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Feature Analysis of Rock Salt Well Logging Data and Applicability Evaluation for Three-Dimensional Modeling

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Abstract: This study focuses on a rock salt exploration project and investigates the geophysical well logging data from six boreholes (DZK1–DZK6). First, the well logging operations are systematically reviewed, including survey objectives, instrumentation, technical parameters, quality control measures, and interpretation results, confirming that the acquired data are complete, accurate, and reliable. Subsequently, in accordance with standards such as the *Technical Specifications for Three-Dimensional Geological Modeling*, the applicability of using the logging dataset to construct a high-precision three-dimensional geological model of the rock salt deposit is comprehensively evaluated from multiple perspectives, including data foundation, technical feasibility, potential risk factors, and expected modeling accuracy. The results indicate that the logging data of the rock salt deposit are of high quality and fully meet the data input requirements for three-dimensional geological modeling. By adopting a scientifically sound technical workflow and appropriate risk mitigation strategies, a three-dimensional geological model with controllable errors and clear geological significance can be successfully established. The model can provide robust technical support for resource evaluation, optimization of mining schemes, and comprehensive utilization of geothermal energy in the mining area.

Keywords: Rock salt deposit; Geophysical well logging; Data characteristics; Three-dimensional geological modeling; Applicability evaluation

Introduction

Rock salt deposits are important non-metallic mineral resources and play a crucial role in the chemical industry, energy storage, and related sectors. Traditional two-dimensional geological maps and cross-sections have inherent limitations in representing the complex spatial distribution and internal structure of rock salt bodies, making them insufficient to meet the requirements of modern mineral development and refined management. Three-dimensional geological modeling technology integrates multi-source geological data and enables intuitive and quantitative reconstruction of subsurface geological bodies and their attributes. It has become a core technical approach in mineral resource exploration and development. However, the accuracy and reliability of three-dimensional geological models are highly dependent on the quality of the input data. Geophysical well logging is a key technique for acquiring continuous, high-resolution subsurface geological information, and its data constitute the core constraints for borehole-controlled three-dimensional geological modeling [1]. Therefore, a comprehensive analysis and evaluation of well logging data are essential prior to the initiation of three-dimensional modeling projects. Based on a rock salt well logging project in which six boreholes have been completed and corresponding interpretation reports have been produced, this study synthesizes multiple technical documents to analyze the characteristics of the logging data and evaluate their suitability for constructing a three-dimensional geological model. The findings aim to provide a reference for the digital modeling of similar rock salt deposits.

1. Overview of the Study Area and Data Sources

1.1 Project Background

In order to determine the occurrence characteristics, thickness, grade, and surrounding rock properties of the ore bodies, a comprehensive geophysical well logging program was conducted for six boreholes (DZK1–DZK6) in the study area. The total drilling depth reached 17,219.35 m. The integrated logging data provide a continuous and high-resolution basis for identifying lithological variations, delineating rock salt layers, and evaluating subsurface geological conditions.

1.2 Data Sources

This study is primarily based on the following documents:

(1) *Geophysical Well Logging Report of a Rock Salt Exploration Project:* This report provides first-hand information on the original logging operations, including project background, field procedures, instrumentation, technical methods, quality control measures, and final interpretation results.

(2) Drilling Core Logging Records of the Rock Salt Exploration Project: These records offer primary geological data obtained from core sampling, including stratigraphic lithology, ore body parameters, and drilling construction information, which serve as essential constraints for geological interpretation.

(3) *Design Report for Three-Dimensional Modeling of Salt Mine Logging Data:* This document systematically outlines the technical workflow, task arrangement, methodological selection, and expected objectives of the three-dimensional geological modeling, providing guidance for data integration and model construction.

2. Characteristics of Rock Salt Well Logging Data

2.1 Logging Tasks and Parameters

The primary objectives of the well logging program were to determine the burial depth and thickness of the rock salt layers, identify surrounding rock lithology, and acquire geothermal parameters. To achieve these goals, a comprehensive suite of logging measurements was deployed, including:

(1) Conventional logging series: Apparent resistivity, compensated density (artificial gamma), natural gamma, spontaneous potential, acoustic transit time, borehole deviation, caliper logging, and borehole temperature. This combination of parameters enables effective lithological identification, stratigraphic division, porosity calculation, and evaluation of reservoir physical properties.

(2) Cement bond logging series: Natural gamma, acoustic amplitude, variable density logging, and magnetic positioning [2]. These measurements are mainly applied to assess the cementing quality of combined exploration–production wells, thereby ensuring the safety and stability of subsequent mining operations.

The multi-parameter and multi-dimensional logging scheme provides abundant information for comprehensively characterizing the geological environment surrounding the borehole and the structural features of the rock salt bodies.

2.2 Instrumentation and Technical Specifications

The logging operations were carried out using the KH-3S integrated digital well logging system, which incorporates nuclear, acoustic, electrical, and magnetic logging modules. The supporting equipment included the CDN-3S density combination probe, the AFAAN-3S borehole temperature probe, and the KHJC-3000 logging winch.

The key technical specifications are as follows:

(1) Measurement ranges: Three lateral resistivity (0–100 kΩ•m), natural gamma (up to 8000 cps), and borehole temperature (0–80 °C).

(2) Sampling interval: All logging curves were recorded with a high-resolution sampling interval of 5 cm, ensuring fine-scale data resolution.

(3) Instrument performance: The logging system supports a maximum depth of 3400 m, with a winch operating range of 0–3500 m and a logging speed of 0–60 m/min. It is equipped with real-time tension monitoring and automatic alarm functions, ensuring operational safety and data stability during deep-well logging.

The selected instrumentation is advanced and fully meets the requirements of rock salt exploration. In particular, the high-resolution sampling capability is critical for accurately identifying thin interbedded salt layers, thereby enhancing the reliability of subsequent three-dimensional geological modeling.

2.3 Quality Grading of Logging Curves

All logging curves from the six boreholes were subjected to on-site quality evaluation. The assessment results indicate that every individual logging curve was rated as Grade A, and the overall borehole quality ratings were also Grade A, with a curve qualification rate of 100%. This demonstrates that all logging curves exhibit clear shapes, distinct geological responses, and strong repeatability, without distortion, deformation, or external interference. The data fully comply with relevant industry standards and can be directly applied to subsequent geological interpretation and three-dimensional modeling.

2.4 Logging Interpretation Results

Based on the high-quality logging data, detailed geological interpretations were successfully completed:

(1) Lithological interpretation: A total of 1,590 stratigraphic layers were interpreted across the six boreholes. Specifically, 267 layers were identified in DZK1, 319 layers in DZK2, 281 layers in DZK3, 192 layers in DZK4, 281 layers in DZK5, and 250 layers in DZK6. These results indicate that the logging data effectively resolve complex stratigraphic sequences with high vertical resolution.

(2) Salt layer interpretation: A total of 372 salt layers were identified, with a cumulative thickness of 1,975.80 m. The cumulative salt thickness in each borehole is as follows: DZK1 (357.7 m), DZK2 (353.4 m), DZK3 (286.75 m), DZK4 (323.3 m), DZK5 (415.35 m), and DZK6 (239.30 m). These interpretation results not only quantify the resource distribution but, more importantly, provide precise top and bottom depths and thicknesses for each salt layer, which constitute the most direct and critical input parameters for constructing a three-dimensional salt body model.

(3) Other parameters: Data related to borehole deviation, borehole diameter, and geothermal conditions (with a maximum recorded temperature of 91 °C) are also reliable. These parameters provide a solid basis for accurate borehole trajectory modeling and further research on the integrated utilization of geothermal energy.

In summary, the rock salt well logging dataset is characterized by comprehensive parameters, high resolution, excellent data quality, and reliable interpretation results, thereby establishing a robust data foundation for high-precision three-dimensional geological modeling.

3. Technical Route and Standard Framework for Three-Dimensional Geological Modeling

3.1 Technical Standards and Regulatory Basis

The project strictly follows the latest national and industry standards, including *General Specification for Solid Mineral Geological Exploration* (GB/T 13908-2020), *Specification for Geological Exploration of Rock Salt Deposits* (DZ/T 0212-2020), *Technical Specification for Three-Dimensional Geological Modeling* (DZ/T 0357-2021), and *Technical Specification for Three-Dimensional Geographic Information Modeling* (GB/T 39335-2020). These standards comprehensively cover the entire workflow of data acquisition, processing, modeling procedures, and result acceptance, and clearly define parameter thresholds and operational requirements. They provide standardized guidance for modeling implementation, ensure the scientific rigor and comparability of results, and serve as authoritative technical references for data processing, model construction, and accuracy validation [3].

3.2 Core Technical Workflow

A nine-step technical workflow was adopted in this project, with the key procedures summarized as follows:

(1) Data collection and preprocessing: Regional geological maps, stratigraphic division data, and related geological information were collected. Logging data were converted into formats compatible with three-dimensional modeling software, followed by

normalization processing and outlier correction to ensure data consistency and reliability.

(2) Model construction:

① Borehole trajectory model: Constructed based on borehole collar coordinates and deviation survey data to accurately represent spatial borehole paths.

② Stratigraphic interface model: Generated using manual stratigraphic interpretation tools in combination with characteristic responses of logging curves (e.g., resistivity inflection points), enabling precise delineation of interfaces between rock salt layers and surrounding host rocks.

③ Rock salt body model: Developed using solid modeling techniques based on the stratigraphic interface model to reconstruct the three-dimensional geometry of the salt bodies.

④ Geophysical attribute model: Logging attributes such as resistivity and natural gamma were assigned to model nodes, and continuous attribute volumes were generated using the Kriging interpolation method.

(3) Model validation: The constructed models were compared with geological drilling data, particularly core intervals, to verify consistency. Quantitative evaluation was conducted using the Root Mean Square Error (RMSE) and the coefficient of determination (R^2). The predefined accuracy targets were as follows: RMSE $\leqslant$ 5 m and $R^2 \geqslant 0.8$ for rock salt thickness; RMSE $\leqslant$ 10 Ω•m and $R^2 \geqslant 0.7$ for geophysical attributes (e.g., resistivity).

4. Applicability Assessment of Logging Data for Three-Dimensional Geological Modeling

4.1 Applicability of the Data Foundation

(1) Data completeness:

The six boreholes are evenly distributed across the exploration area, and the borehole spacing satisfies the basic requirements for inter-well interpolation in three-dimensional modeling, providing sufficient spatial control points. Each borehole contains all core datasets required for model construction, including accurate borehole trajectories (inclination and caliper data), detailed stratigraphic interpretations (lithology and top–bottom boundaries of salt layers), and continuous petrophysical attributes (e.g., resistivity and gamma-ray logs). The data formats are standardized and consistently annotated, eliminating the need for extensive additional conversion or reorganization. Overall, the dataset demonstrates a high level of completeness.

(2) Data accuracy compatibility:

The high resolution of the logging data (5 cm sampling interval) and their Class A quality ratings meet the fundamental input requirements for three-dimensional geological modeling. The interpretation of 372 salt layers, together with their precisely defined top and bottom depths, provides ideal inputs for constructing high-fidelity salt body models. The logging depth error (< 0.1%) and calibration error (< 5%) both fall well within the permissible limits defined by the modeling accuracy targets (e.g., thickness RMSE $\leqslant$ 5 m). In terms of data volume, quality, and diversity, the existing logging dataset fully satisfies the input requirements for three-dimensional modeling and constitutes a solid foundation for building reliable geological models.

4.2 Technical Feasibility Evaluation

(1) Methodological adaptability:

The combined technical approach of “manual stratigraphic interpretation + solid modeling + Kriging interpolation” is well suited to the geological characteristics of the salt deposit in the study area. Rock salt typically exhibits distinct electrical (high resistivity) and radiometric (low gamma-ray) responses, resulting in clear contrasts between salt layers and surrounding rocks on logging curves. These contrasts provide explicit markers for stratigraphic boundary identification, facilitating accurate layer delineation. Manual stratigraphic interpretation allows expert knowledge and regional geological evolution patterns to be incorporated into interface optimization, thereby ensuring the geological rationality and interpretability of the resulting models.

(2) Achievability of modeling objectives:

Based on comparisons with similar domestic and international studies, and considering the advantages of the present dataset—including 5 cm high-resolution sampling, 100% Class A data reliability, and a clear understanding of regional geological controls—a pragmatic modeling objective of an overall error rate $\leqslant$ 15% was established. Previous case studies have demonstrated that comparable accuracy targets can be approached even with lower-quality datasets. Given that the logging data quality in this project exceeds that of several reference cases, it is reasonable to conclude that the predefined accuracy targets (RMSE $\leqslant$ 5 m, $R^2 \geqslant 0.8$) are fully achievable. The selected technical workflow is mature, robust, and highly compatible with both the available data and the geological conditions of the study area, indicating strong technical feasibility.

4.3 Risk Factors and Mitigation Strategies

All engineering projects involve inherent risks; however, the risks associated with this project are considered manageable and controllable.

(1) Data quality risk:

Data quality represents the primary risk factor in three-dimensional geological modeling. In this project, such risks were effectively mitigated during the logging stage through a rigorous quality control system, including pre-operation instrument calibration, real-time monitoring during logging, and multi-level post-acquisition data verification. As all logging data have been rated as Class A, this risk has essentially been eliminated.

(2) Multi-source data integration risk:

Potential inconsistencies in scale, resolution, or accuracy may arise when integrating logging data with external datasets such as regional geological maps. To address this issue, all external datasets were subjected to prior accuracy verification and standardization. A data prioritization framework was established to ensure the dominance of core logging data in the modeling process. In addition, strict data standards and specifications were implemented, and cross-validation among multiple datasets—such as complementary analyses between resistivity and acoustic logging—was employed to reduce integration uncertainties [4].

(3) Model–reality discrepancy risk:

Due to borehole spacing limitations, uncertainty is inevitable in inter-well prediction areas. To mitigate this risk, a closed-loop workflow of "comparative validation–difference analysis–model optimization" was emphasized. Specific optimization measures, such as the introduction of co-Kriging interpolation methods, were incorporated to improve predictive accuracy. Overall, potential risks have been systematically identified by the project team, and targeted, practical mitigation strategies have been formulated, ensuring that project risks remain within acceptable limits.

Conclusion

Through a systematic analysis of logging data from six boreholes in a rock salt deposit and a multi-dimensional evaluation of their applicability for three-dimensional geological modeling, it is concluded that the logging operations were conducted in strict compliance with standards, employing advanced instrumentation and rigorous quality control. The acquired datasets are rated as Class A, characterized by high resolution, high accuracy, and high reliability. The interpretation of 372 salt layers and their associated parameters constitutes an ideal dataset, demonstrating excellent overall data quality. The spatial distribution of the six boreholes, together with data completeness and accuracy, satisfies the requirements of the *Technical Specification for Three-Dimensional Geological Modeling*, providing a solid data foundation for constructing accurate three-dimensional geological models. The proposed four-level modeling workflow—comprising borehole trajectory, stratigraphic interface, rock salt body, and geophysical attribute modeling—integrated with appropriate methods, is well matched to the geological characteristics and data conditions of the study area, enabling the achievement of the predefined accuracy targets and confirming the technical feasibility of the approach. Although risks such as multi-source data integration exist, effective mitigation strategies have been established by the project team, rendering the overall project risk controllable. Therefore, the logging data from this rock salt deposit are highly suitable for three-dimensional geological modeling, offering robust decision support for resource development and utilization and providing a demonstrative reference for similar projects.

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