Shale gas investigations in Denmark: Lower Palaeozoic shales on Bornholm

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The Cambrian to Lower Silurian succession in Denmark is mostly composed of organic-rich black shales that were deposited in an epicontinental sea during a period of high global sea level (Haq & Schutter 2008). The mid-Cambrian to early Ordovician Alum Shale was intensively studied in the 1980s for its source-rock properties (e.g. Buchardt *et al.* 1986). Recent attention has focused on its potential as an unconventional shale gas source (Energistyrelsen 2010). On southern Bornholm, many wells have been drilled through the Lower Palaeozoic succession because of its importance for groundwater exploitation. In western Denmark, only the deep exploration wells Slagelse-1 and Terne-1 have penetrated the Alum Shale, and knowledge of the unit west of Bornholm is thus very limited (Fig. 1).

The project 'Shale Gas in Europe (GASH)' was launched in 2009 to address the European shale gas potential (Horsfield *et al.* 2008) and is organised by the German Research Centre of Geosciences and sponsored by oil and energy companies. It deals with basic research of key aspects of gas shale from regional to reservoir scales, and focuses on four 'natural laboratories', namely the Lower Palaeozoic Alum Shale, the Carboniferous (Namurian) shales, the Lower Jurassic Posedonia Shale and as a reference the North American Barnet Shale. As part of GASH, a European black shale database is under construction in order to facilitate exploration and exploitation of gas shales in Europe. The Geological Survey of Denmark and Greenland (GEUS) has taken part in both the gas shale research and in the national data compilation for the European shale database.

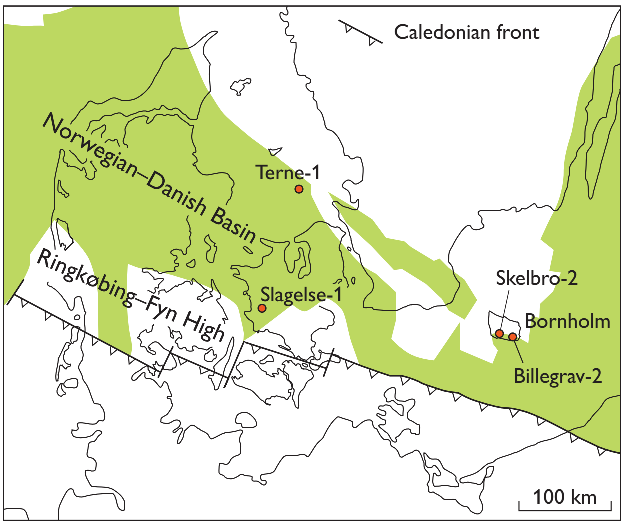

Fig. 1. Map of Denmark showing the distribution of Lower Palaeozoic strata (modified from Buchardt *et al.* 1997) and the location of the Slagelse-1 and Terne-1 exploration wells, and the Skelbro-2 (DGU 246.817) and Billegrav-2 (DGU 248.61) wells.

This paper presents the results of drilling on Bornholm in August 2010 by GEUS with the aim of obtaining fresh core material relevant to shale gas studies within the GASH project (the Skelbro-2 core) and providing new stratigraphic and geochemical information on the Lower Palaeozoic (the Billegrav-2 core). In particular, logging of the Silurian was needed to improve the log-stratigraphical template of Pedersen & Klitten (1990) which will enable the correlation of geophysical logs from non-cored water wells.

Drilling and logging project on Bornholm

The southern part of Bornholm is characterised by a mosaic of fault blocks (Graversen 2010). Outcrops, old core data and logs from water wells were used to find the best drilling locations for the two new wells. Both wells were fully cored and subsequently subjected to an extensive logging programme by GEUS in order to characterise the lithology as well as the water composition and the flow capacity of the fracture systems (Fig. 2). Spectral gamma and density scanning of the cores was subsequently carried out at GEUS.

Skelbro-2 well

The Skelbro-2 well was drilled 275 m east of Skelbro-1 (DGU 246.749; Pedersen 1989). The mid-Ordovician Komstad Limestone is 4 m thick at this locality. The top of the Alum Shale was encountered at 8.5 m below surface, and a total of 33.5 m of Alum Shale was drilled. The well was terminated at 42.9 m in the Lower Cambrian Rispebjerg Member (Læså Formation). The cored succession is virtually identical to the one described by Pedersen (1989) from the Skelbro-1 core.

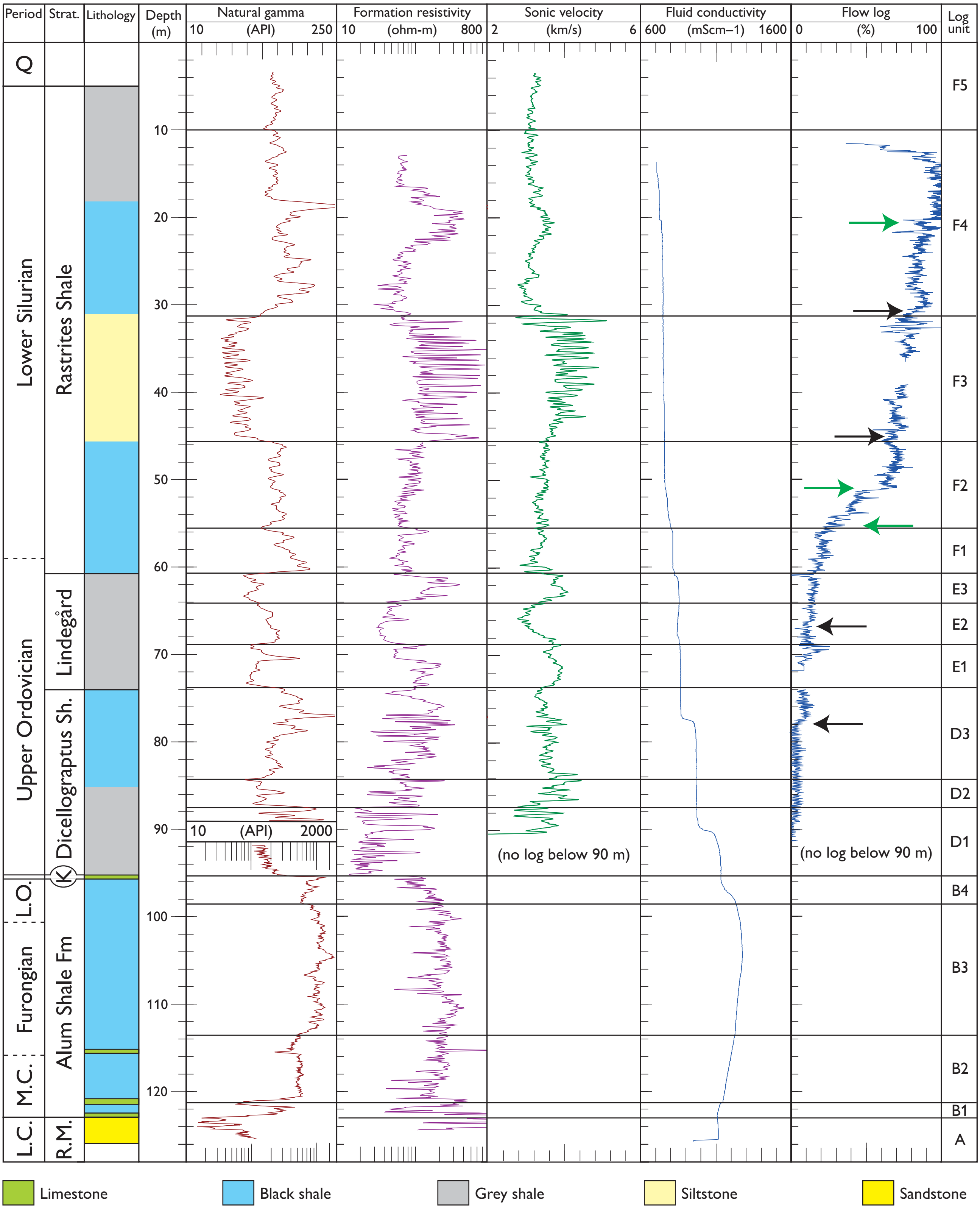

Fig. 2. Stratigraphy, lithology, natural gamma ray, formation resistivity, sonic velocity, fluid conductivity and flow logs for Billegrav-2. Log units **A–F** according to Pedersen & Klitten (1990). Dashed lines: uncertain biostratigraphical boundaries. Green arrows: major inflow zones; black arrows: minor inflow zones. **Q**: Quaternary. **K**: Komstad Limestone. **L.O.**: Lower Ordovician. **L.C.**: Lower Cambrian. **M.C.**: Middle Cambrian. **R.M.**: Rispebjerg Member. **API**: American Petroleum Institute (a standard unit for gamma-ray measurements). Note change in scale for natural gamma at 90 m.

Billegrav-2 well

The Billegrav-2 well was drilled close to locality 14b of Bjerreskov (1975) and 800 m south of the Billegrav-1 well (DGU 247.560; Pedersen 1989). The Silurian Rastrites Shale was cored from 4.5 m below surface down to 60.5 m. The Rastrites Shale comprises light to dark mudstone except for a distinct grey mud- to siltstone unit containing carbonate-cemented sandy beds at a depth between 31.2 and 46.0 m (Fig. 2). The Upper Ordovician includes the Lindegård Formation (previously referred to as the Tretaspis Shale or Tommarp and Jerrestad Mudstones), comprising grey mud- and siltstone and the dark organic-rich Dicellograptus Shale (Fig. 2). The base of the Dicellograptus Shale is located at a depth of 95 m. In its lowermost part the shale contains numerous bentonite beds including a 1 m thick K-bentonite bed that represents an important regional marker bed (Bergström & Nilsson 1974).

The Komstad Limestone is 0.1 m thick and only represented by its basal conglomerate. A thin bentonite rests directly on the Komstad Limestone conglomerate; there is no conglomerate at the base of the overlying Dicellograptus Shale. The Alum Shale Formation is 27 m thick and includes the Middle Cambrian Andrarum and Exsulans Limestone beds that are important regional marker beds (Nielsen & Schovsbo 2006). The base of the Alum Shale was reached at a depth of 122 m, and the well was terminated at 125.9 m in the Rispebjerg Member (Fig. 2).

Log-stratigraphy of the Billegrav-2 well

Correlation of water wells based on gamma variation has served as an effective mean of correlation between wells (Pedersen & Klitten 1990). All gamma-ray, log-defined units identified in nearby water wells can also be recognised in the Billegrav-2 well (Fig. 2). The resistivity and sonic logs provide important additional information (Fig. 2). In the Rastrites Shale, the resistivity is particularly powerful in resolving the lithological variation, since the carbonate-cemented sandy beds in the middle part (the F3 unit) stand out as high-resistivity beds (Fig. 2).

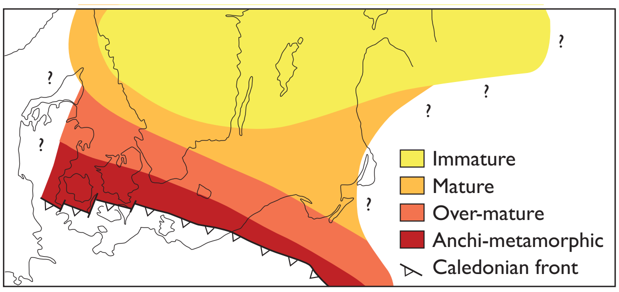

Fig. 3. Maturity of the Lower Palaeozoic sequence based on reflectance of vitrinite-like particles. The thermal maturity increases towards the Caledonian front, reflecting deep burial in Late Silurian to Early Devonian time. Modified from Buchardt *et al.* (1997).

Water-flow zones in the Billegrav-2 well

The flow log from this well clearly indicates that the water flow is related to three major and three minor influx zones (Fig. 2). The majority of the water flow takes place in the lowermost part of the Rastrites Shale at around a depth of 56–50 m. Relatively high water influx is also seen in the Rastrites Shale at about a depth of 20 and 30 m, whereas there is very little water flow from log unit F3 (Fig. 2). Water influx is seen in the Dicellograptus Shale at 77 and 90 m as well as in the uppermost part of the Alum Shale at 96 m. No flow is observed deeper in the well. Interestingly, the conductivity data suggest that the pore water in the Alum Shale has a much higher conductivity than in the shales above, suggesting that it is stagnant. This indicates that the Alum Shale acts as a hydraulic barrier between the silt- and sandstone aquifers below and the shale aquifers above this unit.

Potential shale gas units onshore Denmark

Shale gas units of potential economic interest have to be (1) matured to at least the gas generative stage, (2) organic rich (total organic carbon (TOC) >2 wt%), (3) volumetrically important (thickness >20 m and regionally distributed) and (4) preferentially located away from structurally complex areas. The Lower Palaeozoic succession on Bornholm contains up to 10 wt% TOC in the Alum Shale, up to 5 wt% in the Dicellograptus shale and up to 2 wt% in the Rastrites Shale (Buchardt *et al.* 1986). Also Mesozoic organic-rich units occur in Denmark, but those onshore are all thermally immature to marginally mature (Petersen *et al.* 2008) and thus have no potential for shale gas.

Thermal maturity and burial of the Lower Palaeozoic succession

The thermal maturity of Lower Palaeozoic shales in Denmark is only known from a few wells that all have vitrinite reflectance values >2.5%, indicative of a post-mature rank with regard to oil generation (Fig. 3). The shales are thus theoretically favourable for shale gas. The high maturity reflects deep burial and a high geothermal gradient in Late Silurian – Early Devonian time (Buchardt *et al.* 1997).

The present burial depth of the Lower Palaeozoic can be evaluated from the pre-Zechstein depth map (Fig. 4) that represents the deepest level that can be mapped with some con-

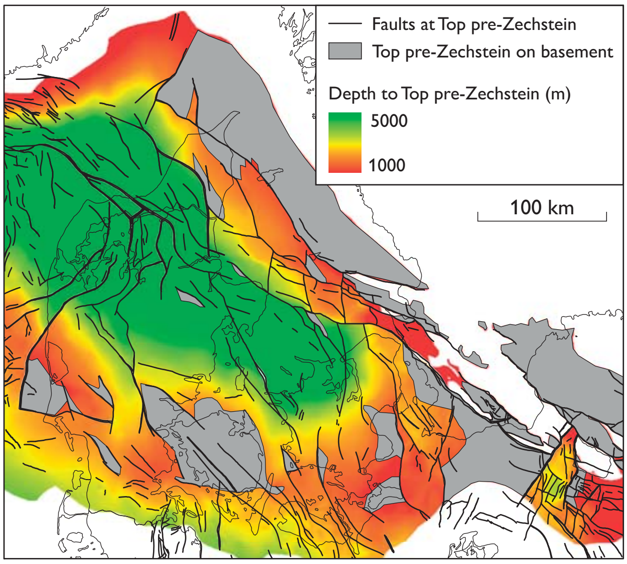

Fig. 4. Depth to the Top pre-Zechstein surface. Note the depocentre in the Norwegian–Danish Basin (>5000 m) and the shallow Ringkøbing–Fyn High (<1000 m). Areas where the Top pre-Zechstein surface coincides with basement are shown in grey. Modified from Vejbæk (1997).

fidence on a regional basis (Vejbæk 1997). Lower Palaeozoic shales are buried to very deep levels in the central parts of the Norwegian–Danish Basin and are probably not within reach of shale gas exploration. Lower Palaeozoic shales buried to moderate depths of 2–4 km occur in a broad belt around the margin of the Norwegian–Danish Basin. Shale gas investigations have focused on this region (Energistyrelsen 2010).

Conclusions

Shale gas research and exploration in Denmark is currently focused on Palaeozoic shales. The prospective units are poorly known in Denmark outside Bornholm. The play involves deeply buried, post-mature shale in which many basic rock properties are still unknown. Key questions that remain to be addressed include the gas storage capacity of the shales, their mineralogy and how they respond to fracturing. The hydrogeology of water wells on Bornholm may provide a test case to assist in unravelling how fracture systems and flow are distributed in the Lower Palaeozoic shales.

Acknowledgements

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