

Three-dimensional Geological Modeling of X Block in Songliao Basin

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Abstract: To address the bottlenecks in the Songliao Basin—namely, the high multi-solution nature of deep tight source-reservoir systems and the difficulty of cross-scale characterization—this paper proposes a three-dimensional, multi-scale modeling approach that integrates geologic facies-controlled constraints with a depth-generating network. At the macroscale, this approach overcomes the limitations of single-well data by strongly integrating inorganic geochemistry, sedimentary facies, and 3D seismic data. Using a sedimentary facies grid as a constraint medium and applying sequential indicator and sequential Gaussian algorithms for mutual property inference, it overcomes the bottleneck of sparse sampling to accurately reconstruct the 3D spatial distribution of effective hydrocarbon source rocks in the target intervals; At the microscopic level, to address the challenge of topological connectivity loss under sparse sampling, a three-way multi-discriminator adversarial network incorporating multi-scale channel attention was introduced. By applying rigid geometric constraints via independent discriminators along the X, Y, and Z axes, the model faithfully reconstructed the directionality and connectivity characteristics of the microscopic pore skeleton. Applications in the Songliao Basin work area demonstrate that this model bridges the information gap between macroscopic facies-controlled evolution patterns and microscopic intelligent reconstruction, providing a feasible, high-precision approach for the three-dimensional quantitative prediction of deep source rocks and reservoirs.

Keywords: Songliao Basin; Sedimentary Facies; Three-dimensional Geological.

1. Overview of the Study Area

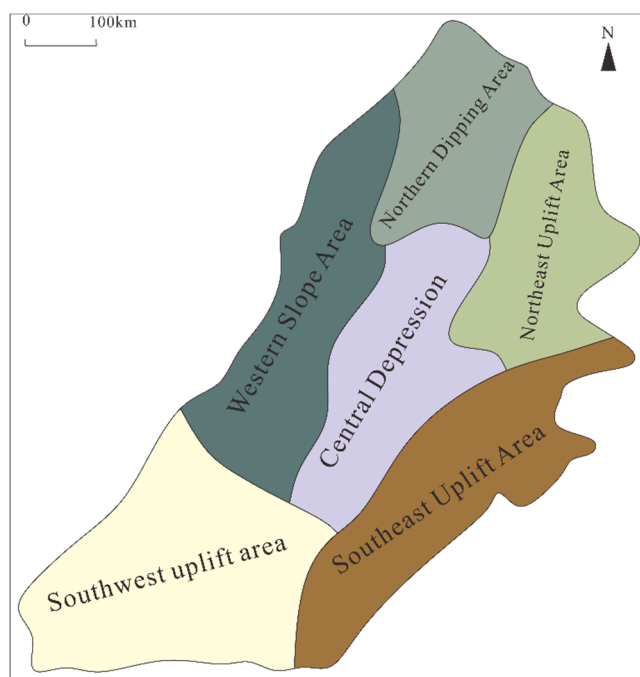


Fig 1. Songliao Basin Location Map

The Da'an Oilfield is located at the northern end of the long-axis anticline within the Da'an-Haitaozi Tectonic Belt on the Honggang Terrace in the central depression of the southern Songliao Basin. It is a long-axis anticline trending northwest-southeast, featuring five faults, most of which trend northwest-southeast, with their strike parallel to the structural axis. It is bordered by the western slope area to the west and the Gulong-Da'an Depression to the east [1] [2]. The Da'an Oilfield features a complete stratigraphic sequence. In

the northern Da'an area, drilling primarily encounters strata above the Lower Cretaceous Quansan Member, with the following sequences encountered from bottom to top: the Quantou Formation, Qingshankou Formation, Yaojia Formation, and Nenjiang Formation; the Upper Cretaceous Sifangtai Formation; the first member of the Mingshui Formation; and Cenozoic Tertiary and Quaternary strata. Clastic material transported from Baicheng in the northwest entered the lake area, forming the shallow-water deltaic depositional system in this region [3] [4]. The Putaohua oil-bearing zone is concentrated in the first member of the Yaojia Formation, consisting primarily of thin interbedded sand-shale units approximately 60 meters thick. The strata predominantly feature an interstratified sequence of gray and muddy siltstones alongside purplish-red, gray-green, and black mudstones of fluctuating thicknesses. Stable, extensive dark mudstone intervals mark the upper and lower boundaries of this unit.

2. Current State of Three-Dimensional Geological Modeling Research

As a major type of sedimentary system and hydrocarbon reservoir, shallow-water deltas have attracted persistent research interest among sedimentologists and petroleum geologists, with extensive studies focusing on their sedimentary characteristics, formation controls and spatial distribution patterns. Early research efforts primarily focused on the macroscopic sedimentary frameworks and internal sandbody architectures of shallow-water delta systems. With the rapid advancement of high-precision geochemical measurements, paleoenvironment reconstruction techniques and multi-parameter seismic data integration approaches, contemporary geological modeling of shallow-water deltas has achieved substantial progress in fine-scale characterization and quantitative interpretation. This study

integrates core samples, well logs, seismic datasets and geochemical evidence to systematically investigate the paleoclimate, paleowater depth, paleogeomorphology and sediment supply conditions of shallow-water deltas, and clarifies the sedimentary setting features and sandbody distribution rules within the study area. This geological modeling investigation on shallow-water delta systems not only elaborates the genetic mechanisms controlling delta development in shallow aquatic environments, but also achieves high-precision delineation of subaqueous distributary channel sand bodies through integrated multi-attribute analysis and deep learning algorithms. On this basis, a targeted sedimentary evolution model for progradational shallow-water deltas is established for the research block. The findings of this work can provide reliable theoretical support and practical references for thin reservoir identification and hydrocarbon exploration development in regions with similar geological backgrounds. Geological modeling studies of shallow-water deltas have not only revealed the formation mechanisms of lower shallow-water deltas but have also enabled high-precision characterization of sand bodies in submerged branch channels through multi-attribute fusion and deep learning techniques. An accretionary shallow-water delta sedimentary model suitable for this region has been established, providing an important reference for thin

reservoir prediction and oil and gas exploration and development under similar geological conditions [9].

2.1. Three-dimensional Detailed Structural Model

A 3D geological model is a three-dimensional representation of subsurface geological structures obtained through inference and interpretation, guided by surface and subsurface data. 3D geological modeling is a process of three-dimensional geological research that, based on 3D geological surveys and studies, analyzes and determines the three-dimensional spatial distribution of geological bodies and uses 3D computer graphics methods to construct a three-dimensional spatial structure of the geology [11-12]. Three-dimensional geological models can be visualized using three-dimensional computer visualization technology. The process of three-dimensional geological modeling is an interdisciplinary research effort involving geology, geophysics, geochemistry, and computer science, and it is one of the key steps in three-dimensional geological research. Three-dimensional geological modeling is a highly complex process that requires extensive geological inference even when underground geological data is abundant.

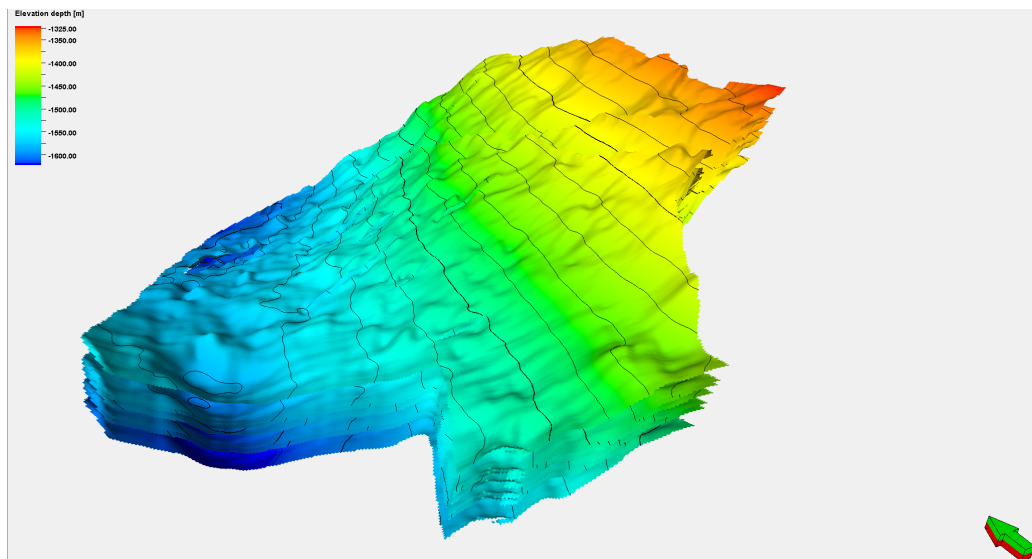


Fig 2. Horizon Model of The Study Area

2.2. Depositional Facies Modeling

Depositional Facies Modeling in the Study area serves as the spatial constraint for subsequent petrophysical property distribution. Because the Central Depression is dominated by rapid lateral transitions within shallow-water deltaic and lacustrine systems, discrete facies modeling utilizes two main geostatistical approaches: Object-Based Modeling is applied to define individual meandering or distributary channels, where geometry parameters—such as channel width, thickness, and sinuosity—are statistically derived from tight well-spacing dense patterns. Alternatively, Sequential Indicator Simulation, a pixel-based approach, is used for broader sand-mud distributions, often conditioned by seismic lithology probabilities or sedimentary facies trend maps. The primary limitation of current facies modeling is the vertical resolution mismatch. Single sandbodies within the thin interbedded sequences fall below the tuning thickness of conventional seismic data. Consequently, current research

increasingly incorporates stochastic inversion data as soft constraints to control inter-well sandbody continuity and connectivity.

Facies gridding treats well-log microfacies interpretations as "hard data" while hardwiring the acoustic impedance volume from deterministic seismic inversion as a spatial "soft constraint." In practice, a Co-Kriging operator maps the 3D seismic volume into 2D facies probability trend grids. This study conducted geostatistical variogram fitting and obtained a primary spatial variation range of 1200 m and a secondary range of 600 m, with the optimal correlation degree between seismic data and sedimentary facies limited to 0.65. Relying on this dual-factor constrained modeling strategy, the present research accurately defines the extension direction and lateral connecting characteristics of thin sand layers, thereby achieving credible geological characterization of inter-well reservoir blank zones.

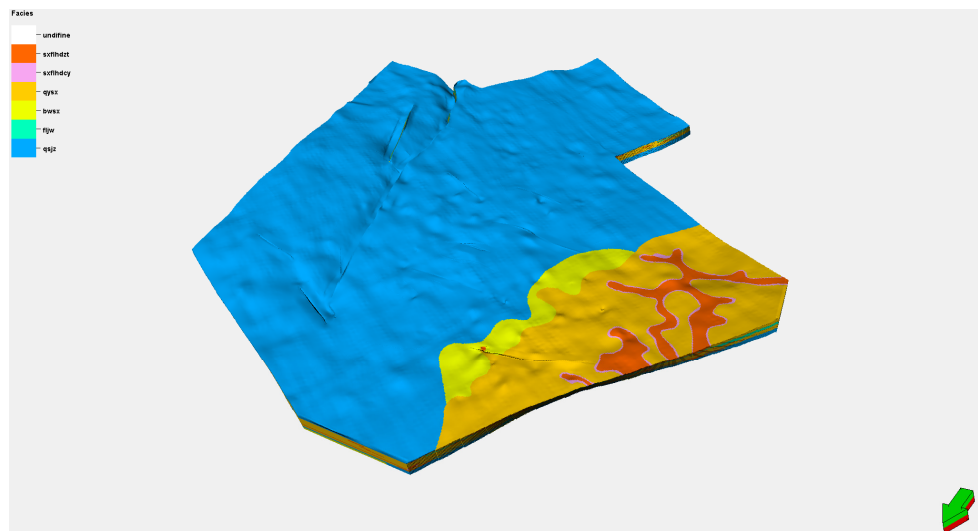


Fig 3. Sedimentary Phase

2.3. Establishment of Three-Dimensional Phased Attribute Model

Combining classic geostatistical theories with facies-controlled modeling criteria, this study utilized variogram fitting to quantitatively characterize the spatial correlation and heterogeneous distribution of major reservoir physical parameters. Subsequent to spatial correlation analysis, sequential Gaussian simulation, a widely validated stochastic modeling technique in petroleum geological research, was employed to simulate the continuous variation characteristics of porosity, permeability and gas-water saturation among scattered well points. This technical workflow achieves fine-scale depiction of the spatial distribution laws of reservoir physical properties in inter-well areas, and ultimately constructs a high-fidelity 3D digital geological model that objectively presents the overall spatial variation features of underground reservoir attributes.

To bridge the gap between static geological characterization and dynamic engineering analysis for tight reservoir exploitation, this study optimized the attribute modeling workflow to map dynamic rock mechanical parameters onto static reservoir grid cells. First, acoustic, density and shear-wave logging datasets were processed to acquire one-dimensional vertical profiles of Young's modulus and Poisson's ratio at individual well sites. The V_p/V_s inversion results derived from pre-stack seismic data were then adopted to expand discrete wellbore mechanical parameters into continuous three-dimensional spatial data.

Finite element numerical simulation was performed after importing the boundary constraints and structural loading parameters of Block X. Through numerical calculation, the study acquired the 3D spatial distribution of maximum and minimum horizontal principal stresses (σ_H and σ_h) within the target block. Numerically derived three-dimensional stress field datasets enable the extraction of formation breakdown pressure and detailed characterization of subsurface stress anisotropy. The research findings provide robust technical support for sweet spot screening, horizontal well trajectory optimization, and quantitative evaluation of hydraulic fracture extension scales during tight gas reservoir development.

3. Conclusion

Relying on field geological datasets from Block X in the Songliao Basin, this study cross-references geophysical prospecting, sedimentary dynamics, and geostatistical modeling to deliver a comprehensive characterization of the target strata. The investigation progressed from fine-scale stratigraphic correlation to the delineation of sedimentary facies tracts, followed by the quantitative mapping of porosity distribution, culminating in a robust 3D structural model. This comprehensive framework serves as the geological baseline for subsequent numerical simulations and related workflows.

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