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Seismic Structural and Petrophysical Conjugated Indicators for Fluid Migration and Retention by Pristine Amplitude Modeling and Inversion

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Abstract

An important issue in the seismic interpretation of faults and fractures is how effectively a given piece of information can infer or reduce uncertainties regarding their textural patterns, geometries, and precise locations. A crucial question arises: which faults and fractures are truly significant and warrant accurate mapping, particularly in relation to hydrocarbon migration and retention? This work demonstrates that conventional mapping of structural heterogeneities using amplitudes alone (e.g., full PDSDM or PSTM converted to depth) does not always reveal the importance of each heterogeneity in controlling fluid behavior or permeability. To optimize geoscientific outcomes and mitigate risks, it is recommended to supplement conventional methods with additional information that more effectively indicates the presence of fluids, such as seismic impedances. This approach aims to minimize the risk of misinterpreting the roles of heterogeneities, which could lead interpreters away from understanding the true hydraulic function of each feature critical to fluid transmission or retention. Misconceptions in this area can jeopardize the economic viability of specific prospects or reservoir production. As energy demands grow, the significance of seismic analysis of natural fractures in hydrocarbons and other fluids has become increasingly prominent. This underscores the need to understand various aspects, including geomechanics, facies characteristics, permeability, porosity, seal efficiency, reservoir architecture, and hydrocarbon migration routes. Natural fractures and faults are essential for all these aspects. In the early phases of exploration, correlating natural fractures and their properties is vital. Identifying fracture zones and understanding structural deformations resulting from regional tectonic stresses is crucial. As the exploration process progresses into the development phase hydrocarbon production, the role of natural fractures becomes even more critical. Various methods for interpreting fractures from seismic data are employed, utilizing mathematical algorithms designed to detect structural heterogeneities. Techniques such as numerical correlation, vector similarity, variance analysis, and curvature analysis are commonly employed. Additionally, the interpreter's geological knowledge regarding seismic patterns of faults and fractures that may correlate with potential geological and petrophysical features is fundamental in selecting and constructing each method or algorithm applied to detect those specifically related to permeability factors and transmissibility. This work explores the technical aspects and benefits of applying algorithms for detecting seismic fracture patterns on pre-qualified data, specifically prepared for coherent noise and unwanted signal attenuation. Utilizing conjugate indicators for diagnosing the role of heterogeneities related to fluid migration, such as seismic amplitudes and impedances, significantly increases the likelihood of success. The results derived from seismic data from the Teapot Dome field in the USA highlight how improved data quality can have a substantial impact on the successful identification of fault and fracture networks.

Introduction

Seismic analyses of faults and fractures can be logically divided into stages that reflect the exploration and production process. During the exploration phase, methods for interpreting structural heterogeneities in seismic data focus on identifying elements that primarily impact the effectiveness of the petroleum system. The resolution required to detect exploratory seismic patterns correlating with subtle faults and natural fractures is generally much higher than that needed for major faults, which involve more pronounced lateral impedance contrasts. As a result, modern algorithms and artificial intelligence methods, such as machine learning, have not consistently succeeded in identifying fractures. While achieving high precision in determining whether a region is already fractured may be challenging, these analyses provide valuable insights into subsurface structures, aiding in effective management of hydrocarbon and other fluid resources. One significant constraint faced by algorithms used to define fractures in seismic data stems from intrinsic resolution limitations and the presence of coherent noise. This work addresses the technical aspects and benefits of applying algorithms for detecting seismic fracture patterns on pre-qualified data specifically prepared for coherent noise attenuation.

Teapot Dome Geological Settings and Tectonic Impact on Fluid Migration and Retention

Even in mature fields or those entering production that have undergone extensive exploration with advanced seismic technologies, there remains potential for new experiments that can yield significant economic benefits. This study presents results from pristine amplitude modeling (Santos et al., 2025) and subsequent inversions on data from the Teapot Dome field in the USA, highlighting differences in detection performance at various levels of coherent noise attenuation and unwanted signal amplitude reduction. Teapot Dome, located in Wyoming, is characterized as an anticline—an arch-like geological structure formed by tectonic forces. The region's tectonic history has played a crucial role in shaping this structure. The formations were significantly influenced by the Laramide Orogeny, a mountain-building event during the late Cretaceous to early Eocene epochs, which caused regional uplift and facilitated anticline development, enhancing hydrocarbon accumulation potential. However, this also introduced structural heterogeneities that can either facilitate or impede fluid transmission and retention. This geological feature exemplifies the relationship between geological structures and fluid migration. Its distinct characteristics, including sedimentary rock layers, the interplay between sandstone reservoirs and cap rocks, and the impact of tectonic events on differential permeability for various fluids, make it a vital site for understanding fluid accumulation and migration processes. In mature areas like Teapot Dome (Curry, 1977), questions often arise about whether new insights can be gained from existing seismic data. The answer lies in the continuous advancement of processing techniques and innovative applications for existing data. By refining methodologies and incorporating new analytical approaches, we can uncover hidden insights and enhance our understanding of the subsurface, improving our ability to identify and characterize natural fractures and faults for fluids. This ongoing investigation not only optimizes resource management but also opens pathways for economic gains in hydrocarbon exploration and production, demonstrating that even well-studied areas can still offer valuable information.

The Qualification of Seismic Data for Teapot Dome

Seismic data holds value based on the interpreter's ability to extract information, which varies significantly among individuals. Each interpreter assigns distinct value to the same seismic data, influenced by their expertise and understanding of the context. When qualifying specific seismic data for interpretative tasks (Santos et al., 2019), several key factors must be analyzed: the geology involved, the acquisition environment, the depths of geological targets, the operational quality of the seismic data (both in acquisition and processing), and the interpretive qualities of the analyzed data.

In qualifying seismic data, the focus should be on the target of interest—in this case, seismic fractures and faults at great geological depths. Once this target is defined, the qualification process must be tailored specifically to it. Key questions arise that are essential for accurate interpretation. First, understanding the type of tectonic stress anticipated in the study area is crucial for interpreting nature and distribution of fractures. Additionally, assessing the amplitude levels associated with structural heterogeneities helps evaluate background noise and the seismic response expected from various geological features.

Another critical aspect is determining the amplitude level that differentiates fractures from faults, as accurately distinguishing these features is vital since they can have different implications for permeability and porosity behavior. This work demonstrates how it is possible to successfully define the continuity of verticalized events; a high level of resolution is essential. Generally, finer resolution is necessary to accurately capture the nuances of verticalized features, such as fractures or gentle faults. This often means that the sampling rate and frequency content of the seismic data must be sufficiently high to discern these details.

In the geometric detection of verticalized features, it is also important to assess their potential permeability for different fluids. Another seismic property should be conjugated to indicate which heterogeneities are permeable to the dominant fluid. New questions then arise: Which of the numerous heterogeneities identified and mapped in previous tasks indicate transmissive or sealing behavior? Understanding the role of seismic impedance is crucial in revealing the behaviors of fluid masses. Furthermore, based on these indications, where can fluid masses either accumulate or escape? This involves spatially identifying the final stages of each heterogeneous fluid route and what these patterns reveal about potential accumulations.

Critique of Sole Reliance on AI Algorithms for Fault and Fracture Mapping: The Essential Role of Impedance Volumes in Fluid Migration Analysis

While AI algorithms have made significant strides in automating the mapping of structural scenarios, including faults and fractures, there are critical shortcomings in their approach to fluid migration and retention. Many of these algorithms focus primarily on geometric aspects—such as size, shape, and orientation of faults—without adequately considering their roles in fluid dynamics. One major issue is their lack of contextual understanding. These algorithms may identify numerous faults based solely on geometric parameters, neglecting how each fault interacts with surrounding geology and fluid flow. For instance, a fault that appears prominent in amplitude may not significantly influence fluid migration if it is poorly connected to permeable pathways or acts as an effective seal. Conversely, smaller, less visually prominent fractures may play a crucial role in enhancing permeability and facilitating fluid migration, yet they could be overlooked by purely geometric analyses. When determining which faults and fractures warrant mapping from a fluid migration and retention perspective, it is essential to prioritize those that significantly impact fluid behavior. Faults exhibiting evidence of reactivation or those with associated secondary fractures should be closely mapped, as they likely influence fluid pathways. Additionally, fractures near reservoir boundaries or within critical stratigraphic layers should be prioritized, as their geometry and connectivity can greatly affect fluid retention and migration. Furthermore, fractures showing evidence of fluid saturation or historical activity in migration should be focal points for mapping efforts. Understanding the relationship between these features and their geological and petrophysical context is critical. This approach necessitates integrating geological and petrophysical seismic indications rather than relying solely on geometric interpretations.

Results

The seismic volume in the depth domain of Teapot Dome, provided by SLB to UFF for this work, contains traces with 247 samples and a sample interval of 5.46 ft. Based on the input amplitude volume, a model of pristine amplitudes was generated. From this model, a pseudo-elastic inversion volume with its impedances was created. The objective is to compare how heterogeneities differ between analyses performed using the ant tracking application from SLB—calculated directly from the input amplitudes—and those derived from the pseudo-elastic impedance volume, which may indicate heterogeneities associated with fluid migration.
By extracting values at the exact XYZ coordinates for each sample of faults and fractures, as well as in potential damage zones caused by tectonic stresses, a significant difference in impedance estimates is noted—not only azimuthally but also in the magnitudes of impedance distributions of the main observed heterogeneities. This is illustrated in Figure 01 with a depth slice at 618 ft: (a) shows the input amplitude data; (b) displays the ant tracking applied to the depth slice in (a); (c) presents the impedance response recorded at the coordinates of the heterogeneities in (b), extracted from the impedance volume illustrated in depth slice (d); (e) depicts the ant tracking applied to the volume shown in depth slice (d); and finally, (f) shows the extracted impedances at the established heterogeneities in the volume illustrated in (e).
It is important to note the significant differences between the images in (b) and (e), both derived from ant tracking, as well as the even greater differences between (c) and (f), both derived from pseudo-elastic inversion samples illustrated in (b) and (e). The larger faults, along with potential fractures and smaller faults, exhibit marked differences that could strategically influence exploration and production processes. If impedances are not considered as crucial factors in defining the sealing potential and transmissibility of structural heterogeneities, these impacts may be overlooked.

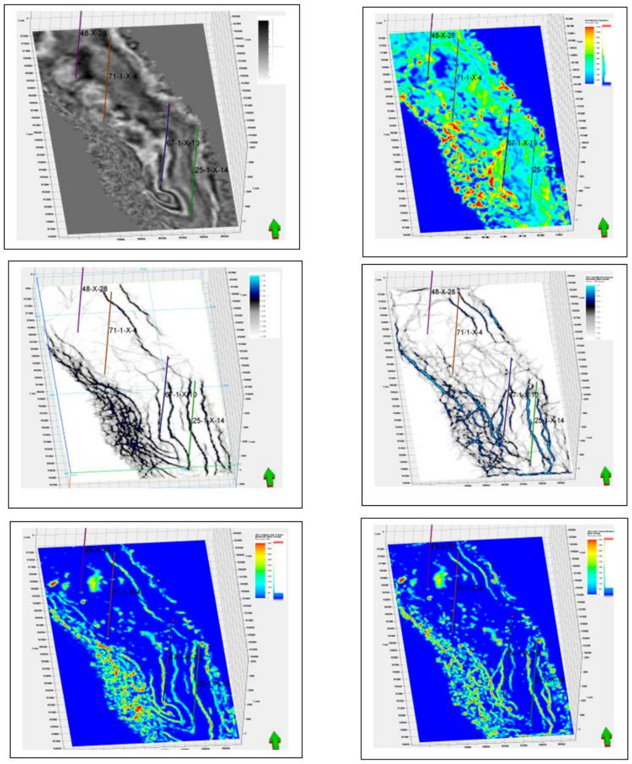

Figure 1: Teapot Dome seismic volumes show depth slices at -618 ft: (a) amplitude input, (b) ant tracking applied to the input illustrated in (a), (c) pseudo-elastic impedance extracted at heterogeneities shown in (b), (d) pseudo-elastic impedance from (a), (e) ant tracking applied to (d), and (f) pseudo-elastic impedance extracted at heterogeneities shown in (e).

Conclusions and Future Studies

Identifying seismic fractures and faults is vital for understanding fluid migration and retention in hydrocarbon reservoirs. This study emphasizes the importance of combining traditional mapping techniques with advanced seismic data analysis to improve interpretation accuracy. As the demand for hydrocarbon resources continues to rise, ongoing research and technological advancements will be essential for optimizing exploration and production strategies. Seismic conjugate indicators are crucial for enhancing the understanding of fractures and faults, particularly regarding their subtle heterogeneities and roles in transmission and sealing. Future studies could focus on developing hybrid methodologies that integrate AI-driven algorithms with geological and petrophysical insights, further enhancing the contextual understanding of fractures and faults, in the fluid context.

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