

Local-geology-aware AVO fluid classification: burial-constrained, non-stationary Bayesian inference and its sensitivity to the uplift guiding horizon

Introduction

Three-dimensional AVO feasibility modelling constrained by burial history predicts the elastic properties of the reservoir sand and the caprock shale — and the resulting AVO signatures — away from well control, by combining maximum-burial estimates with rock-physics depth trends (Avseth and Lehocki, 2021; Lehocki and Avseth, 2021). In areas of strong, laterally varying uplift such as the Hoop area of the Barents Sea, the expected quartz-cement volume of the Stø Fm sandstone changes over short distances, and with it the sensitivity of the AVO response to pore fluid. Where cement is low the fluid response is strong and brine, oil and gas separate cleanly; where cement is high the fluid responses converge and AVO can no longer discriminate fluid. A single, survey-wide (stationary) training set therefore mis-represents the local rock frame at most locations. In this study we demonstrate a non-stationary AVO fluid classification in which the training data are regenerated locally at every map node from the burial-constrained feasibility model, so that the classifier honours the local geology — cement, porosity and elastic contrasts — at each pixel. The non-parametric Bayesian classification of lithology and pore fluid is itself well established (Mukerji et al., 2001); the novelty here is the chain, in which the Bayesian decision rule is driven by spatially varying, feasibility-derived training clouds that track the burial and diagenetic trend. We further examine a practical question the workflow forces upon the interpreter: uplift, and hence maximum burial, is estimated relative to a chosen guiding horizon, and we ask how strongly that choice propagates to the final fluid prediction.

Method and Theory

Maximum-burial maps are estimated by comparing a given FWI velocity volume with a normal shale compaction (velocity–depth) trend to determine net erosion, which is added to present-day depth (Figure 1; Avseth et al., 2021). The burial history then drives Walderhaug (1996) quartz-cementation modelling of the Stø Fm reservoir sandstone, tuned so that the predicted cement matches an independent estimate obtained from rock-physics diagnostics in porosity– V_P space (Avseth et al., 2021). Combined burial and rock-physics modelling (Avseth and Lehocki, 2016) then gives the expected elastic properties of the Stø Fm sandstone and the overlying caprock shale. At every map node, V_P – V_S –density clouds are generated for both the sand and the shale by sampling V_P and density about their feasibility-predicted (most-likely) values, with V_S obtained from V_P through a deterministic Greenberg–Castagna relation. The brine sand cloud is Gassmann fluid-substituted to oil and gas, and the shale-over-sand interface is forward-modelled to its AVO intercept and gradient, giving three intercept–gradient clouds (brine, oil, gas) at the pixel. The calibrated intercept–gradient observation is then classified with a non-parametric Bayesian rule (Mukerji et al., 2001; Avseth et al., 2005). Each fluid's cloud defines a kernel-smoothed density in intercept–gradient space, and evaluating the three densities at the observation yields the posterior probabilities $P(\text{brine})$, $P(\text{oil})$ and $P(\text{gas})$ at that pixel. The observation is assigned to the fluid of maximum posterior probability. The stationary classifier applies the identical rule but with a single cloud built at the Wisting Central well.

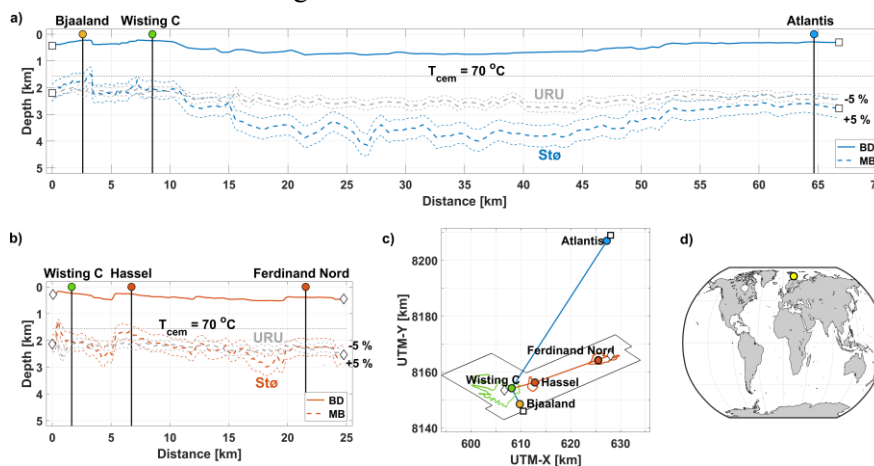


Figure 1 Motivation for the guiding-horizon choice. Estimated maximum burial (MB, dashed) and present-day burial depth (BD, solid) along a south–north profile (a) and a southwest–northeast profile (b) when uplift is guided by Top Stø versus URU; the Top Stø-guided maximum burial sits systematically deeper than the URU-guided estimate. Well location map (c) and study-area location inset (d).

The guiding horizon for uplift estimation is the second variable we test. We compare two choices: the Upper Regional Unconformity (URU), sampled in a $[0, 50]$ m window below the horizon, and the Top Stø Fm reservoir horizon, sampled in a $[-150, -50]$ m window in the overburden above it. Because uplift is estimated from the median FWI velocity in this window relative to the shale trend, the window choice controls the result: the Top Stø window samples the overburden interval 50–150 m above the reservoir, where variable lithology and locally biased acoustic FWI perturb the window median and destabilise the inferred uplift and maximum burial relative to the cleaner URU estimate (Figure 1).

Burial-constrained inputs and AVO feasibility

Figure 2 shows the URU-guided maximum burial together with the corresponding expected quartz-cement volume and porosity along Top Stø Fm. Cement increases and porosity decreases from the south and south-west towards the north and north-east, with cement ranging from close to zero over the southern structures to a maximum over the more cemented north-east around Ferdinand Nord. These spatially varying rock-frame properties are the input to the AVO feasibility modelling.

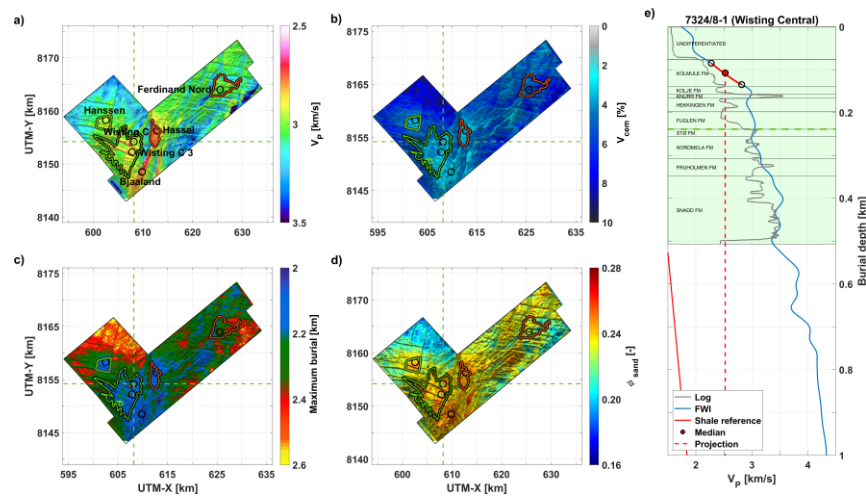


Figure 2 URU-guided maximum burial (lower left) from acoustic FWI velocities (upper left), with the corresponding expected quartz-cement volume (upper centre) and porosity (lower centre) along Top Stø Fm. Velocity and derived uplift at the Wisting Central (7324/8-1) trace shown at right.

The expected AVO class of the Top Stø top reflection (Figure 3) makes the fluid sensitivity explicit. Across the structural highs the three fluids separate in AVO class — gas towards a Class III response against the Class II behaviour of brine and oil — so AVO fluid discrimination stays feasible even at the moderate cement levels of these structures. Sensitivity nonetheless falls as cement stiffens the sand and compresses the brine–oil–gas impedance contrast: at Ferdinand Nord, where the expected quartz-cement volume is already 5–7%, the fluid responses sit at the edge of discriminability. The class derived from the seismic data (a), the modelled response for brine, oil and gas (b–d) and the impedance trends at Wisting Central (e) are shown together. This spatially varying feasibility is precisely what a stationary, single-location training set cannot capture, and what motivates the non-stationary classifier below.

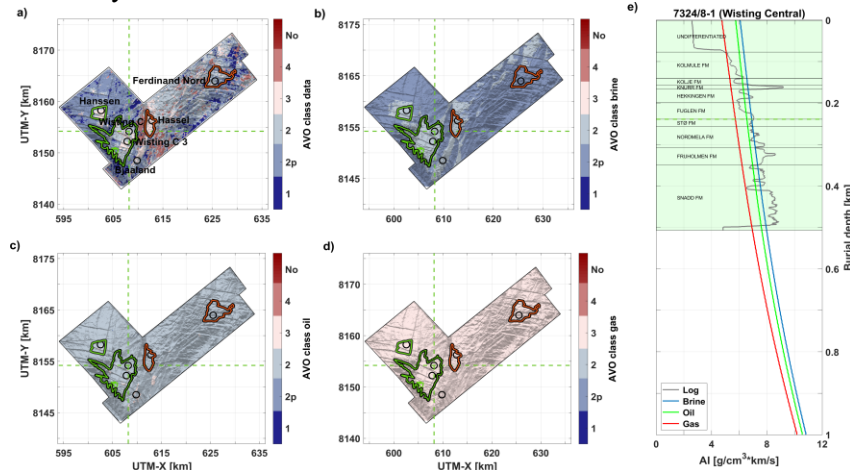


Figure 3 AVO class along Top Stø Fm: the class derived from the seismic data (a), and the URU-guided modelled response for brine (b), oil (c) and gas (d). Brine and oil sit near Class II and gas near Class III, so the fluids remain separable across the low-cement structural highs while sensitivity falls towards the more cemented north-east. Acoustic-impedance trends for brine, oil and gas at Wisting Central (7324/8-1), with lithostratigraphy, are shown in subplot (e).

Non-stationary Bayesian fluid classification

Figure 4 maps the three posterior fluid probabilities under URU guidance for the stationary (top) and non-stationary (bottom) classifiers. Because the non-stationary clouds are rebuilt at every pixel from the local cement, rather than fixed at the single Wisting Central value ($V_{cem} \approx 4.5\%$) of the stationary classifier, the two maps differ — but only modestly under URU guidance, where the cement contrast relative to the Wisting Central baseline is small but locally significant (Figure 2b, cement panel) and the classifiers agree on 87.5% of pixels. Their disagreement is dominated by an oil–brine exchange across the southern sands, shifting the raw horizon composition from brine/oil/gas of 62.2/32.9/4.9% (stationary) to 66.0/27.9/6.1% (non-stationary). The gas changes are smaller and structurally localised (Figure 5b): the non-stationary classifier raises the gas fraction within the Ferdinand Nord polygon from 8.6% to 22.6%, while a thin down-flank ribbon along the Hassel rim reverts gas to oil.

At the six validation wells — four control wells plus two genuine blind discoveries, Hassel and Ferdinand Nord, drilled after the feasibility framework was established — the non-stationary classifier recovers both blind discoveries on the raw per-pixel classification, against the stationary classifier's one: it assigns gas to the Ferdinand Nord well-tie pixel where the stationary classifier reads oil, lifting the non-stationary score to five of six against four of six (the shared miss, Wisting Central 3, is corrected for both by median filtering). The well-tie recovery itself is a raw-classification result (Table 1): filtering returns that pixel to oil, yet gas stays the dominant class within 100 m of the well — seven of thirteen pixels, against none for the median-filtered stationary classifier.

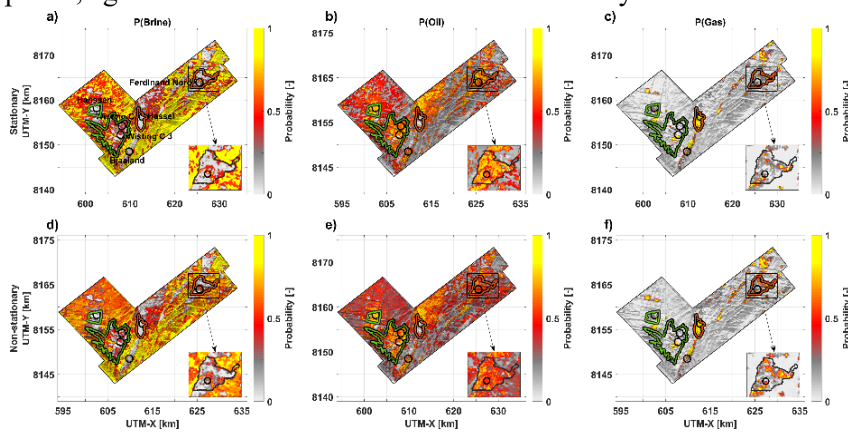


Figure 4 Posterior fluid probabilities under URU guidance for the stationary (top) and non-stationary (bottom) classifiers: $P(\text{brine})$ (a, d), $P(\text{oil})$ (b, e) and $P(\text{gas})$ (c, f). The two classifiers agree on most of the survey; their differences are dominated by oil–brine exchange in the southern sands, with gas changes confined to two structures — gas gained in Ferdinand Nord (oil→gas) and lost along the Hassel rim (cf. Figure 5b).

Post-processing	Classifier	Well-tie	B / O / G (≤ 100 m)
Raw	Stationary	oil	4 / 4 / 5
Raw	Non-stationary	gas	3 / 5 / 5
Median-filtered	Stationary	oil	3 / 10 / 0
Median-filtered	Non-stationary	oil	3 / 3 / 7

Table 1 Ferdinand Nord (blind gas) under URU guidance: predicted class at the well-tie pixel and B/O/G pixel counts within 100 m, for the raw and median-filtered classifications.

Robustness to the guiding horizon

The guiding horizon has a first-order effect on the intermediate model: switching from URU to Top Stø materially changes the estimated maximum burial (see Figure 1a), and with it the modelled cement volume, porosity and the full set of sand and shale elastic properties. The fluid classification, however, is largely preserved across the two guides in this dataset (Figure 5c versus 5d): the southern brine, the intermediate oil and the gas over the cemented north-east are reproduced under both. This is not a universal law but has an identifiable cause here — the fluid discrimination is concentrated in the low-cement southern band, where both guides place the sand in a similarly weakly-cemented state, while the well-tie Walderhaug calibration re-anchors the absolute level for both. Where the two do differ, the URU-guided result is the more stable, being less affected by velocity anomalies, diagenetic effects and possible gas leakage immediately above Top Stø — which is why we prefer URU as the cleaner reference horizon.

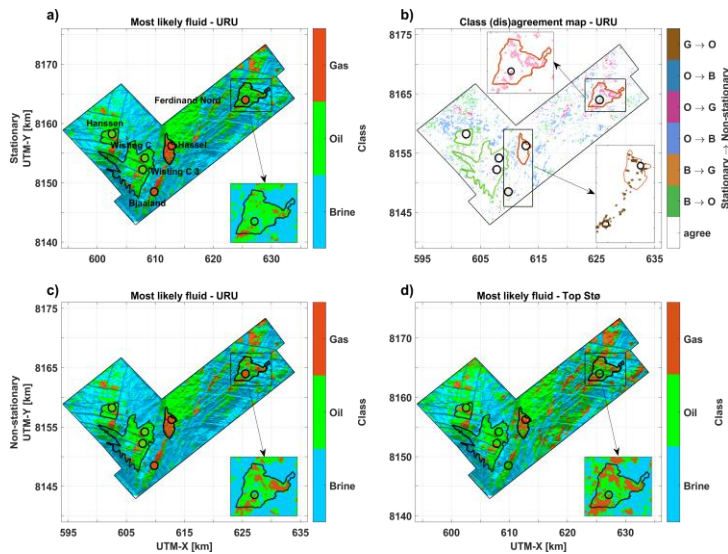


Figure 5 Most-likely fluid (raw, before median filtering) under URU guidance for the stationary (a) and non-stationary (c) classifiers, their pixel-level disagreement map (b, coloured by transition), and the non-stationary result under Top Stø guidance (d). The classifiers agree on 87.5% of pixels; the disagreement is chiefly an oil–brine exchange in the southern sands, with gas added inside Ferdinand Nord and a thin gas-to-oil ribbon along the Hassel down-flank (b). Switching the guide from URU (c) to Top Stø (d) does not change the classification much, except that Top Stø predicts more oil and gas than URU in the cemented flanks.

Conclusions

We have demonstrated a non-stationary, burial-constrained Bayesian classification of the AVO fluid response in which the training data honour the local rock frame at every pixel. Compared with a conventional stationary classifier, the non-stationary classifier produces subtle but structured changes under URU guidance — recovering gas across the Ferdinand Nord polygon and rebalancing oil and brine across the southern sands — while preserving the stationary classifier’s well-validated calls. Although the choice of guiding horizon for uplift estimation has a first-order effect on the modelled burial, cement and elastic properties, the classified fluids are largely preserved between the two guides in this dataset — a consequence of the discrimination residing in the low-cement band and the well-tie calibration re-anchoring the absolute cement level for both guides — with URU preferred as the cleaner reference. By coupling spatially varying rock-physics feasibility to a probabilistic, uncertainty-aware fluid classification, the workflow improves the geophysical de-risking of leads and prospects. Future work will extend the blind-well validation and investigate shale diagenesis through thermal-history rock-physics models. Applying one temperature-aware framework to both shales and sands removes the linear shale velocity–depth trend — which need not hold across the whole area — and captures the smectite-to-illite transition.

Acknowledgements

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