Reservoir Connectivity Analysis by Integrating Probabilistic Distribution of Fluids and Facies with Stochastic Inversion

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Abstract

From an oil industry persspective, we have been challenged at identifying and predicting the effect of reservoir connectivity on fluid flow throughout the life of a field. In the context of today's declining oil price scenario and harder-to-find reserves, with increasing development cost, it is vital to have a well-rounded development and implementation strategy in-place. One of today's challenges is to improve the predictive capability of reservoir continuity and its spatial distribution. There are many situations where continuity is unexpectedly obstructed and impacts the overall re-development programs in the mature fields.

Oil, gas and water fluid in structurally complex channelized or faulted reservoirs can create complex reservoir plumbing relationships and reservoir connectivity can be misunderstood, esspecially in the water flood environment. Variable hydrocarbon contacts can develop when some, but not all, fluids are in pressure communication. Seismic-based reservoir connectivity analysis is a series of steps to integrate structural complexity, stratigraphic units, fluid pressure and composition data into permissible, but non-unique scenarios of fluid contacts and pressures leveraged by seismic inversion derivatives. This new analytical approach has been used in a wide range of reservoirs including clastic and carbonates in the fields around the world.

This paper describes an innovative workflow for reservoir connectivity analysis and highlights the effective integration of probabilistic distribution of fluids and facies with stochastic inversion derivatives and static model. The results from infill drilling program were analyzed by integrating the information from the geological models, 3D seismic, petrophysics, and reservoir engineering data, to better understand the reservoir continuity. The study reveals that effective integration of this information with post drill data provide a more reliable and quantitative prediction of reservoir continuity and helps in designing the future drilling programs and optimizing water flood projects for improved oil recovery.

Materials and Methods

Development of the complex structure reservoirs presents significant challenges especially for brown fields (Figure. 1). In particular, the assessment of lateral and vertical reservoir connectivity between channel sands requires high resolution 3D seismic data and the applications of advanced seismic inversion techniques for fluid and facies predictions. Single rock property such as acoustic impedance (AI)-based lithology discrimination has not always been successful, but compressional and shear velocity ratio (V_p/V_s) is a good lithology indicator.

Geostatistical seismic inversion provides high resolution, equi-probable realizations of elastic properties from integration of well measurements, spatial reservoir continuity (geostatistics) and 3D seismic data. Seismic data quality control procedures and conditioning were incorporated before performing inversion. The seismic data was zero phased using wavelets derived from well-to-seismic ties and spectral balancing applied using a reference angle stack. The rotated and balanced angle stacks were aligned in time to the reference stack. Locally varying and locally smooth, time shifts across all the angle stacks were estimated to flatten the primary events in the final angle stacks.

The geostatistical inversion process uses sequential gaussian simulation which combines kriging with simulated uncertainty. In the simulation process, sets of equi-probable values of simulated properties are created in depth. These values are transformed to time, where synthetic seismic traces are created and compared with the seismic within the simulated interval. The simulated values which are close to actual seismic values are retained as final values for that simulation and interval. In the example presented here, Joint Stochastic Seismic Inversion was conducted to generate realizations of acoustic and shear impedance (AI-SI). The realizations of elastic properties were subsequently used to estimate rock physics-constrained reservoir properties and heterogeneities at a fine scale appropriate for dynamic simulation.

To understand reservoir connectivity (Vrolijk, 2005; Musani et al., 2013) simultaneous seismic inversion followed by stochastic inversion were used to predict AI and V_p/V_s. Probability density functions (pdfs) together with varying property ratios for oil, gas, water, shale and coal were calculated from well log data and integrated with stochastic inversion derivatives to predict fluid and facies volumes. Reservoir probabilities were used in the static model which was further calibrated with the reservoir model to close the loop. Stochastic inversion derivatives were effectively integrated in the static model to propose the appraisal and infill

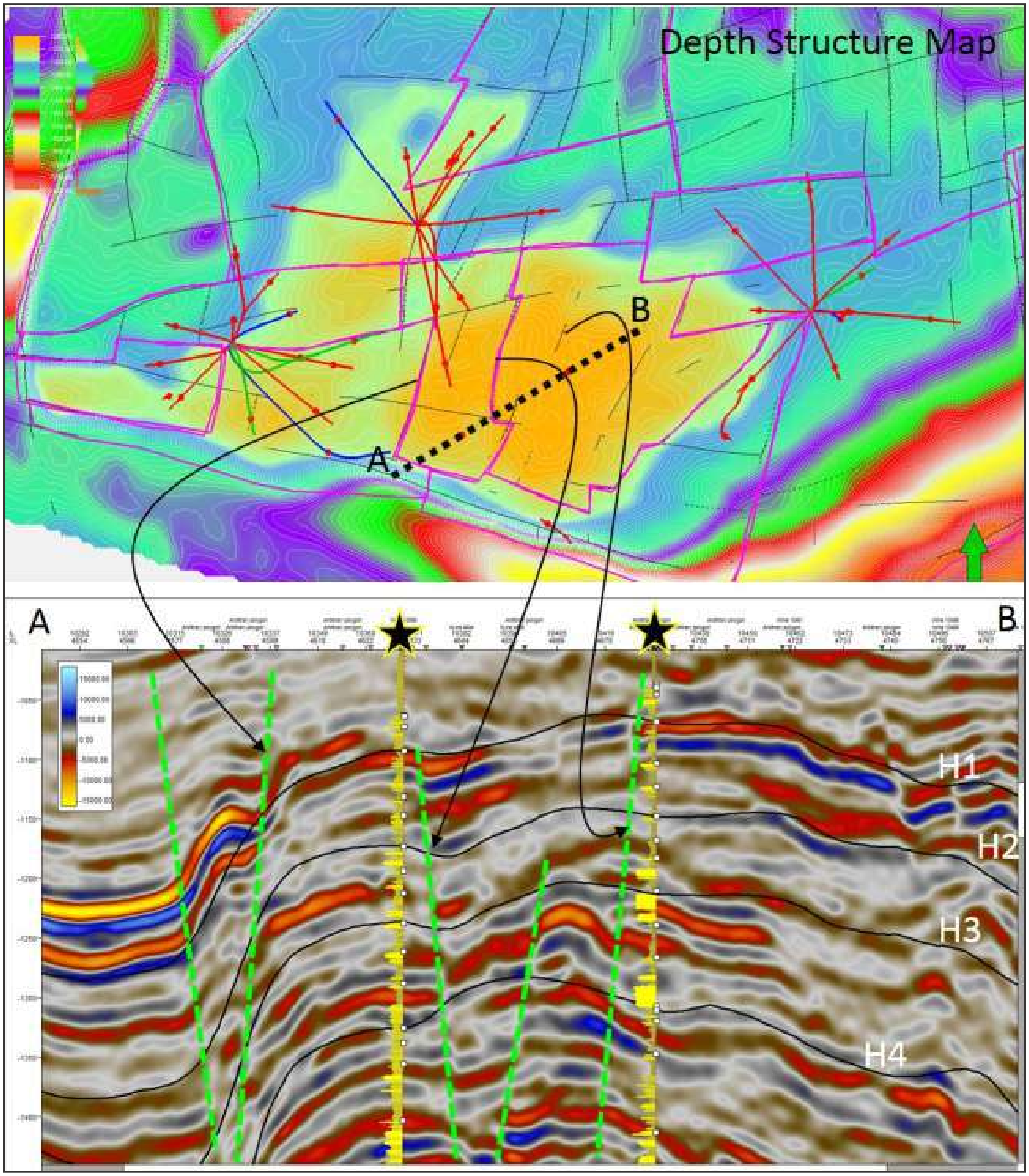

Fig. 1: Fault blocks and corresponding seismic line highlighting the complex structural regime. Different fault blocks are demarcated by major faults in the study area and represented by pink color polygons (upper part), minor faults inside the blocks are marked by thin black lines; Seismic section shows major horizons, faults, and two wells showing gamma ray logs (lower part).

well locations. The integrated workflow for static models is shown in Figure. 2.

The effective use of seismic inversion derivatives implies the probabilistic interpretation that can be incorporated in a systematic way to capture all major factors contributing to the inherent uncertainty associated to reservoir models.

Fluid and Facies Volumes

The results of geostatistical inversion (Rajput, 2014) were used to drive estimates of lithotype probabilities within the zone of interest. A joint probability density function was created for each lithotype including oil sand, shale, gas sand, coal and wet sand that determines the probability that a

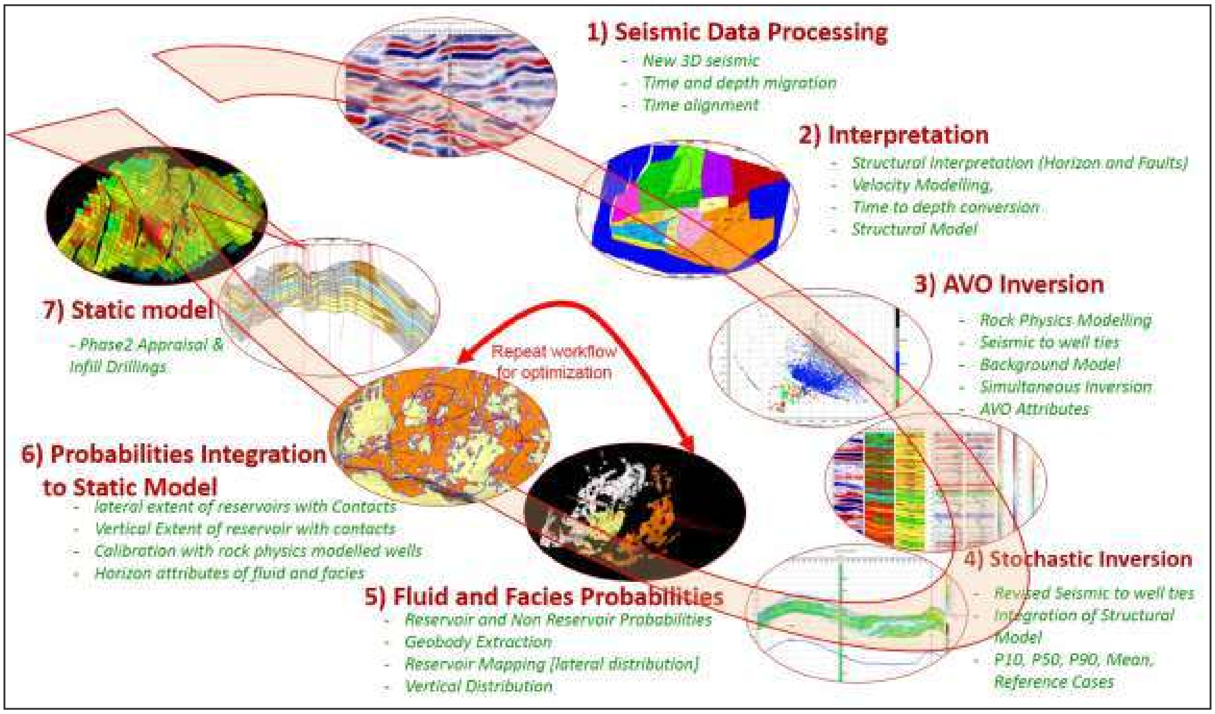

Fig. 2: Stochastic inversion to Static Model integration workflow

particular combination of elastic parameter values represents that lithotype. The prior probability indicates the relative proportion of each lithology that is expected within the region of interest. Then, these lithotype-conditioned pdfs and a priori geological information were combined within a Bayesian inference framework to generate lithology probability volumes from geostatisticaly inverted elastic parameter volumes.

In the geological model, distribution of reservoir properties is improved in the inter-well regions when constrained by seismic data. In the example, reservoir facies and properties, estimated at wells from petro-physical analysis calibrated with core measurements, were propagated in a 3D geological model based on an improved understanding of spatial continuity of the reservoirs and integration of lithotype probabilities estimated from seismic inversion derivatives.

Geological facies are the sedimentary units that have characteristic structural and mineral properties which reflect its depositional environment and diagenesis. Seismic facies are the manifestation of the underlying geologic facies and can be defined as a group of seismic amplitude variations with characteristics that differ from other facies. The petrophysical properties for a facies are unique which can be used to distinguish between oil, water, gas, shale and coal. This single point petrophysical information if integrated with quantitative seismic derivatives, can result in the prediction of the facies volume with less uncertainty.

It is very useful in de-risking and ranking prospects as well as pre/post-drill assessment. The derived volumes offer the probability of the occurrence of hydrocarbon sand at a particular location and more information on reservoir continuity.

To understand the continuity of Miocene Channel System, offshore Malaysia, Bayesian inference criterion was used and the probabilities of occurrence of the fluids and facies were calculated from stochastic inversion derivatives. Multi-dimensional probability density functions were designed for each possible facies (oil, gas, water, shale coal) and then a Bayesian inference technique was used to determine the probabilities for the occurrence of each of the facies at each 3D grid point in depth domain. The models were derived from well logs of the distributions of values for reservoir properties such as facies, lithologies, and fluids (Figure 3).

To this end fluid and facies volumes were used to derive reservoir trends and to understand reservoir connectivity.

Reservoir Continuity

Three different rigs were used to drill 5 oil producers and 4 water injector wells. The wells were designed with three cemented casing strings. Production wells were planned to be open-hole completions with stand-alone screens and swell packers for zonal isolation. Post drill results were analyzed by integrating static models, stochastic inversion driven reservoir probabilities, petrophysical information, and reservoir models to understand reservoir connectivity between the wells. Post drill analysis of new wells offered new insights about the spatial distribution, reservoir parameters and uncertainties in net reservoir thickness which resulted in the necessity of revisiting the geocellular model and integrating the newly available 3D seismic and infill well.

The potential benefits from stochastic seismic inversion derivatives were validated for a reservoir where an appraisal

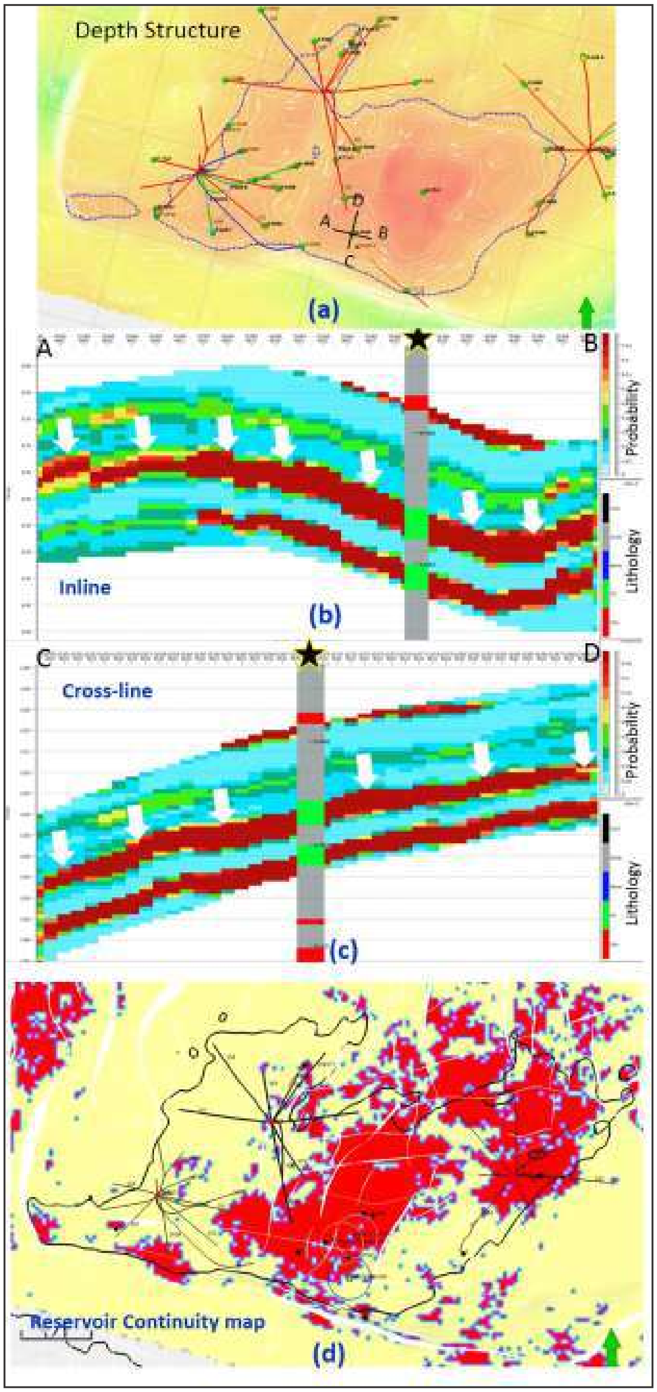

Fig. 3: Stochastic inversion driven reservoir probability sections (b and c) highlight excellent correlation with log lithologies [in-line and cross-line segments are shown, that corresponds to A-B and C-D line shown on depth structure map]. Dotted blue line in 'a' shows oil water contact (OWC) in the field; the wells are projected on depth structure map as solid green dots. Solid white arrows in 'b' and 'c' show oil reservoir continuity. An example of fluid and facies volumes driven reservoir continuity map is shown in 'd'. Red color highlights the presence of reservoir.

cum development well was subsequently drilled. The drilling results indicate that the inversion constrained geological model has correctly predicted the reservoir distribution. Using the inversion attributes in an integrated modeling approach offers improved modeling of the "plumbing" of the reservoir through more reliable estimation of the permeability, water saturation and porosity. These improved reservoir properties have led to increased reserves in an ongoing re-development program of a mature field. The confidence in the predictions was supported by better history match.

An example of reservoir continuity between an oil producer well and water injector well is shown in Figure 4.

Conclusions

Innovation in fossil fuel extraction technologies are driving efficiencies that increase production in mature fields and reduce uncertainties during the development phase. Prediction of structurally complex reservoirs is a recurring challenge to many oil and gas companies seeking to recover more from mature fields. This study illustrates an innovative workflow of integrating stochastic seismic inversion derivatives to derive fluid and facies volumes and reservoir probabilities which were then integrated into the geocellular model to understand the reservoir continuity. The results provide new insights into the spatial distribution of Miocene channel system. Here under are the highlights;

- Effective integration of high resolution seismic data with a powerful 3D stochastic inversion scheme offers measurable benefits in ongoing brown field development program that has a potential to offer the optimization of drilling campaign and overall field development strategy.
- Fluid and facies volumes derived from stochastic inversion derivatives resulted in excellent reservoir probability trends, which then translated into reservoir continuity maps. This study offers substantial benefits in order to plan the water flood program.

Some Thoughts

Reservoir connectivity analysis by integrating probabilistic distribution of fluids and facies with stochastic inversion is a series of analysis and methods that combine geological interpretation of complex depositional environment, stratigraphic units interpretation, and structural interpretation with careful validation of fluid and facies distribution and pressure data to arrive at logically permissible but non-unique predictive models of reservoir connectivity.

The application of this method to different pertoleum reservoir settings in many parts of the world offers a workflow in which complex reservoir geometries can lead to complex fluid and facies relationships. It has been tested to successfully identify infill well locations in mature assets, to tap into previously un-identified reservoirs and to improve reservoir management plan.

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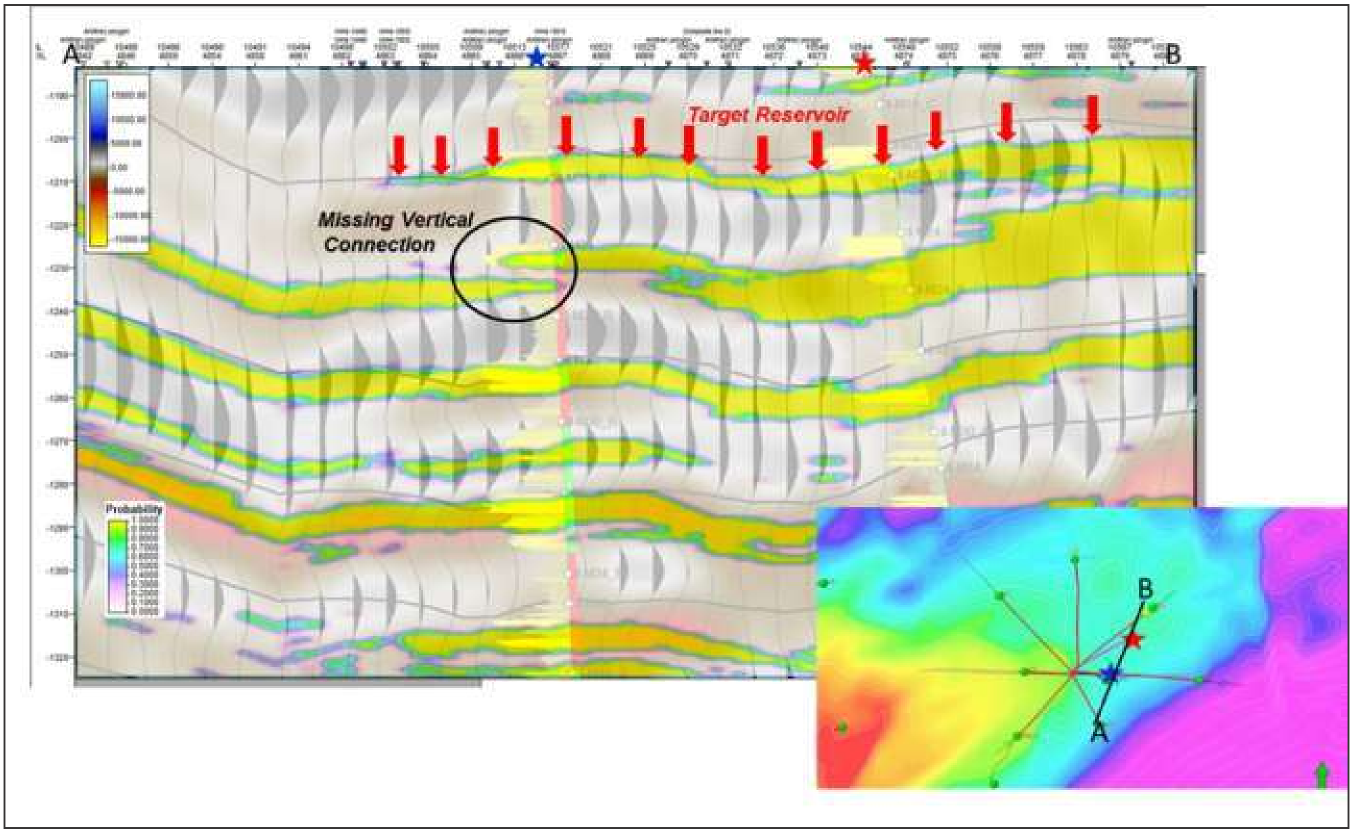

Fig. 4: An arbitrary line passing through water injector well (blue star) and the benefiter well (red star) shows seismic and reservoir probability distribution (yellow) in the background at target reservoir level. Geostatistical inversion driven geobody is highlighted in yellow. The continuity at reservoir level is marked by red arrows.

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