine the primary controls on the petroleum system. The results show that the Breagh structure formed in response to Mesozoic and Cenozoic folding to create a closure of erosionally truncated (subcropping) and highly faulted (compartmentalised) fluvio-deltaic reservoirs of Lower Carboniferous (Dinantian) age at Base Permian Unconformity (BCU) level which are then sealed by Upper Permian (Zechstein Group) evaporites. The absence of the Upper Carboniferous (Coal Measures Group) across the area implies that gas charge comes from Lower Carboniferous coals including those belonging to the Scremerston Coal Group. Halokinesis led to an elongate zone of salt withdrawal above which a narrow graben formed containing thick Mesozoic sediments that are characterised by slow seismic velocities. The faults defining the graben record the effects of listric detachment where withdrawal of the Zechstein group evaporites is greatest and led to the creation of turtleback structures, the full appreciation of which governs depth conversion and accurate mapping at the reservoir level. Regional interpretations show that a late (Paleogene) tilt was also imparted and had an important effect since it led to Breagh lying on a westerly (re-)migration pathway.

Discussion

The discovery of, and subsequent production from, the Breagh gas field in Quadrant 42 of the Southern North Sea (Figure 1) challenges long-held views concerning the limited potential prospectivity of the Mid North Sea High region. The location of the Breagh Field approximately 30 km NW of the major axis of Carboniferous gas fields in the Southern North Sea (SNS) marks it as an outlier. Furthermore, the gas is located in

Lower Carboniferous reservoirs as opposed to the Upper Carboniferous or Permian reservoirs typically associated with SNS gas fields. However, the occurrence of the field attests to a working petroleum system having been active in the area, something that lends encouragement to further exploration efforts in the basin.

We have integrated seismic interpretation of two proprietary 3D pre-stack time migrated (PSTM) volumes (one of which covers the Breagh Field), a regional grid of 2D data acquired as part of the Oil and Gas Authority (OGA) Frontier Basins research program, well log, core description and field-data from coastal exposures in Northumberland. This multi-method approach has been used to identify and interpret the structural and depositional history of the Breagh region and to help determine the primary controls on prospectivity.

The Breagh Field was discovered in 1997 by well 42/13-2 which was drilled by Mobil to a total depth of 2672.8 m (TVDSS), after passing through approximately 400 m of Lower Carboniferous sediments and a gas column that is over 120 m thick. The well is the deepest in the study area and reached total depth within the Scremerston Formation, part of the Farne Group (Figure 2). The seismic data indicates that the Carboniferous sediments continue below well penetration depth and are probably underlain by sediments of Devonian age; including the Kyle Limestone which forms a prominent marker horizon in some areas. The Lower Carboniferous (Dinantian) sediments of the Farne Group (including the Scremerston and Yoredale Formations) accumulated in fluvio-deltaic to shallow-marine depositional environments that were variably influenced by eustatic sea level change, extensional tectonics, and delta abandonment processes (Maynard and Dunay 1999; Collinson 2005). The sandstone reservoirs of the Breagh Field were originally thought to be part of the Scremerston Formation. However, proprietary biostratigraphic analysis and lithological limestone correlation have shown that the sandstone reservoirs are in fact part of the stratigraphically younger Yoredale Formation. The sediments were sourced from northerly quartz-rich Caledonian terranes and transported southwestwards initially depositing into localised fault controlled depocentres that were juxtaposed with buoyant granite-cored highs. Later the faults ceased moving leading to regional subsidence and stratigraphic linkage of the basins (Johnson 1984; Fraser and Gawthorpe 1990). The extensional faults affecting the Carboniferous and older strata are defined by relatively planar geometries (Figure 3 and Figure 4) and are typically orientated NW-SE; these orientations are likely controlled by underlying Caledonian lineaments (Leeder 1982; Fraser and Gawthorpe 2003). The faults rarely affect strata above the Base Permian Unconformity (BPU). It is likely that sedimentation continued throughout the remainder of the Carboniferous (e.g. Namurian and Westphalian) in a similar manner to adjacent offshore and onshore areas. However, uplift, deformation and sub-aerial exposure attributed to the Variscan orogeny eroded most of these later Carboniferous sediments from the Breagh area leaving the Dinantian Yoredale Formation sub-cropping against Upper Permian strata. The Variscan orogeny caused inversion on a regional scale with extensive and well documented evidence present onshore and offshore Britain (Corfield et al. 1996; Glennie and Underhill 1998).

Further south, in a line roughly following the boundary between the two seismic datasets (Figure 1), Permian Rotliegend Silverpit Formation sediments can be observed thickening ~southwards whereas over the Breagh area no Rotliegend material has been encountered and Zechstein evaporites directly overlie the angular unconformity (Figure 3 and Figure 4). A complete Zechstein sequence (i.e. Z1-Z4) is present in some wells and typically comprises halite, polyhalite, and anhydrite although prominent Plattendolomit rafts are easily distinguished in the seismic data. Lower Triassic sediments conformably overlie the Permian and are represented mainly by shales and later sandstones of the Bacton Group. Shales of the Haisborough Group were deposited during the Upper Triassic with thin shale and interbedded anhydrite belonging to the Rot Halite Formation at the base. The Triassic deposits display a uniform thickness across much of the study area and record deposition in effectively a ‘pre-rift’ phase of sedimentation. The conformable Lower Jurassic sediments comprise shales of the Lias Group with Middle Jurassic mixed sandstone and shale deposits belonging to the West Sole Group. The Jurassic sediments vary in thickness in the wells and often display prominent wedge-shaped geometries thickening into fault zones indicative of syn-sedimentary extension (Figure 3) and are characterised by slow velocities in the seismic data.

The extension is characterised by basin-scale listric faults that terminate within lithologically weak rocks, mainly the Zechstein evaporites but also the Triassic Rot Halite. The extension probably began in the Middle to Upper Triassic with faults oriented NNW-SSE and NE-SW that display a curvilinear shape in map view. This Mesozoic extensional episode is linked with extensive halokinesis of the Zechstein evaporites resulting in thin to absent Zechstein deposits within the graben areas and occasional grounding of the overlying Triassic sediments directly against the Carboniferous rocks. Furthermore, the halokinesis and listric extension led to the formation of turtle-back structures, salt diapirs and salt wings in some inter-graben areas, the full appreciation of which governs depth conversion and accurate mapping at the reservoir level. Examples of these features are shown in the geo-seismic sections in Figure 3 and Figure 4. These graben structures and thick wedge-shaped Mesozoic sedimentary deposits and the associated halokinesis represent a ‘syn-rift’ phase of sedimentation.

Uplift and erosion in the Upper Jurassic to Lower Cretaceous has planed off most of the Middle and Upper Jurassic sediments over Breagh. In the south of the study area in wells 42/18-1, 42/18-2, and 42/23-1 (see Figure 1 for well locations) sediments belonging to the Upper Jurassic Humber Group are encountered at seabed (Figure 3). It is likely that these sediments were also deposited over the Breagh area but have subsequently been eroded. However, deformation was relatively minor such that the unconformity is relatively shallow-angle in nature and often difficult to confidently interpret in the seismic data due to the lithological similarity of the deposits in the overlying Cretaceous Cromer Knoll and underlying Jurassic Lias Groups. The Jurassic sediments are unconformably overlain by interbedded sandstones and shales followed by clays belonging to the Cromer Knoll Group that may also have been deposited during syn-sedimentary extension indicating reactivation of the Mesozoic listric fault zones. The Cretaceous Chalk Group occurs gradationally above this and is present over the north of the study area but subcrops to seabed where it is erosionally truncated and therefore not present in the southern part of the study area. The chalks drape over the Mesozoic faults indicating a ‘post-rift’ phase of deposition. No rocks younger than the Cretaceous chalks were encountered in the study area.

Conclusions

The results of this work show that the Breagh Field lies within a partially fault-controlled 4 way dip closed structure in fluvio-deltaic reservoirs of Lower Carboniferous (Dinantian) age at Base Permian Unconformity (BPU) level. The structure formed in response to Palaeozoic folding to create a closure of erosionally truncated (subcropping) and highly faulted (compartmentalised) reservoirs which are then sealed by Upper Permian (Zechstein Group) evaporites. The absence of the Upper Carboniferous (Coal Measures Group) across the area implies that gas charge comes from Lower Carboniferous coals (and potentially also lacustrine, lagoonal, and marine mudstones) within the Yoredale Formation as well as those belonging to the stratigraphically older Scremerston Formation. Alternatively, the gas may have migrated from the traditional Westphalian source area to the SE via fill and spill of intermediary trap structures. Regional interpretations show that an Early Cenozoic (Paleogene) tilt was also imparted and is attributed to the Atlantic opening and associated Icelandic plume emplacement. This had an important effect since it led to the Breagh Field lying on a westerly (re-)migration pathway. Maturation may have begun prior to the Variscan uplift but probably climaxed during the Cretaceous prior to this Paleogene regional tilting. Additionally, the absence of the Rotliegend Silverpit

Formation is likely a critical factor in the success of this field as the gas could accumulate in the high reservoir quality fluvial sandstone deposits of the Yoredale Formation rather than the poor reservoir quality claystone and siltstone deposits of the Silverpit Formation. Understanding the detailed depositional history of the Carboniferous rocks together with the structural evolution of the entire basin is essential for future exploration success around Breagh and further north on to the Mid North Sea High.

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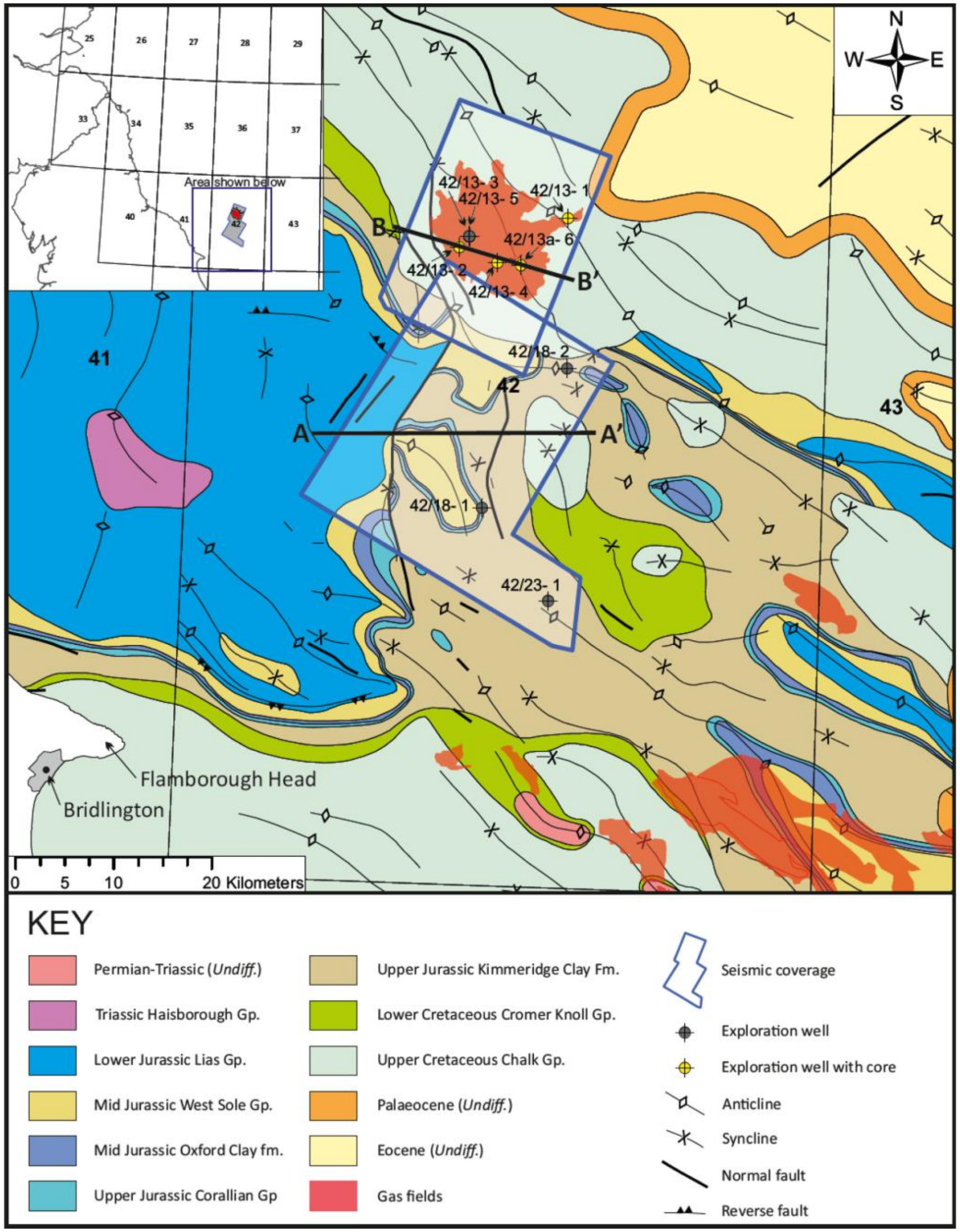

Figure 1. Map showing the offshore geology at sea bed to the northeast of Flamborough Head together with the structures recognised at sea bed all redrafted from BGS data. The Breagh gas field and exploration wells in the study region together with selected additional gas fields are also shown. Inset map shows quads and outline of UK.

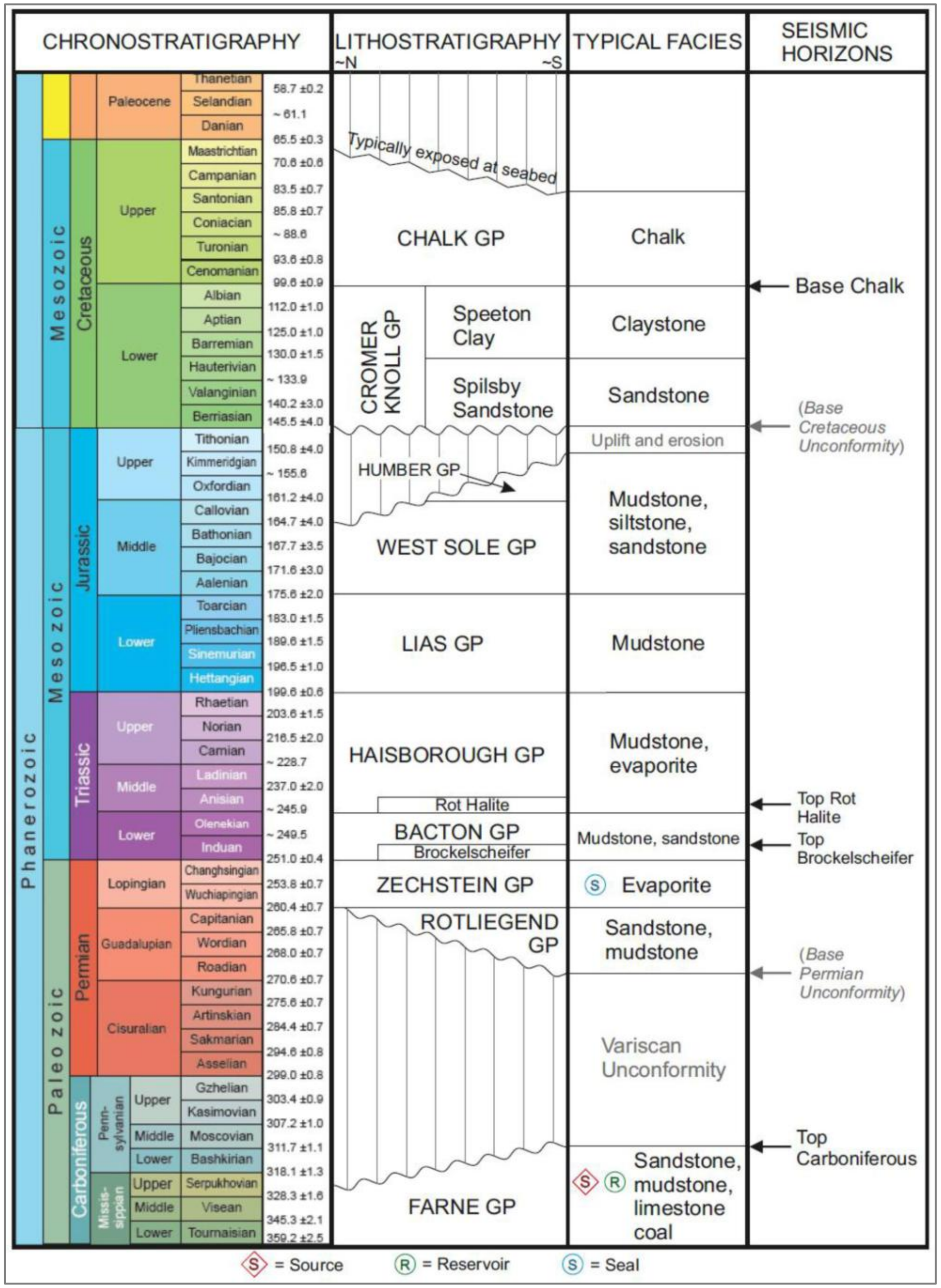

Figure 2. Chronostratigraphic and lithostratigraphic summary diagram for the Breagh area. Typical facies and prominent seismic horizons are also indicated.

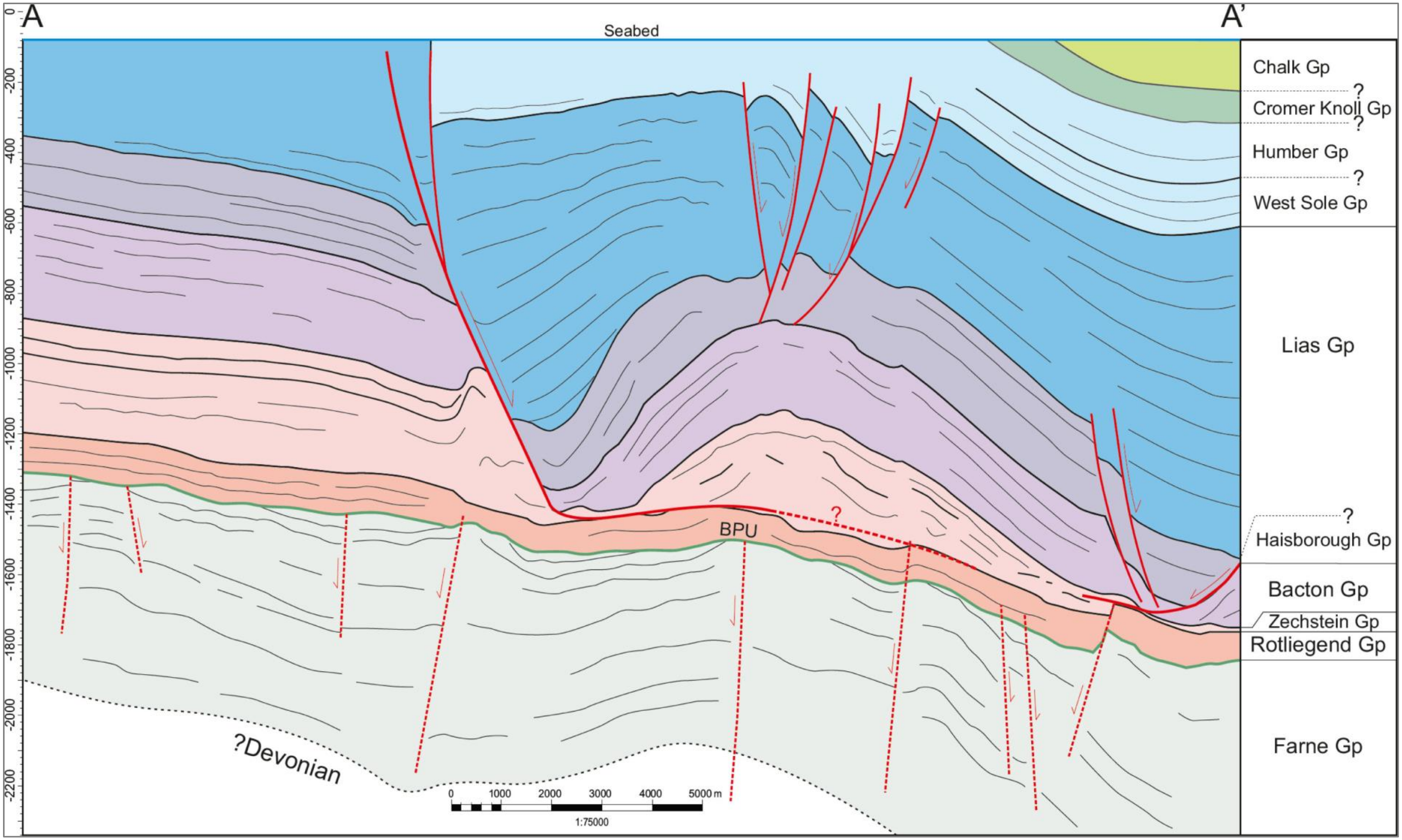

Figure 3. Geo-seismic section orientated west-east located to the south of the Breagh Field showing some of the important features discussed in the text. 3D seismic available to the south of Breagh is of much higher quality thanks in part to the absence of chalk in that area (Figure 1). The seismic is displayed in two way travel time with the time in milliseconds indicated on the left.

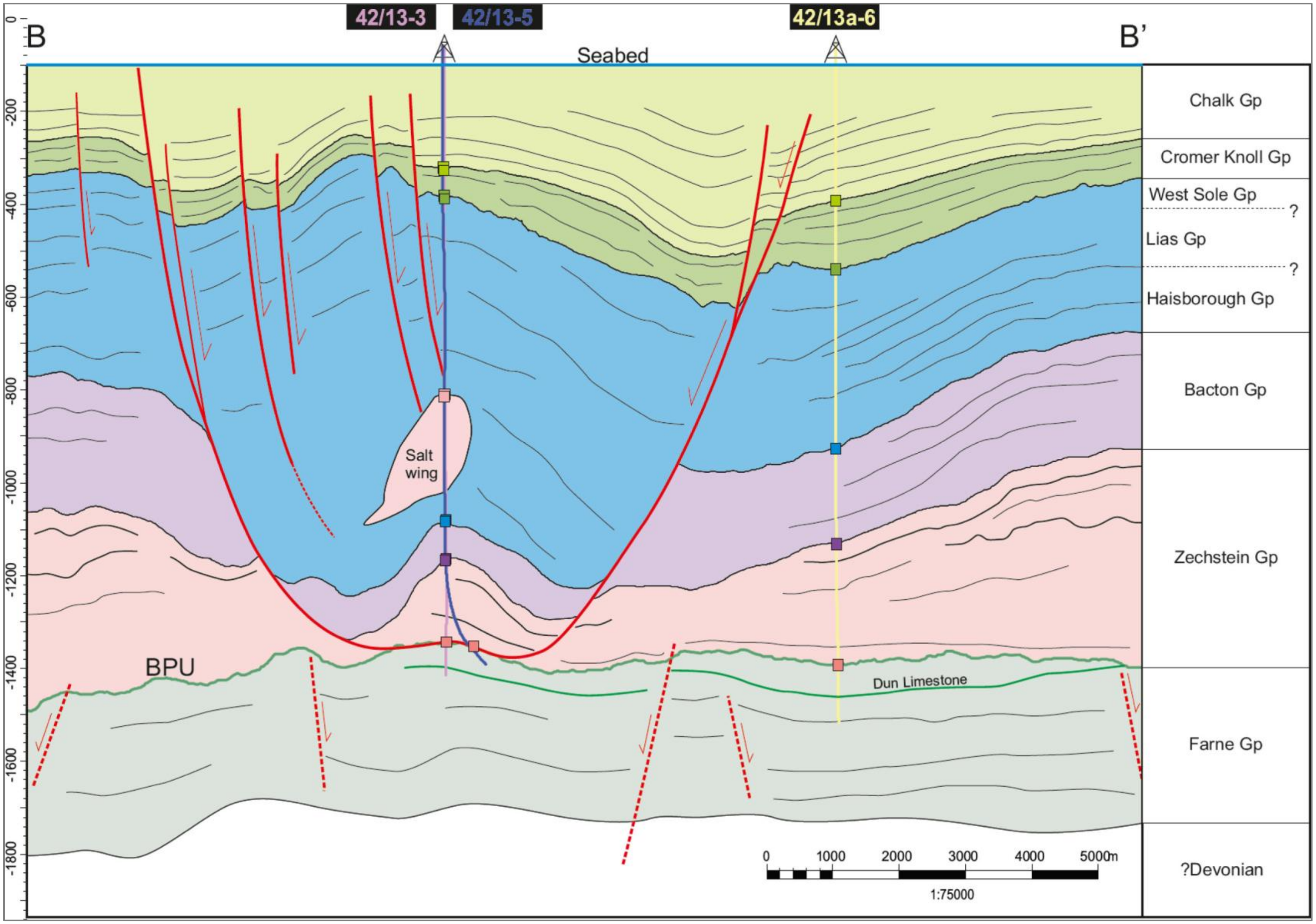

Figure 4. Geo-seismic section orientated WNW-ESE through the Breagh Field. The 3D seismic data over the Breagh Field is of limited quality due to the presence of variably thick Cretaceous chalks and Zechstein evaporites making interpretation and subsequent depth conversion difficult, but all the more important. The section shows a syn-sedimentary graben structure infilled with Mesozoic sediments and including thin Bacton Group deposits. Note the salt mobilisation within the Zechstein Group and the postulated salt wing identified from well data but not easily distinguished on seismic. The seismic is displayed in two way travel time with the time in milliseconds indicated on the left.