

How Does Seismic Data Quality Influence Pore Pressure Estimation and Interpretation?

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Summary

Understanding formation pore pressure distribution is critical not only for the seal integrity and hydrocarbon accumulation column height evaluation of a prospect, but also for the drilling plan and hazard prevention of a well in today's competitive exploration and production environment.

There are two main approaches for pore pressure estimation: geological using basin modeling and geophysical using seismic velocity. In this paper, seismic velocity was used for pore pressure estimation. The impact of the input data quality in terms of signal-to-noise ratio (SNR) and frequency bandwidth on the accuracy of seismic velocity analysis and, ultimately, the reliability of pore pressure estimation were reviewed at selected milestone processing steps that were used to enhance the prestack time migrated (PSTM) seismic data.

It was shown that the prestack data quality in terms of signal-to-noise ratio (SNR) and resolution can significantly affect velocity analysis and the quality of pore pressure estimation when the results are compared to known geophysical, geological, and engineering data. Finally, pore pressure and its related data were used for seal integrity assessment in prospect evaluation and multiple pressure attributes with predicted lithology from inversion were integrated for well design and hazard prevention in drilling with much less uncertainty.

Introduction

Since Pennebaker (1970) showed that pore pressure can be predicted from seismic velocities, many formulations have been introduced with varying success. With recent deepwater drilling, the industry has understood more about pore pressure, its dynamics, and its impact in many E&P activities.

A systematic methodology was developed together with a calibrated pressure model that transforms seismic interval velocities into high density high resolution (HDHR) formation pore pressure and subsequently other pressure related attributes. This calibrated pressure model attempted to go beyond conventional compaction trend consideration and take into account the effect of burial depth, porosity, temperature, and shale diagenesis. First, PSTM seismic data was carefully optimized to enhance its SNR and frequency bandwidth. Then, HDHR anisotropic velocity analysis with 6th-order curved ray formulation was employed to accurately extract a detailed 3D seismic

velocity field for every time sample at every common-mid-point (CMP) location. Tomographic inversion in prestack depth migration (PSDM) and prestack inversion were not considered for velocity estimation in this study mainly because of their higher cost and longer turnaround time.

Land and marine seismic data were used to evaluate the progressive impact of data quality on the accuracy and vertical resolution of the seismic interval velocity field at important milestone steps in the prestack data enhancement workflow. A calibrated pressure model was built after it was correlated with available wells, logs, and drilling data and tested to evaluate its reliability and uncertainty of pore pressure estimation. With blind well testing and real case studies, it was demonstrated that this methodology is practical and effective and can provide valuable information for prospect evaluation, well planning, and drilling risk management ahead of the drill bit.

Pore Pressure Estimation

Input Data Quality and Velocity Extraction Quality

To obtain accurate seismic velocities at the right position, properly migrated PSTM CMP gathers were the starting point. First, they underwent a rigorous processing and quality control sequence to achieve the highest possible SNR by attenuating coherent and random noises. Then, PSTM gathers were further improved by a noble high resolution (HR) enhancement technique without degrading the SNR (Hamarbatan et al, 2006; Smith, 2008). Finally, an anisotropic curved-ray 6th-order velocity analysis (Hake, 1984) was applied to compute HDHR seismic interval velocities for every time sample at every CMP location of the entire 3D volume. The workflow of SNR and resolution enhancements and HDHR velocity analysis was an iterative loop because HR-enhanced PSTM gathers revealed previously undetectable velocity inaccuracy using normal bandwidth data. Thus, additional velocity analysis was required to extract a new velocity field that is more accurate, especially for long offset data.

Figure 1a demonstrates the data quality improvement of a typical PSTM gather at three main processing stages during the data enhancement sequence. The original input PSTM gather exhibits poor quality with multiples, noises, low resolution, and masked non-flatten primaries. The SNR-enhanced gather, after noise attenuation, displays more visible primaries albeit low resolution that is flattened by final velocities after two iterations of data enhancement and velocity analysis. The HR-enhanced gather clearly shows the flattened primaries with optimum vertical resolution.

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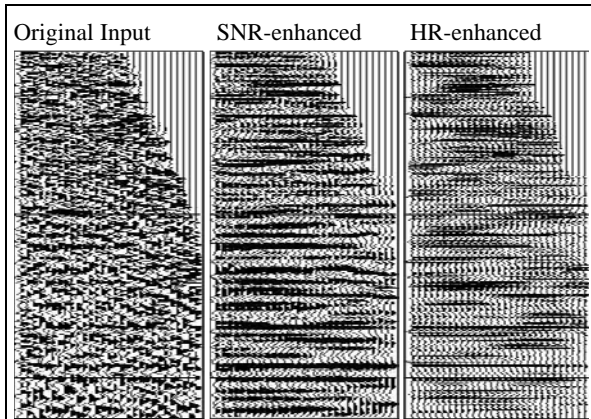


Figure 1a: The progressive improvement of seismic data quality at three main stages through the data enhancement workflow.

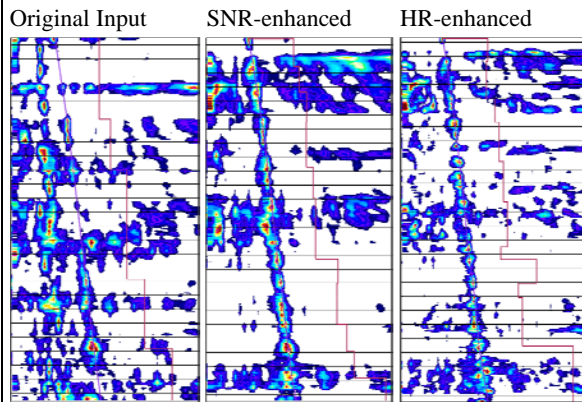


Figure 1b: The progressive improvement of velocity quality at three main stages through the data enhancement workflow.

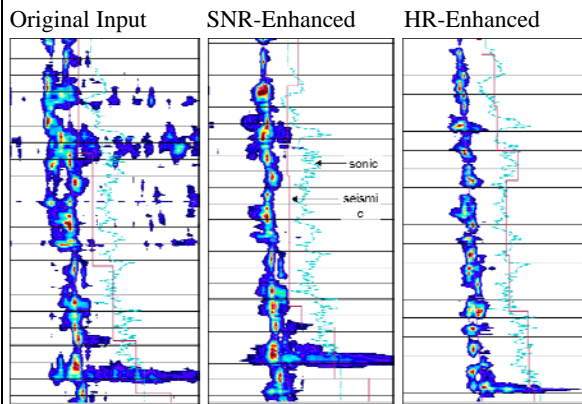


Figure 1c: The calibration with the well and sonic log improves accordingly with the improvements of velocity quality at three main stages through the data enhancement.

Figure 1b displays the corresponding velocity analyses and their quality comparison from the gathers in Figure 1a. The velocity semblances of the original gather exhibits multiples, noises, and obscured velocity trend. In other words, the uncertainty of picking accurate velocity is very high. On the other hand, the velocity analysis of the SNR-enhanced gather shows a clearer trend and more identifiable primaries for velocity picking. Finally, the HR-enhanced gather provides the cleanest velocity trend and sharpest semblances with high confidence for high resolution velocity analysis. Consequently, the interval velocity presented as a step function to the right of the semblances shows that the vertical resolution increases greatly and offers the best chance of detecting thinner beds.

In an ideal situation, this SNR and resolution enhancement sequence with proper velocity analysis offers a HR interval velocity field that improves thin bed detectability and reduces the resolvable thickness from thousands of feet, when initial data quality is poor, down to tens of feet when final input data quality and frequency bandwidth are optimum. Furthermore, the specially implemented curved-ray 6th-order anisotropic velocity analysis algorithm gives a good estimation of geological velocity (as illustrated in Figure 1c) when it is compared to the sonic velocity of a nearby well. This seismic-derived velocity with geological quality can be used for pore pressure estimation, time to depth mapping, and initial velocity for depth imaging.

Calibrated Model and Pore Pressure Estimation

A calibrated pressure model integrating the principles of Bowers (1995) and Dutta (2002) was developed to transform seismic interval velocities to pore pressure by taking into consideration of various factors, including under compaction, burial depth, temperature, shale diagenesis, and inelasticity, that affect subsurface pore pressure. Furthermore, available logs, drilling data, and engineering information such as mud weights, LOT, RFT, and MDT from nearby wells were incorporated into the calibrated pressure mode generation.

Figure 2 displays the estimated mud weights using a calibrated pressure model at a known well location and at a blind well test location from a project in the deepwater Gulf of Mexico. The distance between the two wells is in tens of miles, and the target is around 16,000 feet. The real mud weights applied are denoted as blue triangles and the estimated mud weights are shown as solid red trend. The mud weights vs. depth chart at the calibration well (to the left of Figure 2) illustrates that the calibrated pressure model predicts quite well the pore pressure in terms of mud weights and thus demonstrates its applicability and reliability. When this model was applied to the blind well test using derived HR interval velocity field, the estimated mud weights were very close to the drilling mud weights

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and RFT measurements as shown in the chart to the right in Figure 2. In addition, the calibrated pressure model also provides an uncertainty assessment displayed as a fairway between the green and light blue solid trends around the estimated mud weight trend. The relative tight and consistent fairway displayed in Figure 2 implies a good pressure model was generated and the estimated pressure result was reliable.

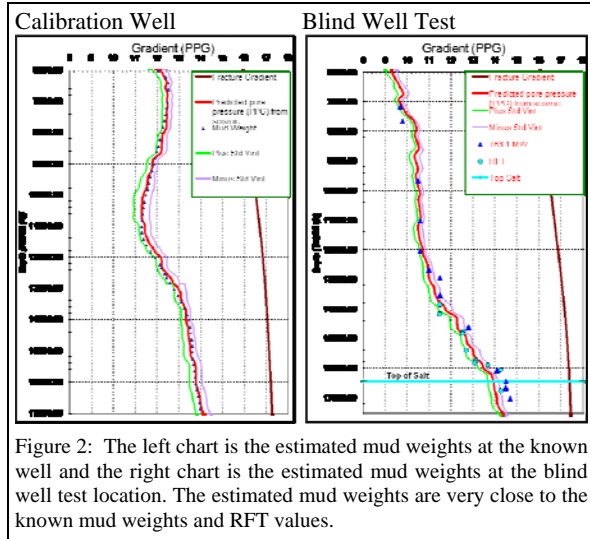


Figure 2: The left chart is the estimated mud weights at the known well and the right chart is the estimated mud weights at the blind well test location. The estimated mud weights are very close to the known mud weights and RFT values.

Case Study and Interpretation

Although pore pressure tends to be associated with well planning and drilling hazards, it also offers tremendous value in the early phase of exploration. It allows us to assess trap seal integrity and hydrocarbon accumulation column height for prospect evaluation, as well as to identify bypass zones and pressure changes when 4D data are available. Moreover, it has been shown that, using seal integrity concept, one might differentiate low saturated gas sands, i.e., a seal breach problem, from saturated sands. This seal breaching analysis using pressure data can complement the AVO analysis in differentiating false anomalies caused by low saturation from valid bright spots.

Seal Integrity Analysis and Interpretation

The following study was conducted using the aforementioned workflow and calibrated pressure model to estimate the reservoir and surrounding formation pore pressure and appraise the prospect seal integrity for an onshore pressure-charged gas play in the Gulf Coast region of the United States. In Figure 3, a 2D PSTM section (seismic in black wiggle with variable area) overlaid with estimated pore pressure in color (blue to orange for high to low pressure variation) demonstrates that the prospect has

excellent fault and top seals because there are no pressure leaks on either sides of the two bounding faults (in white) and no leakage into the overlying formation. The drill bit found gas and confirmed the pore pressure estimation and seal capacity interpretation.

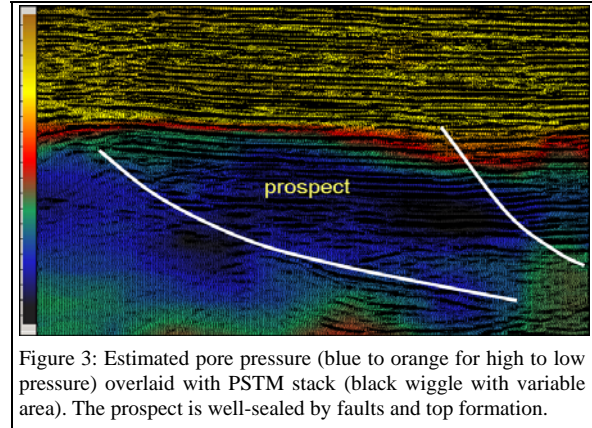


Figure 3: Estimated pore pressure (blue to orange for high to low pressure) overlaid with PSTM stack (black wiggle with variable area). The prospect is well-sealed by faults and top formation.

A detailed 2D display in Figure 3 can assist the evaluation of subtle pressure changes across lithological, stratigraphic, and structural boundaries, but does not give a good idea of spatial pressure variation and 3D pressure cell distribution. On the other hand, a 3D visualization offers a better view of regional pressure distribution. Figure 4 is a snapshot of a 3D visualization exercise of pore pressure distribution for the same prospect in Figure 3. Now, explorationists can quickly visualize and interpret 3D pressure cell distribution, pressure plume, and pressure sink as well as quickly assess any potential seal breaching problems and drilling problems in a region or a basin.

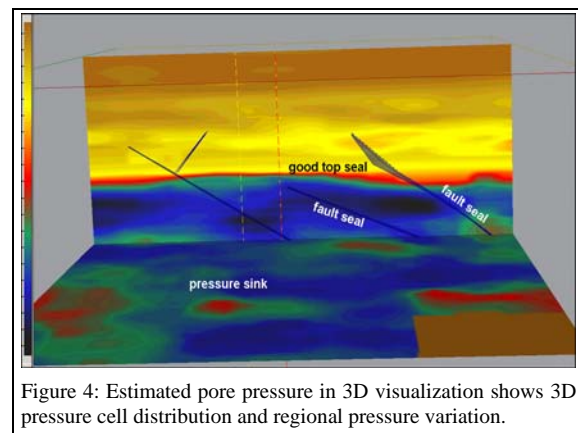


Figure 4: Estimated pore pressure in 3D visualization shows 3D pressure cell distribution and regional pressure variation.

Another powerful 3D visualization is to simultaneously cor-render multiple 3D attribute volumes for integrated

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interpretation. Figure 5 depicts a 3D visualization of a PSTM seismic cube embedded in various pressure attribute cubes, since PSTM stack volume shows structure and stratigraphy better, and pore pressure volumes show fluid dynamics better. It allows explorationists from different disciplines to work together and perform true 3D interpretation by moving, stripping, or intercepting various sub-cubes to evaluate geology, structure, reservoir, pressure, and their interaction – a full integration allows conducting geological and geophysical evaluation by geologists and geophysicists and planning well design and drilling hazard prevention by drillers and engineers. Obviously, with the small scale 2D still photos here, it is very difficult to show the true 3D visualization of pressure interpretation.

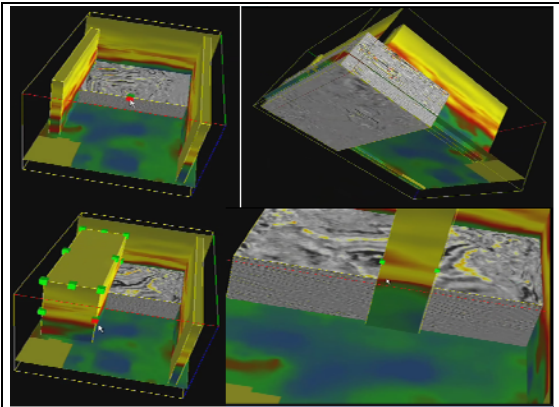


Figure 5: A series of snapshots of a 3D visualization and interpretation session using a combination of multiple 3D PSTM and HDHR 3D pressure attribute volumes.

Integrated Pressure and Lithology Interpretation

The methodology and calibrated pressure model employed produces not only pore pressure but also other pressure attributes such as fracture gradient, mud weight, effective stress, and overburden pressure. Using all of them, drillers and engineers can better carry out well planning for mud program, casing shoe position, and casing string purchase as well as assess drilling risk for wellbore stability, hazard prevention, and reservoir formation protection. In this postmortem study, the operator drilled a deepwater well in the Gulf of Mexico using only 3D seismic volume and the pressure data of two nearby wells that had no indication of abnormal pressure and were less than 2 miles away from the prospect well. It turned out that the well was abandoned due to unexpected abnormal pressure and running out casing strings before reaching the planned total depth (TD).

Figure 6 shows the results of estimated mud weights and acoustic impedance (AI) from poststack inversion. The two sections to the left are the comparison of estimated mud

weights calculated from normal and HR bandwidth prestack data respectively. The section to the far right is the inverted AI from HR-enhanced data. As a blind test, the methodology predicted accurately the abnormal pressure from both normal and HR-enhanced data. Additionally, the estimated mud weights from HR-enhanced data exhibited a fingering pattern of different mud weights that correlates well with a similar sand-shale fingering sequence interpreted from inverted AI volume. According to the petrophysical analysis, AI is a good indicator of lithology in the area. This integrated approach provides a better understanding of 3D pressure cell distribution and drilling risk assessment. If this high pressure cell were limited to a small pocket, the well could have been saved by moving the well slightly away as illustrated in Figure 6 and potential realized the prospect.

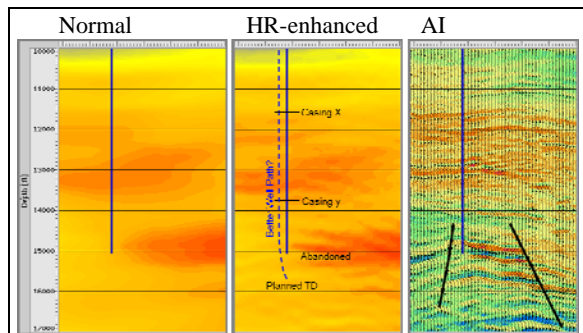


Figure 6: The comparison of estimated mud weights from normal and HR bandwidth data respectively (two sections to the left, with darker orange color for higher mud weights) at the prospect depth, and the inverted AI section (to the far right) for lithology prediction.

Conclusions

Good data quality and high resolution are essential for accurate velocity analysis and ultimately reliable HDHR pore pressure estimation using a properly-calibrated pressure model. Integrating all pressure attributes with lithology and fluid properties from inversion can offer explorationists a competitive edge from prospect evaluation, well drilling, to risk management in various exploration and production activities.

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