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Petroleum System Elements Indicated by Seismic Pristine Amplitude

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Abstract

The description of petroleum systems and their spatial complexity, through seismic post-stack data is a scientifically fascinating and economically crucial topic for both the oil industry and research. Each petroleum system, analyzed within any sedimentary basin and at any scale of geoscientific investigation, is unique in its petrophysical characteristics, geometric distribution, and elastic properties. The interplay between fluid dynamics principles and geological factors—such as rock composition, structure, and diagenesis—further influences these processes. Seismic indicators of these correlations typically rely on stronger amplitudes to help predict the behavior of hydrocarbons within petroleum systems, optimizing exploration techniques and effectively managing resources. Stronger amplitudes usually originate from primary reflected waves in materials with significant lithological contrasts, including unconformities, reservoir tops, salts, volcanics, and carbonates. However, these amplitudes can also be affected by noise—particularly coherent noise resulting from wave propagation effects—as well as certain fluid interactions. In hydrocarbon exploration, there is an increasing demand to utilize all available seismic information across the entire amplitude spectrum—not just the stronger signals, but also the very low-magnitude values typically classified as background. By enhancing these background seismic values, we can reveal variations in permeability associated with different fluid masses, such as those with varying viscosities, gas-oil ratios (GOR), and API grades, often indicated by subtle signal responses with low magnitudes. Integrating seismic concepts of fluid dynamics with geological principles provides valuable insights into the complex processes governing petroleum systems, ultimately enhancing our ability to explore hydrocarbons and other fluids more efficiently. This work emphasizes the renewed significance of seismic indicators related to fluid dynamics, aiming to better understand the roles of water formation and hydrocarbon migration within petroleum systems through the concept of pristine amplitude modeling.

We seek answers to critical questions about how seismic data can depict scenarios that incorporate comprehension of pressure gradient principles, which are essential for understanding fluid dynamics and driving the spatial movement of fluids through porous media. By correlating fundamental concepts of fluid dynamics with petroleum systems, we can suggest how fluids behave in porous media and identify the factors influencing their movement within these systems. This movement is affected by various factors, including fluid viscosity, which influences flow rates. Additionally, seismic images can provide insights into the behavior of regional capillary pressure, which plays a crucial role in this process, as well as the pressure differences across the interface of two immiscible fluids, indicating how and where hydrocarbons may be retained in reservoirs. The primary geoscientific question addressed in this investigation concerns the initial moment and location of fluid movement after its generation within a specific petroleum system—an aspect potentially observable through seismic methods. Understanding this inquiry is vital for comprehending the dynamics of fluid migration. It involves examining the conditions and factors that trigger fluid movement, such as pressure gradients, buoyancy effects, and the properties of the surrounding geological formations. This investigation not only enhances our understanding of subsurface fluid behavior but also aids in predicting the locations of economically viable hydrocarbon deposits.

Introduction

Seismic fluid indicators traditionally emphasize stronger amplitudes, which are crucial for accurately predicting hydrocarbon behavior within petroleum systems. This emphasis on amplitude is essential for optimizing exploration techniques and effective petroleum management strategies. Stronger amplitudes typically arise from primary reflected waves that interact with lithologically diverse materials, such as unconformities, hiatuses, reservoir tops, salts, volcanic formations, and carbonates. These geological features create significant contrasts in acoustic properties, enabling clearer seismic imaging. However, the interpretation of these amplitudes can be complicated by various forms of noise, particularly coherent noise resulting from wave propagation effects. This work highlights the renewed significance of amplitude filtering to build pristine amplitude model seeking indications in fluid dynamics, which are essential for interpreting fluid behavior in various geological settings. By focusing on these indicators, we gain a deeper understanding of water formation and hydrocarbon migration within petroleum systems, allowing us to better predict reservoir locations and optimize extraction methods. As a result, further integration of disciplines fosters more informed decision-making in the management of hydrocarbon resources, ultimately leading to increased productivity and sustainability in the industry.

Post Stack Amplitude Filtering: the qualifying to identify subtle seismic signals

Santos et al. (2019) presents the process of seismic amplitude qualification and demonstrates that it is always possible to develop methods for processing and analyzing seismic data to achieve increasingly accurate results, optimizing the performance of detection applications across different levels of coherent noise attenuation, incoherent noise, and undesirable signals. This process is logically inspired by Claerbout (1963), who adopted concepts of optimum filters for noise suppression in multiple time series. Algorithms based on prediction error and interpolation error were employed to detect P-wave signals from three teleseismic events using the method introduced by Robinson (1963). These filters facilitate the detection of signals in noise with low signal-to-noise ratios. The study found that microseismic noise within the pass band of these instruments is more accurately described as Brownian motion of a surface rather than random waveforms with characteristic directions of propagation. Consequently, single time-series filters perform almost as effectively as multiple time-series matrix filters. Prediction-error filters yielded substantially better results than simple band-pass filters. Additionally, Robinson and Treitel (1969) conducted a study on the detection of a signal immersed in white noise. Their numerical examples illustrate how to evaluate the performance of various filters at different amplitude levels of the signal. They describe two specific digital filters designed to enhance the signal-to-noise ratio of the output compared to the input. The determination of suitable filter coefficients relies on an appropriate definition of the output signal-to-noise ratio. For the matched filter, this ratio is defined as the instantaneous signal power to the instantaneous noise power; in the case of the output energy filter, it is defined by the ratio of the energy of the filtered signal to the average power of the filtered noise, with the averaging performed over the time interval during which the signal occurs. Santos et al. (2025) demonstrate that by reducing stronger amplitudes while simultaneously enhancing weak reflectivities through advanced inversion techniques, we can effectively diminish the magnitude of coherent noise and undesirable stronger primary signals, thereby highlighting weak primary signals associated with regional permeability for fluid masses. This approach involves attenuating post-stack seismic amplitudes to a threshold value, allowing us to create a robust model that heuristically represents the seismic behavior of geological formations prior to any changes induced by fluid saturation, diagenesis, or structural alterations—the pristine amplitude model. Such a model is crucial for amplifying subtle signals indicative of potential fluid presence, thereby clarifying the possible regional distribution of these fluids. This enhanced clarity significantly improves interpretations of critical elements within petroleum systems, including all forms of fluid migration, traps for retention, and the significance of seismic signals derived from seals—both top and lateral—that can contain fluids within potential reservoirs.

Method

Methodologically, pristine amplitudes refer to the original seismic amplitudes that remain from a time immediately following sedimentary deposition or any rock intrusions and extrusions. This effectively filters out noise and undesirable signals derived from pronounced reflectivities, which are generally associated with various geological features such as lithological unconformities, hiatuses, reservoir tops, high-stiffness layers, faults, and other structural and petrophysical elements. By considering that hypothetical geohistorical moment for each seismic CDP data point, we can model this period using contemporary data as input. At that moment, the theoretical reflectivities observed through seismic waves correspond to impedance variations between rock layers deposited at different geological times. For these modeled moments, we heuristically assume that each seismic trace consists of pristine amplitude samples representing the seismic responses of static geological elements. Subsequently, starting from these geohistorical moments, the pristine amplitudes undergo modifications, many of which are correlated with fluid dynamics.

The contemporary registered signal can be described as:

$$S(t) = W(t) * (R_{pristine}(t) + F + T + G + D + N_{coherent}) + N_{non-coherent}$$

where modifiers factors are:

$N_{non-coherent}$ is the additive non-coherent noise part and should be the first signal contamination to be attenuated.

$N_{coherent}$ encompasses all coherent noise contribution derived from apparent attenuation factors (e.g. peg legs, wave conversion, transmission losses). They are the most complex noise to be attenuated once they have important role in the distortion of subtle signals from fluids.

The terms D, representing diagenetic effects; G, encompassing geological modifications (e.g., lithological changes); and T, reflecting tectonic influences, play a significant role in altering pristine amplitudes in relation to contemporary data. However, their influence is here considered less critical compared to the effects of F, which accounts for fluid-related modifications that is our target. The colors of the arrows above the equation schedule progressive levels of attenuation (e.g., in dB steps) to be applied in S(*t*) to achieve the optimal qualification solution for the $R_{\textbf{pristine}}$ model response. Here, such levels are applied using mathematical Extrema Function (Extrema) and differential reflectivity can be derived by any simple inversion process according to the workflow illustrated in Figure 1.

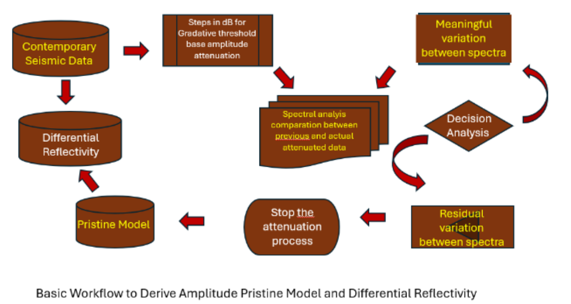

Figure 1: Workflow with main steps for building pristine amplitude modeling and derive related differential reflectivity.

Results and Examples

Throughout the presentation, we showcase several examples that illustrate seismic correlated images applied to the F3 Dutch Sector Block and Buzios field in Brazil (Quintes and Santos, 2023). Each example is linked to the identification and configuration of seismic indicators for various petroleum system elements, with a focus on sourcing, secondary migration, and retention. Figure 2 presents a cartoon simulating seismic impedance for a field with light fluids, highlighting the main petroleum system elements features that can be identified after a simple inversion for differential reflectivities between contemporary input amplitude data and modeled pristine amplitude values.

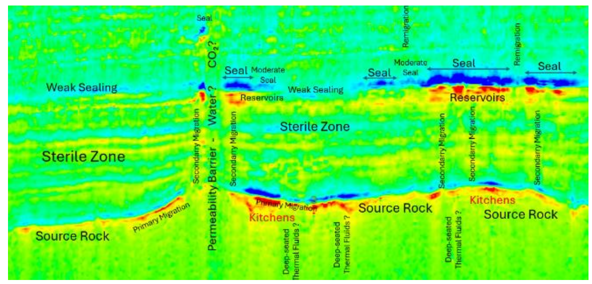

Figure 2: Cartoon illustrating seismic impedance indications for some features related to different petroleum system elements.

Conclusions

Pristine amplitude modeling and further inversion for reflectivities can indicate seismic scenarios related to fluid masses permeability which are crucial to define geometry and location of all petroleum system elements, bringing important uncertainty reduction and optimizing exploration strategies.

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