Seismic facies and rock properties prediction using Direct Probabilistic Inversion: case studies from Australian basins

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SUMMARY

The one-step seismic inversion approach inverts directly from seismic amplitude data to reservoir properties, which makes the propagation of the uncertainties more accurate than the standard two-step approach. Direct Probabilistic Inversion (DPI) is a one-step approach, where information from seismic amplitude versus offset (AVO) data are integrated with the geological knowledge, such as stratigraphic ordering, expected lithologies and fluids within each stratigraphic layer, fluid gravitational ordering, thickness distribution of facies, and transition probability between one facies and the next. The injection of this valuable geologic information, previously ignored in standard deterministic AVO inversions, helps mitigate ambiguities inherent in the seismic method. In this study, DPI is applied to different seismic datasets across different Australian basins to show the efficiency of the method for predicting seismic facies and reservoir properties even for thin reservoir and coal layers despite being below tuning thickness.

Key words: Australian Basins, Seismic Inversion, Direct Probabilistic Inversion.

INTRODUCTION

There are several seismic inversion schemes to estimate reservoir properties from seismic data. The most traditional approach uses two steps to invert from the seismic amplitude data to the reservoir properties. First, the amplitude is inverted into elastic properties, and then, based on rock physics models and statistical classification schemes, those elastic properties are converted to reservoir properties (Bosch et al., 2010). In this case, the seismic inversion for elastic properties may be a deterministic inversion, in which the result is a smooth solution to a regularized problem, or a stochastic inversion, which, although draws multiple realisations from the posterior, is numerically very demanding. In contrast, the one-step approach inverts directly from amplitude to reservoir properties, which makes the propagation of the uncertainties more accurate. Considering that ambiguity is an intrinsic characteristic of seismic inversion because different facies and fluid configurations might present similar elastic responses, robust quantification of uncertainty and facies discrimination is vital for the success of exploratory and development projects.

The injection of relevant and non-redundant information into the inversion process can help to reduce seismic ambiguity. For instance, the average thickness of specific facies, stratigraphic ordering, probability of transition between the facies, and fluid gravitational ordering are useful information that will reduce the solution space dramatically. However, the injection of this information into the inversion process is a challenge and the way that has been done typically has been through inaccurate low-frequency models or prior models. Bayesian inference solutions provide a framework where these issues can be addressed. But, in its standard formulation and given the size of typical seismic volumes it is computationally impossible.

Direct probabilistic inversion (DPI) is a one-step seismic inversion approach that integrates information from standard seismic amplitude versus offset (AVO) data with the geological knowledge of the basins to mitigate seismic ambiguity and resolve beds below traditional resolution limits. To reduce the computational cost related the high dimensional Bayesian inference problem, the DPI approach evaluates all possible geological solutions of the basin in a moving local neighbourhood around each sample point rather than trying to solve the complete seismic trace (Jullum and Kolbjørnsen, 2016). In this study, DPI is applied to different seismic datasets across different Australian basins to show the efficiency of the method for predicting seismic facies and reservoir properties even for thin reservoir and coal layers despite being at the limit of resolution in the seismic.

DIRECT PROBABILISTIC INVERSION

Direct probabilistic inversion (DPI) is a single-step inversion process which inverts pre-stack seismic data directly for geologic facies, based on the Bayesian probabilistic formulation introduced by Jullum and Kolbjørnsen (2016). This approach is extremely flexible and allows to model key geologic information for example as a first order Markov processes. Geological information such as average thickness of a specific facies, stratigraphic ordering, probability of transition between the facies, and fluid gravitational ordering are injected into the prior model. With this previous knowledge, geologically or petrophysically impossible (or highly unlikely) solutions are removed from the prior model and consequently inversion results as water sands predicted directly above oil sands or older stratigraphic units predicted above younger units are avoided.

In Bayesian inference, the prior knowledge is updated based on observations, see for instance Tarantola (2005). It can be expressed as

$$\sigma(m) = c\,\rho(m)L\big(d_{obs} - g(m)\big) \quad (1)$$

where $\sigma(m)$ is the posterior distribution of the model parameters m, $\rho(m)$ is the prior model, and c is a normalising constant. The prior model is updated with the information from the seismic AVO data via the likelihood function L, which measures, in terms of probability, the misfit between forward modelled $g(m)$ and measured seismic AVO data, d_{obs}. The likelihood, L, contains, in addition to a seismic noise model, the combination of a statistical rock physics model from facies to elastic property domain, and a seismic convolutional AVO forward model from elastic properties to the seismic angle-stack domain (Hansen et al.,2018). As such, the solution to this problem can be considered a direct or one-step inversion for facies using seismic AVO data. Under reasonable assumptions and conditions described in Jullum and Kolbjørnsen (2016), Hansen *et al.* (2018), Jakobsen and Hansen (2019), Jakobsen and Hansen (2020) DPI uses a local neighborhood approximation in which the local probability for all facies configurations is found within a small window, which makes the inference problem computationally feasible.

Workflow

The conditioned seismic amplitudes and associated wavelets used as input in the DPI are the same ones used in the standard inversion. Once seismic and wavelets are chosen, a statistical prior model is built based on the available well database (Figures 1 and 2). Note that these wells can be from an area out of the studied survey. Initially, all expected facies within each stratigraphic zone are defined (Figure 1a). Usually, the facies are separated by petrophysical cut-offs to represent lithology and/or fluid fill. After facies are defined, statistics from each facies within each zone are extracted to assist in the facies discrimination. In the following case studies (see section below), the thickness probabilities are used to reduce ambiguity between facies elastically similar (Figure 1b). Then, a transition matrix is created to describe the probability of transitioning between one facies and the next, where the thickness distribution and some geological rules (gravitational and stratigraphic ordering) are incorporated (Figure 1c). For example, compared to relatively thin facies that tend to change to other facies, thick facies present the most likely transition between the same facies. In addition, with the imposed geological rules, only transitions from young formations to old formations are allowed in the case of extensional basins, and the same for the transition from the hydrocarbon-bearing reservoir to the water-bearing reservoir. As a final part of the geological framework, a statistical rock physics model is created for each facies and each zone (Figure 1d). In other words, each zone is treated individually, which reduces the ambiguity caused by the compaction. Differently, the standard inversion uses only one statistical rock physics model for the target interval, in which a relatively shallower shale can have similar elastic properties to a deeper sandstone from another stratigraphic zone, for example. To solve this issue through the standard inversion, one needs to perform two different inversions, one for the shallow part and the other for the deep part, then merge the results.

This geological framework replaces the conventional low-frequency models used in standard inversions. The DPI results are more data-driven and hence less biased by inaccurate low-frequency models. The outputs of DPI (Figure 2) are interpreted surfaces and volumes of the probability of each defined facies that can be used directly in P10, P50, and P90 type risk analysis. Based on these facies probabilities, derived properties can be generated, such as most likely facies, porosity (total or effective) and volume of clay. Most likely facies is the facies with the highest probability, and an estimate of the porosity can be calculated using the following expression

$$Porosity = \big(Probability_{facies\ 1} * Average\ porosity_{facies\ 1}\big) + \cdots + \big(Probability_{facies\ N} * Average\ porosity_{facies\ N}\big) \quad (2)$$

The average porosity acts as a scale factor. As a first estimation of this value, we get the average porosity from the logs (each facies in each zone), then we optimize the parameter to fit the inversion with the logs. To calculate the volume of clay, we follow the same approach.

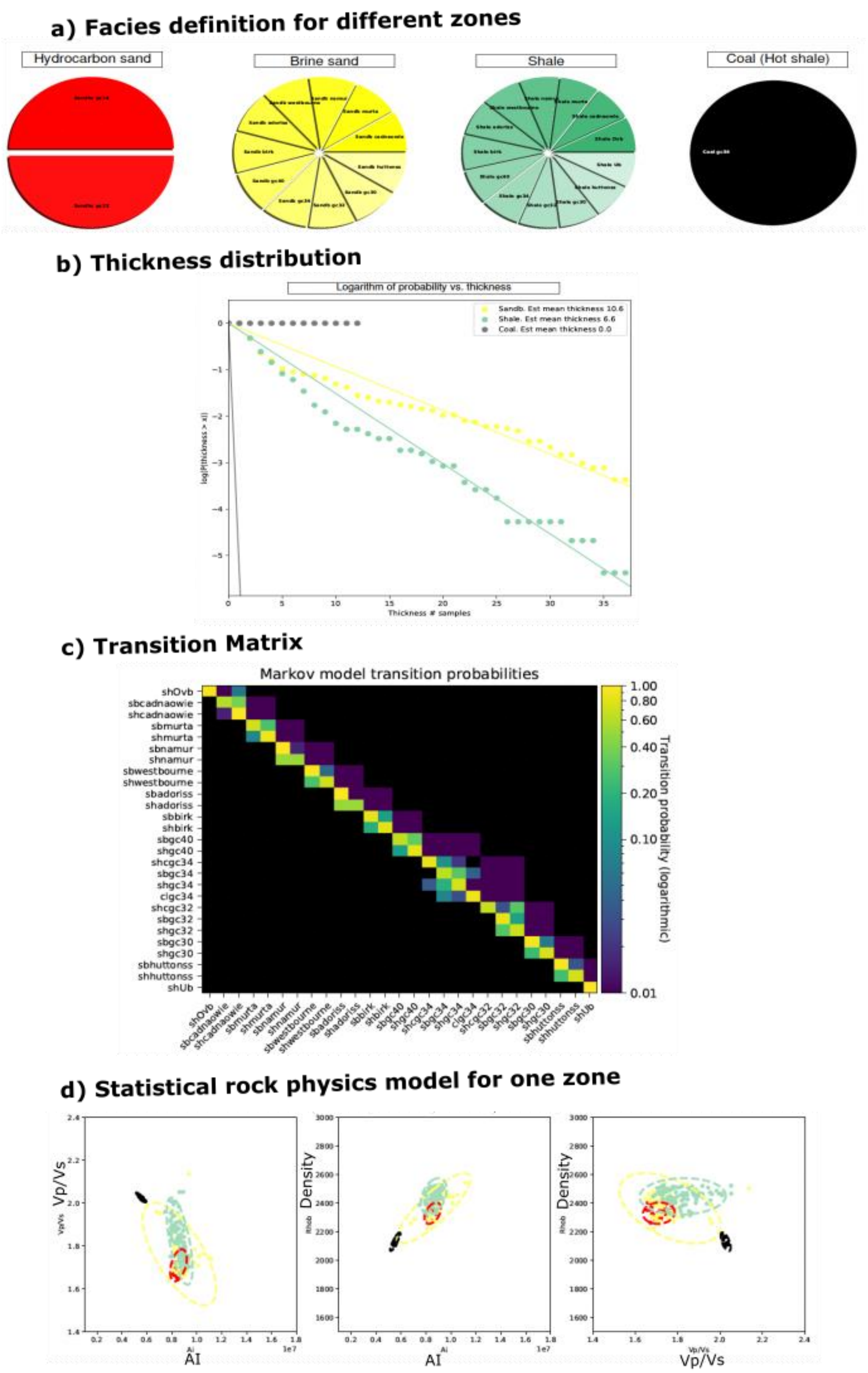

Figure 1. Steps to build the prior model. Data from oil field located in the Cooper–Eromanga Basin, South Australia (see case 1 below).

CASE STUDIES ACROSS AUSTRALIAN BASINS

Case study 1

The seismic data originates from a 3D land seismic survey data covering a producing oil field located in the Cooper–Eromanga Basin, South Australia. The main producing target consists of discrete channel bodies from the middle Birkhead formation of Late Jurassic age. These channel bodies are complex and discontinuous. Along with the complexity and relatively lower quality of the reservoir, some other issues are observed in the studied area: i) the facies discrimination is difficult and ii) the quality of the land seismic data is poor. DPI was applied to evaluate whether the mapping of the complex reservoir model could be improved across the area. From seven wells from the oil field, brine-sandstone, hydrocarbon-sandstone, shale, and coal were defined as the primary facies along 11 different stratigraphic zones resulting in a total of 27 different facies (Figure 1a).

Figure 3a exhibits the DPI result at one well located in the studied area. From left to right, the following is shown: seismic traces from different angle stacks, prior probability distribution, posterior probability distribution resulting from the inversion, the most likely facies (facies with the highest probability in the posterior result), facies logs obtained from the well in two different sample rates (0.5 ms – 5th panel, and 2ms – 6th panel), acoustic impedance log, vpvs log, density log, the volume of clay log, and the probability of 3 most probable facies resulted from the inversion. The prior probabilities were limited by interpreted seismic surfaces and converted into facies probabilities assuming the expected proportions of facies inside each zone. The colours represent the facies (see Figure 1a). It is interesting to compare the result of the most likely facies obtained from the inversion with the facies logs observed in the well at different sample rates. In general, the facies prediction matches well with the observed facies logs, even with thin layers at a sample rate of 0.5ms, which is four times lower than the seismic data sample rate. Thick layers, which are usually challenging to be predicted due to the absence of low-frequency information in seismic data, are also well-defined by DPI (see the thick reservoirs in yellow).

Figure 3b shows the comparison between the effective porosity and volume of clay predicted from the DPI and the observed logs in two different ways at the position of the same well from Figure 3a. From left to right, the first two panels show the comparison in the wiggle mode (red is the well log and blue is the result from the inversion), while the last two panels depict a mini section around the well location and are compared with the petrophysical data. The match between the inversion and the observed logs is good for both petrophysical data, effective porosity and volume of clay.

Case study 2

This case study is from offshore in Western Australia, surrounding gas fields in the Browse basin. Well A (see Figure 4) was drilled as a committed well, targeting a 4-way structure closure within a larger stratigraphic trap defined by Vp /Vs anomaly. The well discovered gas in the Upper Brewster sand (Early Cretaceous). The lowest known gas is structurally below the 4-way lowest closing contour however, uncertainty remains around the trap size and configuration, and reservoir quality and presence. Well B was drilled structurally up-dip of well A and proved the absence of the equivalent Upper Brewster sand but showed up the Lower Brewster sand that was not penetrated by Well A due to operational issues (Figure 4). Unfortunately, the mapping of these reservoirs using the conventional seismic amplitude is challenging due to the absence of clear internal seismic reflections (Figure 4a). The objective of the study is to delimit the Upper and Lower Brewster sands (located between seismic horizons K10 and J25 in Figure 4). A relative extended elastic inversion (EEI) was performed previously but the amplitude values do not reflect the nature of the sands at the well location.

Figure 4b illustrates the probability of hydrocarbon sandstones resulting from DPI along with water saturation logs at the wells positions. High values of probability of hydrocarbon sandstones matches the low values of water saturation. The result of the inversion shows a potential reservoir that was not drilled below Well A (Lower Brewster sand) and illustrates clearly that the Upper Brewster sand pinches out in the direction of Well B. Compared to the seismic amplitude (Figure 4a), the reservoirs are more easily mapped with the results of the inversion. In summary, the resulting probabilistic rock properties provide a robust reservoir characterization and can be used directly in P10, P50, and P90 type risk analysis.

CONCLUSIONS

DPI was applied to different seismic datasets across different Australian basins and showed its efficiency for predicting seismic facies and reservoir properties even for thin reservoir and coal layers despite being at the limit of resolution in the seismic. The resulting probabilistic rock properties provide a robust reservoir characterization and can be used directly in P10, P50, P90 type risk analysis.

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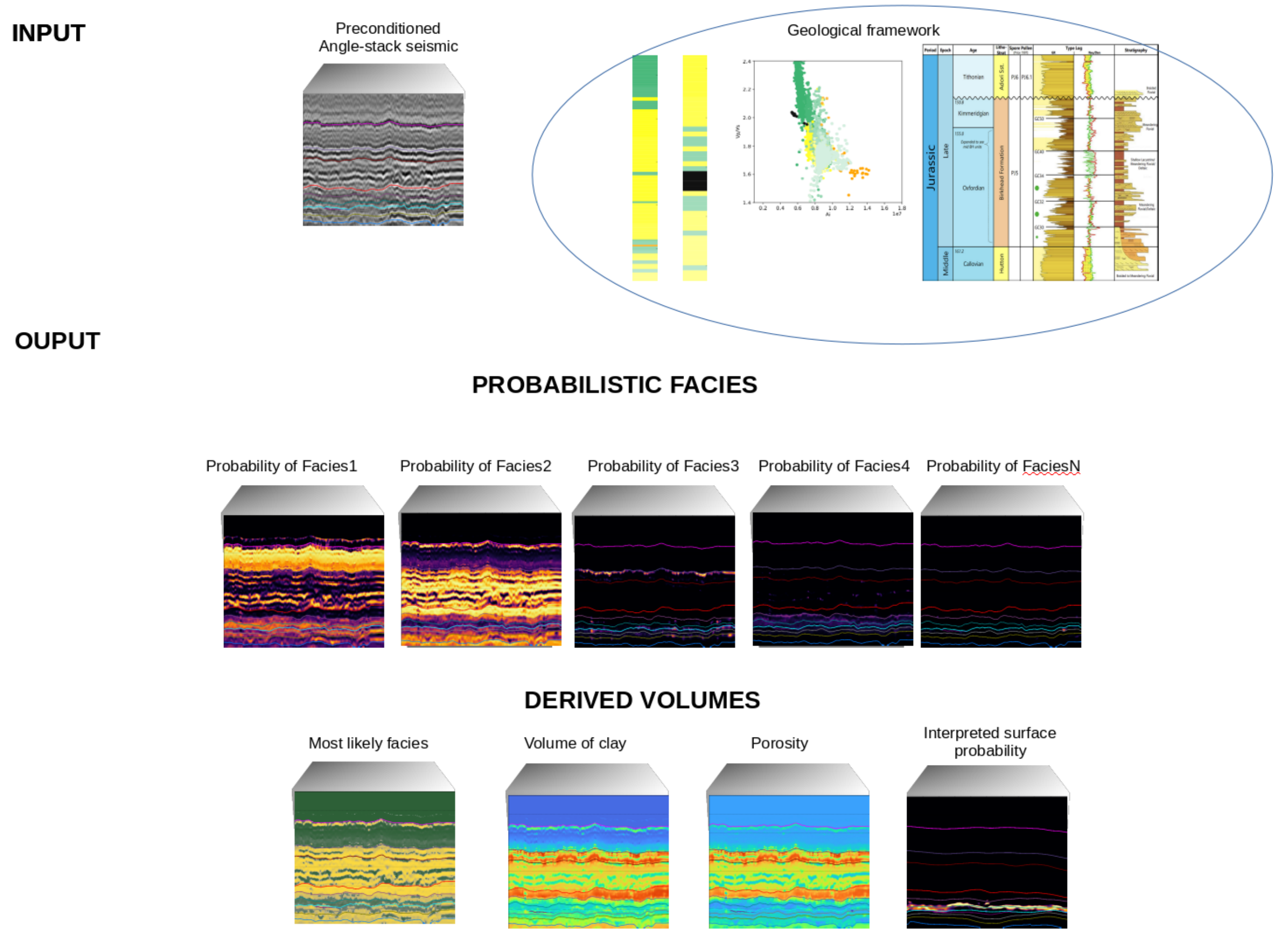

Figure 2. Input, output, and derived volumes from the direct probabilistic inversion. Input is conditioned pre-stack seismic amplitudes sorted by angle of incidence and associated wavelets, and geological knowledge. Output is probabilistic facies and derived volumes are most likely facies, petrophysical properties and interpreted surface probability.

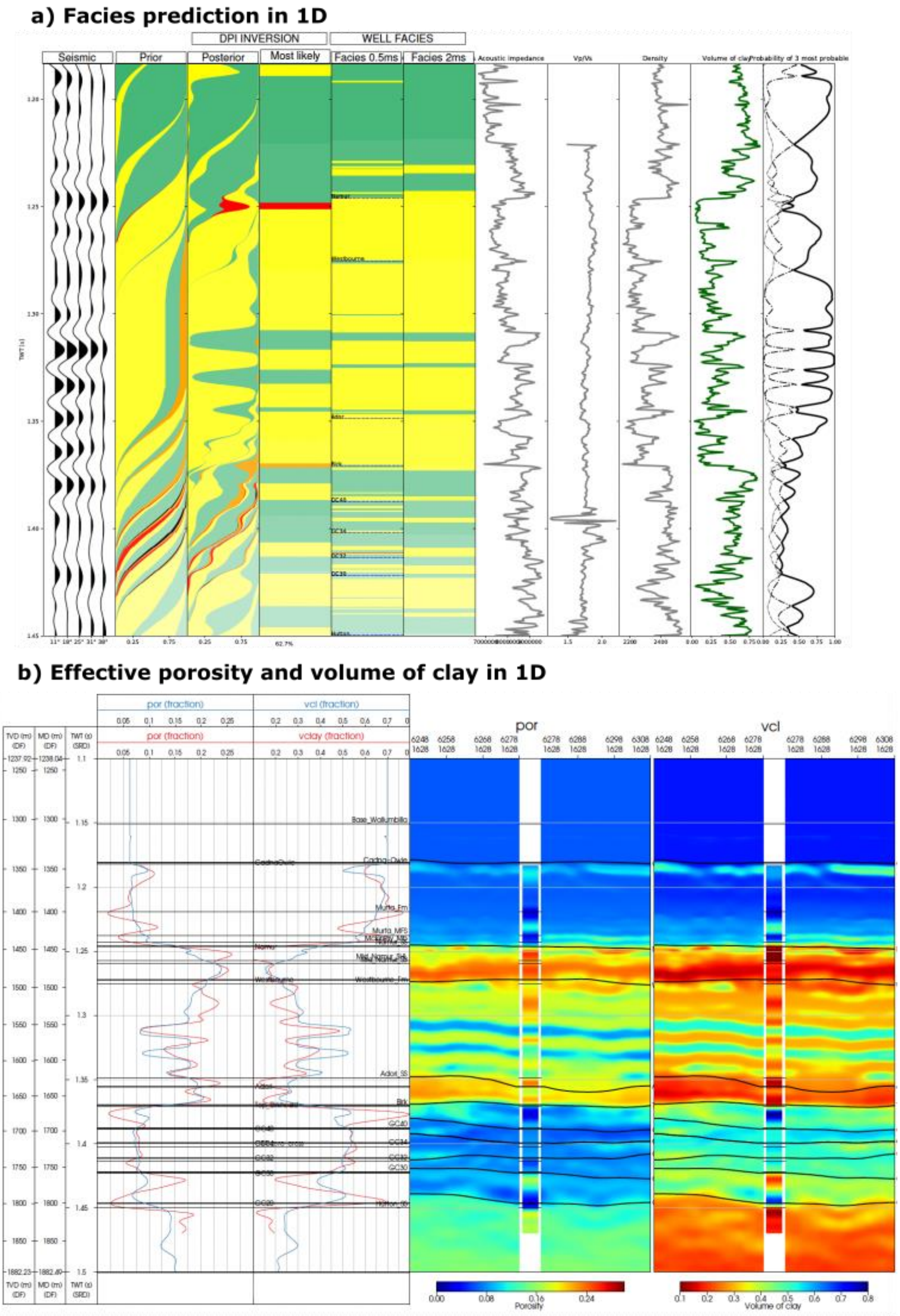

Figure 3. DPI result at well location. A) Facies predictions. Facies colour-code is the same as in Figure 1a. B) Comparison between the effective porosity and volume of clay predicted from the DPI (in blue on the first two panels from left to right) and the observed logs (in red with 70 Hz high cut filter) in two different ways.