

Regional-Scale Subsurface Characterisation Using Rune Inversion and Legacy Seismic Data in the North Sea

Introduction

We present a cost-efficient subsurface characterisation workflow that maximises the value of legacy seismic assets and limited data. The workflow was applied in 2022 on a regional-scale dataset covering 69,660 km², and the results were subsequently evaluated against more than 150 post-inversion wells to assess predictive accuracy and performance statistics. The approach is based on our recently published Rune Inversion methodology (Kalashnikova and Øverås, 2026), which relies on global misfit minimisation between modelled and observed seismic gathers. The method overcomes the limitations of conventional seismic inversion by utilising full moveout information, delivering reliable reservoir property estimates at a low computational cost from both post-stack and pre-stack seismic data. This paper presents the methodology, case study, and validation results from a regional dataset evaluated over several years.

Methodology

Accurate estimation of subsurface elastic properties from seismic data remains a challenging inverse problem due to the non-uniqueness of the solution and the nonlinear relationship between seismic amplitudes and rock properties. Conventional seismic inversion workflows commonly estimate acoustic or elastic impedance first, followed by regression-based transformations to derive velocities (V_p , V_s), and density (ρ). In contrast, Rune Inversion directly estimates independent models for V_p , V_s and ρ by minimising the misfit between observed and synthetic non-NMO seismic gathers.

The misfit function is defined as the L_2 -norm of the difference between the observed (D_{obs}) and synthetic seismic (S_{syn}) gathers:

$$C(V_p, V_s, \rho) = \| D_{obs} - S_{syn}(V_p, V_s, \rho) \|_2^2, \quad (1)$$

where the squared L_2 -norm of a residual vector X is given by

$$\| X \|_2^2 = \sum_{i=1}^N X_i^2, \quad (2)$$

with

$$X = D_{obs} - S_{syn}(V_p, V_s, \rho), \quad (3)$$

and X_i denotes individual seismic samples, while N is the total number of samples in the gather. For a near-offset trace, the reflection coefficient is calculated from the acoustic impedance contrast:

$$R(t) = \frac{V_{p,t+1}\rho_{t+1} - V_{p,t}\rho_t}{V_{p,t+1}\rho_{t+1} + V_{p,t}\rho_t}. \quad (4)$$

The synthetic near-offset seismic trace is then generated by convolving the reflectivity series with the seismic wavelet:

$$S(h_0, t) = R(h_0, t) * W(t), \quad (5)$$

where $W(t)$ is the seismic wavelet and h_0 is the near offset.

For pre-stack data, angle-dependent reflectivity is calculated using either the Shuey approximation or the full Zoeppritz equations (Shuey, 1985; Zoeppritz 1919). The incidence angle is estimated from offset and RMS velocity using the Walden equation (Ogagarue and Chukwuocha, 2010) as

$$\theta(h, t) = \arcsin\left(\frac{V_p(t)}{V_{p,RMS}(t)} \sin\left(\arctan\left(\frac{h}{t}\right)\right)\right). \quad (6)$$

The key difference from conventional inversion is that moveout is not removed before inversion. Instead, the moveout trajectory is included in the forward modelling and used as an additional inversion constraint:

$$t_{NMO}(t, h) = \sqrt{t^2 + \frac{h^2}{V_{p,RMS}^2}}. \quad (7)$$

The synthetic gather is therefore generated as a function of the elastic model and moveout behaviour:

$$S_{syn} = F(V_p, V_s, \rho), \quad (8)$$

where F includes reflectivity calculation, wavelet convolution, angle-dependent amplitude modelling, and moveout transformation.

In this formulation, V_p affects both reflection coefficients and moveout, ρ controls impedance contrast, and V_s contributes to the angle-dependent amplitude response. The inversion therefore uses both amplitude and kinematic information from the seismic gather.

For post-stack seismic data, where offset gathers are unavailable, an equivalent gather is generated from the available stacked trace by assuming that the stacked trace approximates a near-offset response. Reflectors are then distributed along moveout trajectories calculated from the smoothed velocity model. This allows a two-parameter search for independent V_p and density from post-stack data. When pre-stack data are available, the method can perform a three-parameter search for V_p , V_s , and ρ .

Thus, Rune Inversion estimates elastic parameters by directly minimising the global misfit between observed and synthetic non-NMO gathers. The method avoids NMO-stretch artefacts, does not require impedance inversion as an intermediate step, and does not rely on regression-based rock-property relationships.

Examples

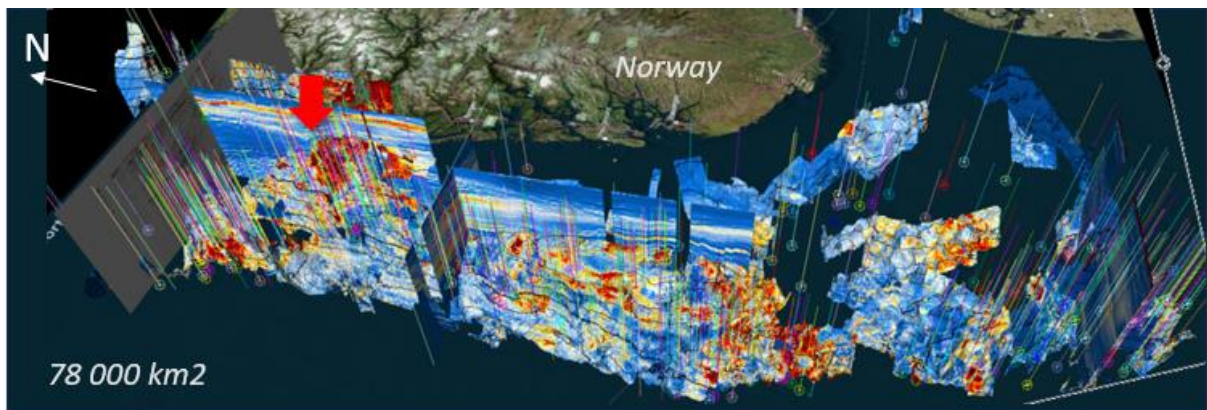


Figure 1 Post-stack Rune Inversion results from the Norwegian Continental Shelf (North Sea) showing a best reservoir quality attribute (yellow–red colours) derived from P-wave velocity and density.

Figure 1 presents a regional overview of the North Sea dataset, illustrating the scale of the application of Rune Inversion to publicly available legacy post-stack seismic data. Low-frequency V_p and ρ models were constructed utilising 10 interpreted structural horizons and 722 public wells released up to 2018. The derived P-wave velocity and density volumes (a cross-sectional example is shown in Figure 2) were subsequently used to characterise reservoir quality. The computation was performed using 500 CPU cores and took 4.5 days.

To obtain reservoir properties, the Gyllenhammar formula was applied to derive volume of clay (V_{clay}) from V_p and ρ (Gyllenhammar, 2022), from which total porosity (ϕ) was calculated using the conventional density-porosity relationship. The multiplication of porosity by the sand fraction ($1 - V_{clay}$) yielded a best reservoir quality attribute (Figure 1). This approach is designed for a binary sand–shale system and does not explicitly evaluate other reservoir lithologies. However, carbonate reservoirs with similar V_p and ρ characteristics may occasionally be highlighted by the attribute.

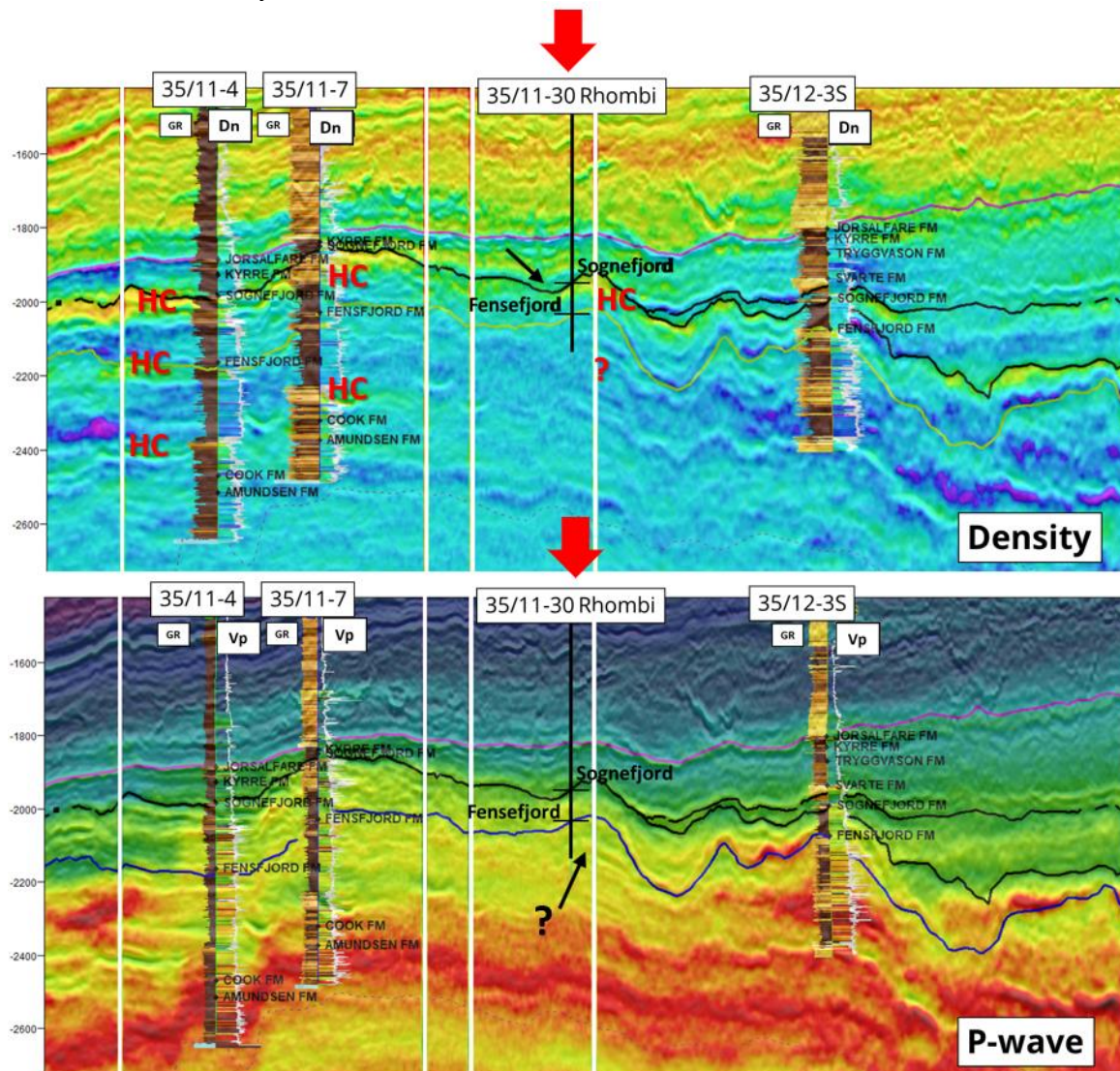


Figure 2 Example of post-stack Rune Inversion separating P-wave (top) velocity and density (bottom) from legacy post-stack seismic data. Sections are overlaid with seismic data in dense display. At the Rhombi discovery (red arrow; see also Figure 1), the 41-m gas-filled sandstone interval is characterised by a clear decrease in density (yellow colours). Velocity and density logs are displayed on the right side of the wells, while gamma-ray logs are shown on the left.

Workflow validation was performed on 164 post-inversion wells drilled between 2019 and 2024. Predictions were compared with reported formation and rock descriptions and scored as 1 (correct), 0.5 (partial match), or 0 (missed). Table 1 illustrates the validation procedure using four representative examples. Well 35/11-30 Rhombi, drilled in November 2024, was assigned a score of 0.5 because the reservoir above the Fensfjord Formation was correctly predicted, while the weaker sand response below the BCU would likely not have been recognised as a prospective reservoir (Figure 3). Analysis of all wells yielded an average prediction success rate of 87% for reservoir-quality sandstones.

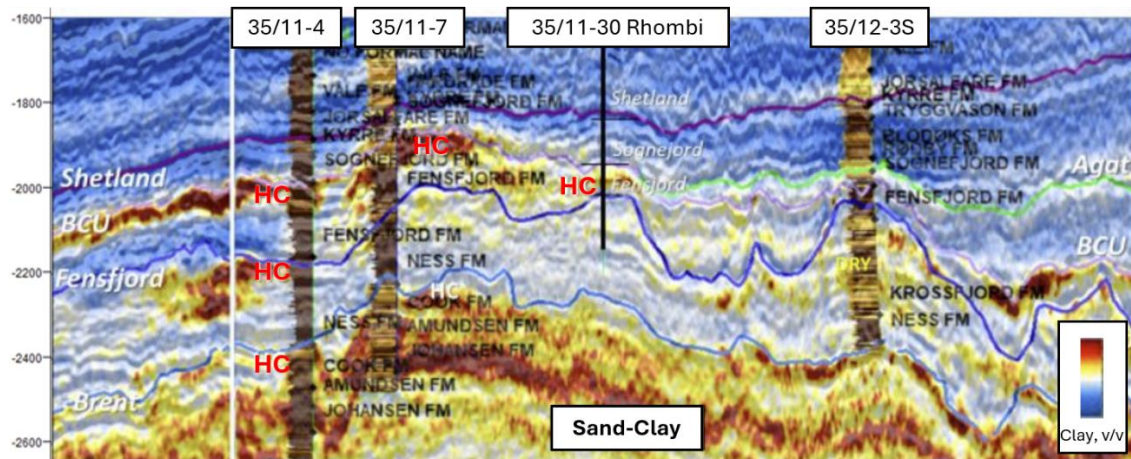


Figure 3 Sand-clay prediction derived from the P-wave and density volumes with inserted gamma-ray logs; overlaid on seismic data in dense display. Yellow-red colours indicate potential sandstones.

Table 1 Examples of post-inversion well validation and prediction scores.

Well name	Release date	Content	Drilling result	Inversion prediction	Indicator
30/6-31 S	25.04.2020	DRY	Thin cemented sands, no HC	Poor sand, low porosity, slight density drops	1 - correct
36/7-5 S	1.5.2024	OIL/GAS	Agat FM sands, discovery	Good reservoir sands, high porosity, density drops	1 - correct
35/11-30	14.11.2024	OIL/DRY	41 m gas-sandstone in the Sognefjord FM/ 72 m in the Fensfjord FM	Strong indicator in first interval, weak in the second.	0.5 - partial match
25/11-H-1H	23.05.2024	OIL	Balder FM, thin sands	Not enough resolution	0 - missed

Conclusion

The Rune Inversion method provides a cost-effective framework for rock property characterisation. Bypassing conventional limitations, it eliminates NMO-stretch artifacts and delivers reliable elastic properties. Validation on legacy data against 164 wells confirms an 87% success rate, offering a scalable, rigorous alternative for reservoir characterisation.

References

- Gyllenhammar, C.F. [2020]. Calculating a synthetic density curve using volume of clay and velocity. *First Break*, **38**, 45–49.
- Kalashnikova, V., and R. Øverås. [2026]. Robust Subsurface Velocity and Density Estimation via Seismic Inversion With Global Misfit Minimisation and Full-Offset Moveout. *Geophysical Prospecting*, **74**(1): <https://doi.org/10.1111/1365-2478.70124>
- Ogagarue, D. O., and A. C. Chukwuocha. [2010]. Application of Cross- Correlation for Global Velocity Quality Control in Seismic Imaging. *Australian Journal of Basic and Applied Sciences*, **4**(10): 4696–4703.
- Shuey, R. T. [1985]. A Simplification of the Zoeppritz Equations. *Geophysics*, **50** (4), 609–614.
- Zoeppritz, K. [1919]. “Über Reflexion und Durchgang Seismischer Wellen durch Unstetigkeitsflächen.” *Göttinger Nachrichten*, **1**, 66–84.