DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/23

Seismic velocities in the chalk, NE part of the South Arne Field

Contribution to the Chalk Background Velocity project

Ole Vejbæk & Peter Japsen

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Introduction

For the purpose of analysing the suitability of high resolution stacking velocities as support for the construction of low-frequency models, a subset a velocity cube has been investigated. Low-frequency models are needed in connection with inversion of seismic data for acoustic impedance, because low frequencies, and thus the absolute level of the acoustic impedance, are not directly contained in the seismic data. To overcome this problem, standard stacking velocities, horizontal velocity analysis (HVA) data or more sophisticated processed data (as used here) may be utilised in this construction. The velocity cube used in this study has been produced by GX-Technology EAME Ltd. in august 2003 in connection with a pre-stack depth migration (PSDM) processing of a 3-D seismic data set covering the entire South Arne Field. A subset of this cube covering the north-eastern quadrant around the Rigs-2 and Modi-1 wells has been selected for the analysis (Fig. 1).

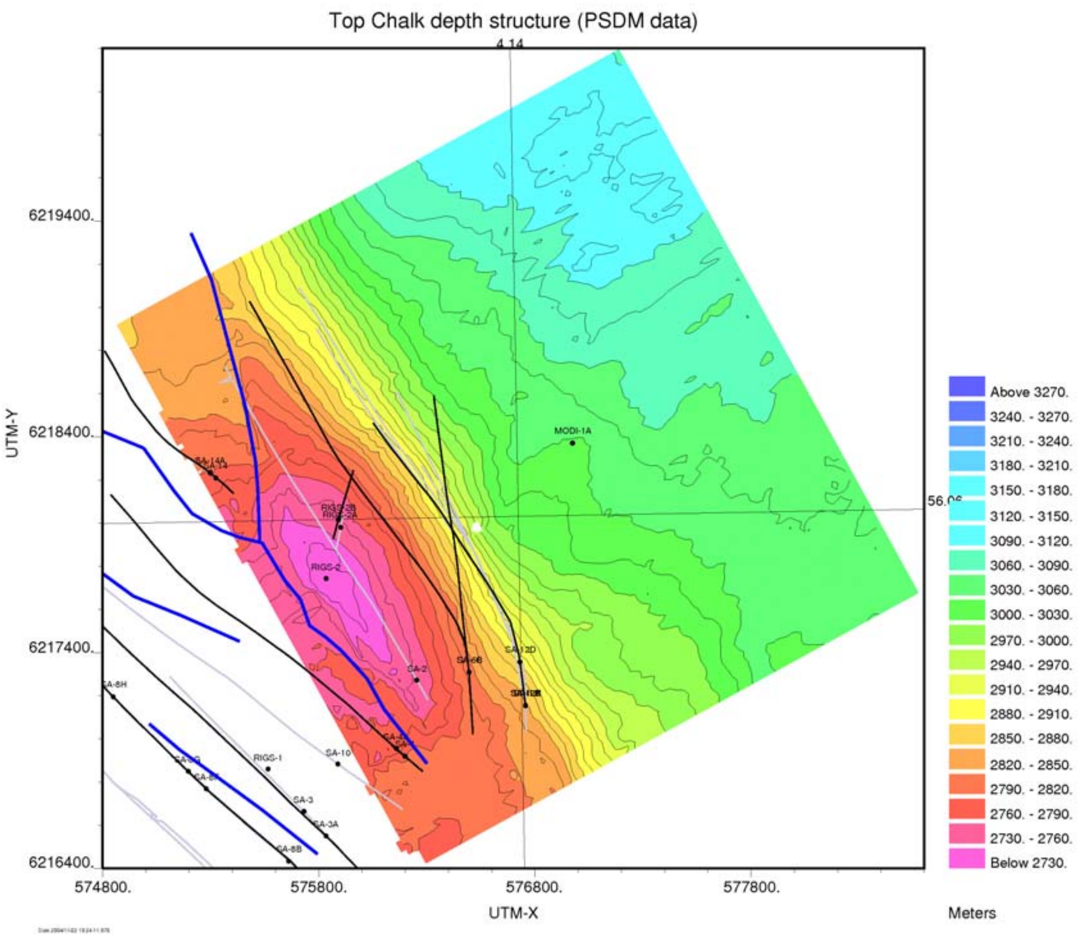

Figure 1. *Top chalk depth structure map interpreted directly on PSDM data. The mapped area shows the extent of the subset 3-D velocity data-set analysed in this report.*

In order to get a precise sampling of the velocity-cube, the Top Chalk, Top Tor and Base Chalk reflectors have been re-interpreted on the PSDM data that are depth converted with a velocity field contained in the analysed velocity cube. In order to reduce the data volume while still maintaining a representative sampling, only every eight trace has been included in the analysis (original line and trace interval is 12.5 m). The sample rate is 10 m, the line number interval is 2986 – 3216, and the trace interval is 1480 – 1690.

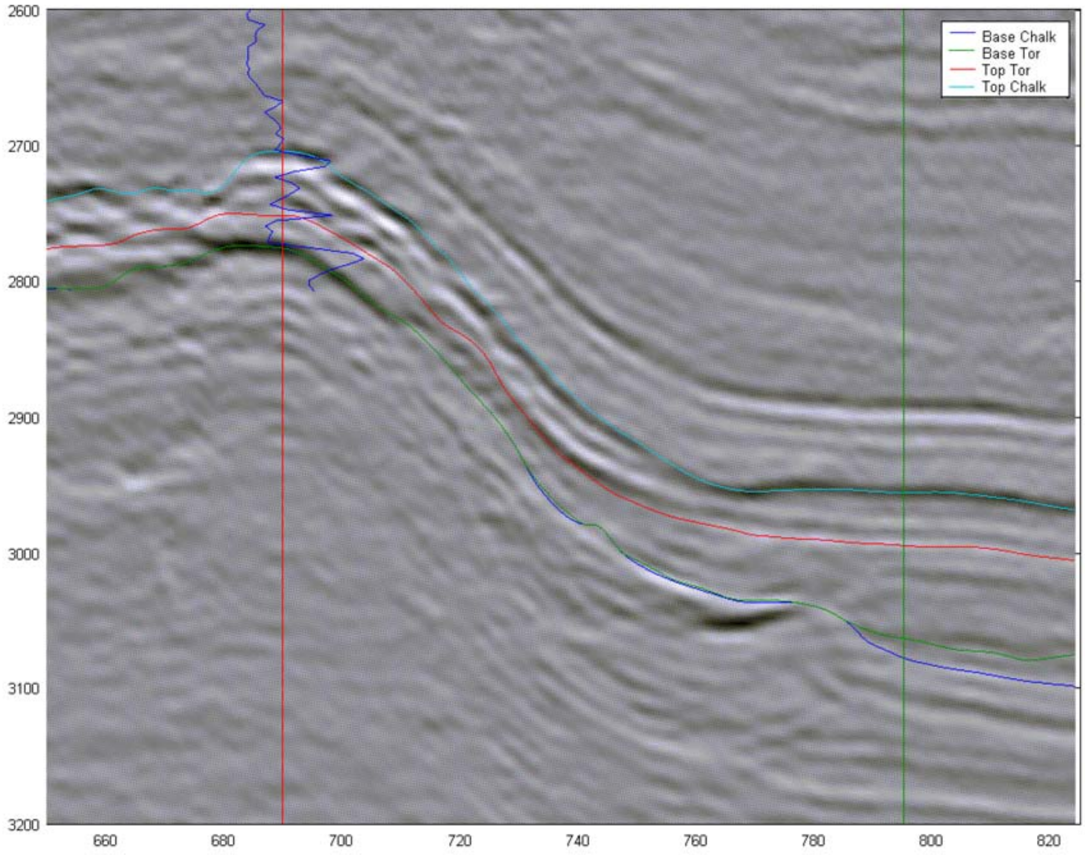

Figure 2. *West – east seismic section across the analysed sub volume. As opposed to the data used in this report, this section is in two-way time. The red vertical line shows the position of the Rigs-2 well, and the green is the Modi-1 well location.*

The selected seismic velocity data set covers a considerable depth range (Figs. 1 and 2), and the data should ideally capture any depth dependency of velocity. The volume also straddles fully oil saturated reservoir sections (around Rigs-2), residual oil saturations (around Modi-1) and presumably fully brine saturated rock (east of Modi-1). In order to give an impression of the data set Figure 3 shows the seismic traces included in the analysis.

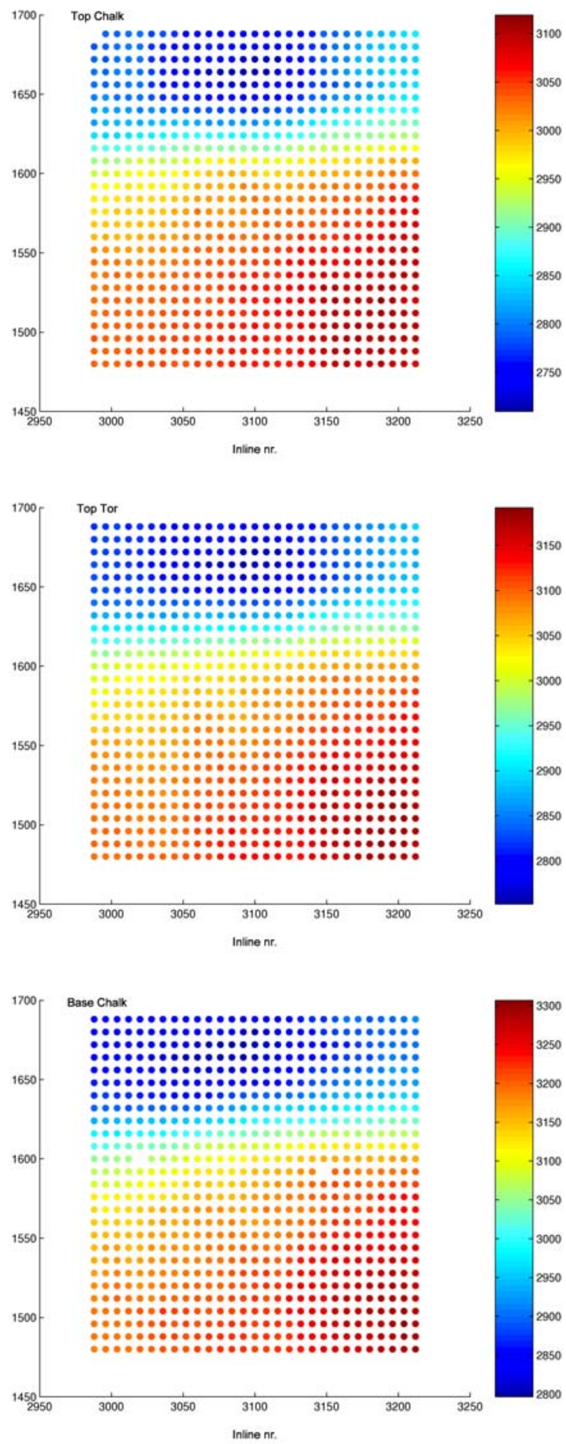

Figure 3. *The analysed data set with colour-coding showing depth in metres to Top Chalk (upper), Top Tor (middle), and Base Chalk (lower). Every dot corresponds to a seismic trace included in the analysis (every 8th trace corresponding to 100 m intervals). NW is to the right. Y-axis is cross-line number.*

The Tor Formation

The seismic velocities of the Tor Formation show the expected depth dependency from the depth-variation in the sample volume (compare Figs 1, 2 & 4). We can compute an average velocity-depth gradient, *k* (m/s/s = 1/s) from the densest parts of the data cloud in Figure 4:

$$k = \frac{3800 - 2900 \quad (\text{m/s})}{3200 - 2800 \quad (\text{m})} = \frac{900}{400} = 2.25 \quad 1/s$$

This estimate matches the normal velocity-depth trend of Japsen (1998, 2000) that predicts a gradient of 2 1/s for chalk velocities around 3000 – 3500 m/s.

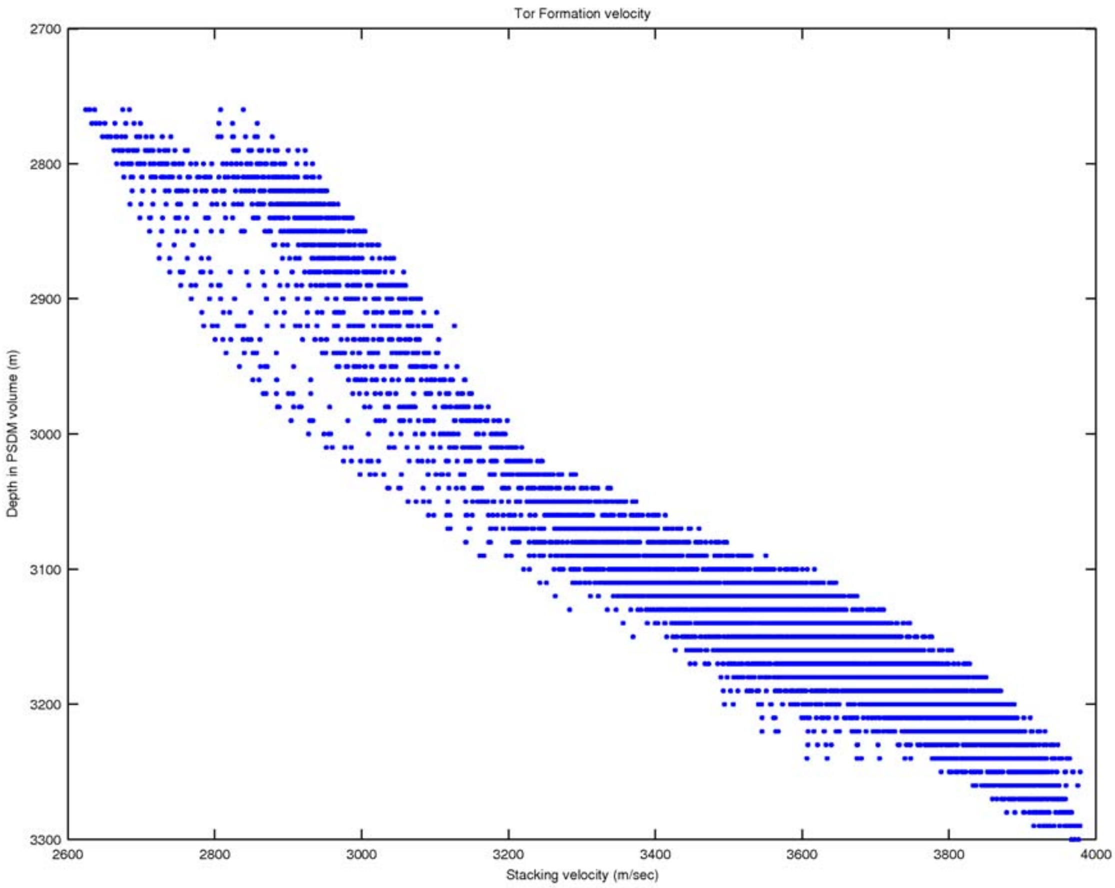

Figure 4. *Seismic velocities from the Tor Formation in the 3-D data set within the studied sub volume. The analysed depth interval can also be seen on Fig. 3 top and middle panel. Horizontal striation is due to the 10 m sample rate in the traces.*

The overall mean Tor Formation velocity in the extracted data set is 3477 m/sec, which is much below what would be expected from the present depth when compared to the normal velocity depth trend for chalk (Fig. 5; Japsen 2000). The chalk formation overpressure in the Rigs-2 well is in the order of 14.8 MPa according to the completion report and 14.5 according to Dennis et al. (2004). Assuming overburden densities of around 2000 kg/m^3 and 1000 kg/m^3 for bulk rock and water a correction for over-pressure would result in a depth shift of 1450 m (see Japsen 1998). However, the depth shift of 1800 m is needed to obtain a match between the data and the normal velocity depth trend (Fig. 5). After this depth shift we observe that the depth trend in the stacking velocity data mimics that of the normal compaction depth trend.

Observed average Tor Formation velocity in the high-porous parts of the Rigs-2 well is around 2600 m/sec (117 ms/ft; Fig. 6) corresponding to porosities exceeding 40%. This velocity ties well with the stacking velocity (dot in Fig. 5), and it appears that the interpreted stacking velocities have been calibrated with the Rigs-2 data. The velocities are, however, too low as compared to the normal velocity-depth trend even after correction for overpressure. The discrepancy corresponds to a depth shift of c. 300 m (1800 m – 1500 m) that may reflect a considerable preservation-effect from early hydrocarbon invasion at a time when the effective stress was less (corresponding to 300 m more shallow burial). Likewise the high porosity in Rigs-2 may be interpreted to reflect early hydrocarbon migration (Hansen 2003, Vejbæk et al. 2005).

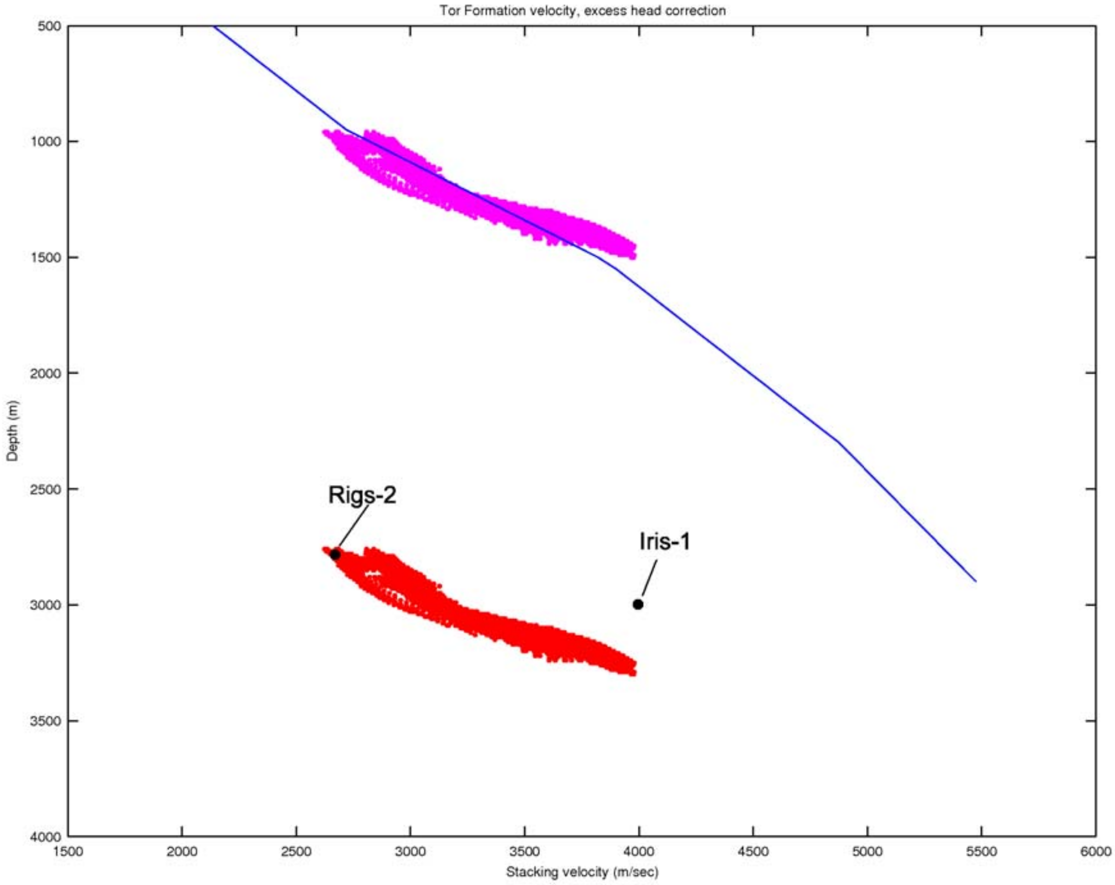

Figure 5. *Original stacking velocities for Tor Formation data are here shown in red. After a depth shift of 1800 m, the population (in magenta) falls on the normal velocity – depth trend (from Japsen 2000).*

In Figure 5 we observe that the velocity-level from Rigs-2 continues down-dip with a steady gradient. However, the nearby Iris-1 well does not match the level of the stacking velocities, but is exactly consistent with the normal velocity-depth trend after correction for overpressure.

Also studies by Hansen (2003) suggest the abnormally high porosities in Rigs-2 (and thus the low velocities), to result from early hydrocarbon invasion effects, and to vanish already in the Modi-1 well where porosities in the Tor Formation are around 20%. The Modi-1 well lacks sonic log data, and contain residual oil saturations (Sw ~80%). It may be surmised that the transition from the crestal parts of the South Arne structure where hydrocarbon preserving effects are important to where they do not occur is likely to be rather abrupt. It is possible that the velocity analysis is incapable of handling such abrupt changes. It thus appears that too much emphasis has been placed on the Rigs-2 well in the construction of the velocity cube. A low-frequency model for acoustic inversion constructed on the basis of the velocity cube is thus expected to be erroneous.

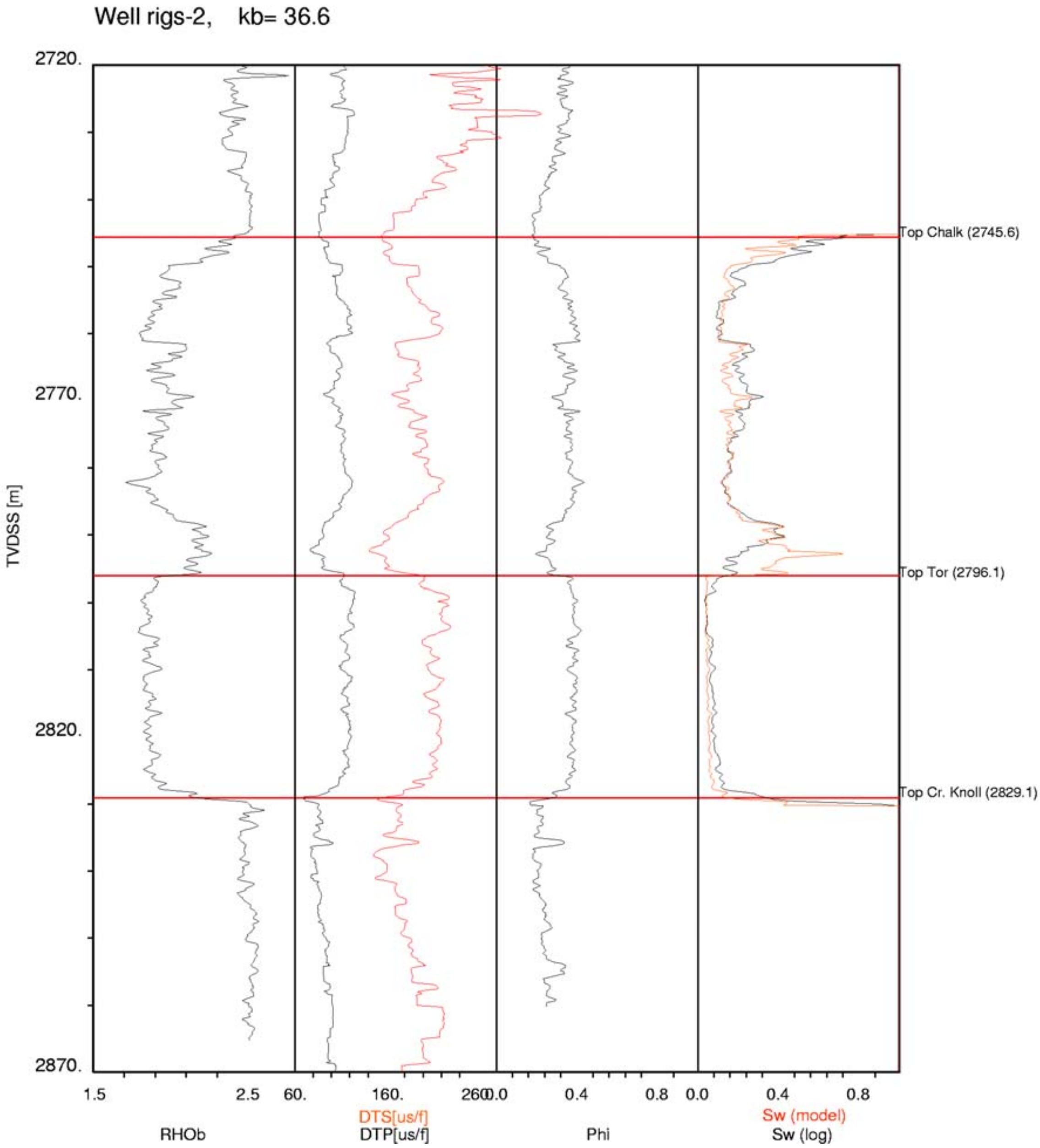

Figure 6. *Rigs-2 logs. Note that sonic logs are reciprocal velocity values.*

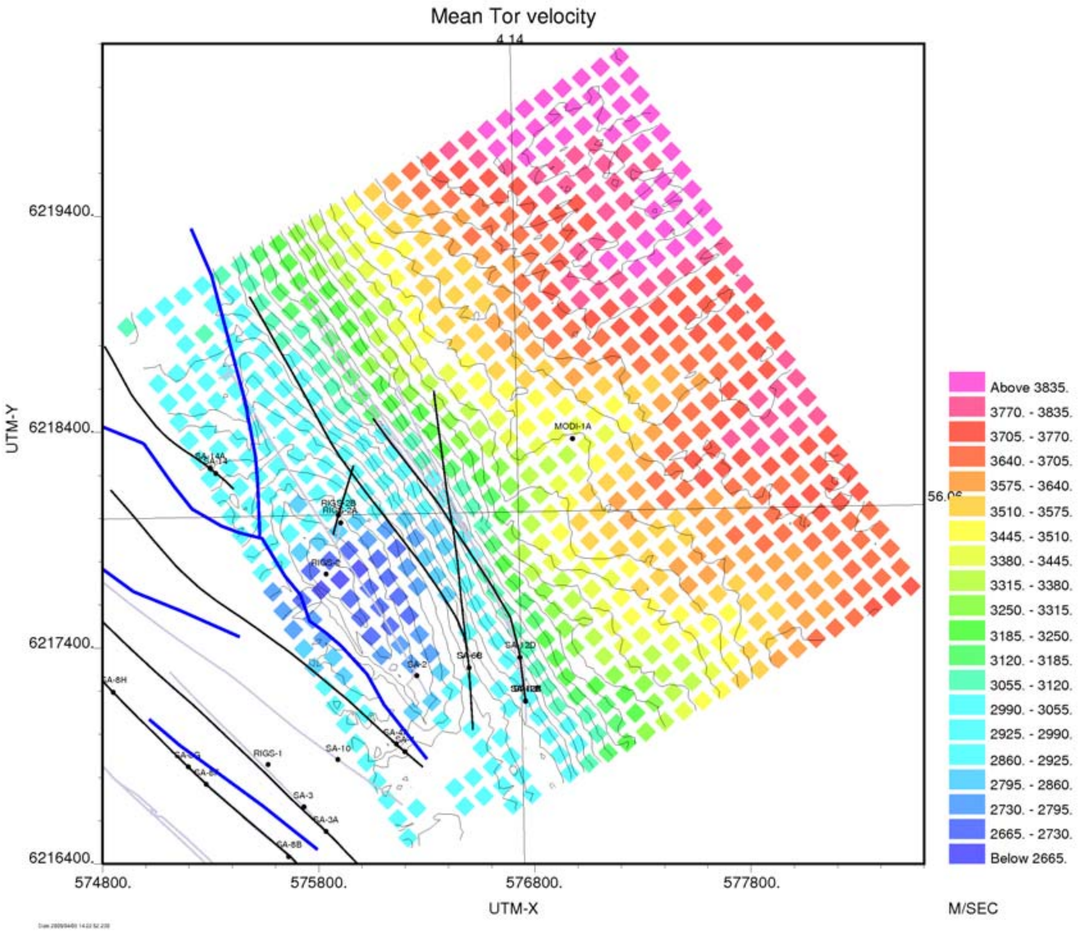

Figure 7. *Mean Tor Formation stacking velocities with Top Chalk depth contours from Fig. 1 superimposed. Each square is the average velocity in one trace. Average velocities are clearly following depth variations smoothly.*

The Ekofisk Formation

An analysis similar to that for the Tor Formation has been applied to the Ekofisk Formation (Fig. 8). The stacking velocities are also quite low, and a depth correction of 1800 m is needed to align the data with the normal velocity dept trend (Fig. 9). The velocities for the Ekofisk Formation are also below the expected for this depth, corresponding to too high porosities. Mean Ekofisk velocity in the cube is, however even lower than for the Tor Formation, at 2710 m/sec. When looking at the Rigs-2 well data, porosity is not quite as high on average as in the Tor Formation in spite of lower velocities. It may therefore be surmised that the stacking velocity cube, like the well-log velocity data (Fig. 6), are reflecting a higher clay content than the Tor Formation.

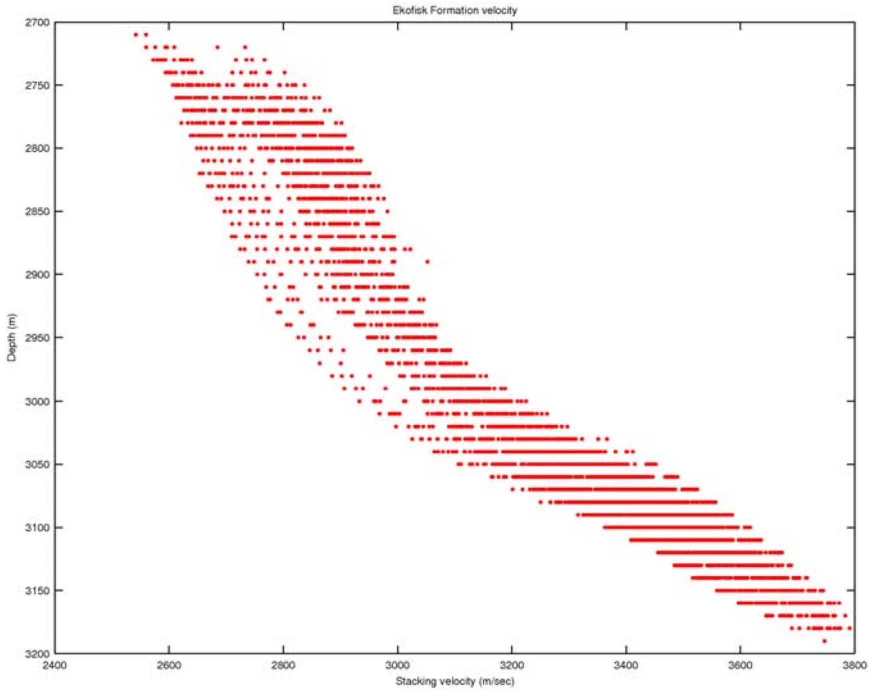

Figure 8. *Stacking velocities for the Ekofisk Formation extracted from the velocity cube within the area depicted in Fig. 1. Horizontal striation is due to the 10 m sample rate in the traces.*

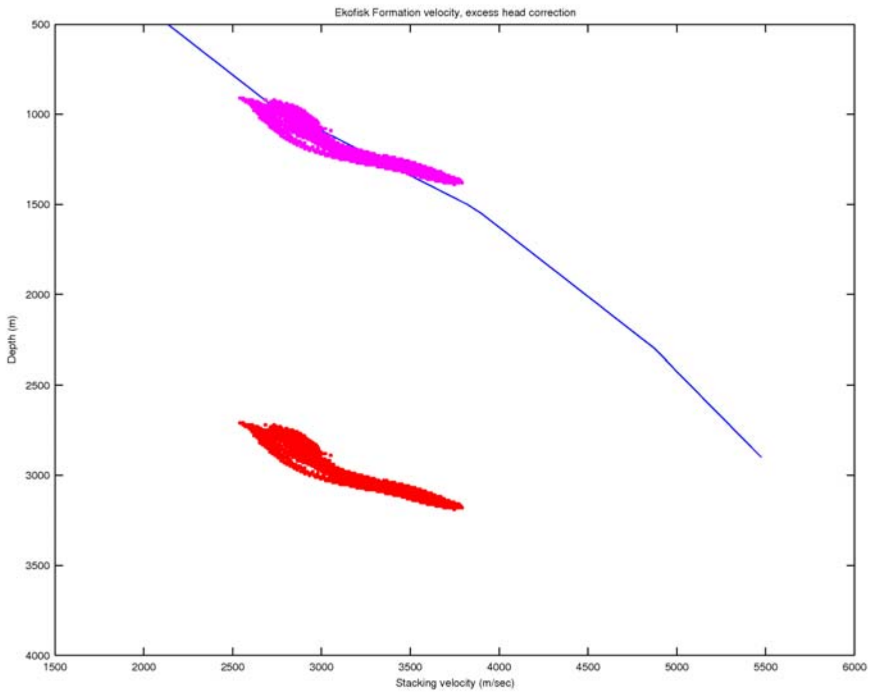

Figure 9. *Original stacking velocities for Ekofisk Formation data are here shown in red. After a depth shift of 1800 m like for the Tor Formation, the population (in magenta) falls on the normal velocity – depth trend (from Japsen 2000).*

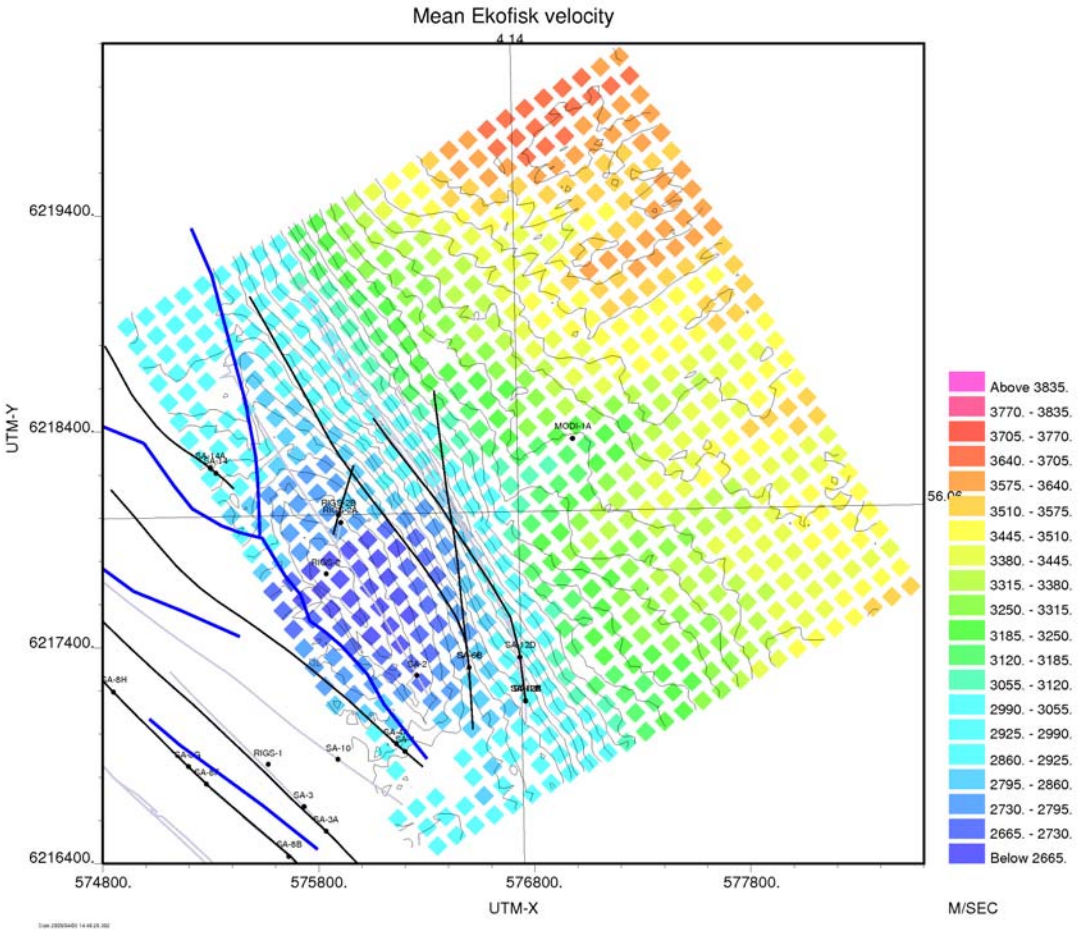

Figure 10. *Mean Ekofisk Formation stacking velocities with Top Chalk depth contours from Fig. 1 superimposed. Each square is the average velocity in one trace. Average velocities are clearly following depth variations smoothly, but velocities are slightly lower than for the Tor Formation (compare Fig. 7).*

Discussion

In the above analysis we have concluded that the velocity cube obviously is affected by the Rigs-2 well data, and that this well is likely to represent a local anomaly in terms of porosity and velocity. This porosity anomaly is suggested to be the result of early oil charging in the Rigs-2 well and its immediate vicinity. Therefore the down flank prediction of the Tor and Ekofisk formation velocities from the seismic data is expected to yield too low velocities as also hinted by the Iris-1 well velocities. However, it could be argued that the low velocities are just an effect of oil charging, and not hydrocarbon preserving effects. Even in Modi-1, residual oil saturations were encountered (Sw ~80%) which due to the non-linear effect of mixed fluid compositions would lower moduli and velocity almost as much as the fully oil charged chalk (Sw <20%). In order to investigate this assertion, some simple fluid substitution calculations have been done using the properties listed in Table 1.

As stated above, the porosity in the Tor Formation in the Rigs-2 well is around 40% with a P-wave velocity close to 2600 m/sec. The water saturation in the well is well below 20%

and substitution to 80% brine has almost no effect as consistent with the highly non-linear effects of fluid mixtures on velocity. Replacing fluids to 100% brine has some effect by increasing to 2800 m/sec. The present Tor Formation depth in Rigs-2 is around 2800 m and a correction for over-pressure results in an effective depth of close to 1400 m. The normal velocity depth trend should be 3620 m/sec. The early hydrocarbon preserving effect on velocities in Rigs-2 may thus be estimated to be around 820 m/sec equivalent to around 400 m of burial. Fluid effects alone are thus not capable of explaining the too low velocities observed in the velocity cube down dip of the Rigs-2 well location.

	ρ (g/cm^3)	K (GPa)	G (Gpa)
Oil	0.633	0.52	0
Water	1.035	2.96	0
80% brine	0.955	1.53	0
Chalk 0%	2.710	71.00	30

Table.1: Properties in the form of density (ρ), bulk modulus (K), and shear modulus (G).

Porosity		100% brine	80% brine
0.2	Vp (m/s)	4400	4.277
	Vs (m/s)	2300	2.308
	Rho (g/ccm)	2.375	2.359
	K (GPa)	29.22833	26.405
	G (GPa)	12.56375	12.564
0.4	Vp (m/s)	2800	2.555
	Vs (m/s)	1400	1.411
	Rho (g/ccm)	2.04	2.008
	K (GPa)	10.6624	7.771
	G (GPa)	3.9984	3.998

Table 2: Calculated properties for Rigs-2 type chalk for two different porosities at two different fluid compositions.

Summary

The seismic velocity cube is clearly strongly tied up well data from the Rigs-2 well, and this may result in propagation of the properties of the chalk in this well down-flank. The velocity at the Rigs-2 well location is seen to be smoothly continuous with the entire east flank velocity distribution such that only a gradual depth dependency is seen. If velocities are depth shifted 1800 m, this depth dependency is nicely consistent with the normal velocity depth trend for chalk. However, the Rigs-2 well (and immediate vicinity) is most probably a local anomaly due to porosity preservation from early hydrocarbon invasion. The high porosity and low velocity encountered in both Tor and Ekofisk formations in this well are thus a local anomaly little lateral extent. The down flank velocity prediction from the seismic velocity cube is therefore expected to be wrong. Velocities in the Rigs-2 well are over 1000 m/sec too low compared to a normal velocity depth trend even considering overpressuring. Of these 1000 m/sec about 200 is attributed to fluid effects (oil content) leaving about 800 m/sec to be attributed to porosity preservation from early hydrocarbon invasion. This figure corresponds to about 400 m of burial. The porosity preservation effect from early hydrocarbon invasion is removed by subtracting 400 m from the first depth shift of 1800 m (above). This leaves a depth shift of 1400 m consistent with observed overpressure.

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