Review of hydrocarbon potential in East Denmark following 30 years of exploration activities

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Between 1993 and 2017, Denmark was one of the largest oil exporting countries in Europe having gained this position from its share in the highly prolific Danish Central Graben. However, outside the Central Graben few prospects have been adequately mapped, due to a lack of data in these so-called 'white areas.' As such, their potential for hydrocarbon accumulation remains uncertain. This paper presents an update of the prospect and play types in this area outside the Danish Central Graben, east of 6°15′E longitude (Fig. 1), based on results from the last 30 years of exploration activities. The paper is part of a resource assessment made by the Geological Survey of Denmark and Greenland (GEUS) to the Danish Energy Agency (Schovsbo & Jakobsen 2017) and is an update of a former review of the area made in 1987 (Thomsen *et al*. 1987). The succeeding exploration efforts have not changed the overall low expectation for the play types in the area. Here, we show that an uncertain resource is associated with both the Zechstein carbonate play in the North German Basin and the Upper Triassic – Lower Jurassic sandstone and lower Palaeozoic shale gas plays in northern Jylland. However, questions remain as to the source of hydrocarbons in the western offshore area. Specifically, we are unable to confirm (or refute) whether these structures are sourced via long-distance migration of hydrocarbons from the Danish Central Graben.

Exploration history

With the 1995 amendments to the Danish Subsoil Act, an Open Door Procedure (ODP) was established for the area east of 6°15′E (hereafter termed the Open Door Area or ODA; Fig. 1) as a consequence of diminishing interest and lack of competition between oil companies in this part of the Danish sub surface. The flexibility of the ODP allowed licences to be awarded without holding an actual licensing round and especially sought to motivate small oil companies with innovative ideas to pursue oil and gas exploration. However, the Danish Government is currently preparing new legislation that will prohibit oil and gas exploration onshore and in inner Danish waters, thus terminating new oil and gas exploration activities within a substantial part of the ODA.

The exploration activities resulting from the ODP in 1996 are briefly summarised in Table 1, Fig. 1 and below. For a full account of the activities prior to 1996, we refer to Thomsen *et al*. (1987) for the period up to 1983, and Danish Energy Agency (1995) for the period up to 1994. Following the implementation of the ODP in 1995 and until 2017, 27 licences were awarded resulting in the drilling of 5 wells (Erik-1, Karlebo-1, Felsted-1, Løve-1 and Vendsyssel-1) and the collection of various geochemical and airborne surveys as well as 6700 km 2D and 688 km^2 3D seismic surveys. (Table 1; Figs 1, 2, 3). Except for the lower Palaeozoic shale gas play only the established plays have been tested and the introduction of the ODP has not led to increased drilling activity in eastern Denmark. On the contrary, activities began to stagnate in the 1970s when exploration focus shifted abruptly to the Danish Central Graben, following the success of the A-1 well.

Play types and concepts

Thomsen *et al*. (1987) identified the following plays to be relevant in the Danish area outside the Danish Central Graben, namely the Cambrian sandstone and Rotliegend sandstone, Zechstein carbonate, Bunter sandstone, Rhaetian (Triassic)–Jurassic sandstone, and Upper Cretaceous – Danian chalk plays (Fig. 4). In addition to these plays, unconventional shale gas and oil plays have since been identified and are included in this brief review. Here, the description is focused on data acquired from hydrocarbon exploration and/or from geothermal activities that have occurred since the Thomsen *et al*. (1987) review.

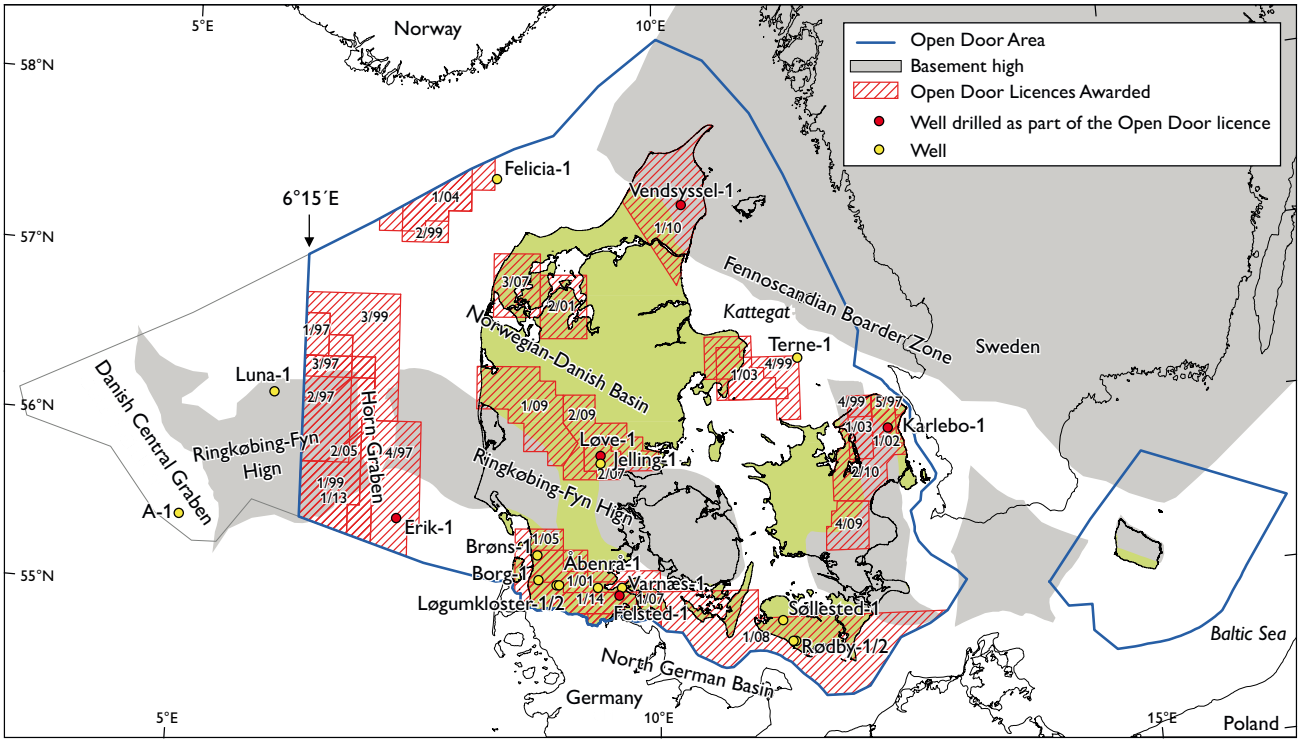

Fig. 1. Open Door licences awarded between 1996–2017 and wells mentioned in the text. For details, see Table 1.

Cambrian Sandstone Play

Hydrocarbon production from Cambrian sandstones sourced from lower Palaeozoic shales occur in the Baltic Sea and onshore Poland and Lithuania. Similar sandstones occur throughout Denmark with potential source and seal provided by the Alum Shale Formation (Fig. 4A). In Denmark, expulsion and migration of hydrocarbons occurred during the Palaeozoic Caledonian Orogeny. Thermal modelling based on results from the Terne-1 well (drilled in 1985) in Kattegat and from the Vendsyssel-1 well (drilled in 2015) has, however, highlighted the significant risks related to reservoir quality and retention of hydrocarbons for this play in Denmark. This implies that it is highly unlikely that the Cambrian sandstones hold significant hydrocarbon resources, as previously stated by Thomsen *et al.* (1987).

Lower Palaeozoic Shale Gas Play

Thermogenic gas trapped in deeply buried Palaeozoic shales represents a new play, explored as part of three licenses (4/09, 1/10, and 2/10; Table 1) and in similar shales in Sweden and Poland (Schovsbo & Nielsen 2017). Although studies carried out by the U.S. Geological Survey (Gautier *et al.* 2014) and by European geological surveys (Zijp *et al.* 2017) indicate a considerable resource potential in Denmark, exploration of this play is still limited, and representative well data and production test data for the shales in Denmark are lacking. The Vendsyssel-1 exploration well revealed gas in the Alum Shale Formation, however, no test production was carried out, so the commercial potential is still unknown. The well was drilled within a so-called 'sweet spot', defined as an area with expected highest gas content (Schovsbo *et al.* 2014). Results from this well revealed the Alum Shale to be 40 m thick, compared to 180 m in Terne-1. It also contained much less gas than similar prospective parts of Poland, which leads to less favourable expectations for future activities, overall.

Rotliegend Sandstone Play

Permian aeolian sandstones form excellent reservoirs in the Netherlands, Germany and the UK, and similar facies are present in Denmark (Thomsen *et al.* 1987). The play occurs along the northern and southern margins of the Ringkøbing–Fyn High as well as in the Horn Graben (Fig. 1). The Rotliegend play has only been tested by a few wells (e.g. Felicia-1, drilled in 1987; and Borg-1, drilled in 1988). All wells penetrating the Rotliegend are characterised by the lack of hydrocarbon shows, indicating that filling of the structures from Palaeozoic sources is not likely due to a lack of mature *in situ* source rocks or the absence of a migration route from other mature source rocks (Beha *et al.* 2008).

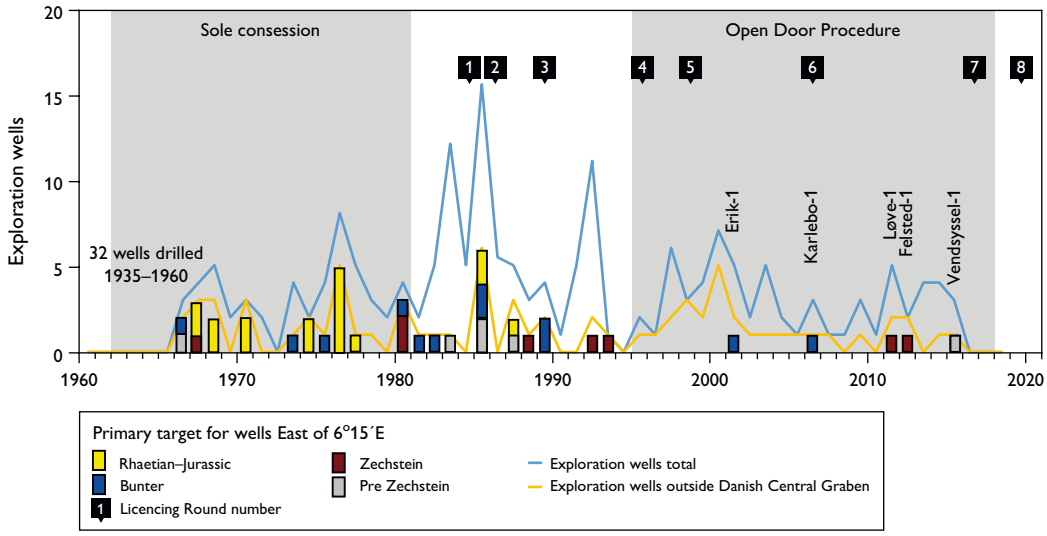

Fig. 2. Drilling activities and concession rounds in Denmark 1960–2017. Based on Thomsen *et al.* (1987) for the period up to 1983. After the Open Door Procedure (ODP) was established the licencing rounds included only the area West of 6°15´E. Licences based on the eighth licence round have not yet been awarded (application deadline 1 February 2019).

The possibility of long-distance migration of hydrocarbons from the Danish Central Graben into structures in the western part of ODA was tested in two licences (1/97 and 2/97). This work included geochemical surveys and reprocessing of existing seismic data. However, the results were inconclusive regarding the hypothesis of long-distance hydrocarbon migration.

Zechstein Carbonate Play

Zechstein carbonates sourced by organic-rich intra (Z-1 and Z-2) carbonate beds and/or the Kupferschiefer occur in northern Germany and Poland and have been extensively explored within the ODA. The presence of oil in the Løgumkloster wells, as well as hydrocarbon shows in the Brøns-1 and Åbenrå-1 wells, confirm the presence of a Zechstein play along the southern edge of the Ringkøbing–Fyn High.

Eight licences focusing on the Zechstein carbonates play south (1/01, 1/05, 1/07, 1/08 and 1/14) and north (2/07, 1/09 and 2/09) of the Ringkøbing–Fyn High have been awarded. The licensing work included collection of seismic data, geochemical analysis of samples, and drilling of the Felsted-1 and Løve-1 wells. Hydrocarbons were found in Zechstein carbonate in the Felsted-1 well, but the gas contained

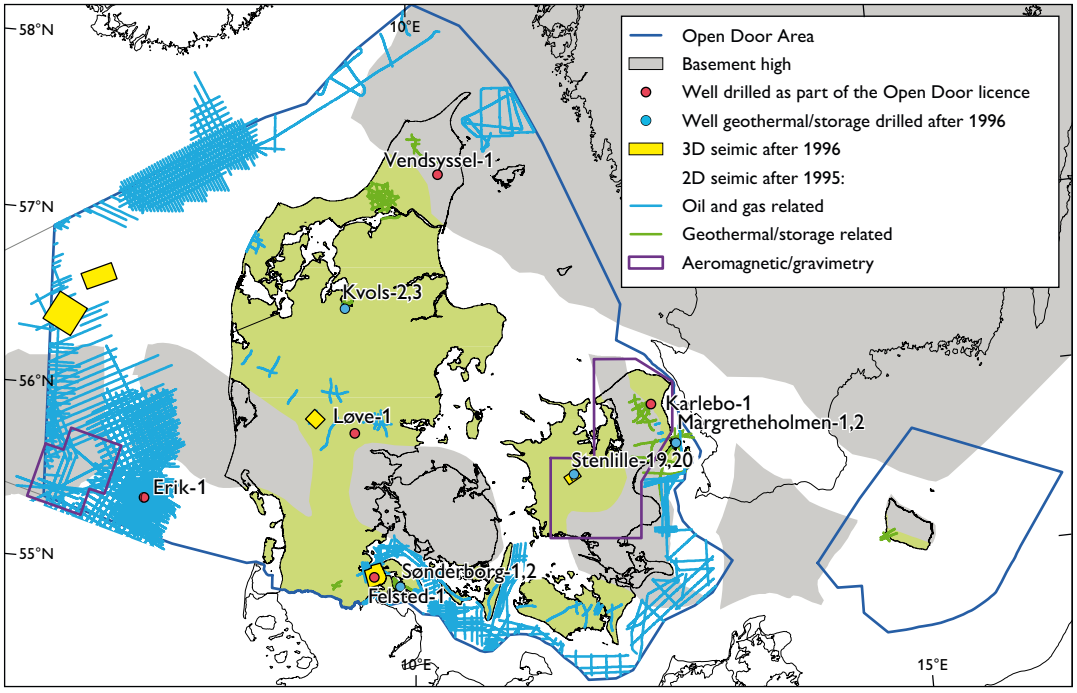

Fig. 3. Seismic data, aeromagnetic/gravity survey and wells drilled after 1995.

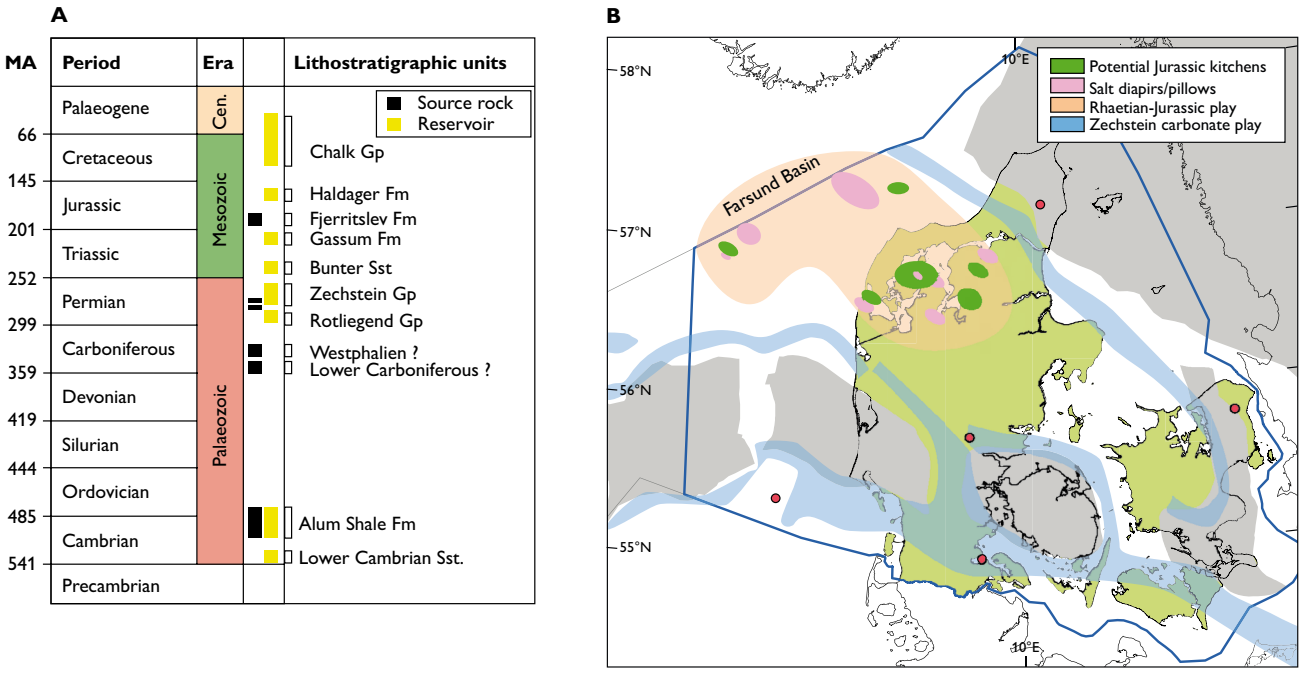

Fig. 4. **A**: Stratigraphical column with petroleum system elements for the Norwegian-Danish Basin. **B**: Zechstein and Rhaetian–Jurassic play map. Fm: Formation, Gp: group, Sst: Sandstone. For map legend, see Fig. 1. Based on Thomsen *et al.* (1987) and Petersen *et al.* (2008).

more than 90% N_2. The results of the exploration work confirmed the presence of hydrocarbons in the Zechstein carbonates but have not proven the presence of prospects of an economical size. New information on the presence of source rocks has not been established.

On the northern flank of the Ringkøbing–Fyn High the Jelling-1 well (drilled in 1992) penetrated only 3 m into Zechstein carbonates and no source rocks were identified. Also, the Løve-1 well (drilled in 2011) was dry with no indication of source rocks. The exploration in the northern part of the Ringkøbing–Fyn High has thus not provided any new or positive indications of good reservoir intervals nor the presence of source rocks.

Bunter Sandstone Play

Good to excellent quality Lower Triassic reservoirs are widespread in Denmark (Mathiesen *et al.* 2010; Kristensen *et al.* 2016). The presence of N_2 gas in Bunter in the Tønder structure confirmed the possibility of a Triassic play in the area, but it is dependent on the presence of structural closures and migration from mature source rocks. Drilling on salt structures (Varnæs-1, Rødby-1, -2, and Søllested-1, drilled 1952–1982) found no traces of hydrocarbons. Therefore, the Triassic play in the North German Basin is uncertain with the lack of source rocks being the biggest risk factor.

In the Horn Graben, two licences (4/97 and 1/99) with a Bunter sandstone play as the target have been awarded. One dry well was drilled (Erik-1, 2001), which confirmed the results from previous wells in the area and verified the good reservoir properties of this interval. A basin modelling and structural development study of the area (Beha *et al.* 2008) revealed the lack of mature source rocks as the biggest determining factor for the presence of hydrocarbons at this location.

Rhaetian–Jurassic Sandstone Play

Until 1987, the bulk of the drilling activity in the ODA was directed towards the Rhaetian–Jurassic sandstone reservoirs in the Norwegian–Danish Basin (Fig. 4B). Based on the available source rock analysis and maturity modelling it appears that only minor amounts of hydrocarbons may have been generated and expelled from Lower Jurassic shales in deep rim synclines around the salt diapirs (Petersen *et al.* 2008).

The Rhaetian–Jurassic sandstone play was investigated in licences 2/99 and 1/04 (Fig. 1). As part of the work programme for license 1/04, a comprehensive 2D seismic survey was carried out along with source rock screening of existing wells. The evaluation report for these wells stated that there are no mature source rocks in the area. Mature Lower Jurassic source rocks (with respect to oil generation) were, however, present in the Farsund Basin located in the Norwegian sector (Fig. 4B). But none of the investigations associated with the licences suggested mature hydrocarbons in rim

Table 1. Summary of hydrocarbon exploration activities in the Open Door Area (ODA) after the establishment of the Open Door Procedure (ODP) in 1996.

License	Operator	New data acquired	Primary target
1/97	Agip	Seismic: 81 km 2D, 347 km² 3D	Chalk sourced Danish Central Graben
2/97	Amerada		Palaeocene sandstones sourced from Danish Central Graben
3/97	Amerada		Palaeocene sandstones sourced from Danish Central Graben
4/97	Mærsk	Seismic: 4014 km 2D; well: Erik-1	Bunter sandsone sourced from Carboniferous sources
5/97	Odin	Geochemical survey	Haldager/Gassum sandstone sourced from Fjerritslev Fm
1/99	Agip	Seismic: 213 km 2D; geochemistry and aeromagnetic survey	Bunter sandsone sourced from Carboniferous sources
2/99	Gustavson		Haldager/Gassum sandstone sourced from Fjerritslev Fm
3/99	Anschutz	Seismic: 165 km 2D, 225 km² 3D	
4/99	Amerada		Cretaceous sandstone sourced from Jurassic shales
1/01	Minijos Nafta	Geochemical survey	Zechstein carbonates sourced from Z1/Z2 basin facies or Kupferschiefer
2/01	Sterling	Geochemical survey	
1/02	Tethys	Well: Karlebo-1	Mesozoic sandstones sourced from Zechstein or lower Palaeozoic shales.
1/03	Tethys	Geochemical survey	
1/04	DONG	Seismic: 1661 km 2D	Gassum/Haldager sandstone sourced from Fjerritslev Fm or intra-Gassum
1/05	Wexco	Seismic: 37 km 2D, 105 km² 3D; well: Felsted-1; Geochemical survey	Zechstein carbonates sourced from Z1/Z2 basin facies or Kupferschiefer
2/05	Elko	Well: Luna-1 with licence 1/11	Long-distance migration from Danish Central Graben
1/07	Geo-Center-Nord	Seismic: 20 km 2D	Zechstein carbonates sourced from Z1/Z2 basin facies or Kupferschiefer
2/07	Jordan	Well: Løve-1	Zechstein carbonates
3/07	DONG	Seismic: 50 km 2D; seabed cores; geochemical survey	Haldager sandstone sourced from Fjerritslev Fm
1/08	Danica	Seismic: 38.5 km 2D; geochemical survey	
1/09	Danica	Seismic: 2D, 3D; geochemical survey	Zechstein carbonates
2/09	Danica	Seismic: 2D, 3D; geochemical survey	Zechstein carbonates
4/09	Schuepbach		Lower Palaeozoic shale gas
1/10	Total	Well: Vendsyssel-1	Lower Palaeozoic shale gas
2/10	Total	Aeromagnetic and gravimetric survey	Lower Palaeozoic shale gas
1/13	Nikoil		Zechstein carbonates
1/14	Jutland Petroleum		Zechstein carbonates turbidites sourced from Stinkkalk/shale

A complete record of data collected as part of each license is provided in Schovsbo & Jakobsen (2017).

synclines around salt structures, nor did they verify filling of structures by migrating hydrocarbons from mature source rocks in the Norwegian sector.

Rhaetian–Jurassic sandstones charged from local Lower Jurassic kitchens – areas where source rocks have reached suitable temperature and pressure to generate hydrocarbons – located in deep rim synclines, were targets in licence 3/07 in western Jylland (Fig. 1). The work programme did not result in any drilling activities, since only a limited hydrocarbon generative potential – in terms of maturity and quality – of the source rock is expected to be present in the area.

Upper Cretaceous – Danian Chalk Play

The chalk play is highly prolific in the Danish Central Graben where it is the single most important reservoir. In this play the Maastrichtian–Danian chalks are sourced by Upper Jurassic to lowermost Cretaceous marine shales and sealed by Paleogene shales or intra-chalk tight zones. However, outside the Danish Central Graben area, maturity modelling indicates that these Jurassic shales may not have reached oil-maturity. Therefore, the play in the ODA has to rely on long-distance migration from the Danish Central Graben as tested by the two licences (1/97 and 2/97). However, the investigations did not yield a final conclusion on the existence of long-distance migration from the Danish Central Graben into the ODA.

Conclusions

The Danish area east of 6°15′E contains several plays including the lower Palaeozoic unconventional gas, Zechstein carbonate in the North German basin and the Rhaetian (Triassic) – Lower Jurassic sandstone in northern Jylland. However, exploration activities have not been able to demonstrate the existence of commercial quantities of hydrocarbons. For the Zechstein carbonate play, all identified structures appear to be of limited size, the reservoir quality is generally poor, and the presence of source rocks is uncertain. The Rhaetian–Jurassic sandstone plays depend on local kitchens developed around salt diapirs. Current data suggest that kitchen areas are

limited in extent. The Palaeozoic shales appear to be thinner than expected and to include less gas than similar prospective shales in Poland.

Exploration activities during the past 30 years (including the ODP) confirm the presence of the previously identified uncertain plays in the ODA. The ODP has not identified new conventional plays and has not proved or disproved the major unknowns in the area, namely the presence of mature source rock. Instead, data gathered for these activities have highlighted the excellent reservoir properties of Rhaetic–Jurassic and Bunter sandstones as particularly appropriate geothermal reservoirs.

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