Calculating a synthetic density curve using a volume of clay and velocity

Carl Fredrik Gyllenhammar[1*] proposes a new method to calculate synthetic density as a function of the sonic slowness (the reciprocal of velocity) and the calculated volume of clay.

Introduction

The computation of acoustic impedance (AI) requires both density (DEN) and sonic (DT) log data. However, in most exploration wells the DEN tool is only available in the reservoir section. The most common technique to generate a synthetic density log using other logs, is the Gardner equation or often referred to as *Garner's rule* (Gardner et al, 1974):

$$DEN = a*Vp^{b}, \tag{1}$$

where a is a constant at 0.31 when Vp is in *m/s* and b is 0.25. Gardener's conclusion was that there is simple systematic relationship between velocity and density. Sonic (DT) is often run from about 200 m to 300 m below seabed down to TD (true depth or end of the well). Therefore, Gardner's rule is convenient, allowing us to compute DEN from Vp. Even though, there are other similar equations, such as e.g. Nwozor et al., 2017, the Gardner's rule became the most commonly used transform equation. Despite the fact that Gardner found an empirical relationship between Vp and DEN, the equation does not represent rock properties fully. In addition to the DT log, the gamma ray (GR) log and the resistivity log is run in combination at the same time and same length. The volume of clay (Vcl) can be calculated from the GR log. This study proposes that the relationship between DEN, Vp and Vcl, can describe the rock properties more accurately than empirical constants in Gardner's rule. A synthetic calculated DEN (DEN_syn) can therefore be calculated as a function of DT and the Vcl rather than just the DT.

Background

Eight hundred exploration wells offshore Norway (e.g. the muli-client product SuperGrid: available from CaMa GeoScience AS) have been interpreted in detail. One hundred and twenty wells cover the Barents Sea, 230 wells cover the Norwegian Sea and 450 wells cover the North Sea. The interpretation workflow includes calculation of the Vcl, porosity and water saturation (Sw). The calculated Vcl combined with the DT curve are used to compute a synthetic density curve (Gyllenhammar, 2016).

The method and detailed workflow as well as the equations that have been derived are demonstrated on well 6407/8-6 in the Norwegian Sea. Commonly, raw well data are relinquished in Norway two years after the wells are completed, or earlier if the production licence is relinquished. Figure 1 shows a log data set from this well drilled in 2013 by Equinor. This well was chosen because it has the Nuclear Magnetic Resonance log (NMR) and the pulsed neutron spectrometer (SPEC) in addition to a conventional wireline acquisition log set. The NMR log gives an independent measurement of the porosity to quality control (QC) of the neutron-density calculated porosity, and the SPEC log gives an independent measurement of

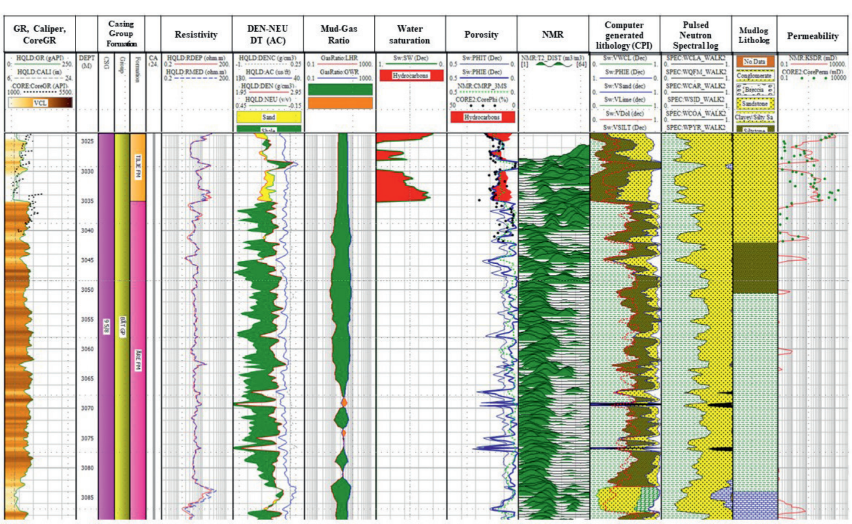

Figure 1 CPI of well 6407/8-6. The log tracks from left: GR and CoreGR; tracks for depth; formation and calliper; resistivity; NEU-DEN-DT; mudgas ratio; Sw, NMR (T2-disp); CPI; minerals from SPEC log; mudloggers lithology, core permeability and NMR permeability track.

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the Vcl. Part of the section has core data as well. The core measured porosity is used in the QC process. However, there is always an uncertainty with depth matching core measurements with wireline logs as the core depth is measured referenced to the drill string depth while the wireline data is a function of the wire length. This can be seen in the GR-track, Figure 1, where the core GR curve in black versus the wireline GR, shows a mismatch ranging from 2 to 6.2 m.

It is important to emphasise that the Vcl can be calculated only from GR. In wells where salt water-based drilling fluid (conductive) is used, a good Vcl can also be calculated from the spontaneous potential (SP) log alone. The method and equation for SP is the same as the one shown later for the GR.

6407/8-6 is the Bauge field discovery well, located in the south-eastern part of the Halten Terrace in the Norwegian Sea, just west of Hyme and Draugen. Oil was found in the Ile, Tilje and Åre formations. In this case study, the transition between Åre and Tilje was chosen ranging from the Upper Triassic (Rhaetian) up to Early Jurassic (Pliensbachian). The Åre Formation consists of alternating sandstones and mudstones interbedded with coals, possibly coastal plain to delta plain deposits (Dalland et al., 1988). The overlying Tilje Formation is heterolithic and consists of very fine to coarse-grained sandstones, interbedded with shales and siltstones. The formation is interpreted to be deposited in a tidal-dominated nearshore marine to intertidal environment (Dalland et al., 1988). This depositional environmental description is representative for the section of 6407/8-6 used in this case study.

Calculating the volume of clay

The Vcl evaluation from the GR (VclGR) log suggests that the shales in both Tile and Åre formations are very heterogenous, probably a result of varying clay mineralogy. A typical petrophysical workflow starts with environmental correction of the logs, then splicing all sections to get a complete log. The log analysis starts with calculating the volume of clay, then the porosity and the hydrocarbon (HC) saturation. The quality control of the logs is done while calculating the porosity. That is when it is possible to evaluate if the borehole is good enough to use the Neutron (NEU)-DEN logs for porosity evaluation for example.

		Neutron (p.u.) NEU	Density (g/cm³) DEN
Clean Sand 1	A	-0.04 (NEUA)	2.65 (DENA)
Clean Sand 2	B	0.3 (NEUB)	2.05 (DENB)
100% Clay	C	0.5 (NEUC)	2.58 (DENC)
	D	NEU	DEN

Table 1 The values of A, B and C from the neutron-density cross-plot (Figure 2).

All clay minerals are radioactive. Therefore, the Vcl is a function of the GR response. But different clay minerals have a different level of radioactive energy (MeV) (Serra, 2008). In addition, clays with high organic content (source rocks) have a high uranium response. Using the GR log as the only Vcl indicator necessitates that the clay mineralogy must be constant from seabed to TD. In the North Sea, the clay composition is very complex (Thyberg et al., 2000). Vcl can also be calculated from the NEU-DEN (VclND) cross-plot (Figure 1a) and the DT-DEN (VclSD) crossplot (Figure 1b) (Schlumberger, 1989).

Firstly, the VclND is calculated in the consolidated section (in most cases below 1500-2000 m). The unconsolidated sections often have severe wash-outs and the tool reads low density and high neutron porosity. The data plots in the upper right part of the NEU-DEN cross-plot (Figure 2a). In this case the NEU-DEN calculated volume of clay becomes inaccurate and the gamma ray should be used. In Figure 1 the 100% clay point is fixed at the 0.5 pu NEU value and 2.58 g/cc DEN value. This value is picked empirically based on interpreting not only 800 wells offshore Norway, but also in the UK and the Gulf of Mexico. Figure 2a shows a graphical way to calculate the VclND from the neutron density cross-plot. The perpendicular line from C to line A-B represents unit 1, or VclND=1. The length of the perpendicular line from any point in D to A-B will then be VclND. There are data points that will always be outside these limits, while the Vcl range will be bound by 0 and 1. This graphical method was described in the log interpretation principle, application by Schlumberger in 1989 (Schlumberger, 1989). The graphs in Figure 2 are an ordinary Cartesian coordinate system and the algebraic solution for any point in D (VclND) is:

$$\mathrm{VclND} = \frac{(\mathrm{DENB}-\mathrm{DENA})\mathrm{x}(\mathrm{NEU}-\mathrm{NEUA})-(\mathrm{DEN}-\mathrm{DENA})\mathrm{x}(\mathrm{NEUB}-\mathrm{NEUA})}{(\mathrm{DENB}-\mathrm{DENA})\mathrm{x}(\mathrm{NEUC}-\mathrm{NEUA})-(\mathrm{DENC}-\mathrm{DENA})\mathrm{x}(\mathrm{NEUB}-\mathrm{NEUA})}, \quad (2)$$

where DENA, DENB, DENC NEUA, NEUB, NEUC are the constant shown in the Table 1, and DEN and NEU are the measured logs values.

Secondly, VclGR is calculated from the GR log using equation 3. The VclGR is based on the simple GR index calculation assuming all clay minerals have the same density and the same radioactive intensity:

$$\mathrm{VclGR} = \frac{\mathrm{GR}-\mathrm{GRcl}}{\mathrm{GRcl}-\mathrm{GRsd}}, \quad (3)$$

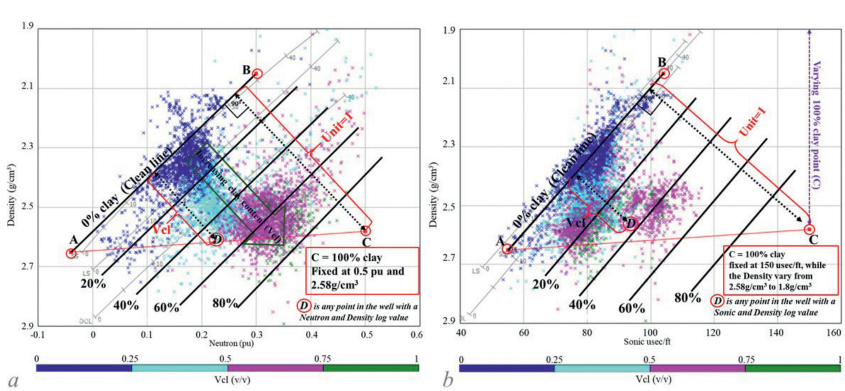

Figure 2 a) the NEU-DEN cross-plot and b) the DT-DEN cross-plot for the well 6407/8-6.

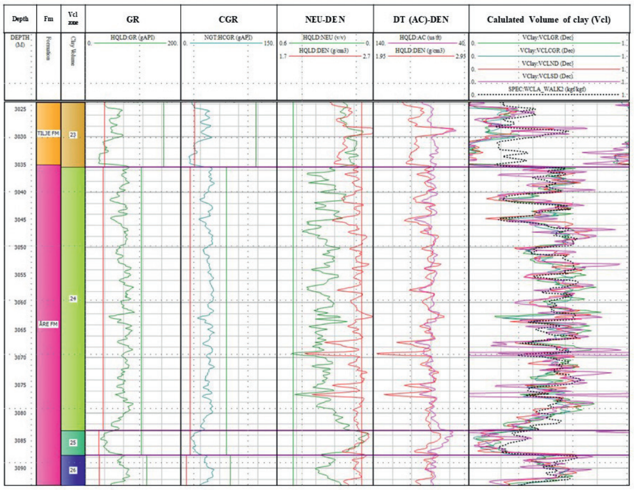

Figure 3 Well 6407/8-6. Tracks from left: Depth; Formation; VclGR zonation; GR with the clean (GRsd) and the 100% clay (GRcl) boundaries; CGR-track the same. The final track compares all independently calculated Vcl; VclGR, VclCGR, VclND and VclSD with the spectral WCLA.

		Sonic (Usec/ft)	Density (g/cm³)
Clean Sand 1	A	55 (DTA)	2.65 (DENA)
Clean Sand 2	B	104 (DTB)	2.05 (DENB)
100% Clay	C	150 (DTC)	2.58 – 1.8 (DENC)
	D	DT	DEN

Table 2 The values of A, B and C on the sonic-density cross-plot (Figure 2).

where GR is the log measured value, GRsd is the GR value in clean sand (red vertical line, GR-track in Figure 3) and GRcl is the GR value in 100% clay (green vertical line, GR-track in Figure 3) (Dewan, 1983).

In the GR track in Figure 3, the red boundary line is the GRsd, the 100% sand (clean) boundary (red line). The green boundary line to the right is the GRcl, the 100% clay boundary. Natural gamma rays come from three radioisotopes: potassium ^{40}K, thorium ^{232}Th and uranium ^{238}U. The GR tool measures the sum while the computed gamma ray (CGR) measurement is only the sum of the radiation from potassium and thorium. The uranium component is normally concentrated in the organic material and shale with high condensation of organic material (Serra, 2008). In such source rocks, the VclGR can overestimate the volume of clay minerals. Different clay minerals have different concentrations of potassium and thorium. Illite have, for example, about 10 times more potassium than montmorillonite, and are therefore much more radioactive. The GRcl boundary may be at 250 API in a montmorillonite-rich mudrock while only 120 API in illite rich mudrock.

The last track in Figure 3 compares VclGR, VclCGR, VclND and VclSD. The WCLA is the independent measurement of Vcl using the SPEC tool. Out of the 230 wells interpreted in the Norwegian Sea there are 20 wells where the SPEC tool was run. According to Schlumberger (personal communication, 2020), the WCLA is normally 90% correct with respect to the total clay mineral volume. In all 20 wells, the VclND using the same constant 100% Vcl point gives the best match with the WCLA. A small regular increase of the 100% clay API value is expected as a function of compaction, but having to apply shifts of the GRsd and GRcl in both directions to make VclGR match the VclND can be a function of changing clay mineralogy, and can be a useful lithostratigraphic tool.

The final Vcl is the average sum of the VclGR, VclCGR and VclND if they are all available (Vcl_Av).

Vcl (VclSD) calculated from the sonic-density cross-plot

The VclND and VclSD is calculated using the same method. The cross-plot to the right in Figure 2b shows the graphical method to estimate VclSD. The 100% clay point C is no longer a fixed point due to a sediment compaction, the 100% clay point C must shift with increasing overburden pressure (Gyllenhammar, 2003). In principle, compaction has an effect on the NEU-DEN relationship as well, but this study has shown that the uncertainty created by setting the NEU-DEN 100% clay point fixed is limited.

The 100% clay point is shifted to make the VclSD match the VclND. One can easily observe on Figure 3 that the VclSD is more spiky than any other calculated Vcl. That is why VclSD is not a preferred Vcl calculation method among petrophysicists. Nevertheless, for these computations, the information we have from the inverted seismic is only the Vp and DEN curves, and inverted seismic has some level of smoothing, making VclSD relatively reliable.

On Figure 2b, the 100% clay point is moving up the Y-axis from 2.58-150 to 1.8, 150. Using trial and error on all these wells, it was discovered that while fixing the 100% clay point to the X-axis at 150 usec/ft, a good Vcl fitting was achieved when setting the Y-axis value at 2.58 g/cm3 and reducing it with increasing compaction to 1.8 g/cm^3 (increasing depth). The algebraic solution for any point D (VclSD) is:

$$\mathrm{VclSD} = \frac{(\mathrm{DENB}-\mathrm{DENA})x(\mathrm{DT}-\mathrm{DTA})-(\mathrm{DEN}-\mathrm{DENA})x(\mathrm{DTB}-\mathrm{DTA})}{(\mathrm{DENB}-\mathrm{DENA})x(\mathrm{DTC}-\mathrm{DTA})-(\mathrm{DENC}-\mathrm{DENA})x(\mathrm{DTB}-\mathrm{DTA})}, \quad (4)$$

where DENA, DENB, DENC DTA, DTB, DTC are the constant shown in the Table 2, and DEN and DT are the measured logs values.

In this case Vcl is no longer the variable. The Vcl that substitutes VclSD in equation 4 is the Vcl_Av. By substituting all integers in the equation with constants from table 2 and replacing VclSD with Vcl_Av, the equation can be rearranged. The synthetic density curve is then a function of the sonic value and the Vcl_Av. Since we are moving the C point, there will be a solution of the DEN_syn (equation 5 to 10) for every DENC varying from 2.58 to 1.8 g/cm^3:

$$\mathrm{DEN\_syn} = 1.093 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.58} \quad (5)$$

$$\mathrm{DEN\_syn} = 0.9135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.4} \quad (6)$$

$$\mathrm{DEN\_syn} = 0.8135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.3} \quad (7)$$

$$\mathrm{DEN\_syn} = 0.7135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.2} \quad (8)$$

$$\mathrm{DEN\_syn} = 0.6135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.1} \quad (9)$$

$$\mathrm{DEN\_syn} = 0.5135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=2.0} \quad (10)$$

$$\mathrm{DEN\_syn} = 0.4135 \text{ x } \mathrm{Vcl} + 3.325 - (0.01224\mathrm{xDT}), \text{ when DENC=1.9} \quad (11)$$

$$DEN\_syn = 0.3235 \text{ x } Vcl + 3.325 - (0.01224xDT), \quad \text{when DENC=1.8} \tag{12}$$

It has been noticed by other authors that the density and velocity are also a function of Vcl. For example, Castagna showed in 1985 that both Vp (compression velocity) and Vs (shear velocity) can be written as a function of porosity (φ) and Vcl (Castagna et al., 1985):

$$Vp = 5.81-(9.42\varphi) - (2.21Vcl). \tag{13}$$

Freund showed in laboratory experiments that

$$Vp/Vs = 1.55 + (0.56\varphi) + (0.43Vcl) \text{ (Freund, 1992).} \tag{14}$$

Figure 4 shows the match one can achieve by calculating synthetic density using equation 5-12. A well that is 5000-m deep will require at least three different calculated synthetic densities (DEN_syn) that must be spliced. For the extended sonic curve where there is no Vcl available, it is recommended using these equations and a constant Vcl between 0.4-0.6, rather than a Gardner type equation.

Application to the seismic inverted data

The aforementioned method has been tested using 37 released wells on Haltenbanken, offshore mid-Norway (multi-client project of AGGS AS, covering the Norwegian Sea, 2020). The result shows that an acceptable match between the density curve and the calculated synthetic density curve is achieved while the density value for the 100% clay point (Figure 2b) is decreasing from 2.58 to 1.8 g/cc with increasing compaction. Following this operation, the sonic curves were extended up to the seabed by splicing with check shot-corrected seismic interval velocities and extended down to 6000 m using seismic-derived interval velocities at the deepest well. The corresponding synthetic density curves were calculated. With increasing depth, the 100% clay point shift was adjusted. Where no calculated Vcl curve was available Vcl was set to 0.5 using the same equations. The resulting DEN syn curves were then spliced to make one final DEN_syn from 0 depth to beyond 6000 m.

The velocity and density curves were used to construct initial velocity models for post-stack inversion. In total, there were 37 well locations with high-quality sonic, density and Vcl curves covering the total depth of the seismic grid. The inverted velocity and density volumes were produced using a new post-stack inversion algorithm 'Rune Inversion' (PSS-GEO, 2019). At every bin of the grid (25 m x 25 m), one density curve and one slowness curve (usec/ft) was generated. Using equation 4, it is possible to calculate a Vcl volume. Further, the attribute to highlight good porosity sandstones is computed as

$$Atribute = (1 - Vcl)\varphi, \tag{15}$$

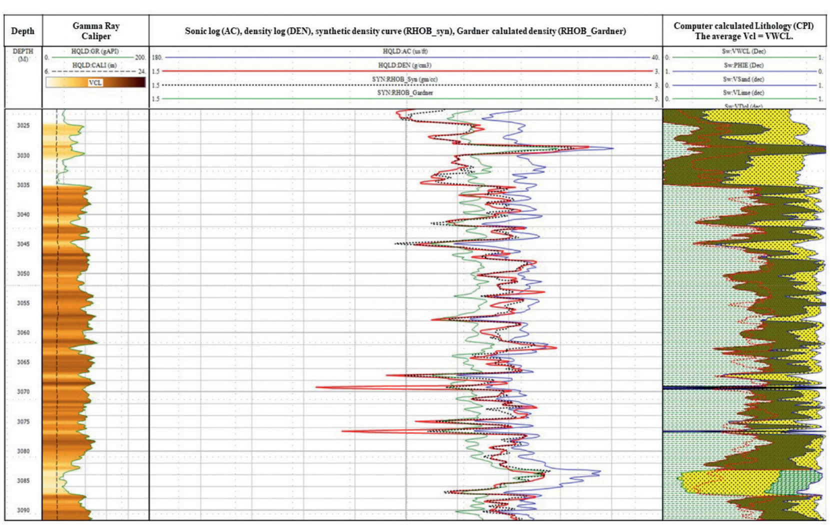

Figure 4 Well 6407/8-6. The wide central track shows a match between the DEN-Syn (RHOB_syn) and the real density curve. A comparison is shown in the sonic curve and the Gardner-derived synthetic density curve. The last track shows the average clay volume used with the Spectral WCLA as a red dotted line.

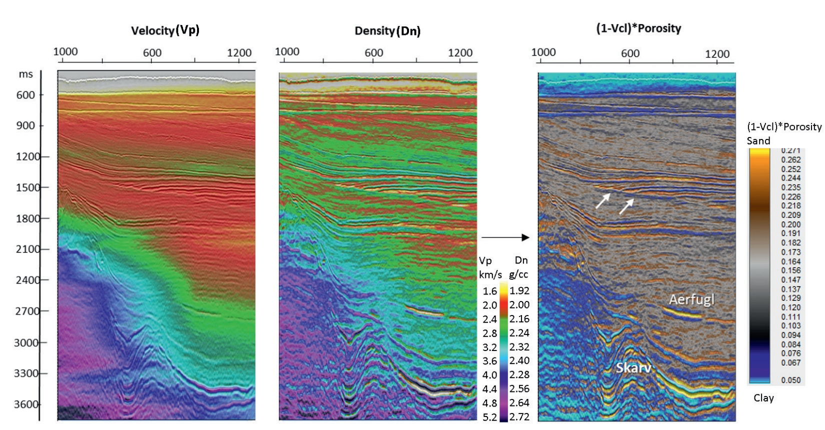

Figure 5 Example of rock properties estimation using proposed equation 4 with relationship of Vcl, Dn and Velocity. Note that porosity was calculated using question 16. Inverted publicly available seismic data to velocity (a) and density (b), were used to compute rock properties for two-minerals components: Vcl and 1-Vcl (as sand) (c). Aerfulg and Skarv (oi&gas) field sandstones were properly predicted using proposed question 4. Notice the wedge with alternating sandstones and clays are perfectly resolved using question 4 as well (Data courtesy Pre-Stack Solution–Geo AS).

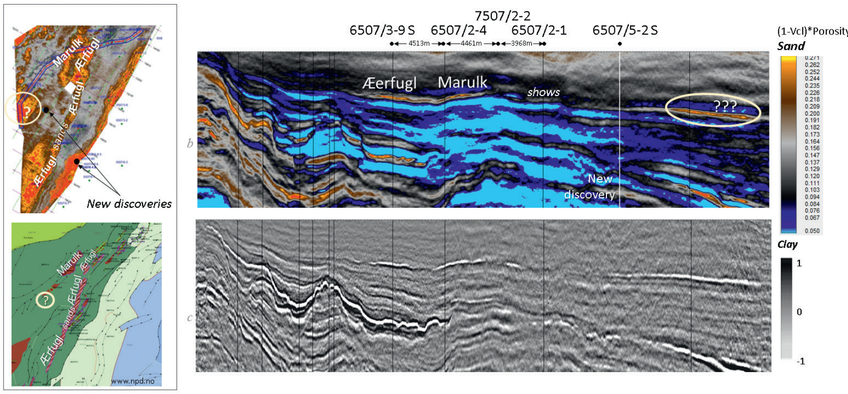

Figure 6 A comparison example of data interpretation using computed attribute (b) (by questions 4, 15 and 16) and stacked seismic data (c). The arbitrary line going through the Aerfugl and Marulk sandstone reservoirs (a). The predicted sunstones are perfectly matched to all known discovered sands. (a) Is a time slice along the top Lysing formation, which shows a very accurate prediction of Aerfugl sandstone, matching the recent (2019) discoveries and proposing another sandstone with good properties in the Lysing formation (Data courtesy Pre-Stack Solution–Geo AS).

where φ is expressed from:

$$\mathrm{Dn} = \varphi_1 \rho_{\mathrm{fl}} + \left(1-\varphi_1\right)\left(\mathrm{V}_{\mathrm{cl}}\rho_{\mathrm{clay}} + \left(1-\mathrm{V}_{\mathrm{cl}}\rho_{\mathrm{sand}}\right)\right), \tag{16}$$

Where DEN is the inverted seismic density, ρ_{clay} is a density of clay minerals, ρ_{sand} is a density of the quartz, ρ_{fl} is a density of fluid equal to 1g/cc, assuming water saturation 100%, ρ_{sand} is 2.65g/cc, ρ_{clay} is 2.58g/cc, and the media is of normal compaction with no erosion. The result of these computations is shown in Figures 5 and 6, confirming that adjusting the value of computing Vcl from the inverted seismic volumes enables us to get a reasonable compositions estimation.

It has been shown that there is a linear relationship between the sonic-density and Vcl. The sonic is by definition time divided by distance, as either usec/ft or sec/m. The velocity is the reciprocal and the relationship between velocity and slowness is a rational function, not linear. Secondly, velocity is a vector quantity that denotes the rate of change of position with respect to time, while slowness is simply a unit like density. Thus, the relationship between the velocity-density and Vcl is a complex rational relationship. By converting seismic velocity to slowness, the link to the log analysis becomes simpler and the inversion appears more accurate.

Conclusion

In this work, I have demonstrated that density can be expressed as a function of the velocity (slowness) and volume of clay, unlike the commonly used velocity function. It has been shown that this synthetic calculated density curve matches the original density curve much better than velocity transform functions such as the Gardener's formula. The acoustic impedance is a function of velocity and density. Using only Gardner or any other velocity-based density computation, the acoustic impedance becomes a constant multiplied on squared velocity – increasing uncertainty significantly. Expressing density from the proposed relationship of volume of clay and slowness enables us to reduce uncertainly, bringing more rock values to the estimation. Furthermore, applying this relationship (equation 4) of velocity-density pairs generated from the Rune Inversion and adjusting the 100% clay point calculation, a very good distribution of sand and clay within the seismic cube has been achieved. The sand reservoirs match well with the known reservoirs, as well as showing yet to be discovered reservoirs.

Acknowledgements

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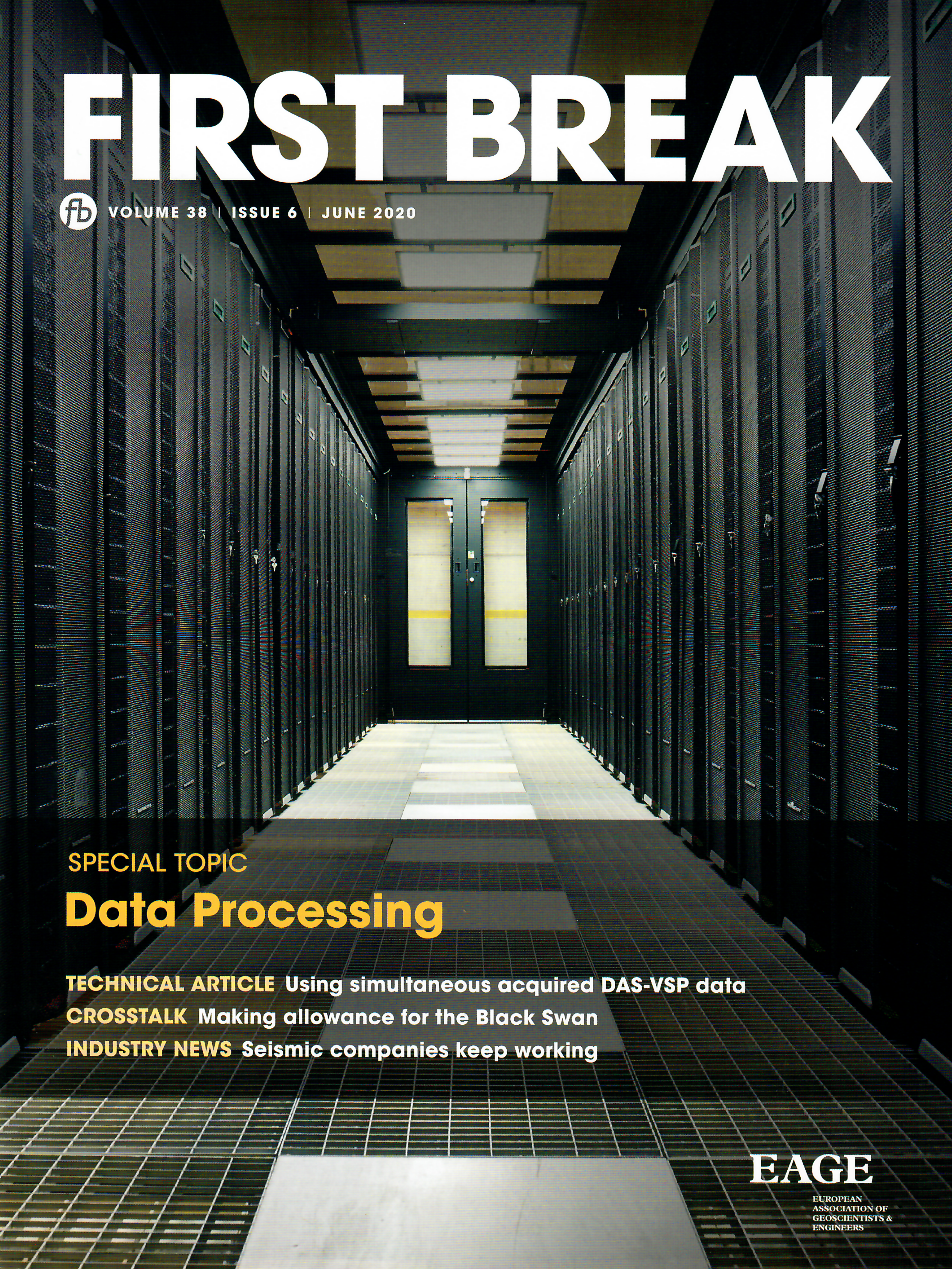

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