Mapping porosity anomalies in deep Jurassic sandstones – an example from the Svane-1A area, Danish Central Graben

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Hydrocarbon-bearing Upper Jurassic sandstone reservoirs at depths of more than 5000 m may form a future exploration target in the Danish Central Graben (Fig. 1). The Upper Jurassic sandstone play in the Danish sector has historically been less successful than in the neighbouring Norwegian and British sectors of the North Sea. This is mainly due to poor reservoir quality of the sandstones. However, the discovery in 2001 of an oil accumulation at a depth of more than 5000 m in the Svane-1 well has triggered renewed interest in the Upper Jurassic High Temperature – High Pressure (HTHP) sandstone play in Danish waters. The Jurassic plays comprise sandstone reservoirs deposited in a variety of environments, ranging from fluvial to deep marine.

This paper presents a study of a minor area around the Svane-1A well in the Tail End Graben (Fig. 1). The objective was to map acoustic impedance variations and hence to identify porosity anomalies associated with Jurassic sandstone units.

Interpretation in a tectonic setting such as the Jurassic HTHP petroleum system in the Danish part of the Central Graben is hampered by low seismic vertical resolution. However, by combining regional seismic mapping with inversion results and petrophysical log analysis, such obstacles can be tackled by mapping acoustic impedance variations. Application of seismic inversion techniques for porosity prediction in sandstone is a standard geophysical tool (Dolberg *et al.* 2000). Petrophysical analysis of well-log data from the upper part of the Jurassic sandstones encountered in the Svane-1A well shows a relationship between acoustic impedance (AI) and total porosity (PHIT), see later. This log-derived AI-PHIT relationship can be applied to transform acoustic impedance variation into porosity variation, when the acoustic impedance is predicted from seismic inversion of a 2D profile, and can be used to locate porosity anomalies associated with sandstone intervals in the area around the Svane-1A well.

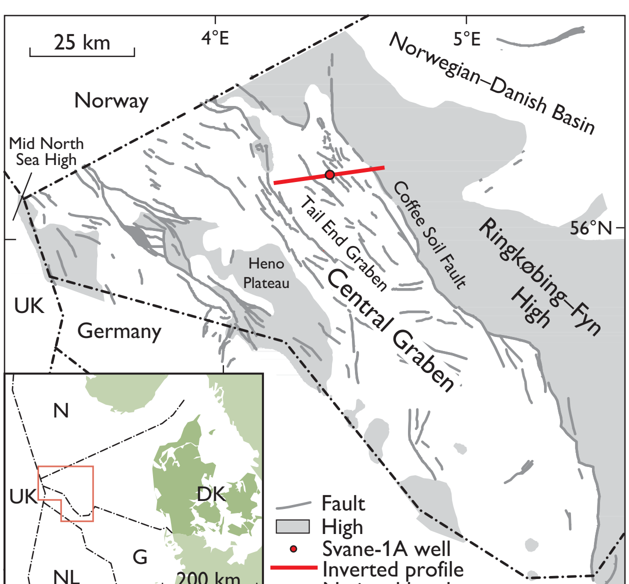


Fig. 1. Map of the Danish Central Graben showing the location of the Svane-1A well and the 2D seismic profile that was inverted for acoustic impedance.

Setting

The Danish Central Graben is part of the Jurassic North Sea rift complex and consists of a system of NNW–SSE-trending half-grabens bounded by the Coffee Soil Fault and the Mid North Sea High (Fig. 1; Japsen *et al.* 2003; Møller & Rasmussen 2003). Rifting took place from the Middle Jurassic and persisted into the Early Cretaceous. The syn-rift sedimentary fill is dominated by mudstone with subordinate layers of sandstone. In some stratigraphic intervals, the mudstone is rich in organic matter (Petersen *et al.* 2010).

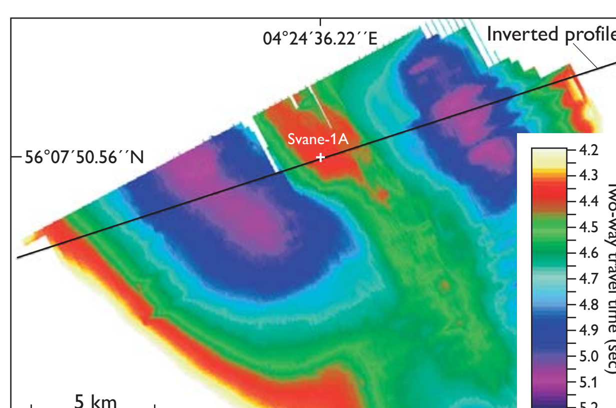


Fig. 2. Two-way travel time structure map of the intra-Kimmeridgian marker horizon corresponding to the top of the drilled Svane-1A sandstones.

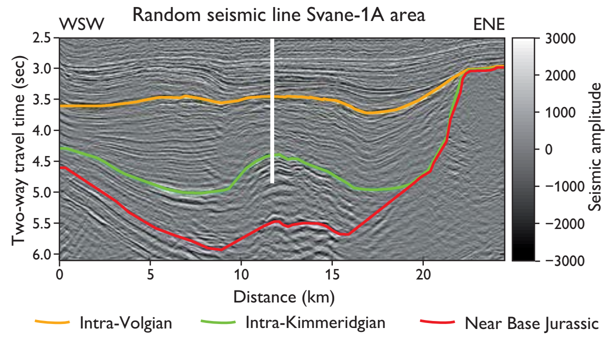


Fig. 3. The input for the seismic inversion is a 2D seismic profile extracted from the 3D PAM_99 survey with three interpreted intra-Jurassic marker horizons: intra-Volgian, intra-Kimmeridgian and Near Base Jurassic. The Svane-1A well location is indicated by the white line. Note the alternating high and low amplitude layers below the intra-Kimmeridgian marker horizon.

The Svane-1A area

The Svane-1A well is located on a 4-way-dip closure structure at an intra-Kimmeridgian level in the northern part of the Tail End Graben (Fig. 2). It is one of the deepest wells ever drilled in Denmark (total depth 5952 m). The structure map of an intra-Kimmeridgian marker horizon corresponding to the top of the Svane-1A sandstones shows that the well is located on a NNW–SSE-oriented structural high along the basin axis bounded by two depocentres (Fig. 2).

Upper Jurassic sandstone with dry gas was encountered at 5311 m. Unfortunately, no cores or sidewall cores were collected due to unstable borehole walls. At depths over 5400 m, the sandstone layers in Svane-1A are characterised by porosities of 15–24% and low permeabilities. The Svane-1A well is situated in a HTHP environment with overpressures of 8630 psi at a depth of 5350 m, which may imply that the pore pressure is close to the fracture pressure according to Johannessen *et al.* (2010).

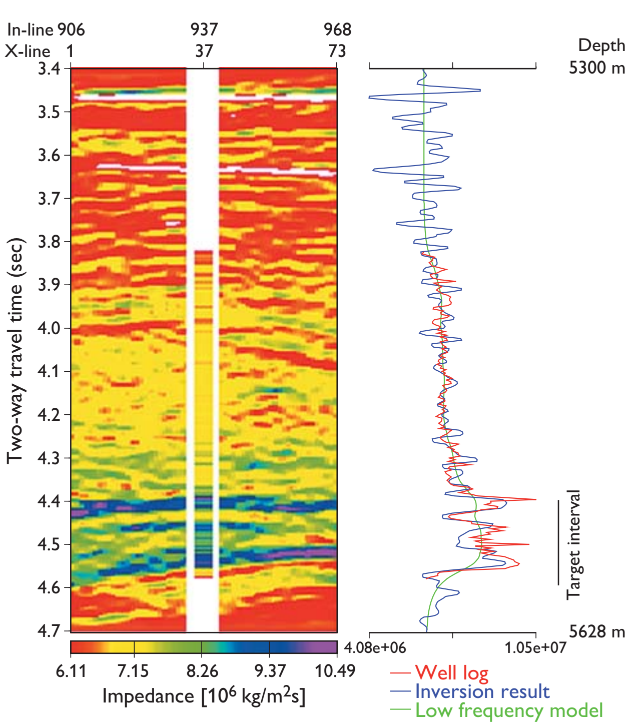


Fig. 4. Quality control of the absolute acoustic impedance inversion result. **A**: Section of the inversion result with the acoustic impedance log inserted at the well location. **B**: Comparison between the acoustic impedance trace estimated at the well location (blue), the low frequency model at the well location (green) and the acoustic impedance well log (red).

Seismic inversion for acoustic impedance

Seismic inversion is the process of transforming seismic reflection data into quantitative rock properties such as acoustic impedance (AI) using reflection seismic data constrained by borehole data in order to describe a possible reservoir. Acoustic impedance is the product of the rock density and the compressional P-wave velocity, which are both commonly measured in boreholes as the bulk density and the sonic velocity. A log-derived AI-PHIT relationship based on the petrophysical well log is used to transform the inversion-derived AI into total porosity (PHIT). Seismic inversion for acoustic impedance was carried out using the 2D ISIS seismic inversion software. The inversion algorithm is a deterministic approach based on a simulated annealing algorithm (Maver & Rasmussen 1995; Rasmussen & Maver 1996).

Both seismic and well-log data were used for the inversion. The input data consist of a 2D seismic profile (Fig. 3) and raw log data (sonic and density) as well as the time-depth data from the Svane-1A well.

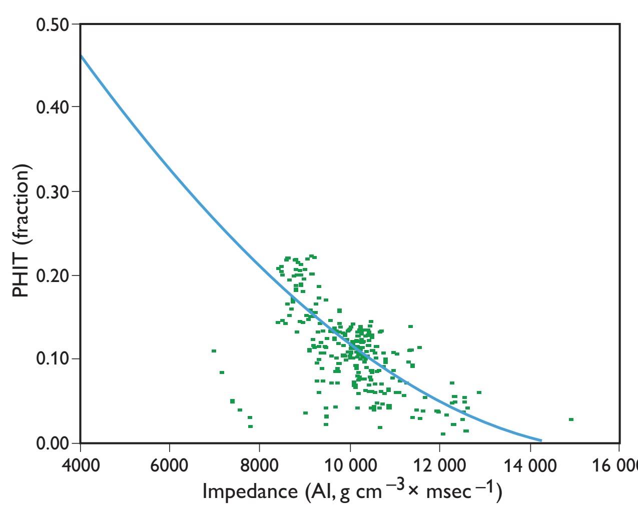
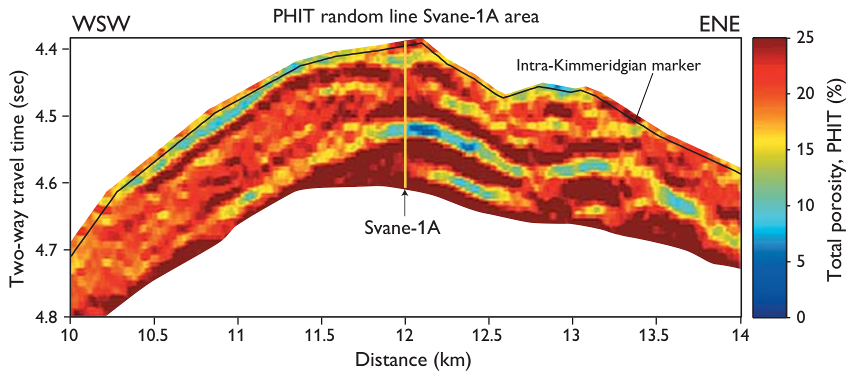


Fig. 5. Cross plot of the log-derived acoustic impedance (AI) versus the log-derived total porosity (PHIT), based on the Svane-1A sonic and density log data from 5300–5627.93 m.

Fig. 6. Close-up of the 2D total porosity (PHIT) variation around the Svane-1A well, showing the PHIT variation below the intra-Kimmeridgian marker horizon along part of the inverted 2D seismic profile between faults A and C (Figs 7, 8). The high porosity (>25%) between 4.55 and 4.6 sec TWT at the well location is an artefact due to underestimation of the absolute acoustic impedance in the inversion (see text and Fig. 4). The shape of the PHIT profile is governed by the limited depth interval 5300–5628 m, for which the applied AI-PHIT transform is defined, corresponding to a time window of 200 msec below the intra-Kimmeridgian marker horizon.



In order to ensure a well-to-seismic tie, the available time-depth data were used to create a reflectivity series with the same sampling rate (4 msec) as the input seismic data and to convert the log data from a depth to a two-way travel time (TWT). The acoustic impedance was calculated by multiplying the calibrated density log and the velocity log derived from the calibrated sonic log. The reflectivity series was computed by differentiating the acoustic impedance series. After the log calibration, the Svane-1A wavelet was estimated by deriving the convolution operator between the reflectivity log and the seismic trace at the well location using a least squares wavelet estimation method. The length of the wavelet was estimated over the Jurassic target interval to 4.2–4.58 sec TWT.

In general, seismic data have limited frequency bandwidth at the low and high ends. The (missing) low frequencies contain the critical information concerning the absolute values of impedance. In order to invert for absolute acoustic impedance, a low frequency model is needed to introduce the sub-seismic frequencies into the seismic inversion result. The 2D low frequency model is constructed by laterally extrapolating the final calibrated impedance log from the Svane-1A well between three interpreted horizons extracted from the 3D seismic PAM_99 survey to guide and yield the absolute level of acoustic impedances along the seismic 2D profile.

Evaluation of the absolute acoustic impedance inversion result is shown with the acoustic impedance log inserted at the well location (Fig. 4). An excellent fit is seen between the inverted log trace (blue), the low frequency model log trace (green) and the well log trace (red) at the top (4.4 sec TWT) and bottom (4.45 sec TWT) of the target sandstone interval. However, it is important to notice that the inversion result (blue line) underestimates the absolute acoustic impedance in the deeper parts of the sandstone interval. This will lead to an overestimation of the porosity in this interval.

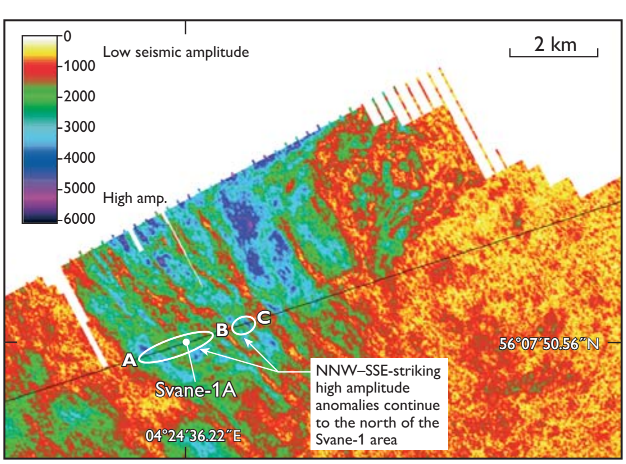


Fig. 7. Seismic amplitude extract from a 65 msec time window below the intra-Kimmeridgian marker horizon. NNW–SSE-trending high amplitude anomalies (blue colours) continue to the north of the Svane-1A well. **A**, **B** and **C** mark the location of faults (see Fig. 8).

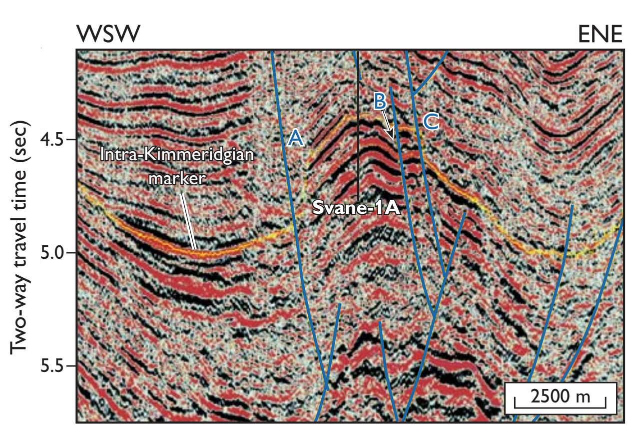


Fig. 8. Close-up of the 2D seismic section across the Svane-1A well (black). Notice the high amplitude reflections below the intra-Kimmeridgian marker horizon (yellow) between faults **A**, **B** and **C** (blue).

Calculating porosity from acoustic impedance

Cross-plotting the log-derived acoustic impedance (AI) and the log-derived total porosity (PHIT) using the Svane-1A sonic and density log data from the depth interval 5300–5628 m results in an AI-PHIT transform obtained from a second-order polynomial regression line (Fig. 5):

$$PHIT = 0.8176 - 1 \times 10^{-4}AI + 3 \times 10^{-9}AI^2$$

where porosity is given in fraction and AI in g cm^{-3} × msec^{-1}.

The AI-PHIT transform, which is valid for the limited depth interval 5300–5628 m corresponding to a time window of 200 msec below the intra-Kimmeridgian marker horizon, can be applied to convert the 2D acoustic impedance inversion result into a 2D total porosity (PHIT) profile in this time window (Fig. 6). This 2D PHIT profile is a close-up of the central part of the inverted seismic profile at the 4-dip closure. The PHIT profile shows the lateral distribution of porosity anomalies below the intra-Kimmeridgian marker horizon around the well location.

Alternating high (15–25%) and low porosity (5–15%) layers are seen below the intra-Kimmeridgian marker horizon. In the time window 4.47–4.51 sec TWT, the modelled porosities are up to 5% too high as a consequence of underestimation of the absolute acoustic impedance in the deeper parts. The derived total porosity values show good agreement with the observed Svane-1A well porosities (up to 20–22% in the upper sandstone units), and indicate the presence of high porosity intervals off-structure down along the flanks of the structural high.

Porosity prediction tool

The existence of Upper Jurassic sandstones with high porosities (15–25%) has been demonstrated in the Svane-1A well and interpreted from the inversion result. Thus an important question concerns the lateral extension and distribution of these sand-rich layers, and the challenge is to predict the location of yet undrilled high-porosity sandstone layers away from the well. For this purpose, a seismic amplitude extraction map for a narrow time window of 65 msec below the intra-Kimmeridgian marker horizon was created to illustrate the lateral distribution of porosity anomalies in the vicinity of the Svane-1 well (Figs 7, 8).

The seismic amplitude extraction map indicates that high amplitudes associated with the high porosity sandstone unit are concentrated along NNW–SSE-trending anomalies that extend to the north of the Svane-1A area (Fig. 7). A close-up of the seismic data shows a correlation between fault planes (Fig. 8 A–C) and low amplitude features on the amplitude extraction map (Fig. 7). The amplitude extraction map also implies high lateral variability in the distribution of porosity anomalies corresponding to lateral variations in reservoir quality over the area. A possible new target area for further exploration could thus be located further to the north along the Svane structure where high amplitudes prevail. The application of seismic inversion data based on well-log data, seismic data and a thorough geological model can significantly increase the possibility for finding new targets.

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