GCStaged Stochastic Inversion*

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General Statement

This article starts with a staged stochastic inversion scheme that was applied in a southern North Sea Carboniferous setting. The objective was:

1) To understand the seismic character as functions of subcropping, fluid-fill, net-over-gross, tuning and over- and underburden effects.

2) To map key horizons, including certainty quantification.

3) To characterize the reservoir in terms of properties.

The result: Whereas fluid-induced seismic features known from seismic observations could not be produced with modeling, the inverted properties do respond to reservoir sections as proven by well data.

Characterizing Westphalian reservoir sections of the Carboniferous Fairway in the southern North Sea – with geographic extend from the Dutch D-blocks into the UK Quad 44 – is and always has been challenging due to limited seismic data quality at this depth of investigation. As the reservoirs themselves are virtually transparent on seismic data, in most cases the actual reservoir definition is based on geologic constructions using mapped horizons shallower and deeper in the section. Also, their fluvial nature causes internal inhomogeneity which is hard to capture in deterministic property models.

To complement established approaches, a more quantitative route was pursued for both the actual mapping of horizons, including uncertainty quantification, as well as characterization of the reservoir interval in terms of reservoir quality. To this end, a series of inversion-related studies were initiated focusing on the Wingate Gas Field. This column presents results of one of such studies.

Geologic Setting

The fluvial Ketch and Murdoch formations of Late Westphalian C and Early Westphalian B age, respectively, build the typical reservoirs for gas production in the Carboniferous Fairway in the southern North Sea. The best reservoir qualities in these are formed by stacked channel sandstones, which have limited lateral extent and connectivity, as visualized by analog outcrops (Figure 1).

Between the Ketch and Murdoch formations lie the Cleaver and Westoe formations. Sedimentologically, the Cleaver is an alternating shale-sand sequence with hardly any coal, whereas the Westoe Coal Formation has significant coal content.

The Murdoch Sandstone itself is part of and the top-section of the Caister Coal Formation. Both the Westoe and Caister Coal formations show distinct seismic character due to low-impedance coal streaks interbedded in the background shale. In 3-D structural terms, the Carboniferous section is split by multiple orientations of faults, each with separate (re-)activation history.

As the coal layers causing the distinct seismic character for the Westoe and Caister formations exhibit truncation, splitting and merging, reliably tracking the correct “regional” marker is not trivial. In cases where the Westoe Coal Formation has been eroded, a realistic risk exists of misinterpreting the actual Top Caister Coal Formation erroneously as Top Westoe.

Lastly, as the gross package thickness changes laterally and well-control is sparse, constructing the reservoir intervals as described by J.J. Lynch (2004) can be misleading, albeit the only proven method.

Seismic Challenges

Because the Westphalian reservoir sections are virtually transparent against the background shales, the proven method is to map regionally consistent events, and to construct the reservoir sections through geologic modeling as Lynch described.

Moreover, extensive forward modeling shows non-stationarity of the top-Ketch and top-Cleaver picks, primarily depending on the net-over-gross and potential coal content in relation to tuning, causing any mapping to carry a degree of ambiguity (Figure 2). Despite the fact that seismic features related to fluid-induced effects are observed in the area, it has not yet been possible to validate this under modeled conditions.

Staged Stochastic Inversion

In conventional stochastic inversion, a range of viable target properties is predicted by varying the input model and testing the result against measured seismic. In this situation however, although well log data showed that both input model (pseudo-log properties) and target properties (porosity, sand content) can be quite similar for the various Carboniferous reservoirs, actual reservoir behavior in terms of production can be considerably different. Therefore, the conventional inversion was modified such as to first invert for the geologic formation, validate its viability, and only then to invert for reservoir properties. This has two advantages:

1) First, probability volumes for the presence of a certain geologic formation are created, together with associated Top Formation presence and certainty maps, which constitutes a fully automated and human-bias-free interpretation.

2) Second, after validating and fixing the geologic formation, the actual target property inversion can be executed with the input model specific for that unit, also considering additional constraints.

This “staged” inversion concept was implemented in the OpendTect stochastic HitCube inversion. Conventional HitCube inversion consists of two major steps: stochastic pseudo-well modeling and synthetic to seismic matching described in Ayeni et al., (2008).

The first step starts with building the model (sedimentological) framework based on the well data with stochastic definition of thicknesses and rock properties. In this case, thicknesses are taken from well control while considering analog outcrop understanding (Figure 1). The properties include those required for forward seismic modeling and any others of interest, such as porosity or coded lithology. They can be drawn from normal or uniform distributions derived from well log data, or defined as constants, linked through formulas, or through functions. This modeling is followed by the generation of a large number of pseudo-wells, which represent possible geological scenarios not necessarily encountered by actual wells, and which are spatially unaware. For these pseudo-wells, corresponding synthetic seismic traces are computed.

The second step is the inversion itself. Performed trace-by-trace, the matching process ranks pseudo-wells at each trace location based on the similarity between the synthetic and measured seismograms within a selected time window along a provided seismic horizon. Thereafter, a user-defined number of pseudo-wells are combined to output a statistical estimate of the modeled properties – for example, average and standard deviation of porosity or probability of each lithology.

The “Staged” HitCube inversion as deployed on this project for stochastic mapping and characterization of the intra-Carboniferous extends the conventional implementation on the following points:

1) First, as the Westphalian sequence is angularly truncated by the Base Permain Unconformity with Silverpit Formation on top, the pseudo-well modeling had to focus on a 150-900 meter thick interval, which is rather large compared to previous HitCube studies, such as a 4-D Hit Cube for seismic inversion in the North Sea’s Blake Field.

The framework model consisted of target Ketch and Caister units together with sufficient over- and underburden. Pseudo-wells were generated by gradually removing units below Silverpit to simulate this subcropping pattern.

To adequately capture the associated variability of the geologic as well as the rock-physical frame, a total of 7000 pseudo-wells were input to the conventional HitCube inversion along the Base Zechstein seismic horizon within [-24, 350] ms window to produce formation probability volumes based on 100 best models, as well as (maps of) the probability interface, i.e. fully automated and human-bias free interpretations of the intra-Carboniferous formations (such as displayed in Figure 3). This first extension enables the validation of derived geologic scenarios.

2) Second, porosity (Figure 4) and lithology were predicted using a second and modified HitCube iteration.

The Base Zechstein to Top Caister interval was subdivided into seven chunks of 150-meter bin width with 50-meter overlap, based on its thickness, using additional (manual) interpretation. Sets of around 5,000 pseudo-wells were created for each chunk satisfying the thickness constraints.

A two-stage HitCube inversion was run for each chunk separately. One hundred models that have the best match in a [-24, 350-meter] time gate around Base Zechstein were selected first. Then, on a sample-by-sample basis, a local waveform match in a [-24, 24] ms window was computed. Only the realizations exceeding such local fit above 0.65 correlations were kept to produce probabilistic results such as displayed in Figure 4. Thus, the thickness constraint and the long gate matching ensured selection of geologically reasonable models, while the local matching passed only those parts of these models that locally matched the measured seismic. Statistical estimates of lithology and porosity were generated using the modified HitCube inversion.

Results

Because of the large number of pseudo-wells used during the two inversion cycles, possible geologic scenarios and rock-physical properties beyond actual well control were captured, analyzed in 2-D gathers (such as Figure 1 and Figure 2) and verified against actual seismic. The ultimate product of this is the fully automated and human-bias-free interpretation for Top Caister, for which the probability volume is displayed in Figure 3.

Although its reliability, of course, is dependent upon the input seismic quality, on a detailed level it does suggest viable 3-D geologic configurations that probably would be rejected by a human interpreter.

It should be noted, though, that sufficiently “under-burden” should be captured to generate sufficiently long synthetic-to-seismic correlation length in the matching process. The “falsepositive” indicated in Figure 3 with arrow A is believed to find its nature in this. As reservoir property distributions in this part of the Carboniferous are quite tight (typical porosity range is between 9 and 15 percent), the sensitivity of inversion-based output properties proves quite dependent on the input seismic quality.

An example section through the inverted porosity volume is displayed in Figure 4: Indicated with B is a porosity lineament that corresponds to good quality sandstone as proven by well data. The very local high-porosity feature at C and associated lower-porosity streaks to the left were also confirmed by drilling. Directly to the right of C, the result seems to be affected by data-quality and not related to geology.

Conclusions

The “staged” stochastic inversion implemented in a modified HitCube scheme is capable of producing results that can help the seismic interpreter with understanding of the seismic beyond actual well-control. As such, it complements the proven conventional approach outlined by Lynch (2004) in a more quantitative manner and allows us to better understand the uncertainty of the 3-D structural configuration.

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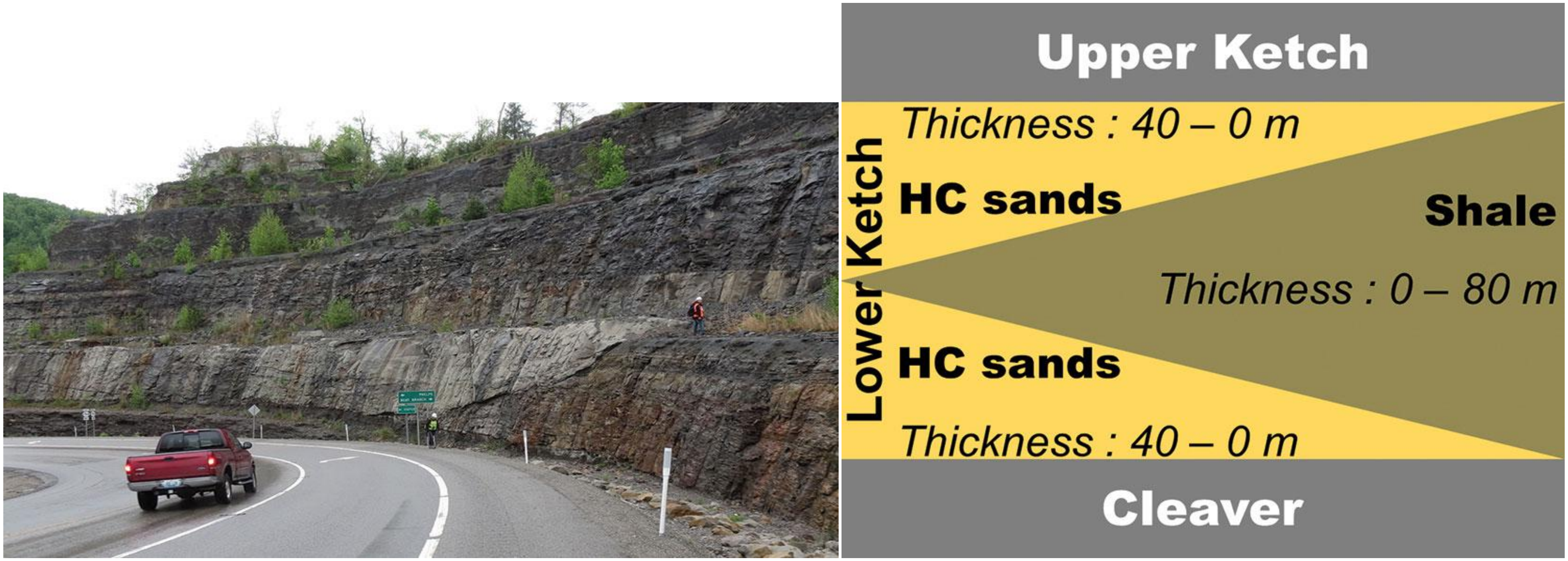

Figure 1. Carboniferous outcrop example from Kentucky (USA) showing the abrupt delimitation of a channel body in background shales (left), and synthetic modeling such a feature by using a shale-wedge in between two sand bodies (right). Synthetic results for this model are presented in Figure 2.

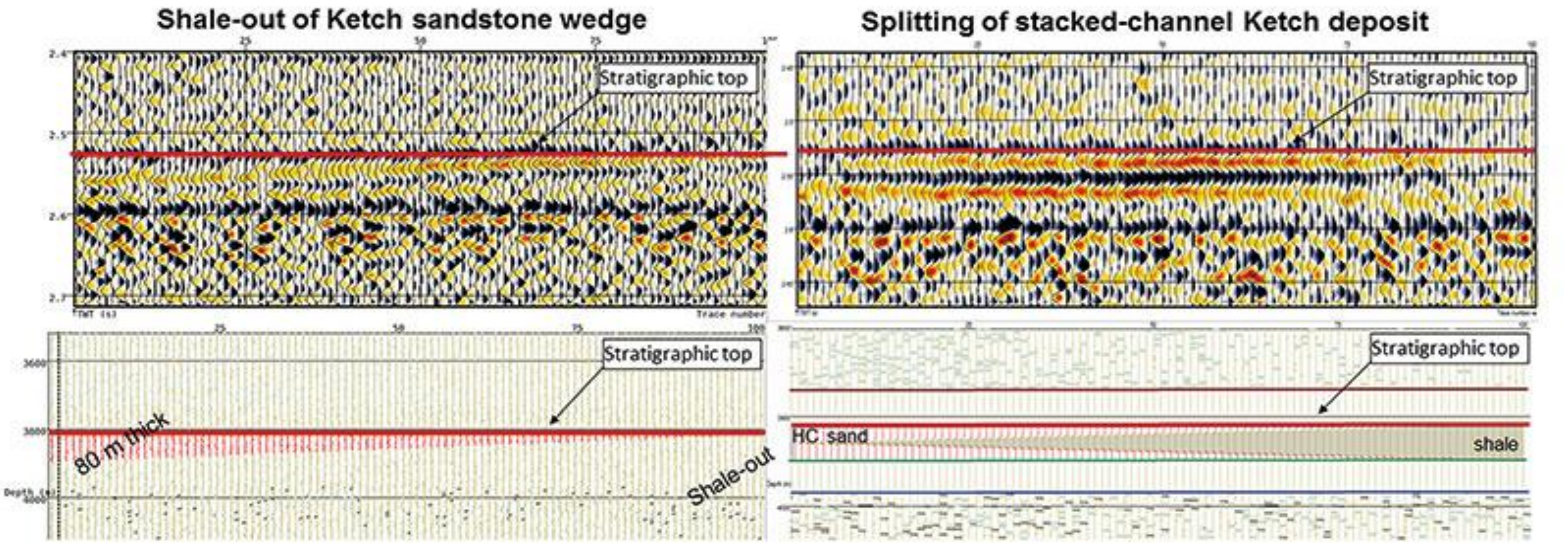

Figure 2. Synthetic seismic modeling result for analog outcrop derived models. Pseudo-wells representing an extended definition of the rock-physical framework have been used to construct these displays. Left, the continuous shale-out of a single sandstone wedge is modeled. Right, the demerging of a stacked-channel sequence is modeled according to the model from Figure 1. Note the indicated stratigraphic tops on the seismic display, and the non-stationarity of the associated seismic pick.

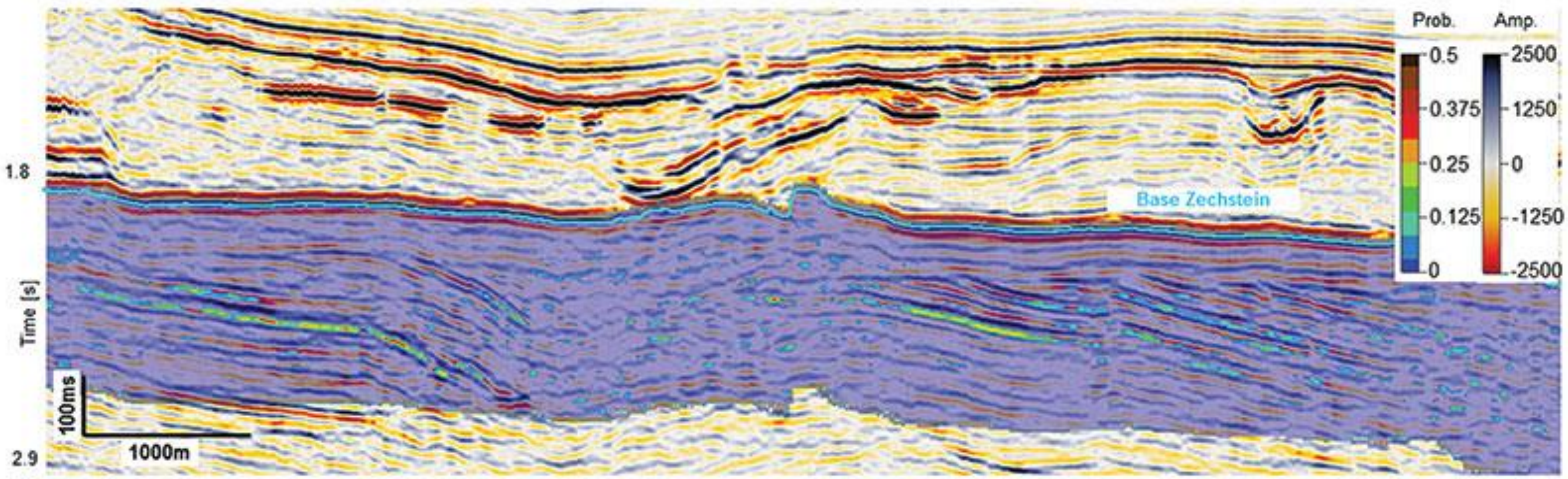

Figure 3. Top Caister probability volume, as the interface between the Westoe and Caister formations probability volumes, displayed on top of seismic data. The detected Top Caister (green to red color indicates high probability of being there) matches interpretations (not displayed) relatively well, provided seismic data is at least reasonable. In the left of the image, detection is very good. Indicated with A is a "false positive," likely due to insufficient under-burden in the pseudo-well population.

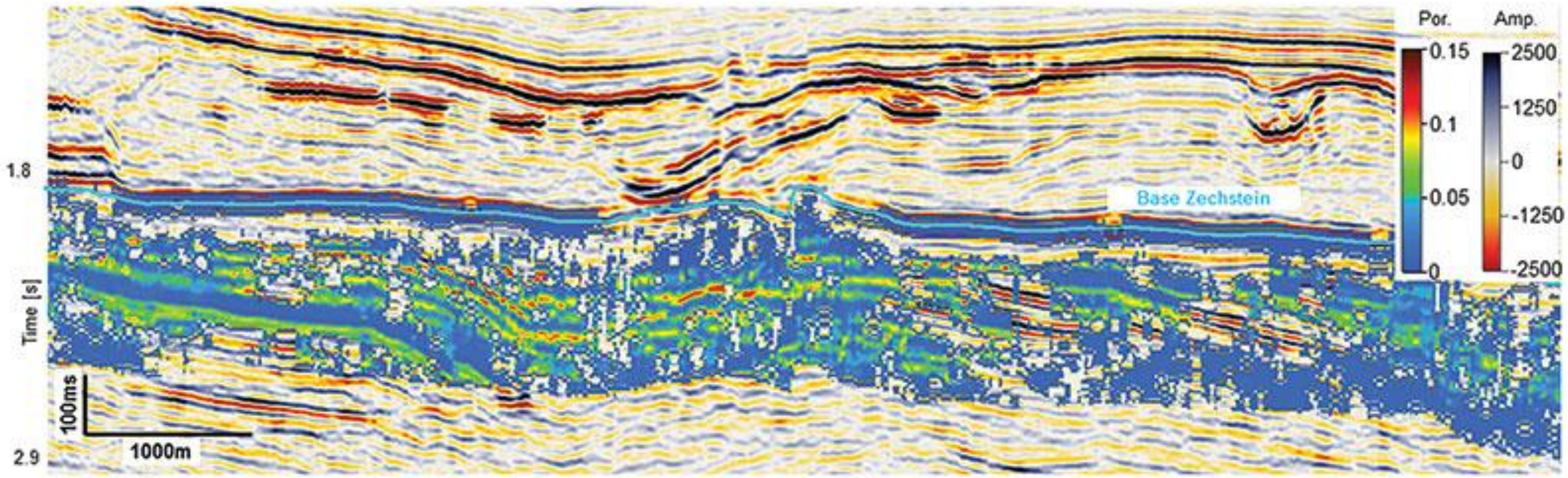

Figure 4. HitCube inverted porosity; yellow/red indicates high porosities. The porosity streak at B was validated by well data. Feature C was proven to be a localized stacked channel complex, shaling-out to the left, hence the weaker response there.