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"*Time-lapse seismic interpretation is similar to solving a puzzle with different possible answers, and uncertainty is an inherent part of this process. The interpretation derived by solely 4D seismic data may not provide sufficient information to reduce the attached uncertainties in the 4D interpretation, particularly for more complex geology and fluid interactions.*"

Stepwise uncertainty reduction in time-lapse seismic interpretation using multi-attribute analysis

Masoud Maleki

A key component of reservoir monitoring is the knowledge of fluid movement and pressure variation. This information is vital to update reservoir models, and, consequently, in helping to improve model-based reservoir management and decision-making processes. However, in practice, varying levels of uncertainty are inherent in the 4D seismic interpretation. The complex nature of some 4D seismic signals emphasizes the role of the competing effects of geology, rock and fluid interactions. Hence, a reliable 4D interpretation requires an interdisciplinary approach that entails data analysis and insights from geophysics, engineering and geology. In this study, a stepwise workflow was introduced to reduce the uncertainties in the 4D seismic interpretation and to identify the improvements required in order to perform better reservoir surveillance. In parallel, the workflow demonstrates the use of engineering data analysis in conducting a consistent interpretation, and encompasses the 3D and 4D seismic attributes with engineering data analysis. Herein, the proposed workflow could be a standard approach for reservoir model updating of various fields by revealing the hidden information inside the 3D and 4D seismic data. It could also provide a valuable source to utilize the long-term value of 4D seismic data for reservoir monitoring studies.

Stepwise uncertainty-reduction workflow

Figure 1 shows the workflow for analyzing the cause and shape of 4D seismic signals where each stage is defined with a color. The concept of the proposed workflow is the fact that when more information is available, the previous interpretation would be analyzed and consequently modified to reduce the uncertainties inherent to the qualitative interpretation. The first level of approach is similar to the traditional qualitative interpretation used to locate and explain the main 4D signals of the reservoir. For this primary interpretation, the time -lapse difference of the root mean square (dRMS) amplitude is used.

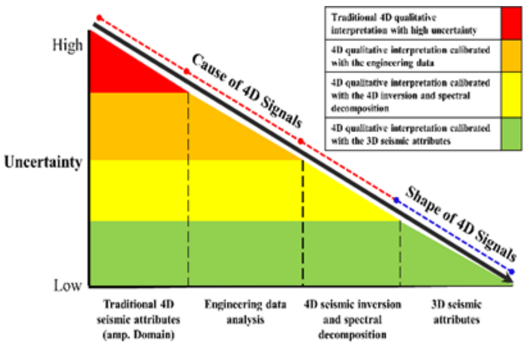


Figure 1*: Workflow scheme of reduction uncertainties in 4D seismic qualitative interpretation.*

In the second stage, dRMS results are combined with engineering data to shed more light on the 4D interpretation. For example, the production and injection data from the wells are used as control measures to investigate the validity of the 4D seismic interpretation. Then the previous interpretation is integrated with more advanced 4D seismic attributes (i.e., inversion and spectral decomposition). The purpose of this is to reduce uncertainty related to these 4D signals to evaluate if they are noise effects or genuine 4D changes (validation stage). In the final stage of the workflow, 3D seismic attributes are used to tie geological information and individual stratigraphic features to 4D signals in order to reduce uncertainty in the 4D seismic interpretation (detail stage). These 3D attributes include spectral decomposition, acoustic impedance, similarity and ant-tracking. They serve twin purposes: first, to imply reservoir heterogeneity and, secondly, to explain the shape of the 4D signals that are related to reservoir heterogeneity, or, indeed, the absence of 4D signals in some regions.

Stepwise uncertainty-reduction workflow

A deep-water Brazilian offshore field located in the northern Campos Basin (heavy-oil field) is evaluated in this work. The reservoir is composed of a stratigraphically trapped, poorly consolidated turbiditic sandstone (Maleki et al., 2019). Ocean-bottom cable (OBC) technology was chosen in a Permanent Reservoir Monitoring setting (PRM) to acquire the 4D seismic data for this field because of the need to monitor waterflood containment, as well as waterflood progression, on a flexible acquisition schedule. The very high repeatability of the acquisition and processing flow signaled the acquisition of high-quality seismic data with acceptable repeatability, allowing the possibility of obtaining most information from the 4D seismic data analysis. The 4D seismic dataset used here comprises post-stack seismic from the 2013 base and 2016 monitoring surveys. In addition, a detailed analysis was performed on production-history data in an attempt to extract some valuable information from the engineering domain for integration into the 4D seismic interpretation (i.e., static pressure, salinity analysis and hydraulic communication between the wells).

Results and discussion

Accordingly, the main 4D signals from the dRMS map (in a window of the top to base reservoir) were coupled to the engineering data analysis in order to have a preliminary interpretation (**Figure 2a**). The softening anomalies of S1 and S2 might be driven solely by increases in gas saturation. In fact, this suggests that gas-saturation effects overrode the pressure effects on the dRMS attribute around producers P2, P3, P5 and P6. This interpretation suggests that the gas is trapped, probably due to the reservoir structure. Anomalies H1, H2, H3 and H4 highlight hardening 4D signals, indicating that the injected water is replacing reservoir fluid. Alternatively, different levels of hardening strength were observed in the reservoir around injectors I5 and I2 (inside the anomalies H2 and H4 in **Figure 2a**). It led us to question the interpretation of water movement as part of these anomalies lay around the base of the reservoir. It might be related to movement of aquifer water near the base of the reservoir, either due to flooding by injected water. The hardening anomalies A1, A2 and A3 could be attributed to the aquifer influx reaching the base of the reservoir, as the anomalies are more concentrated there.

Meanwhile, several sharp dRMS anomalies are combined with some uncertain signals and carry complex layers of uncertainty (black arrows pointing to regions in **Figure 2a**). Herein, the dRMS attribute was used in conjunction with the 4D inversion and 4D spectral decomposition to provide a more detailed 4D qualitative interpretation (**Figures 2b**, **2c and 2d**). The locations of water injection and the main softening effects (anomalies S1 and S2) were captured, with the results being similar when compared to the dRMS, 4D impedance and 4D spectral decomposition. An interesting point relates to the softening shades surrounding the hardening anomalies H1, H2, H3 and H4 around the injectors with two possible interpretations (pointed by black arrows in **Figure 2**): 1. the interface between the injected and aquifer water develops a salinity transition zone and this phenomenon was apparent by a softening shade around the injector, 2. the softening effects could be related to pushed-oil in these regions, and we expect softening 4D signals that are not cancelled out by injected water, due to the accumulation of oil. It should be noted that this region could be interesting for further infill drilling campaigns.

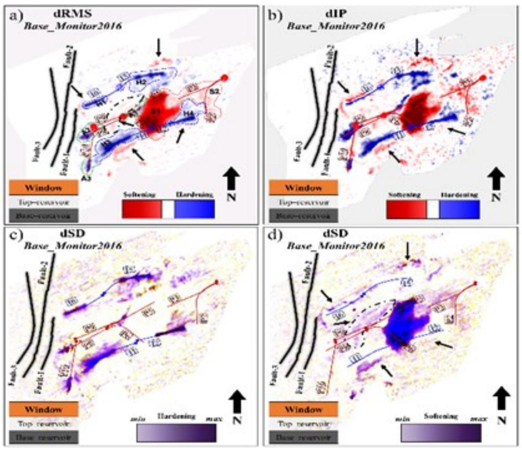


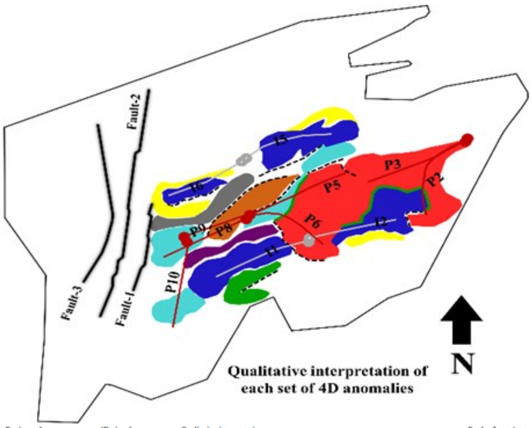
***Figure 2**: Maps of 4D differences throughout our workflow in detection of the causes of 4D anomalies.*

Moreover, we investigated the specific semblance and characteristics of 4D signals using various 3D seismic attributes. We believe that successful 4D seismic qualitative interpretation (aiming to reduce uncertainty) relies upon a pivotal step of detailed 3D seismic interpretation. The 3D similarity, ant-tracking, spectral decomposition and impedance attributes were promising in the identification of the shape of 4D signals, and the key features that are responsible for the dynamic reservoir behavior. Not shown here due to the lack of space.

Eventually, we categorized the anomalies in terms of the type of 4D signals and their most certain interpretation, and the interpreted nine geological trends through our uncertainty-reduction workflow (**Figure 3**). After completing this stepwise uncertainty-reduction workflow, we could rank the certainty of 4D interpretation for each anomaly and rank them to the certainty terms of A, B and C, meaning high, mid and low certainties, respectively.

Conclusions

Ambiguities in qualitative 4D interpretation present technical hitches when using solely 4D seismic attributes due to the interdisciplinary nature of reservoir monitoring. The proposed stepwise is an interdisciplinary workflow that allows a fast-track discovery and cohesive 4D qualitative interpretation that might trigger new insights. In particular, it provides phenomenal inputs for reservoir characterization and monitoring to update the dynamic and static models of the aforementioned field and to integrate with the data-assimilation techniques. The interpreted map of 4D anomalies enhances potential areas and their uncertainties, which can assist infill drilling studies. In addition, the workflow gives a significant advantage when applied to fields with a permanent reservoir monitoring (PRM) system, as the new information is added to the sequence once the seismic data are acquired.



Region colour	4D signal	Qualitative interpretation	Rank of certainty
Red	Softening	Gas going out of solution	A
Brown	Softening	Gas going out of solution	B
Dark blue	Hardening	Flooded by injected water	A
Light blue	Hardening	Flooded by aquifer water	A
Yellow	Softening	Combination of bypassed oil and salinity transition zone	A
		Increase in pore pressure due to injector wells	C
Green	Softening	Bypassed oil	A
		Salinity transition zone	B
		Increases in pore pressure due to injector wells	C
Grey	No signal	Unswept oil zone	A
Purple	No signal	Combination of gas going out and back into solution, and injected water	B

***Figure 3**: Qualitative interpretation of each set of 4D anomalies and Description of colored regions. Dashed-black lines highlight the interpreted geological trends.*

References

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*Maleki, M., Danaei, S., Davolio A., Schiozer D.J. (2020). Step-wise uncertainty reduction in time-lapse seismic interpretation using multi-attribute analysis. Petroleum Geoscience 27, (3) .

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Masoud Maleki holds a B.Sc. in Mining Engineering from Iran University of Science and Technology, a M.Sc. in Geophysics from University of Tehran and a PhD in Petroleum Geoscience and Engineering from UNICAMP. He is a researcher at UNISIM since 2018, working on integration between 4D seismic, reservoir simulation and machine learning.

"We have shown that by integrating the seismic and engineering domains in a stepwise uncertainty-reduction scheme, it is possible to identify most likely causes and shapes of ambiguous 4D signals."

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