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Integrated seismic analysis of the Chalk Group in eastern Denmark—Implications for estimates of maximum palaeo-burial in southwest Scandinavia

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ABSTRACT

The origin of the topography of southwest Scandinavia is subject to discussion. Analysis of borehole seismic velocity has formed the basis for interpretation of several hundred metres of Neogene uplift in parts of Denmark. Here, refraction seismic data constrain a 7.5 km long P-wave velocity model of the Chalk Group below the Stevns peninsula, eastern part of the Danish Basin. The model contains four layers in the ~860 m thick Chalk Group with mean velocities of 2.2 km/s, 2.4 km/s, 3.1 km/s, and 3.9–4.3 km/s. Sonic and gamma wireline log data from two cored boreholes represent the upper ~450 m of the Chalk Group. The sonic velocities are consistent with the overall seismic layering, although they show additional fine-scale layering. Integration of gamma and sonic log with porosity data shows that seismic velocity is sensitive to clay content. In intervals near boundaries of the refraction model, moderate increases in clay content correlate with reduction of porosity and increase in velocity. Higher clay contents do not further increase velocity. The reduction of porosity and increase in velocity are interpreted as clay causing increased pressure dissolution and cementation. The interpreted velocities are systematically higher than values of a chalk velocity curve determined in previous studies, and it is estimated that a significant part of the velocity anomaly may be explained by the presence of clay. The remaining velocity anomaly can be explained by 450–500 m palaeo-burial of the Chalk Group. The burial anomaly will be over-estimated by ~150–200 m if the analysis is based on the average Chalk Group velocity and clay content is disregarded. Burial anomaly values of ~450–600 m result if the strongest velocity contrast at ~600–650 m depth is interpreted to be a result of diagenetic effects, consistent with the clay-corrected estimates within uncertainty.

1. Introduction

The Upper Cretaceous–Danian (Lower Paleocene) Chalk Group extends over large parts of the North Sea area, the Danish Basin, and the Ringkøbing–Fyn basement high (Fig. 1; Japsen, 1998; Vejbæk et al., 2003; Ziegler, 1990). The thick Chalk Group consists mostly of carbonates (Surlyk et al., 2003, and references therein), but near the eastern basin margin close to the transition zone between the Baltic Shield and the Danish Basin influx of siliciclastic sediments may exist at different levels (Brotzen, 1959; Erlström et al., 1997; Vejbæk et al., 2003).

Carbonates generally show large variability in seismic velocity due to lithology variation, diagenetic effects, burial and compaction, and pore volume, type and fluid (Anselmetti and Eberli, 1997; Eberli et al., 2003; Wang, 1997). A number of studies conducted over the past four decades have investigated factors controlling the velocity of chalk in the North Sea area (Fabricius, 2003; Fabricius et al, 2007, 2008; Japsen, 1998, 2000b; Scholle, 1977; Sclater and Christie, 1980), and a compilation of a large number of laboratory measurements of elastic properties of chalk from the Danish area shows dependency of porosity, pore type, pore fluid and cementation (Fabricius, 2007). Curves describing the increase in chalk velocities due to burial and compaction have been developed for the Danish area and used for mapping of overpressured and overcompacted areas (Japsen 1998, 2000a,b; Japsen and Bidstrup, 1999).

The driving mechanisms, amount and timing of uplift and exhumation of Scandinavia is subject of debate (Anell et al., 2009; Japsen, 1998, 2000a; Japsen et al., 2007; Japsen and Bidstrup, 1999; Jordt et al., 1995; Lidmar-Bergström et al., 2000; Lidmar-Bergström and Bonow, 2009; Nielsen, 2002; Nielsen et al., 2005, 2009a,b; Sclater and Christie, 1980). Burial anomalies of the marginal areas of the North Sea and Danish Basin region of up to several hundred metres have been interpreted by comparison of sonic log velocities of Chalk Group strata with ‘standard curves’ for velocity–depth relations for

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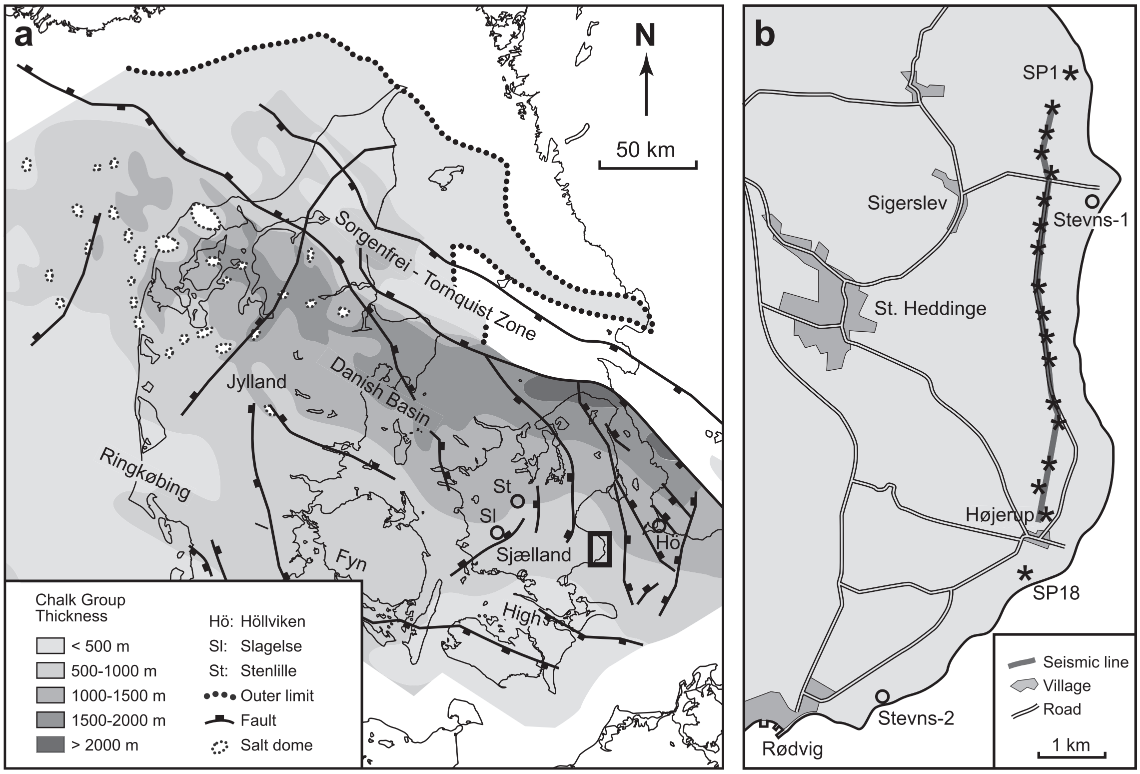

Fig. 1. (a) Simplified map of the Chalk Group thickness variation based on the regional studies of Vejbæk et al. (2003). The region has been subject to episodes of subsidence and inversion of localised structures, and it is characterised by a NW–SE-oriented fault zone system (Liboriussen et al., 1987; Erlström et al., 1997; Mogensen and Jensen, 1994; Thybo, 2001; Vejbæk and Britze, 1995; Ziegler, 1990). Circles show location of the Stenlille, Slagelse and Höllviken boreholes. Box indicates the study area on the Stevns peninsula. (b) Refraction seismic line with shot points (asterisks). The locations of the Stevns-1 and Stevns-2 boreholes are shown. Modified after Stemmerik et al. (2006) and Nielsen et al. (2010). Fig. 1a and b are shown by permission.

chalk sediments (Japsen, 1998, 2000b; Japsen and Bidstrup, 1999). These burial anomalies have been suggested as the result of general Neogene uplift in the western and southwestern Scandinavian region, including the Norwegian mountain ranges and southern Sweden (Japsen, 1998, 2000a). The values of uplift of the Danish Basin area interpreted by Japsen (1998, 2000a,b) and Japsen and Bidstrup (1999) are significantly larger than the corresponding values predicted by a geodynamic model, which explains uplift of Scandinavia as mainly driven by climatic effects (Nielsen, 2002; Nielsen et al., 2009a). By mass balance calculations of sediment and eroded rock volumes based on results from seismic interpretation and analysis of present topography, Anell et al. (2010) interpreted significant uplift of the main Paleic surface in southern Norway around the early Oligocene, although some topography along the western margin of Norway may be pre-Cenozoic.

Here, the study area is the Stevns peninsula of Sjælland located in the eastern part of the Danish Basin (Fig. 1). Previous seismic profiling indicates that the Chalk Group is ~900 m thick close to the Stevns peninsula (Lykke-Andersen and Surlyk, 2004), and sonic log information from the Danish Basin area shows that the Chalk Group is characterised by seismic P-wave velocities in the range of ~2500–4500 m/s (Japsen, 1998, 2000a; Nielsen and Japsen, 1991; Vejbæk et al., 2003). Jurassic and Lower Cretaceous siliciclastic sediments typically constitute a low-velocity zone below the Chalk Group (Nielsen and Japsen, 1991). The maximum burial anomaly has been estimated to amount to be ~500 m for the Stevns peninsula based on extrapolation and interpolation of values obtained from scattered boreholes (Japsen and Bidstrup, 1999). This value is somewhat lower than the ~750 m of burial anomaly indicated by an earlier burial anomaly map presented by Japsen (1998), which was based on an earlier version of the velocity–depth curve for the Chalk Group. Burial anomaly values of 400–550 m have been interpreted for the Stevns peninsula area based on regional reflection seismic mapping and integration of well log data (Vejbæk et al., 2003).

This study presents new values of maximum burial anomaly for the eastern Danish Basin area based on an approach in which results from integrated refraction/reflection seismic and log data interpretation are compared with the chalk velocity curve presented by Japsen and Bidstrup (1999) and Japsen (2000b). The seismic velocity structure of the Chalk Group is interpreted by analysis of controlled-source refraction /wide-angle reflection seismic data. The seismic velocity model is compared to coincident normal-incidence reflection seismic data, sonic and gamma log data, and porosity data from boreholes located close to the seismic profile line. The seismic velocity structure of the Chalk Group is interpreted in terms of changes in lithology, porosity reduction caused by cementation, and burial/compaction, and new values of burial anomaly of the eastern part of the Danish Basin are presented.

2. Refraction and wide-angle reflection seismic model

The refraction/wide-angle reflection seismic data were collected along a 7.5 km long N–S oriented line on the Stevns peninsula (Fig. 1). In total, 176 seismic recorders each mounted with a 4.5 Hz vertical component geophone were distributed along the middle 6 km of the line, and 18 explosive sources were detonated along the line of investigation; two of these sources were placed off the northern and southern end points of the line of recorders. The dynamite charge size ranged from 0.3 kg to 1.0 kg, and the explosives were placed at the bottom of 3–4 m deep drill holes. The Chalk Group is covered by a ~5 m thick layer of Quaternary clay till (GEUS, 2009).

Data examples from shotpoints 3, 8, and 17 are representative for the data set as a whole (Fig. 2). The signal-to-noise ratio of the record section of shot point 17 is poor as compared to the data quality of the