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Article

Seismic Attribute Analysis of Gas Hydrate Stability Zones in the Gulf of Mexico: Implications for Subsurface Fluid Flow and Sediment Deformation

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Abstract

Gas hydrates are ice-like compounds formed from water and methane under high-pressure, low-temperature conditions in marine sediments. They influence sediment stability, fluid flow, and hydrocarbon distribution in continental margin settings. This study employs advanced seismic attribute analysis to investigate the gas hydrate stability zone (GHSZ) in the Gulf of Mexico and to assess the relationship between hydrate presence, subsurface fluid flow, and sediment deformation. Seismic attributes, including coherence, amplitude, and spectral decomposition, were applied to 3D seismic reflection datasets covering structurally complex regions of the northern Gulf of Mexico. These attributes were used to map bottom-simulating reflectors (BSRs), gas chimneys, and fault/fracture systems. Results indicate that gas hydrate stability zones are strongly associated with structural highs, fault intersections, and areas of enhanced deformation. The study finds that fault-controlled fluid pathways significantly influence hydrate distribution and sediment deformation patterns, highlighting the need to integrate seismic attribute analysis in hydrate resource assessment and geohazard evaluation. These findings provide new insights into fluid migration mechanisms and sediment dynamics in hydrate-bearing marine environments.

Keywords: gas hydrates; seismic attributes; fluid migration; sediment deformation; gulf of mexico

1. Introduction

Background

Gas hydrates are crystalline, ice-like compounds in which gas molecules—primarily methane—are trapped within a lattice of water molecules under conditions of high pressure and low temperature. These deposits are widely distributed along continental margins, permafrost regions, and deep marine sediments, making them one of the largest unconventional hydrocarbon resources on Earth. Estimates suggest that the total amount of methane stored in gas hydrates globally exceeds that of all known conventional fossil fuel reserves combined.

The Gulf of Mexico is a particularly important region for gas hydrate research due to its complex geological setting, active hydrocarbon systems, and extensive sedimentary deposits. In the northern Gulf of Mexico, thick accumulations of fine-grained sediments, combined with high rates of sedimentation and tectonic activity, create favorable conditions for the formation and preservation of gas hydrates. These hydrates are typically found within the gas hydrate stability zone (GHSZ), a subsurface interval defined by specific pressure temperature conditions that allow hydrate formation.

Beyond their energy potential, gas hydrates are also significant from an environmental and geohazard perspective. The destabilization of hydrates, which may occur due to changes in temperature, pressure, or sediment disturbance, can lead to the release of methane gas into the ocean and atmosphere, contributing to greenhouse gas emissions. Additionally, hydrate dissociation may weaken sediment strength, increasing the risk of submarine landslides and seafloor instability. As a result, understanding the distribution and dynamics of gas hydrate systems is critical for both energy resource assessment and environmental risk management.

2. Literature Review

Over the past several decades, seismic reflection methods have become one of the most widely used tools for identifying and characterizing gas hydrate systems in marine environments. One of the most prominent seismic indicators of gas hydrates is the bottom-simulating reflector (BSR), which typically marks the boundary between hydrate-bearing sediments and underlying free gas. BSRs are characterized by their reverse polarity relative to the seafloor reflection and their tendency to mimic the seafloor topography.

Traditional seismic interpretation techniques have been complemented in recent years by the application of advanced seismic attribute analysis. Attributes such as coherence, amplitude variation, spectral decomposition, and root-mean-square (RMS) amplitude have proven effective in enhancing subtle subsurface features that may not be visible in conventional seismic sections. These attributes allow for improved detection of structural elements such as faults and fractures, as well as fluid-related features including gas chimneys, acoustic blanking zones, and localized deformation structures.

Previous studies (e.g., Xu & Ruppel, 1999; Zhang & McMechan, 2006) have demonstrated the utility of seismic attributes in estimating hydrate saturation and identifying gas-bearing sediments. Other researchers have highlighted the importance of fault systems and structural deformation in controlling fluid migration pathways and hydrate accumulation. In many continental margin settings, faults and fractures act as conduits for methane-rich fluids migrating from deeper hydrocarbon reservoirs into the hydrate stability zone.

Despite these advances, there remains a lack of comprehensive studies that integrate multiple seismic attributes to simultaneously evaluate gas hydrate distribution, subsurface fluid flow, and sediment deformation within a unified analytical framework. In particular, the relationship between seismic attribute signatures, structural controls, and hydrate system dynamics in the Gulf of Mexico is not yet fully understood. This gap underscores the need for more integrated and high-resolution analyses.

Research Objectives

The primary aim of this study is to investigate the spatial distribution and controlling mechanisms of gas hydrate systems in the northern Gulf of Mexico using advanced seismic attribute analysis. Specifically, the study seeks to:

- Map gas hydrate stability zones (GHSZ) using multiple seismic attributes, including amplitude, coherence, and spectral decomposition.
- Identify and characterize subsurface fluid migration pathways, such as faults, fractures, and gas chimneys, that facilitate methane transport.
- Examine sediment deformation patterns associated with hydrate accumulation and fluid flow, including compaction features and structural disturbances.
- Assess the implications of these findings for methane hydrate resource exploration and marine geohazard evaluation.

By addressing these objectives, this study aims to provide a more comprehensive understanding of the interactions between geological structures, fluid migration processes, and gas hydrate systems. The results are expected to contribute to improved exploration strategies and risk assessment in hydrate-bearing marine environments.

3. Geological Setting

The Gulf of Mexico represents one of the most extensively studied passive continental margin basins in the world and serves as a key region for understanding hydrocarbon systems and gas hydrate dynamics. The basin originated during the Late Triassic to Jurassic period as a result of rifting associated with the breakup of the supercontinent Pangaea. This tectonic evolution led to the

formation of a broad marine basin that subsequently accumulated thick sequences of sediments over millions of years.

A defining feature of the Gulf of Mexico's geological framework is the presence of extensive Jurassic evaporite deposits, particularly the Louann Salt. These salt layers have undergone significant deformation due to differential loading and gravitational instability, resulting in widespread salt tectonics. The movement of salt has produced a variety of structural features, including salt domes, diapirs, ridges, and associated fault systems. These structures play a critical role in controlling sediment distribution, structural deformation, and hydrocarbon migration pathways throughout the basin.

During the Cretaceous and Cenozoic eras, the basin experienced sustained sedimentation driven by major river systems such as the Mississippi River and the Rio Grande. These rivers delivered large volumes of clastic sediments into the basin, resulting in thick accumulations of shales, sandstones, and carbonate deposits. Rapid sediment loading and progradation of the continental shelf led to the development of growth faults and listric normal faults, particularly along the continental slope region.

In the northern Gulf of Mexico, the interplay between sedimentation, salt tectonics, and gravitational processes has created a highly complex structural framework. Growth faults are commonly associated with sediment loading and extend downward into deeper stratigraphic levels, while listric faults exhibit curved geometries that flatten with depth. These fault systems often form interconnected networks that significantly influence subsurface fluid flow. In many cases, faults act as conduits that facilitate the upward migration of hydrocarbons and methane-rich fluids from deeper reservoirs toward shallower sedimentary layers.

The region is characterized by active petroleum systems, with both thermogenic and biogenic methane contributing to fluid generation. Thermogenic methane originates from the thermal decomposition of organic matter at depth, whereas biogenic methane is produced through microbial activity in shallow sediments. These methane sources migrate through fault systems and fracture networks into the gas hydrate stability zone (GHSZ), where suitable pressure and temperature conditions allow for the formation of gas hydrates.

Gas hydrates in the Gulf of Mexico are typically found within fine-grained sediments on the continental slope, where water depths and geothermal gradients support hydrate stability. Seismic reflection data have identified widespread bottom-simulating reflectors (BSRs), which mark the base of the hydrate stability zone and often exhibit polarity reversal relative to the seafloor reflection. In addition to BSRs, other seismic indicators such as gas chimneys, acoustic blanking zones, and high-amplitude anomalies provide evidence of active fluid migration and hydrate presence.

Structural features, including fault intersections, salt-related deformation zones, and structural highs, exert a strong control on the spatial distribution of hydrate accumulations. These areas often exhibit enhanced permeability and fluid flow, making them favorable locations for methane accumulation and hydrate formation. Furthermore, localized sediment deformation associated with fluid overpressure and hydrate dynamics can influence the mechanical properties of the sediments, contributing to slope instability in certain regions.

Overall, the geological complexity of the northern Gulf of Mexico—characterized by thick sedimentary sequences, active salt tectonics, extensive fault systems, and dynamic fluid migration processes—makes it an ideal natural laboratory for investigating gas hydrate systems. Understanding the interplay between these geological factors is essential for evaluating hydrate resource potential, assessing geohazards, and improving models of subsurface fluid flow in marine sedimentary environments.

4. Data and Methodology

4.1. Data Source

High-resolution 3D seismic reflection datasets covering $\sim 500 \text{ km}^2$ of the northern Gulf of Mexico. Acquisition parameters: 25–50 m bin spacing, vertical resolution $\sim 10\text{--}15 \text{ m}$.

4.2. Seismic Attribute Analysis

Coherence attribute: To detect faults and fractures.

Amplitude anomalies: To identify gas-charged sediments and BSRs.

Spectral decomposition: To map subtle variations in sediment texture and deformation zones.

Root-mean-square (RMS) amplitude maps: To highlight potential fluid migration pathways.

4.3. Structural and Spatial Analysis

Fault and fracture systems were interpreted from seismic attribute maps.

Spatial correlation between BSRs, chimneys, and deformation zones was analyzed using GIS and 3D visualization tools.

4.4. Analytical Framework

Attribute thresholds were calibrated using known hydrate-bearing cores and previous exploration wells.

Areas of enhanced seismic amplitude or discontinuity were classified as potential hydrate accumulation or fluid migration zones.

5. Results

5.1. Identification of Gas Hydrate Indicators

The interpretation of the 3D seismic reflection dataset revealed the widespread occurrence of gas hydrate indicators across the study area in the Gulf of Mexico. One of the most prominent features identified is the presence of multiple bottom-simulating reflectors (BSRs), which occur at depths consistent with the predicted gas hydrate stability zone (GHSZ). These BSRs exhibit characteristic seismic signatures, including polarity reversal relative to the seafloor reflection and a geometry that mimics the seafloor topography.

The spatial distribution of BSRs indicates that gas hydrates are not uniformly distributed but are instead concentrated along structural highs and slope edges. In several locations, BSRs appear discontinuous or segmented, suggesting variations in hydrate saturation and local geological conditions.

In addition to BSRs, gas chimneys were identified through amplitude anomalies and coherence attribute analysis. These chimneys are characterized by vertical zones of reduced seismic amplitude and disrupted reflectors, indicating the presence of gas-charged sediments and upward fluid migration. The alignment of these chimneys with deeper structural features suggests that they represent active or paleo-fluid migration pathways transporting methane-rich fluids toward the hydrate stability zone.

5.2. Fault and Fracture Networks

Seismic attribute analysis, particularly coherence and variance attributes, enabled the detailed mapping of fault and fracture systems within the study area. The results show the presence of numerous listric normal faults and growth faults, which extend from deeper stratigraphic units into the shallow sedimentary sequences.

These faults are predominantly oriented along regional structural trends and often display curved geometries that flatten with depth. Many of the identified faults intersect the gas hydrate stability zone, indicating a direct structural linkage between deeper hydrocarbon sources and shallow hydrate-bearing sediments.

A notable observation is the strong spatial association between fault intersections and high-amplitude seismic anomalies. These anomalies are interpreted as zones of increased gas concentration or hydrate accumulation. The intersection of multiple fault planes likely enhances permeability and facilitates focused fluid migration, thereby promoting localized hydrate formation.

Furthermore, fracture networks associated with faulting appear to increase sediment permeability, creating interconnected pathways that allow methane-rich fluids to migrate efficiently through the subsurface. This structural framework plays a critical role in controlling both the distribution and intensity of hydrate accumulation.

5.3. Sediment Deformation

Spectral decomposition and other frequency-based seismic attributes were used to identify zones of sediment deformation within the hydrate-bearing intervals. The results reveal localized areas of compaction, subtle folding, and disrupted stratification, particularly in regions associated with active fluid migration.

These deformation features are most prominent near fault zones and gas chimneys, suggesting a strong link between fluid flow processes and sediment mechanical behavior. The upward migration of gas can generate overpressure within the sediment column, leading to deformation such as bending of reflectors, minor faulting, and localized subsidence or uplift.

In addition, some areas exhibit acoustic blanking and chaotic seismic facies, which are indicative of gas-charged sediments and disturbed depositional structures. These features may result from the combined effects of hydrate formation, gas expansion, and sediment instability.

The concentration of deformation features in structurally complex zones highlights the interaction between tectonic processes and fluid dynamics, suggesting that both factors contribute to shaping the subsurface architecture of the hydrate system.

5.4. Spatial Correlation

A comprehensive spatial analysis of the seismic attributes and interpreted features reveals a strong correlation between gas hydrate indicators, fluid migration pathways, and structural elements. BSRs, gas chimneys, faults, and deformation zones are consistently co-located within specific क्षेत्रों of the study area.

In particular, regions characterized by intersecting faults and structural highs exhibit the highest density of hydrate-related anomalies. These areas likely represent zones of enhanced methane supply, where structural permeability allows efficient fluid migration into the hydrate stability zone. The convergence of multiple migration pathways at fault intersections further increases the likelihood of hydrate accumulation.

Conversely, areas with fewer structural features or limited fault connectivity show weaker seismic signatures associated with hydrates, suggesting lower methane flux and reduced hydrate formation.

6. Discussion

6.1. Implications for Fluid Migration

The results of this study provide strong evidence that fault and fracture systems play a critical role in controlling the migration of methane-rich fluids within the Gulf of Mexico. The integration of seismic attribute analysis reveals that many of the identified faults extend vertically from deeper

stratigraphic intervals into the shallow subsurface, effectively connecting hydrocarbon source rocks with the gas hydrate stability zone (GHSZ).

Gas chimneys observed in amplitude and coherence attribute maps are frequently aligned with these fault planes, indicating that they represent focused pathways of vertical fluid migration. These chimneys are characterized by disrupted reflectors and zones of reduced seismic amplitude, which are commonly associated with gas-charged sediments. Their spatial alignment with fault systems suggests that structural discontinuities significantly enhance permeability and facilitate the upward movement of methane.

Furthermore, fault intersections appear to act as critical nodes within the migration network, where multiple fluid pathways converge. These intersections likely promote increased fluid flux due to enhanced fracture connectivity and permeability. As a result, such مناطق become highly favorable for methane accumulation and subsequent hydrate formation. The findings therefore highlight the importance of tectonic structures in governing both the direction and intensity of subsurface fluid flow in marine sedimentary environments.

6.2. Sediment Deformation and Hydrate Accumulation

The interaction between gas hydrate formation and sediment deformation represents a key aspect of hydrate system dynamics. The results indicate that hydrate accumulation can significantly influence the mechanical properties of marine sediments. The formation of hydrate crystals within pore spaces reduces sediment porosity and permeability, while the presence of free gas beneath the hydrate stability zone can generate localized overpressure.

These processes contribute to a range of deformation features, including compaction, bending of reflectors, and minor folding observed in the seismic data. In some areas, spectral decomposition results reveal subtle stratigraphic disturbances that are likely associated with fluid migration and hydrate formation. These deformation features are particularly concentrated near fault zones and gas chimneys, suggesting a strong coupling between structural controls, fluid flow, and sediment mechanics.

In addition to being influenced by fluid migration, deformation zones may also act as secondary pathways for fluid flow. Fracturing and mechanical disruption of sediments can increase permeability, allowing methane-rich fluids to migrate more efficiently through the subsurface. This feedback mechanism enhances hydrate formation by continuously supplying methane to the hydrate stability zone. Consequently, sediment deformation is not only a response to hydrate processes but also an active component in sustaining fluid migration systems.

6.3. Comparison with Previous Studies

The findings of this study are consistent with a growing body of research that emphasizes the importance of structural controls on gas hydrate systems. Previous studies (e.g., Xu & Ruppel, 1999; Zhang & McMechan, 2006) have demonstrated that bottom-simulating reflectors (BSRs) and hydrate accumulations are often closely associated with underlying free gas zones and fluid migration pathways.

The observed spatial relationships between faults, gas chimneys, and hydrate indicators in this study align with earlier work conducted in similar continental margin settings. These studies have shown that structural highs, fault intersections, and zones of enhanced permeability are key عوامل influencing hydrate distribution. The results presented here reinforce these interpretations by providing additional evidence from integrated seismic attribute analysis.

Importantly, this study demonstrates that the use of multiple seismic attributes—rather than reliance on amplitude data alone provides a more comprehensive and reliable method for identifying hydrate-related features. Coherence, spectral decomposition, and RMS amplitude attributes collectively enhance the visualization of faults, chimneys, and deformation zones, allowing for a more detailed characterization of the subsurface. This integrated approach represents a significant

improvement over traditional seismic interpretation techniques and offers a more robust framework for analyzing hydrate systems.

6.4. Implications for Energy Resources and Geohazards

Gas hydrates represent a potentially significant unconventional energy resource due to the large volumes of methane they contain. The identification of structurally controlled hydrate accumulations in this study suggests that exploration efforts should focus on مناطق where fault intersections and structural highs enhance methane supply and accumulation. By targeting these مناطق, it may be possible to improve the efficiency of hydrate resource exploration and reduce uncertainty in resource estimation.

However, the presence of gas hydrates also poses important geohazard risks. Hydrate dissociation, which can be triggered by changes in pressure, temperature, or sediment disturbance, may lead to the release of methane gas and a reduction in sediment strength. This process can destabilize submarine slopes and potentially result in mass wasting events such as submarine landslides.

The association of hydrate accumulations with structurally complex and deformational مناطق further increases the risk of geohazards, as these areas are already characterized by mechanical instability. Therefore, understanding the spatial distribution of hydrate-bearing sediments and their relationship with fault systems is essential for both safe offshore development and environmental risk assessment.

Overall, the findings of this study highlight the dual importance of gas hydrate systems as both a valuable energy resource and a potential geohazard. Integrating seismic attribute analysis with structural interpretation provides a powerful tool for evaluating these systems and supports more informed decision-making in marine exploration and hazard mitigation.

7. Conclusion

Seismic attribute analysis is an effective tool for mapping hydrate stability zones and associated fluid migration pathways.

Fault intersections and structural highs control hydrate distribution and influence sediment deformation.

Integration of multiple attributes provides a comprehensive picture of subsurface processes, useful for energy exploration and geohazard assessment.

Future work should combine attribute analysis with well-log data and numerical modeling to refine hydrate resource estimation and hazard prediction.

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