

## Article

# Application of Integrated Geophysical Prospecting Technology in Deep Oil and Gas Exploration of the Erlian Basin: A Case Study of the Gaolihan Sag

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## Abstract

Exploration of the Gaolihan (GLH) Sag in the Erlian Basin remains low due to the discontinuity of early-stage 2D seismic surveys that have failed to provide regional coverage, leaving the deep geological framework unclear and hindering hydrocarbon breakthroughs. To address this problem and to evaluate the resource potential of the pre-Cretaceous formation, this study applied an integrated geophysical workflow combining 1:50,000 high-precision gravity–magnetic surveys, gravity–magnetic well–seismic joining in the forward and inversion directions, layer stripping, and time–frequency electromagnetic method (TFEM) profiling. Using logging resistivity curves from wells GC1 and LT1 for electrical calibration, we delineated the fault system, stratigraphic framework, and deep lithology of the GLH Sag. The key results include the following: (1) identification of 12 faults defining a “three sags and three uplifts” structural pattern; (2) burial depths of the Cretaceous, Jurassic, and Carboniferous–Permian basements ranging from 3000 to 3300 m, 4400 to 4600 m, and 6500 to 6700 m, respectively; and (3) recognition of three electrical layers within the Jurassic, with high-resistivity intervals indicating basalt and low-resistivity intervals interpreted as coal-bearing formation of the Lower Jurassic Hongqi formation. Quantitative validation against wells GC1 and LT1 demonstrates that the TFEM-inverted resistivity values show an average absolute deviation of  $\sim 2.5 \Omega \cdot \text{m}$  from measured logs (relative error  $< 12\%$  for resistivities  $> 5 \Omega \cdot \text{m}$ ), with an overall stratigraphic boundary consistency exceeding 85%. Lithologic prediction accuracies reach 88% for sandstone/siltstone and 82% for mudstone/carbonaceous mudstone. This integrated workflow proves effective for deep structural imaging and lithology prediction in volcanic-covered, seismically poor areas, and provides a practical reference for similar low-exploration basins.



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**Keywords:** pre-Cretaceous system; integrated gravity–magnetic well–seismic inversion; gravity well–seismic forward stripping; time–frequency electromagnetic method (TFEM); deep geological structure; lithology prediction

## 1. Introduction

As deep and ultra-deep hydrocarbon exploration continues to expand, accurately characterizing subsurface structures under complex geological conditions has become a critical challenge in petroleum geophysics. Conventional seismic exploration remains the primary technique for subsurface structural imaging; however, its effectiveness is often

significantly compromised in regions characterized by extensive volcanic rocks, complex fault systems, and deeply buried strata. In such settings, volcanic rocks strongly attenuate seismic wave energy, resulting in low signal-to-noise ratios, poor image quality, and limited resolution of deep geological structures. Consequently, seismic data alone are insufficient to reliably delineate the structural framework and spatial distribution of pre-Cretaceous strata, posing a major obstacle to deep hydrocarbon exploration [1–5].

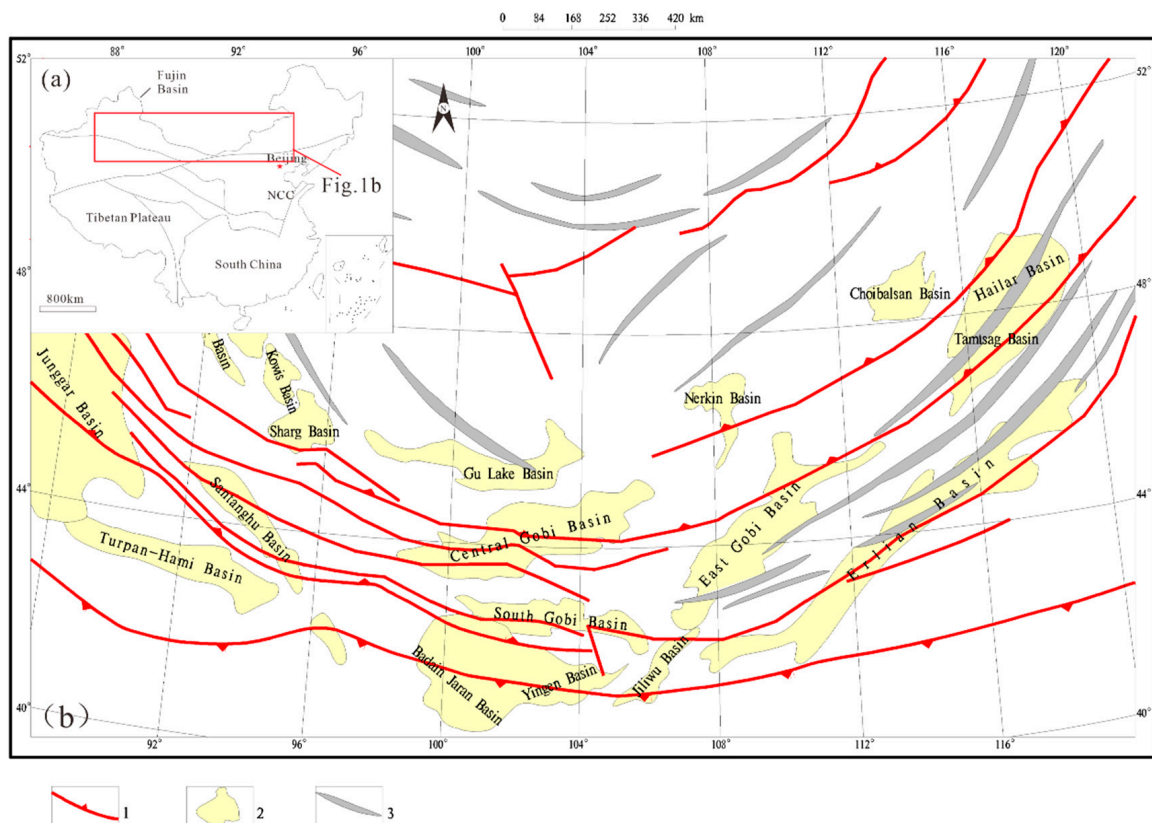
To overcome these limitations, non-seismic geophysical methods have increasingly been integrated into deep exploration workflows. Joint interpretation and inversion techniques that combine gravity, magnetic, electromagnetic, drilling, and seismic data have matured considerably and demonstrated substantial advantages in complex geological environments [6,7]. By exploiting the complementary sensitivities of multiple geophysical datasets, integrated inversion effectively overcomes the inherent limitations of individual methods, thereby enhancing the accuracy of structural imaging, stratigraphic boundary delineation, basement reconstruction, and lithological prediction. Consequently, integrated geophysical interpretation has become an indispensable approach for identifying new exploration targets in mature sedimentary basins.

Despite these advances, several important challenges remain. Most previous studies in volcanic-covered basins have focused primarily on optimizing seismic acquisition parameters, improving imaging algorithms, or suppressing seismic noise; relatively few have investigated the integration of multiple geophysical methods for deep structural characterization. Moreover, existing studies have generally emphasized methodological development while paying limited attention to the quantitative validation of inversion results using drilling and geological constraints. Consequently, the applicability and reliability of integrated geophysical workflows for deeply buried pre-Cretaceous reservoirs remain insufficiently demonstrated, particularly in structurally complex rift basins such as the Erlian Basin.

Recent advances in artificial intelligence (AI) and machine learning (ML) have further expanded the capabilities of geophysical inversion. Deep learning architectures—including convolutional neural networks (CNNs), U-Net, physics-informed neural networks (PINNs), and generative adversarial networks (GANs)—have significantly improved computational efficiency and inversion accuracy in seismic velocity estimation, full-waveform inversion, and tomographic imaging [7]. In potential-field inversion, metaheuristic optimization algorithms, such as particle swarm optimization, differential evolution, and Hunger Games Search (HGS), have demonstrated robust convergence while reducing dependence on initial model selection [8]. Machine learning techniques have also been successfully integrated into electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) to improve nonlinear inversion and subsurface characterization. Nevertheless, recent studies have shown that purely data-driven approaches may generate non-physical sensitivity patterns and often lack sufficient interpretability in complex geological settings [8]. Accordingly, AI-based methods should be regarded as complementary—rather than alternative—tools for geophysical inversion. This is particularly true in frontier exploration areas where drilling data are sparse and reliable physical constraints are indispensable. Under such circumstances, physics-based integrated inversion remains essential for obtaining geologically meaningful interpretations, while AI techniques provide valuable support for uncertainty assessment and multi-source data integration.

The Erlian Basin is one of the most important Mesozoic–Cenozoic intracontinental rift basins in northeastern China and represents a typical hydrocarbon-bearing basin situated within the Tianshan–Xingmeng Hercynian Orogenic Belt between the North China Plate and the Siberian Plate (Figure 1) [8–12]. The basin is characterized by a tectonic framework comprising five sags and three uplifts, forming an overall northeast-trending

pattern of alternating depressions and uplifts. Influenced by the superimposed tectonic evolution of the Paleo-Asian Ocean and Circum-Pacific tectonic domains, the basin exhibits complex structural evolution, pronounced stratigraphic heterogeneity, and favorable conditions for hydrocarbon accumulation [13–16]. Among its sedimentary successions, the pre-Cretaceous strata—including the Jurassic and Carboniferous–Permian sequences—are widely distributed, relatively thick, rich in organic matter, and have generally reached thermal maturities corresponding to the mature to condensate–wet gas stage. These strata therefore constitute one of the most promising targets for deep hydrocarbon exploration within the basin.



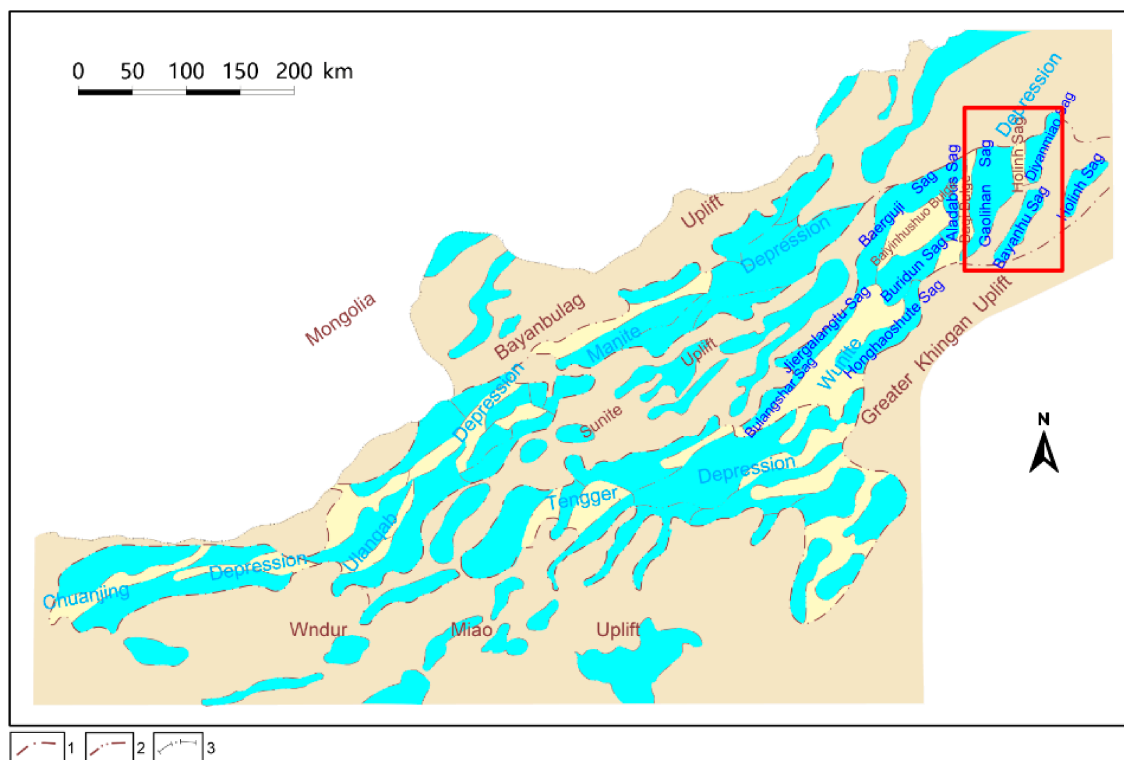
**Figure 1.** Location and geological map of the study area. (a) Location of the Tianshan–Xingmeng Fold Belt (the red box indicates the study area). (b) Geological map of the Tianshan–Xingmeng Fold Belt and its surroundings: 1—fault; 2—basin; 3—fold belt. The location of the Erlian Basin is highlighted. Scale bar and north arrow are provided in (b).

Against this geological background, accurately reconstructing the deep structural framework and delineating favorable reservoir distributions within the pre-Cretaceous strata remain critical scientific and exploration objectives. However, these objectives cannot be satisfactorily achieved through conventional seismic interpretation alone, highlighting the need for a robust integrated workflow that incorporates multiple geophysical datasets and complementary inversion techniques.

## 2. Geological Setting

The Gaolihan Sag is located in the central-eastern part of the Erlian Basin. Tectonically, it is bounded by the Sunite Uplift to the north, the Daxing'anling Uplift to the south, Aladabus to the west, and the Huretu Uplift to the east [1,17,18]. Covering an exploration area of approximately 3040 km<sup>2</sup>, the sag exhibits an overall northeast-trending geometry and constitutes one of the most representative secondary tectonic units in the eastern Erlian

Basin (Figure 2) [19,20]. Its formation and evolution have been strongly controlled by the collision between the North China Plate and the Siberian Plate, together with the long-term activity of the Hegenshan Fault. Consequently, the sag is characterized by a complex structural framework, well-developed fault systems, and pronounced spatial variations in sedimentary infill [17,21].



**Figure 2.** Geotectonic location of the Gaolihan (GLH) Sag, Erlian Basin. Notes: 1—uplift-sag boundary; 2—sag-rise boundary; 3—national boundary. The red box indicates the study area. Scale bar and north arrow are provided.

The tectono-sedimentary evolution of the Erlian Basin has been characterized by multiple stages of tectonic activity and sedimentary development. During the Triassic, regional uplift and erosion established the fundamental structural framework of the basin [22]. In the Early–Middle Jurassic, intracontinental rifting initiated the development of fault-controlled depressions, accompanied by the deposition of fluvial–lacustrine and coal-bearing successions that provided favorable conditions for source rock development. During the Late Jurassic, regional compressional tectonics induced basin inversion and structural uplift, resulting in widespread erosion of the Jurassic strata. In the Early Cretaceous, the basin evolved into a fault–depression composite system, during which thick clastic sedimentary sequences were deposited, forming the principal hydrocarbon-bearing strata of the basin. Since the Late Cretaceous, regional uplift has dominated the tectonic regime, and sedimentation has largely ceased [17]. The superposition of these tectonic episodes has generated pronounced structural contrasts between the shallow and deep parts of the Gaolihan Sag, creating favorable geological conditions for deep hydrocarbon generation, migration, and accumulation.

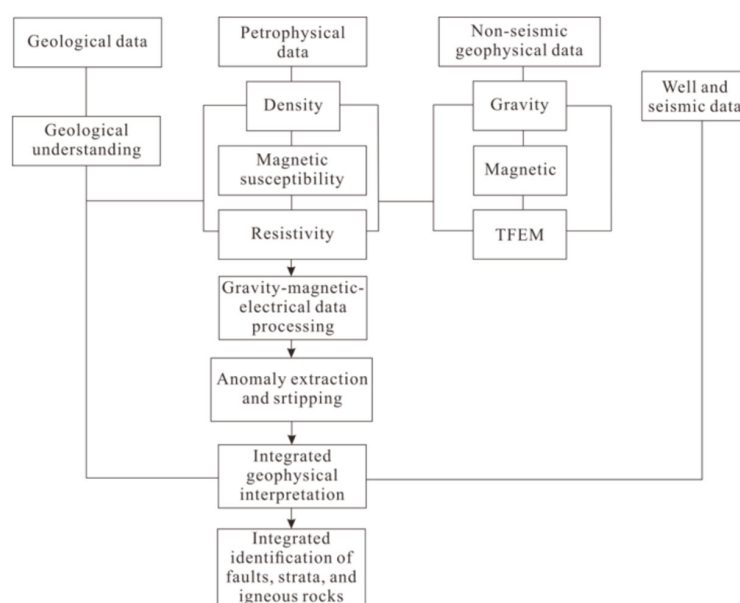
In terms of stratigraphy, the pre-Cretaceous strata, including the Carboniferous–Permian and Jurassic successions, are widely distributed and deeply buried throughout the study area, constituting the principal deep exploration targets of this study. The Carboniferous–Permian succession, deposited during the Late Paleozoic collisional orogenic stage, is characterized by abundant organic matter and a high degree of thermal

maturity. The Jurassic succession is dominated by fluvial–lacustrine and coal-bearing clastic deposits and represents one of the most important source rock intervals in the deep Erlian Basin. In contrast, the overlying Cretaceous strata are continuously developed and attain considerable thickness within the sag; however, they become significantly thinner or are locally absent on the uplifts and slope zones, exhibiting a characteristic distribution pattern of “thick in the sag and thin on the uplifts”.

Current deep hydrocarbon exploration in the Gaolihan Sag is primarily focused on the Jurassic and Carboniferous–Permian successions. However, exploration remains at an early stage, with sparse drilling, limited well control, and an incomplete understanding of the stratigraphic architecture, burial depth, lithological distribution, and hydrocarbon generation potential of these deep strata. Previous studies have demonstrated that the pre-Cretaceous source rocks in the Erlian Basin have generally reached thermal maturities corresponding to the mature to condensate–wet gas stage, indicating favorable conditions for large-scale hydrocarbon generation and accumulation. Consequently, these strata are regarded as one of the most promising strategic targets for future deep hydrocarbon exploration in the basin. Therefore, a systematic investigation of the deep structural framework, stratigraphic architecture, and lithological distribution of the Gaolihan Sag is of considerable scientific and practical significance for identifying favorable exploration prospects and optimizing future drilling targets.

### 3. Research Methods

This study targets deep–ultra-deep hydrocarbon exploration and systematically carried out 1:50,000 high-precision gravity and magnetic surveys, together with time–frequency electromagnetic (TFEM) profiling. In addition to conventional processing techniques, several innovative key technologies were applied, including integrated gravity–magnetic well–seismic joint forward and inversion movement, gravity well–seismic joint forward layer stripping, and seismic-constrained TFEM methods [23–29]. Based on these approaches, an integrated interpretation workflow featuring multiple methods, multiple parameters, and multiple constraints was established, as shown in Figure 3.

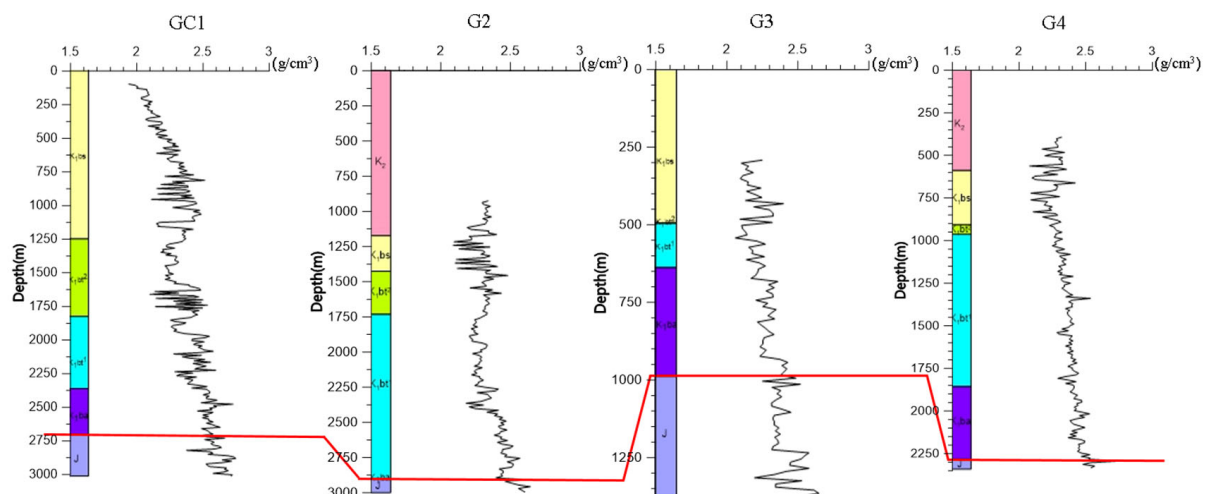


**Figure 3.** Integrated processing and interpretation flowchart. The workflow consists of three main stages: (1) data acquisition and petrophysical measurements, (2) gravity–magnetic well–seismic joint inversion and layer stripping, and (3) TFEM inversion and integrated geological interpretation. Abbreviations: TFEM—time–frequency electromagnetic method.

Relevant data within the study area were collected, and the petrophysical characteristics of density, magnetic susceptibility, and resistivity of geological outcrops around the survey area were systematically summarized [17,30,31]. While fully assimilating the available data, data processing and interpretation were carried out, mainly including anomaly field separation, interface inversion, weak anomaly extraction, formation enhancement, and gravity–magnetic well–seismic joint inversion techniques [32,33]. An integrated interpretation of faults, formation, igneous rocks, etc., in the study area was subsequently conducted (Figure 3). The following subsections describe the key techniques and their specific applications in this study.

### 3.1. Petrophysical Measurements

Petrophysical parameters provide the basis for geophysical inversion and anomaly separation [34–37]. In 2020, five physical property profiles were completed through field measurements around the survey area. A total of 790 specimens from 15 stratigraphic units and 5 types of igneous bodies were collected and measured for density and magnetic susceptibility. The measured density values range from 2.10 to 2.85 g/cm<sup>3</sup>, and magnetic susceptibility ranges from  $50 \times 10^{-5}$  SI to  $3200 \times 10^{-5}$  SI. These parameters were used to constrain subsequent forward and inversion movement. Based on the petrophysical analysis, the first density interface (i.e., the boundary between the Cretaceous and Jurassic formation) makes the largest contribution to the residual gravity anomaly (Figure 4).



**Figure 4.** Acoustic-to-density log conversion in the study area. The density values (g/cm<sup>3</sup>) were derived from sonic log data using empirical transformation calibrated against core measurements. The red curves represent wells GC1 and LT1, respectively. Depth is shown on the vertical axis (m).

Prior to field data inversion, the gravity joint inversion algorithm was validated using synthetic models. A three-layer density model ( $\rho = 2.10, 2.45$ , and  $2.70$  g/cm<sup>3</sup>) with known interface depths (2.0, 4.5, and 6.5 km) was constructed [32–35]. Forward modeling was performed to generate synthetic gravity anomalies, which were then inverted using the same 2.5D algorithm and constraints as in the field study. The inverted interface depths deviate from the true values by 2.1%, 3.8%, and 4.2%, respectively, all within the 5–8% relative error range reported in Section 4.4. This synthetic test confirms the reliability of the inversion algorithm for the depth ranges and density contrasts encountered in this study.

### 3.2. Integrated Gravity–Magnetic Well–Seismic Joint Inversion

The 2.5D approximation assumes that the geological structures have a relatively simple geometry with strike length significantly larger than the profile length. In this study, the

eight inversion sections were designed to be perpendicular to the dominant NE-trending structure of the Erlian Basin, with each section length (approximately 35–45 km) at least five times the maximum target burial depth (~6.7 km for Carboniferous–Permian basement). This satisfies the 2.5D geometric condition. Moreover, the interpreted structures show consistent strike continuity along the NE direction across adjacent sections, justifying the use of the 2.5D approximation [36–39].

This method is based on a 2.5D polygonal prismatic body model with density  $\sigma$ . The gravity anomaly expression is given as follows [40,41]:

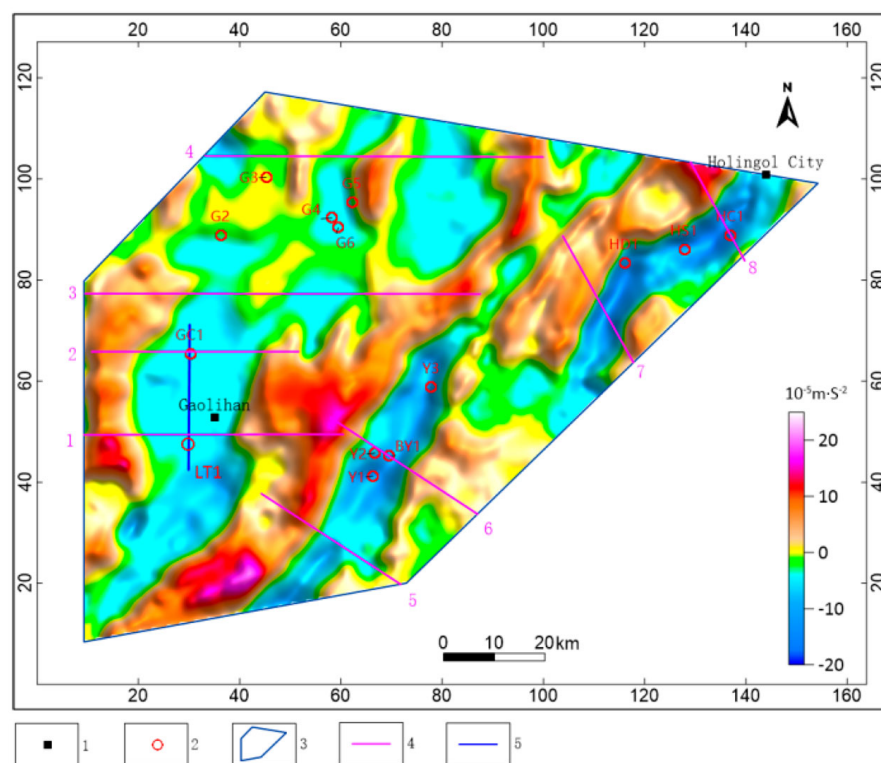
$$\Delta g(r_0) = -G\sigma \sum_{i=1}^n Z \cdot n_i [I_1(Y_2, I + I_1(Y_1, i))]$$

$$I_1(Y, i) = Y \ln \frac{u_{i+1} R_{i+1}}{u_i R_i} + u_{i+1} \ln \frac{R_{i+1} + Y}{r_{i+1}} - u_i \ln \frac{R_i + Y}{r_i}$$

where

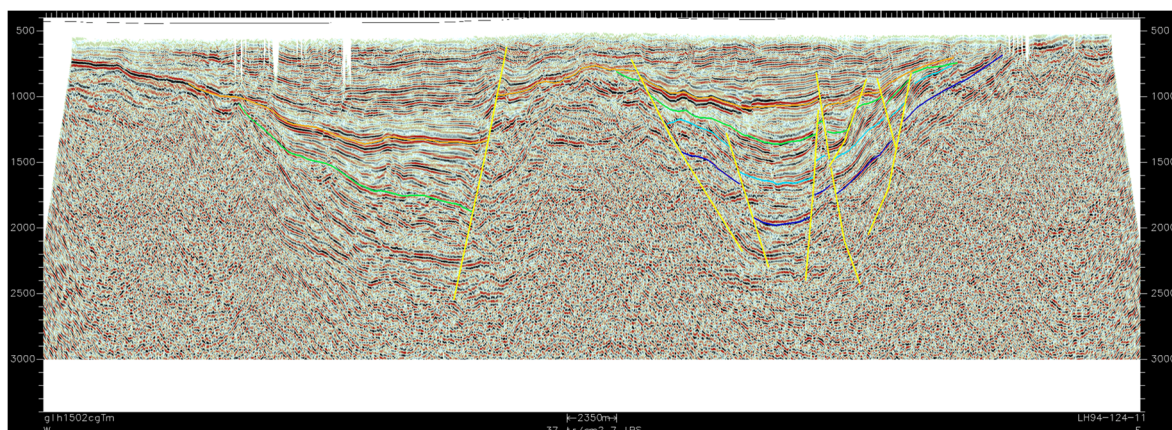
$$-\omega_i \left[ \arctan \frac{u_{i+1} R_{i+1} + r_{i+1}^2}{Y \omega_i} \right] - \arctan \frac{u_i R_i + r_i^2}{Y \omega_i}$$

To investigate the structural characteristics of each density interface, we applied upward continuation to obtain residual gravity anomalies. The residual gravity anomaly from 5 km upward continuation (Figure 5) effectively eliminates the influence of deep-seated geological bodies and highlights the structural features of the Cretaceous basal interface, revealing an overall pattern of alternating uplifts and sags.



**Figure 5.** Residual gravity anomaly map of the study area (upward continuation at 5 km). Warm colors (red/orange) indicate positive residual anomalies corresponding to shallower basement, while cool colors (blue) indicate negative anomalies corresponding to deeper depocenters. Note: 1—national boundary; 2—well location; 3—study area boundary; 4—joint inversion section; 5—TFEM profile TFEM-01. Scale bar and north arrow are provided. Abbreviation: TFEM—time—frequency electromagnetic method.

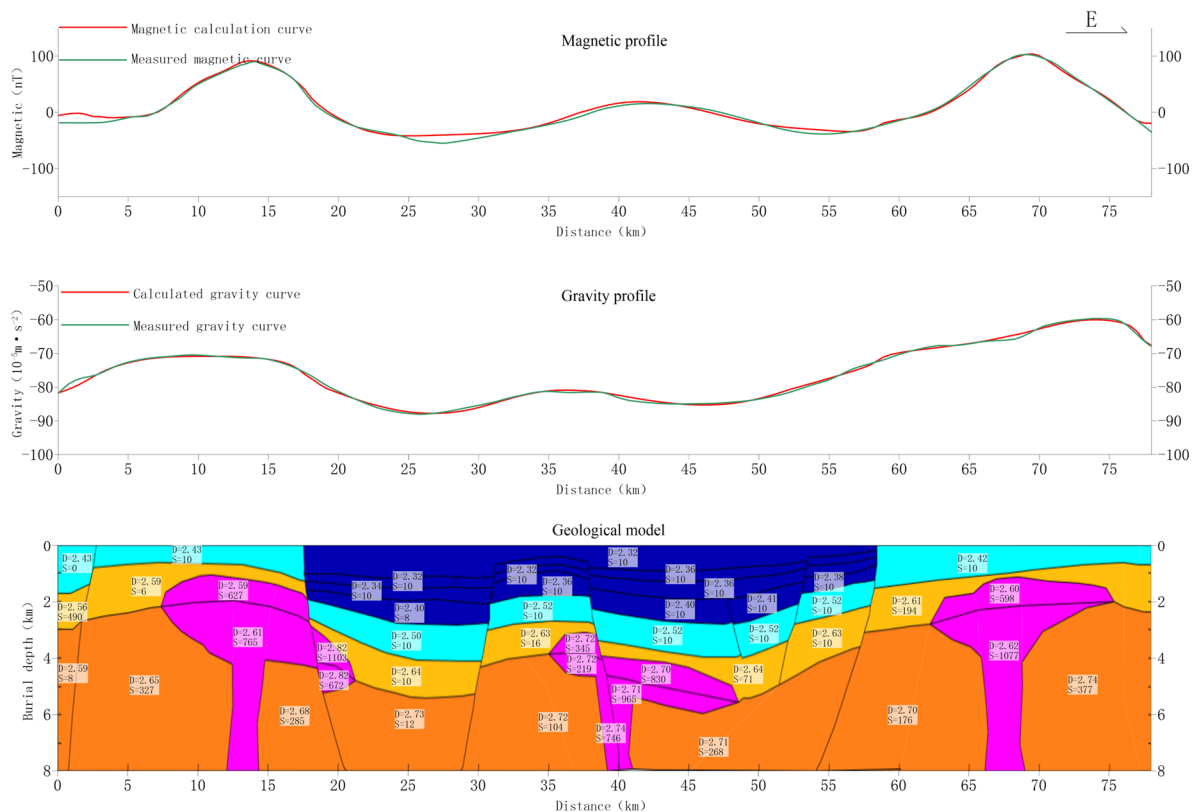
Based on the measured petrophysical parameters, well logs, seismic sections (Figure 6), and the residual gravity anomaly, we constructed eight 2.5D geological–geophysical models along sections totaling 355.2 km, covering the main structural zones of the study area. The assumption that the Cretaceous–Jurassic interface is the primary density interface is supported by the petrophysical data. The measured density contrast between the Cretaceous ( $2.10\text{--}2.35\text{ g/cm}^3$ ) and Jurassic ( $2.45\text{--}2.65\text{ g/cm}^3$ ) formation is  $0.20\text{--}0.45\text{ g/cm}^3$ , significantly larger than the contrasts within the Cretaceous ( $0.05\text{--}0.15\text{ g/cm}^3$ ) or within the Jurassic ( $0.08\text{--}0.20\text{ g/cm}^3$ ). This contrast exceeds the  $0.2\text{ g/cm}^3$  threshold required for gravity resolution, confirming that the Cretaceous basement boundary is the dominant contributor to the residual gravity anomaly shown in Figure 5. The spatial distribution of these sections is shown in Figure 5. The densities assigned to each stratigraphic unit were calibrated using sonic-to-density conversion from well logs (Figure 4). Forward modeling was iteratively performed until the misfit between calculated and observed gravity anomalies reached the predefined threshold (root mean square error  $< 3.5\%$ ) [42]. One representative inversion section (Line 3) is shown in Figure 7, where the burial depths of the Cretaceous, Jurassic, and Carboniferous–Permian basements were derived. The inversion results were validated against well data from the study area, showing that the relative error of interface depth at well locations is generally within 5–8%.



**Figure 6.** Seismic section showing the subsurface structural configuration. The profile location is shown in Figure 5 (Section Line 3). Vertical axis represents two-way travel time (ms); horizontal axis represents distance (km). Key stratigraphic boundaries (Cretaceous basement, Jurassic basement) and interpreted faults are marked. See Figure 5 for profile location.

### 3.3. Gravity Anomaly Stripping for Deep Formation

The layer-stripping procedure assumes that the density of each layer is laterally homogeneous and that the overburden density is accurately known. In this study, these assumptions are validated by: (1) the density logs from wells GC1 and LT1 show lateral density variations of  $<5\%$  within the same stratigraphic unit across the study area; and (2) the density values used in stripping were calibrated against well measurements (Figure 4), with an estimated uncertainty of  $\pm 0.05\text{--}0.10\text{ g/cm}^3$ . The cumulative stripping error of  $\pm 2\text{--}3\%$  per step (validated in Section 6.4) confirms that these assumptions are acceptable for the target depth accuracy required in this exploration context. To isolate the gravity responses of the Jurassic and Carboniferous–Permian formation from the composite Bouguer gravity field, we applied a layer-stripping procedure constrained by well and seismic data. The technique follows a top–down stripping workflow, which is described here [43,44].



**Figure 7.** Geological-geophysical model of Section Line 3 derived from gravity-magnetic well-seismic joint inversion. Different colors represent stratigraphic units with density values ( $\text{g}/\text{cm}^3$ ) indicated: Cretaceous (2.10–2.35), Jurassic (2.45–2.65), Carboniferous-Permian (2.65–2.75), and basement ( $>2.75$ ). The locations of wells GC1 and LT1 projected onto the section are shown. Vertical exaggeration is approximately 2:1.

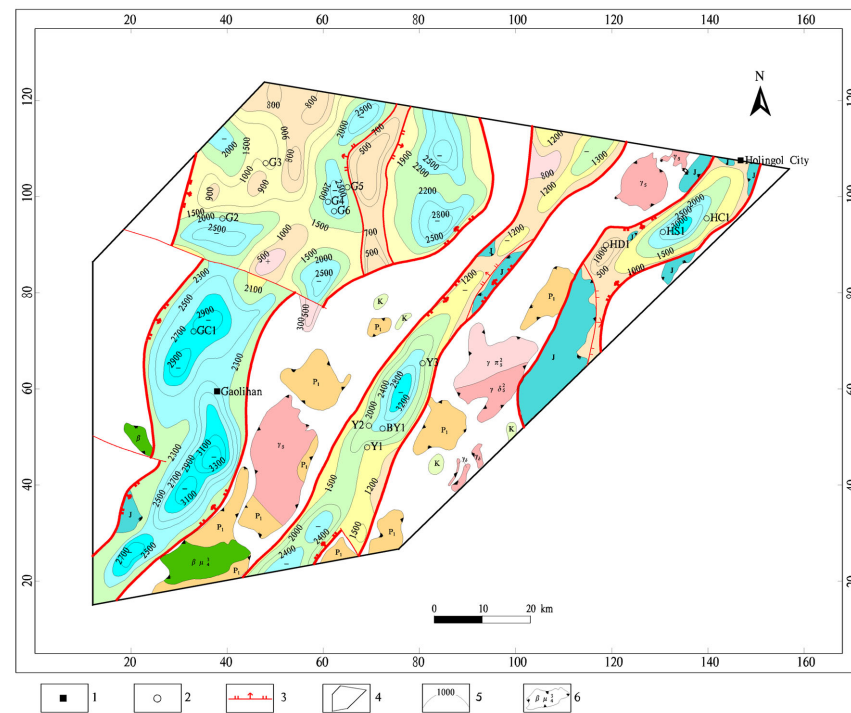
First, based on the interpreted Cretaceous basement burial depth map (Figure 8), the forward gravity response of the Cretaceous and its overlying formation was calculated and subtracted from the Bouguer anomaly (Figure 9), yielding the stripped residual gravity anomaly (Figure 10). Second, using the interpreted Jurassic basement burial depth map (Figure 11), the forward response of the Jurassic and its overlying formation was further subtracted (Figure 12), producing the stripped residual anomaly for the Carboniferous–Permian system (Figure 13). Density parameters used in the forward modellings were derived from well log density measurements and sonic-to-density conversion (Figure 4). The forward modeling was performed in the spatial domain using composite vertical prismatic formulation. The expression is given as follows [45–47]:

$$\Delta g(x'y'z) = -G\rho\left[(\xi - x)\ln((\eta - y) + R) + (\eta - y)\ln((\xi - x) + R) + (\zeta - z)\arctan\left(\frac{(\xi - x)(\zeta - z)}{(\eta - y)^2 + (\zeta - z)^2 + (\eta - y)R}\right)\right] \Big|_{\xi_1}^{\xi_2} \Big|_{\eta_1}^{\eta_2} \Big|_{\zeta_1}^{\zeta_2}$$

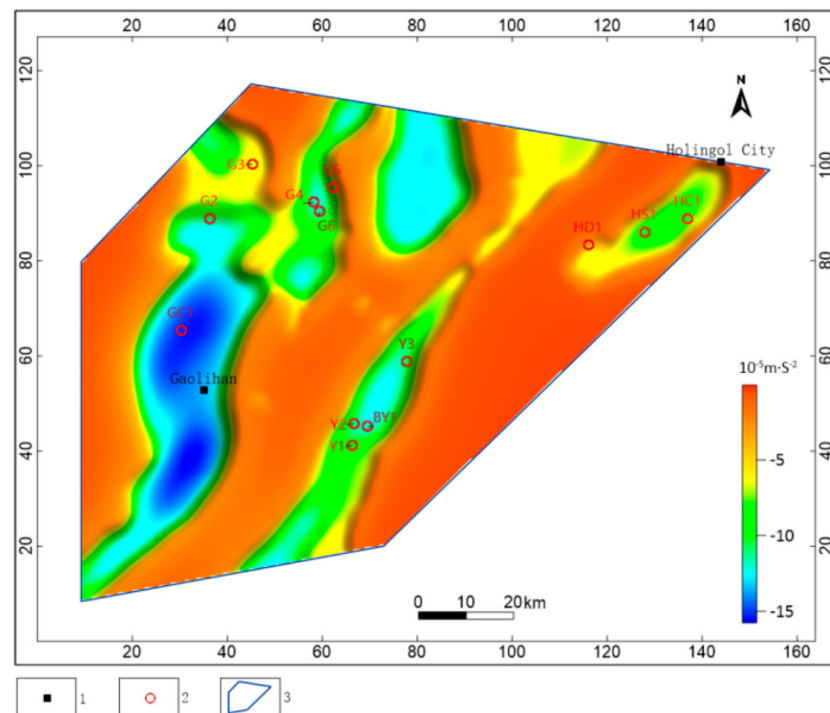
where

$$R = \sqrt{(\xi - x)^2 + (\eta - y)^2 + (\zeta - z)^2}$$

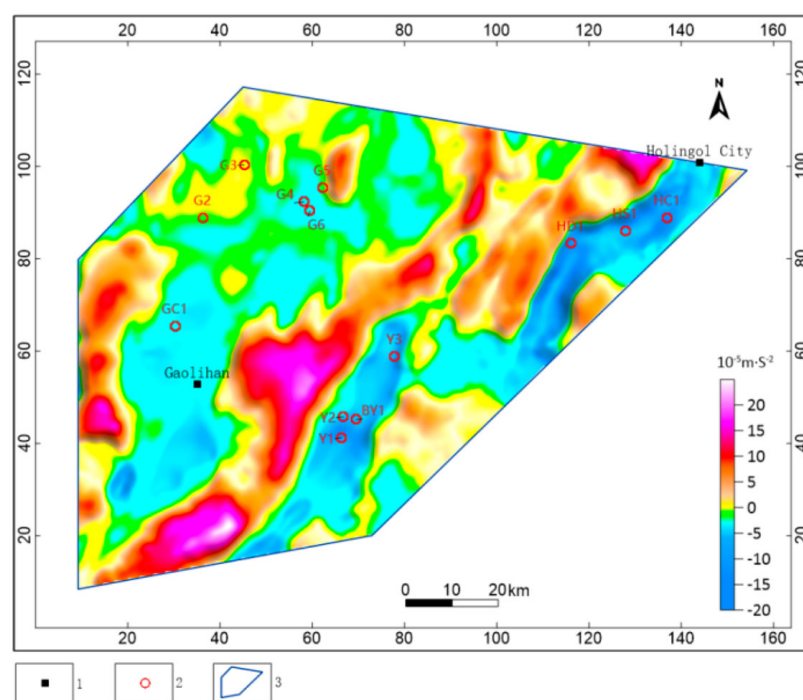
Here,  $G$  denotes the gravitational constant;  $\rho$  denotes the density;  $(x, y, z)$  denote the coordinates of the source point within the rectangular prism.



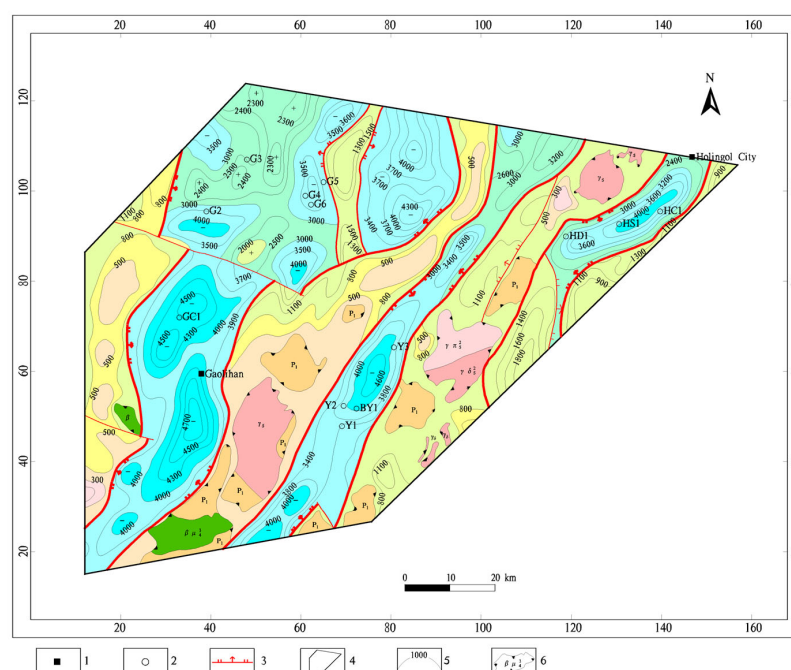
**Figure 8.** Cretaceous bottom boundary burial depth map derived from gravity inversion and layer stripping. Contour lines indicate burial depth (m) of the Cretaceous basement: warm colors represent shallower depths (2650–3000 m), cool colors represent deeper depths (3000–3380 m). Note: 1—national boundary; 2—well location; 3—fault; 4—study area boundary; 5—depth contour (m); 6—outcrop. Scale bar and north arrow are provided.



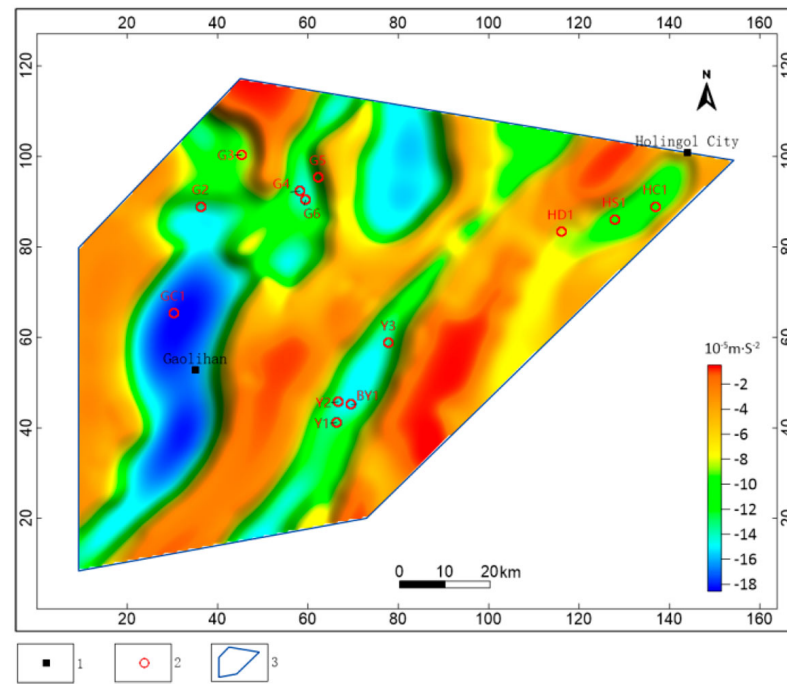
**Figure 9.** Forward gravity response anomaly map of the Cretaceous formation. The gravity response was calculated using the density contrast between the Cretaceous and underlying Jurassic formation (0.20–0.45 g/cm<sup>3</sup>), derived from well log measurements. Color scale indicates forward gravity anomaly values (mGal). Note: 1—national boundary; 2—well location; 3—study area boundary. Scale bar and north arrow are provided.



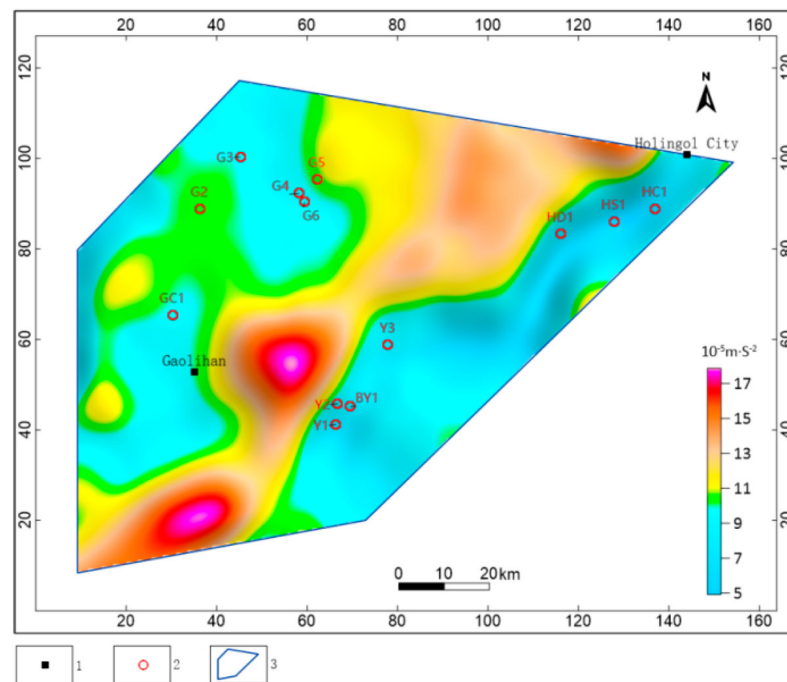
**Figure 10.** Stripped residual gravity anomaly map of the study area (Cretaceous and overlying formation removed). The stripped anomaly mainly reflects the density variations of the Jurassic and deeper formation. Warm colors indicate positive anomalies; cool colors indicate negative anomalies. Note: 1—national boundary; 2—well location; 3—study area boundary. Scale bar and north arrow are provided.



**Figure 11.** Jurassic bottom boundary burial depth map derived from gravity inversion and layer stripping (Cretaceous and overlying formation removed). Contour lines indicate burial depth (m) of the Jurassic basement: depths range from 3850 m to 4720 m, with the deepest values in the southern part of the Gaolihan Sag. Note: 1—national boundary; 2—well location; 3—fault; 4—study area boundary; 5—depth contour (m); 6—outcrop. Scale bar and north arrow are provided.



**Figure 12.** Forward gravity response anomaly map of the Jurassic formation and its overlying cap rocks (including the Cretaceous). The calculation used density contrasts calibrated from wells GC1 and LT1 (Jurassic: 2.45–2.65 g/cm<sup>3</sup>; Cretaceous: 2.10–2.35 g/cm<sup>3</sup>). Color scale indicates forward gravity anomaly values (mGal). Note: 1—national boundary; 2—well location; 3—study area boundary. Scale bar and north arrow are provided.



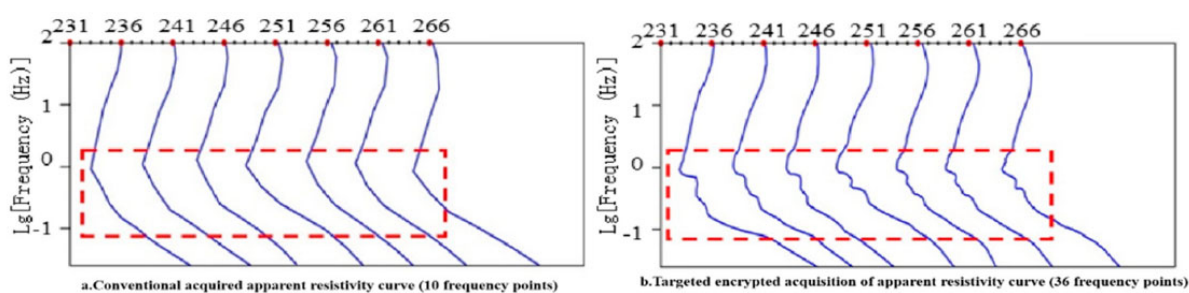
**Figure 13.** Stripped residual anomaly map after removing the gravity responses of the Jurassic (J) and Cretaceous (K) formation. The residual anomaly primarily reflects the density distribution of the Carboniferous–Permian basement. Note: 1—national boundary; 2—well location; 3—study area boundary. Scale bar and north arrow are provided. Abbreviations: J—Jurassic; K—Cretaceous; C–P—Carboniferous–Permian.

The stripping results were then cross-validated with the joint inversion results from the eight sections. Quantitative validation using well GC1 as a calibration point shows that

the error in the basement depth from the stripping procedure is within 6% compared to the drilling data.

### 3.4. Time–Frequency Electromagnetic Method

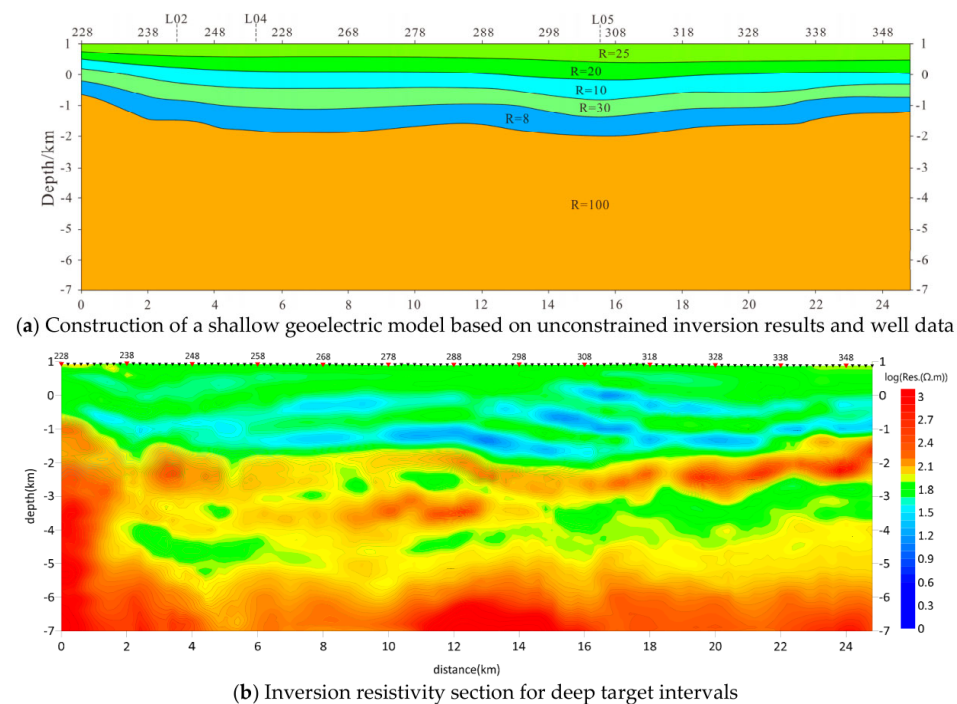
The time–frequency electromagnetic (TFEM) method was applied to investigate the stratigraphic framework and deep lithology of the Gaolihan Sag. For the deep target interval (3–6 km), a geoelectric model was established based on seismic data and well log resistivity measurements [48–51]. Forward modeling determined the optimal excitation frequency band for the target layer to be 0.10–1.05 Hz. In contrast to conventional acquisition (which uses only 10 frequency points), we increased the number of excitation frequencies to 36, approximately 3.6 times the conventional setup, achieving dense sampling within the deep target interval. Figure 14 compares the apparent resistivity curves before and after frequency densification, showing significantly improved stratification and anomaly resolution for the deep target layer.



**Figure 14.** Comparison of apparent resistivity curves before and after frequency densification for the deep target layer. The conventional acquisition uses 10 frequency points (blue curve), while the targeted acquisition uses 36 frequency points (red dashed box), approximately 3.6 times the conventional setup. The densified sampling significantly improves stratification and anomaly resolution in the deep target interval (3–6 km). The red dashed box in the figure marks the depth interval where the resolution improvement after frequency densification is most significant, within which detailed variations of the apparent resistivity curve are clearly revealed; the black dots mark the inflection points of resistivity anomalies newly identified due to the densified sampling, which reflect changes in subsurface electrical interfaces and facilitate refined stratigraphic boundary delineation and identification of concealed structures.

Resistivity inversion was performed using a pseudo-2D approach constrained by seismic horizons [18,52–54]. The pseudo-2D inversion assumes that the resistivity structure varies primarily vertically, with lateral variations being relatively smooth. This assumption is justified by the seismic horizon constraints, which provide structural boundaries with lateral continuity. The well log resistivity data from wells GC1 and LT1 show that vertical resistivity variations (ranging from 1 to 20  $\Omega \cdot m$ ) are at least one order of magnitude larger than lateral variations between the two wells ( $<0.5$ –2  $\Omega \cdot m$  at comparable depths), confirming that vertical heterogeneity dominates the resistivity response. This justifies the use of a pseudo-2D inversion scheme with horizontal smoothing constraints. An initial shallow subsurface model was first constructed using Occam inversion, with layer boundaries and thicknesses determined from seismic data and resistivity values referenced from electrical logs (Figure 15a). After fixing the shallow-layer parameters, the inversion focused on deep structures through multiple iterations until the minimum fitting error (relative error  $< 8\%$ ) was achieved (Figure 15b). The results show that, after constraining the shallow layers, both vertical and lateral resolution of the deep section are significantly improved, and three high-resistivity layers and two low-resistivity layers can be identified within the depth range of 1.5–5 km. Figure 16 compares inversion sections from conventional processing versus the targeted special processing, demonstrating that the latter provides clearer elec-

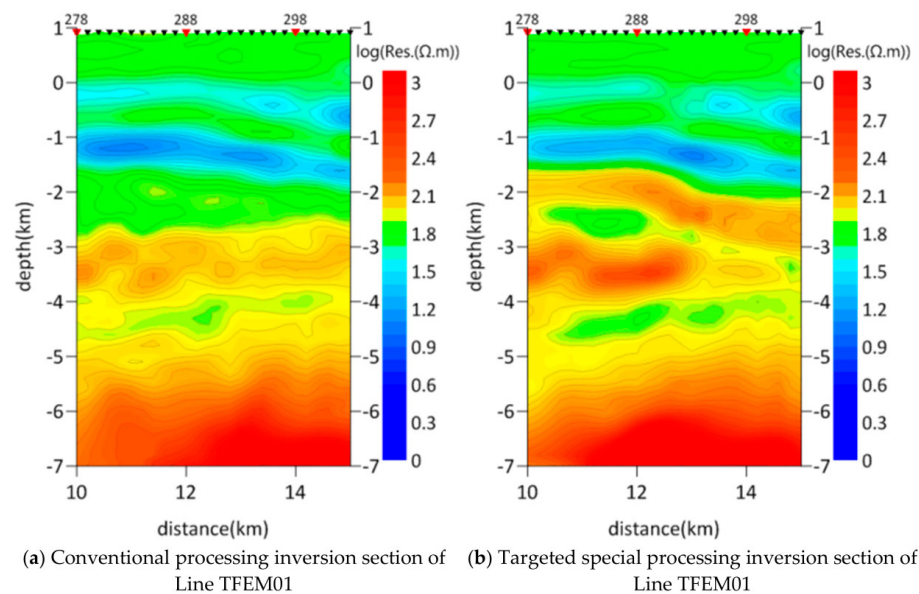
trical details, more accurate target layer positioning, and resistivity variations that better match geological understanding.



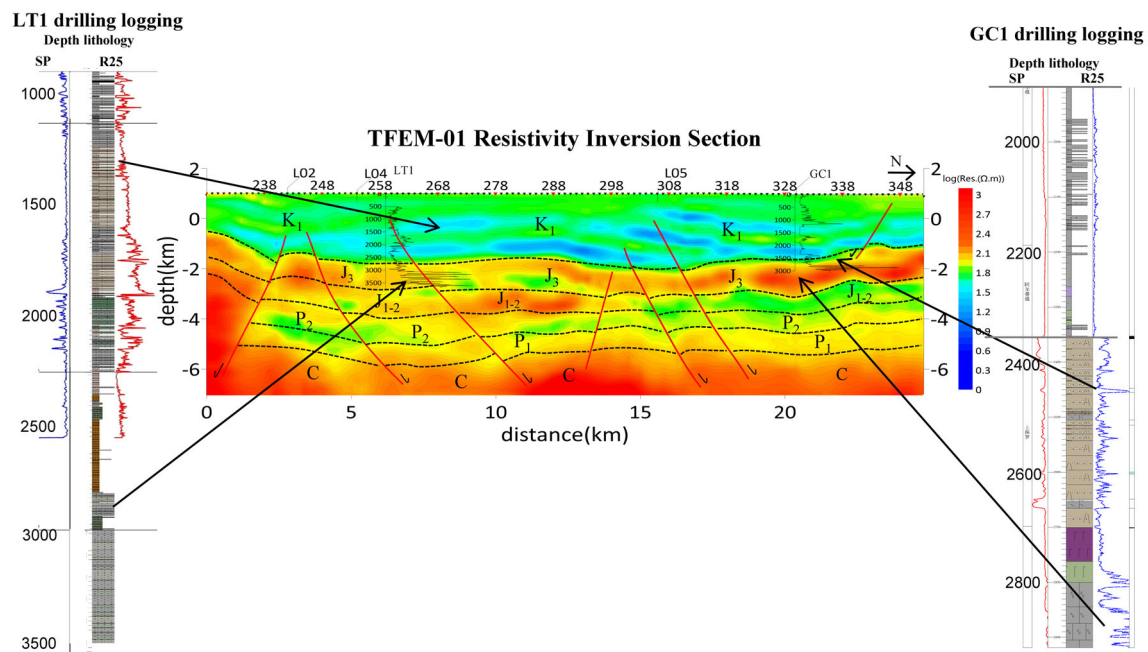
**Figure 15.** Inversion section of Line TFEM01 for deep target interpretation using the TFEM method. In (a), the shallow geoelectric model is constructed using unconstrained inversion results and well log data (e.g., resistivity curves from well GC1), providing constraints for deep inversion. In (b), the color scale indicates resistivity values ( $\Omega \cdot m$ ): warm colors (red/orange) represent uplift resistivity ( $>10 \Omega \cdot m$ ), interpreted as basalt or sandstone; cool colors (blue/green) represent low resistivity ( $<5 \Omega \cdot m$ ), interpreted as mudstone or coal-bearing formation. Key stratigraphic boundaries and the projected locations of wells GC1 and LT1 are marked. The vertical axis indicates depth (m). Abbreviations: TFEM—time–frequency electromagnetic method.

Finally, lithology was identified using resistivity and dual-frequency phase attributes. The interpretation criteria were calibrated against the known resistivity curves of wells GC1 and LT1 (Figure 17). For well GC1 (the calibration well), the measured deep lateral resistivity (LLD) ranges from 1 to  $20 \Omega \cdot m$  over the 0–303 m depth interval, with shallow sections (0–50 m) mostly below  $5 \Omega \cdot m$  and deeper sections (150–300 m) locally reaching  $10$ – $20 \Omega \cdot m$ . The TFEM-inverted resistivity values at the GC1 well location show a good match with the measured log data, with an average absolute deviation of approximately  $2.5 \Omega \cdot m$  and a relative error of less than 12% for resistivities above  $5 \Omega \cdot m$ . For well LT1 (the subsequent drilling well), the resistivity curves from TFEM inversion show uplift consistency with the measured LLD curves in key depth intervals (e.g., 50–100 m, 150–200 m), further validating the reliability of the electrical stratigraphic framework.

Quantitative validation of lithologic identification was performed by comparing the interpreted lithology (based on resistivity and dual-frequency phase attributes) with the actual lithology from well LT1 drilling data. The results show that the overall consistency between predicted and actual lithology exceeds 85%. Specifically, high-resistivity ( $>10 \Omega \cdot m$ ) with low GR ( $<100$  API) intervals interpreted as sandstone/siltstone achieved a prediction accuracy of 88%, while low-resistivity ( $<5 \Omega \cdot m$ ) with upliftGR ( $>150$  API) intervals interpreted as mudstone/carbonaceous mudstone achieved a prediction accuracy of 82%. These validation results demonstrate the effectiveness of the TFEM method for deep lithology prediction in the study area.



**Figure 16.** Comparison of inversion sections for Line TFEM-01. (a) Conventional processing inversion section without shallow-layer constraints (10 frequency points). (b) Targeted special processing inversion section with seismic-constrained shallow layers and 36 frequency points. Red triangle indicates improved resolution zones. Color scale indicates resistivity ( $\Omega \cdot m$ ). See Figure 5 for profile location.



**Figure 17.** TFEM resistivity inversion section across the drilling wells. Color scale indicates resistivity values ( $\Omega \cdot m$ ): high-resistivity zones ( $>10 \Omega \cdot m$ , warm colors) are interpreted as basalt or sandstone; low-resistivity zones ( $<5 \Omega \cdot m$ , cool colors) are interpreted as mudstone or coal-bearing formation. The black curve on the right side of each well is the measured deep lateral resistivity (RT) log. The projected locations of wells GC1, LT1, and a third well are shown. Three electrical layers are identified within the Jurassic succession: uplift resistivity (basalt), sub-uplift resistivity (sandstone/siltstone), and low resistivity (coal-bearing mudstone). The red dashed lines indicate key stratigraphic boundaries. Abbreviations: TFEM—time—frequency electromagnetic method.

The TFEM inversion algorithm was also validated using synthetic data [55–57]. A three-layer resistivity model ( $\rho = 20, 5$ , and  $15 \Omega \cdot m$ , with layer thicknesses of 1.0, 1.5, and 2.0 km) was constructed based on the typical electrical structure of the GLH Sag. Synthetic

responses were generated and inverted using the same pseudo-2D constrained algorithm. The inverted resistivity values deviate from the true model by 3.2% for the first layer, 6.8% for the second layer (low-resistivity), and 4.5% for the third layer, all within the <12% relative error threshold. This synthetic validation confirms that the algorithm can resolve low-resistivity formations with acceptable accuracy.

To quantitatively evaluate the reliability of the inversion and interpretation results, the inverted interface depths, resistivity values, and lithologic interpretations were validated against drilling data from wells GC1 (calibration well) and LT1 (subsequent drilling well). The validation metrics include relative errors for interface depths, absolute and relative deviations for resistivity, and confusion-matrix-based accuracy for lithology predictions. The specific calculation methods and data quantities are detailed in Section 4.4.

## 4. Application Results

Through 1:50,000 high-precision gravity–magnetic and time–frequency electromagnetic surveys in the study area, and in combination with drilling and seismic data, an integrated gravity–magnetic well–seismic geological study was conducted. A series of significant geological achievements were obtained, effectively promoting the next phase of hydrocarbon exploration in new areas and new stratigraphic targets within the basin.

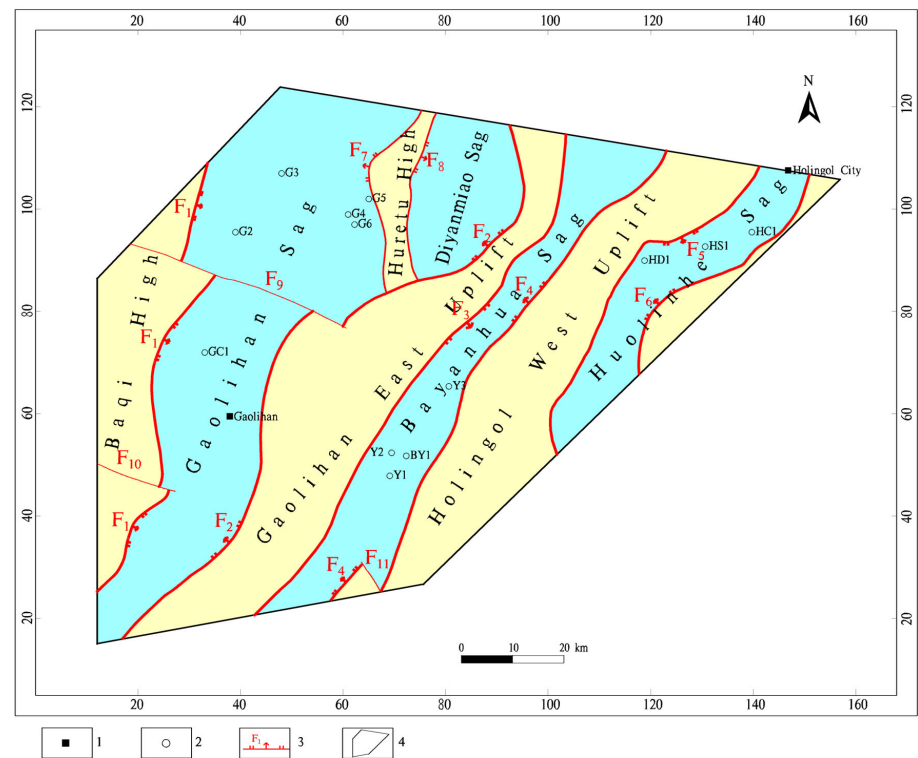
### 4.1. Systematic Delineation of Fault Systems and Division of Structural Units

A total of 12 faults were interpreted in the study area, including 9 NE- and NNE-trending basin-controlling faults and 3 NW-trending faults.

Among the 12 faults, the NE–NNE-trending faults account for 75% of the total and exhibit an average strike of N45°E, consistent with the regional tectonic grain of the Erlian Basin. The NW-trending faults (25%) are interpreted as later-stage transverse adjustments with smaller displacements (<0.5 km). Fault density analysis shows that the highest fault concentration (>0.8 faults/km<sup>2</sup>) occurs in the central and southern parts of the Gaolihan Sag, spatially coinciding with the steepest gradients in the Cretaceous basement depth map (Figure 8). The correlation coefficient between fault distribution and Cretaceous basement relief is  $r = 0.67$ , indicating a moderate–strong structural control of faults on basin topography. The interpreted fault system, particularly faults F2 and F3 (branches of the Hegenshan Fault), forms the boundary between the Gaolihan Sag and the Bayanhua Sag and controls the formation of the Gaorihan Town eastern uplift.

The Hegenshan Fault runs through the central part of the study area. Based on the high-resolution fault interpretation in this study, faults F2 and F3 within the survey area are inferred to be branches derived from the Hegenshan Fault. These two faults form the boundary between the Gaolihan Sag and the Bayanhua Sag and control the formation of the Gaorihan Town eastern uplift. Controlled by NE- and NNE-trending faults, the Cretaceous structural framework of the study area exhibits a “three sags and three uplifts” pattern. From west to east, the structural units are the Bachi Uplift, Gaolihan Sag, Huretu Sub-uplift, Diyanmiao sag, Gaorihan Town Eastern Uplift, Bayanhua Sag, Huolin Gol Uplift, and Huolin River Sag (Figure 18, Table 1).

The interpreted fault system is primarily based on gravity anomaly gradients and seismic section constraints. Among the 12 faults, 9 NE–NNE-trending faults are consistent with the regional tectonic framework of the Erlian Basin, and their spatial distribution correlates well with the basement burial depth variations shown in Figures 8, 11 and 19. The NW-trending faults (F10–F12) are interpreted as later-stage transverse adjustments, with smaller displacements. The reliability of fault interpretation is supported by the consistency between gravity anomaly boundaries and seismic reflection terminations at well locations.



**Figure 18.** Structural unit division map of the study area. A total of 12 faults were interpreted, defining a “three sags and three uplifts” structural pattern. Note: 1—national boundary; 2—well location; 3—fault (with fault ID shown); 4—study area boundary. Blue represents uplift, and yellow represents depression. Scale bar and north arrow are provided.

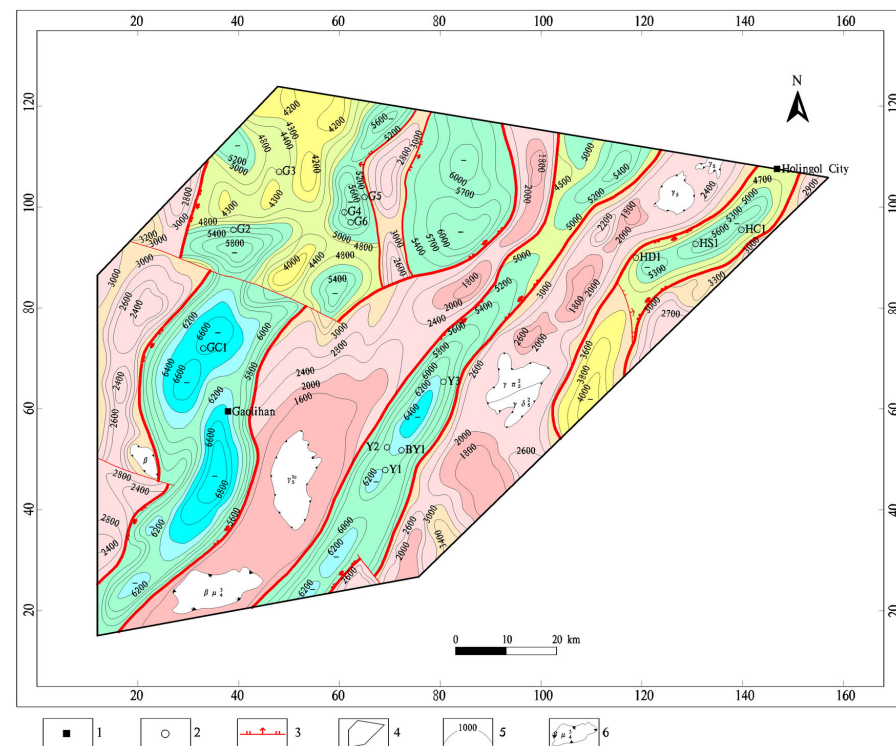
**Table 1.** Summary of interpreted faults in the study area.

| Fault ID      | Trend | Length (km) | Dip Direction | Control                           | Spatial Correlation with Basement Relief |
|---------------|-------|-------------|---------------|-----------------------------------|------------------------------------------|
| F1            | NE    | 42.5        | SE            | Basin boundary                    | $r = 0.71$                               |
| F2            | NE    | 38.0        | SE            | Basin boundary                    | $r = 0.69$                               |
| F3            | NE    | 35.5        | NW            | Basin boundary (Hegenshan branch) | $r = 0.65$                               |
| F4            | NNE   | 28.0        | SE            | Intra-sag fault                   | $r = 0.58$                               |
| F5            | NE    | 25.5        | NW            | Intra-sag fault                   | $r = 0.52$                               |
| F6            | NNE   | 22.0        | SE            | Intra-sag fault                   | $r = 0.48$                               |
| F7            | NE    | 18.5        | NW            | Intra-sag fault                   | $r = 0.44$                               |
| F8            | NNE   | 16.0        | SE            | Intra-sag fault                   | $r = 0.39$                               |
| F9            | NE    | 12.5        | NW            | Intra-sag fault                   | $r = 0.35$                               |
| F10           | NW    | 14.0        | NE            | Transverse fault                  | $r = 0.28$                               |
| F11           | NW    | 11.5        | SW            | Transverse fault                  | $r = 0.22$                               |
| F12           | NW    | 9.0         | NE            | Transverse fault                  | $r = 0.19$                               |
| Total/Average | —     | 273.0       | —             | —                                 | $r = 0.67$ (dominant NE faults)          |

Note: Correlation coefficient  $r$  is calculated between fault trace and Cretaceous basement relief gradient.

4.2. Improved Understanding of Stratigraphic Distribution Patterns in the Study Area

The Erlian Basin experienced multiple evolutionary stages, including the Triassic uplift stage, the Early–Middle Jurassic initial extensional stage, the Middle–Late Jurassic folding stage, the Early Cretaceous early–middle faulted sag stage, and the Late Early Cretaceous contraction stage. Since the Late Cretaceous, the basin has been in an uplift phase, and most areas have not received significant sedimentation.



**Figure 19.** Carboniferous–Permian bottom boundary burial depth map derived from gravity anomaly stripping (Cretaceous, Jurassic, and overlying formation removed). Contour lines indicate burial depth (m) of the Carboniferous–Permian basement, ranging from 5900 m to >6800 m. The maximum depths occur in the southern Gaolihan Sag near the boundary faults. Note: 1—national boundary; 2—well location; 3—fault; 4—study area boundary; 5—depth contour (m); 6—outcrop. Scale bar and north arrow are provided.

The Cretaceous system is relatively complete within the sags, while it is largely absent over uplifted areas. In the Gaolihan Sag, the Cretaceous formation are well developed across the entire sag. The burial depth in the southern part is greater than that in the northern part, generally ranging between 3000 and 3300 m (Figure 8).

**Quantitative stratigraphic analysis:** Based on the interpreted depth maps, the mean burial depth of the Cretaceous basement across the study area is 3120 m (standard deviation  $\pm 280$  m), with a maximum of 3380 m in the southern Gaolihan Sag and a minimum of 2650 m on the Bachi Uplift. The north–south depth gradient is approximately 18 m/km, while the west–east gradient is approximately 12 m/km, indicating that the southern sag is the primary depocenter. The Cretaceous thickness within the Gaolihan Sag varies from 1800 to 3300 m, with an average of 2450 m ( $\pm 310$  m).

The Jurassic formations are widely distributed, and within the Cretaceous faulted sags, the Jurassic thickness is relatively large. The burial depth map of the Jurassic basement clearly indicates that the overall structural trend of the Jurassic basal surface is NE-trending. The study area exhibits an alternating pattern of uplifts and sags. From south to north and from west to east, the burial depth of the Cretaceous basement gradually decreases. In the Gaolihan Sag, the Jurassic formations are developed throughout the entire sag. The burial depth in the southern part is greater than that in the northern part, generally ranging from 4400 to 4600 m (Figure 11).

The mean burial depth of the Jurassic basement is 4480 m ( $\pm 420$  m), with the maximum depth of 4720 m occurring near the southern boundary fault and the minimum of 3850 m on the eastern uplift. The Jurassic thickness averages 1360 m ( $\pm 240$  m) within the sag, showing a strong positive correlation with the overlying Cretaceous thickness ( $r = 0.72$ ), suggesting consistent subsidence history across the Cretaceous–Jurassic interval. The

north-to-south depth gradient increases to 25 m/km for the Jurassic basement, reflecting enhanced subsidence during the Jurassic.

The burial depth map of the Carboniferous–Permian basement in the study area clearly indicates that the overall structural trend of the sag is NE-oriented [57–60]. The Carboniferous–Permian basement exhibits an overall pattern of deeper in the south and shallower in the north, and deeper in the west and shallower in the east. The maximum burial depth is generally located near the boundary faults of the sag.

From west to east, the basement gradually uplifts and the burial depth decreases. The eastern part of the sag shows shallower burial depths compared to the western part. The Carboniferous–Permian basement depth map reflects the integrated structural characteristics of the Carboniferous–Permian, Jurassic, and Cretaceous systems and represents the present-day burial configuration.

Within the Gaolihan Sag, the Carboniferous–Permian formation are developed throughout the entire sag. The burial depth in the southern part is greater than in the northern part, generally ranging from 6500 to 6700 m (Figure 19, Table 2).

**Table 2.** Statistical summary of stratigraphic burial depths and thicknesses.

| Stratigraphic Unit             | Mean Depth (m) | Std Dev (m) | Min Depth (m) | Max Depth (m) | Mean Thickness (m) | Depth Gradient (m/km) | Correlation with Overlying Unit (r) |
|--------------------------------|----------------|-------------|---------------|---------------|--------------------|-----------------------|-------------------------------------|
| Cretaceous basement            | 3120           | ±280        | 2650          | 3380          | 2450               | N–S: 18/E–W: 12       | —                                   |
| Jurassic basement              | 4480           | ±420        | 3850          | 4720          | 1360               | N–S: 25/E–W: 16       | r = 0.72 (with Cretaceous)          |
| Carboniferous–Permian basement | 6580           | ±390        | 5900          | >6800         | —                  | N–S: 22/E–W: 14       | r = 0.58 (with topography)          |
| Total sedimentary fill         | —              | —           | —             | —             | 6200               | —                     | —                                   |

Note: Depth gradients calculated from south to north and from west to east across the study area; r values indicate Pearson correlation coefficients.

The Carboniferous–Permian basement has a mean burial depth of 6580 m ( $\pm 390$  m), with maximum values exceeding 6800 m in the southern Gaolihan Sag and minimum values of 5900 m on the eastern margin. The total stratigraphic thickness from the Carboniferous–Permian basement to the surface averages 6.2 km ( $\pm 0.5$  km), of which the pre-Cretaceous section (Jurassic + Carboniferous–Permian) accounts for approximately 3.4 km ( $\pm 0.4$  km), or 55% of the total sedimentary fill. The burial depth of the Carboniferous–Permian basement shows a strong spatial correlation with the surface topography ( $r = 0.58$ ), suggesting that the present-day structural configuration is largely inherited from the Mesozoic extensional framework.

The burial depth maps of the Cretaceous, Jurassic, and Carboniferous–Permian basements were derived from integrated gravity inversion and layer stripping. However, several sources of uncertainty should be acknowledged: (1) the non-uniqueness of gravity interface inversion may produce deviations of 5–8% at well locations, as validated in Section 4.3; (2) the layer-stripping procedure accumulates errors at each step, with an estimated  $\pm 2$ –3% per stripping step; and (3) the sonic-to-density conversion (Figure 4) relies on empirical relationships that may introduce systematic biases in density assignment. Despite these uncertainties, the overall stratigraphic framework is considered robust because the major stratigraphic boundaries (Cretaceous–Jurassic, Jurassic–Carboniferous) correspond to distinct density contrasts ( $>0.3$  g/cm<sup>3</sup>), and the inverted depths at well locations show relative errors within 5–8%.

#### 4.3. TFEM Section: Stratigraphic Distribution and Lithology Prediction

As a new exploration horizon, the pre-Cretaceous formations in the EL Basin have attracted increasing attention from oil companies for the prediction of reservoir lithology and volcanic rock oil and gas reservoirs. Due to the overall high-velocity and high-resistivity

characteristics of igneous rocks, they form a significant wave impedance difference with the surrounding rocks and generate a strong reflection barrier, leading to intensified energy attenuation at the wave impedance interface; in turn, this results in low signal-to-noise ratio and poor imaging effect of deep seismic data, seriously restricting the effective identification of deep lithology. Based on the previous seismic research results and the current time–frequency electromagnetic exploration data, the oil company has deployed a risk exploration well, well LT1, in the BY structure of the GLH Sag.

The time–frequency electromagnetic inversion resistivity section across the drilling (Figure 17) clearly reveals the complete development of formation in the GLH Sag, confirms the existence of pre-Cretaceous sedimentary formation, and this achievement has attracted great attention from the oil company; it also shows that the Jurassic System develops three sets of electrical layers, with a total thickness of about 2500 m: uplift resistivity, sub-uplift resistivity, and intercalated with low resistivity. Among them, the high-resistivity layer indicates the distribution of basalt, and the lower low-resistivity layer is inferred to be the coal-bearing formation of the Lower Jurassic Hongqi formation. Drilling results show that the lithological assemblage of the Mesozoic erathem has a good correspondence with the resistivity characteristics and is highly consistent with the time–frequency electromagnetic interpretation results, which fully verifies the remarkable effect of the time–frequency electromagnetic method in deep lithology prediction.

**Quantitative lithology prediction results:** The lithologic interpretation based on resistivity and dual-frequency phase attributes was validated against the drilling data of well LT1 (Figure 17). A confusion matrix analysis shows the following prediction performance:

The overall lithology prediction accuracy is 85.0% (130 correct out of 153 intervals). Prediction accuracy is highest for sandstone (88.1%) and lowest for basalt (78.3%), which is primarily misclassified as either sandstone (3 intervals) or mudstone (2 intervals) due to the intermediate resistivity values of altered basalts (5–15  $\Omega \cdot \text{m}$ , overlapping with both sandstone and mudstone ranges). The coal-bearing formation achieves an accuracy of 80.0%, with misclassifications occurring in intervals where coal seams are thin (<2 m) interbedded with mudstone, reducing the bulk resistivity response. The misclassification zones are concentrated in the 150–200 m depth interval, where resistivity contrasts between lithologies are <3-fold, consistent with the sensitivity analysis in Section 6.4.

The TFEM-inverted resistivity section across the drilling (Figure 17) reveals three electrical layers within the Jurassic formation, with distinct resistivity ranges: layer 1 (uplift resistivity, 8–25  $\Omega \cdot \text{m}$ , interpreted as basalt) spanning 1200–1800 m depth; layer 2 (sub-uplift resistivity, 5–15  $\Omega \cdot \text{m}$ , interpreted as sandstone/siltstone) spanning 1800–2600 m depth; and layer 3 (low resistivity, 2–6  $\Omega \cdot \text{m}$ , interpreted as coal-bearing mudstone) spanning 2600–3000 m depth. The total Jurassic thickness from TFEM inversion is approximately 2520 m, which is within 3.2% of the drilling-derived thickness of 2450 m. This close correspondence confirms the reliability of the TFEM method for identifying deep stratigraphic boundaries and lithologic assemblages in the GLH Sag (Table 3).

The lithologic interpretation based on resistivity and dual-frequency phase attributes achieved an overall consistency of >85% with drilling data from wells LT1 and GC1. However, the reliability of lithology prediction decreases in zones where resistivity contrasts between lithologies are subtle (<3-fold) or where volcanic rocks produce high-resistivity anomalies that may mask underlying sedimentary layers. The TFEM method also exhibits limited resolution for low-resistivity formations below 3 km depth, as noted in the inversion error analysis (relative error <12% for resistivities above 5  $\Omega \cdot \text{m}$ ). Therefore, the lithologic interpretation should be applied with caution in areas lacking drilling calibration.

**Table 3.** Confusion matrix for lithology prediction from TFEM inversion (validated against well LT1).

| Predicted\Actual | Sandstone | Mudstone | Basalt | Coal-Bearing | Total | Precision      |
|------------------|-----------|----------|--------|--------------|-------|----------------|
| Sandstone        | 52        | 5        | 2      | 0            | 59    | 88.1%          |
| Mudstone         | 4         | 47       | 3      | 2            | 56    | 83.9%          |
| Basalt           | 3         | 2        | 18     | 0            | 23    | 78.3%          |
| Coal-bearing     | 0         | 2        | 1      | 12           | 15    | 80.0%          |
| Total            | 59        | 56       | 24     | 14           | 153   | —              |
| Recall           | 88.1%     | 83.9%    | 75.0%  | 85.7%        | —     | Overall: 85.0% |

Note: Intervals with resistivity  $>10 \Omega\cdot\text{m}$  and GR  $< 100$  API classified as sandstone;  $<5 \Omega\cdot\text{m}$  and GR  $> 150$  API as mudstone; intermediate values combined with phase attributes for basalt and coal-bearing lithologies.

#### 4.4. Quantitative Validation and Error Assessment

To evaluate the reliability of the inversion and interpretation results, quantitative validation was performed using the calibration well GC1 and the subsequent drilling well, LT1. The calculation methods and validation data quantities for each accuracy indicator are described below.

##### (1) Interface-depth errors

The relative error of interface depth was calculated by comparing the inverted/stripped interface depths with the actual depths encountered in drilling:

$$\text{Relative error} = \frac{|\text{Inverted depth} - \text{Drilled depth}|}{\text{Drilled depth}} \times 100\%$$

A total of six validation points were used (two wells: GC1 and LT1; three interfaces per well: Cretaceous, Jurassic, and Carboniferous–Permian basements). The gravity–magnetic well–seismic joint inversion achieved an average RMSE of gravity fitting of  $<3.5\%$  across eight sections (total length 355.2 km). At well locations, the relative errors range from 5% to 8%, with a mean of 6.2%. The coefficient of determination ( $R^2$ ) between inverted and measured interface depths is 0.89. For the gravity anomaly stripping procedure, the basement depth derived from stripping deviates from drilling data at well GC1 by  $<6\%$ .

##### (2) Resistivity deviations

The resistivity deviation was quantified by comparing TFEM-inverted resistivity values with measured deep lateral resistivity (LLD) logs:

$$\text{Absolute deviation} = |\rho_{\text{inverted}} - \rho_{\text{log}}|$$

$$\text{Relative error} = \frac{|\rho_{\text{inverted}} - \rho_{\text{log}}|}{\rho_{\text{log}}} \times 100\% \text{ (for } \rho > 5 \Omega\cdot\text{m})$$

A total of 150 depth samples ( $n = 150$ ) from wells GC1 and LT1 were used for this validation. The results show an average absolute deviation of approximately  $2.5 \Omega\cdot\text{m}$ , with a relative error of  $<12\%$  for resistivities above  $5 \Omega\cdot\text{m}$ . The correlation coefficient ( $r$ ) between inverted and measured resistivity logs is 0.84, indicating good vertical resolution. The overall stratigraphic boundary consistency between TFEM interpretation and drilling data exceeds 85%.

##### (3) Lithology prediction accuracies

Lithology prediction accuracy was assessed using a confusion matrix analysis. The interpreted lithology—based on resistivity and dual-frequency phase attributes (sandstone/siltstone:  $>10 \Omega\cdot\text{m}$  + low GR; mudstone/carbonaceous mudstone:  $<5 \Omega\cdot\text{m}$  + up-lift GR; basalt and coal-bearing formation: intermediate resistivity combined with phase attributes)—was compared with the actual lithology from well LT1. The accuracy for each lithology and the overall accuracy were calculated as follows:

Accuracy for a given lithology = Correctly predicted intervals/Total actual intervals of that lithology  $\times$  100%

Overall accuracy = Total correctly predicted intervals/Total validation intervals  $\times$  100%

A total of 153 intervals from well LT1 were used for validation (Table 3). The overall accuracy is 85.0%, with sandstone/siltstone achieving 88.1% (59 intervals), mudstone/carbonaceous mudstone 83.9% (56 intervals), basalt 78.3% (23 intervals), and coal-bearing formation 80.0% (15 intervals). The misclassification zones are concentrated in the 150–200 m depth interval, where resistivity contrasts between lithologies are <3-fold, consistent with the sensitivity analysis in Section 6.4.

These validation results collectively demonstrate the reliability of the integrated geophysical workflow and provide a quantitative basis for the interpretation of deep geological structures and lithologic distributions in the Gaolihan Sag (Table 4).

**Table 4.** Summary of inversion validation metrics.

| Method/Parameter                              | Validation Metric                                   | Value                            | Data Quantity                               | Reference Data        |
|-----------------------------------------------|-----------------------------------------------------|----------------------------------|---------------------------------------------|-----------------------|
| Gravity–magnetic well–seismic joint inversion | RMSE of gravity fitting                             | <3.5%                            | 8 sections, 355.2 km                        | Eight sections        |
|                                               | Interface depth relative error                      | 5–8% (mean 6.2%)                 | 6 points<br>(2 wells $\times$ 3 interfaces) | Well locations        |
|                                               | R2 between inverted and measured depths             | 0.89                             | 6 points                                    | Wells GC1 and LT1     |
| Gravity anomaly stripping                     | Basement depth deviation                            | <6%                              | 1 point (well GC1)                          | Well GC1 calibration  |
| TFEM resistivity inversion                    | Average absolute resistivity deviation              | $\sim 2.5 \Omega \cdot \text{m}$ | 150 depth samples                           | Well GC1 log          |
|                                               | Relative error ( $\rho > 5 \Omega \cdot \text{m}$ ) | <12%                             | 150 depth samples                           | Well GC1 log          |
|                                               | Correlation coefficient (rr)                        | 0.84                             | 150 depth samples                           | n = 150 depth samples |
| Lithology prediction                          | Overall accuracy                                    | 85.0%                            | 153 intervals                               | Well LT1              |
|                                               | Sandstone accuracy                                  | 88.1%                            | 59 intervals                                | Well LT1              |
|                                               | Mudstone accuracy                                   | 83.9%                            | 56 intervals                                | Well LT1              |
|                                               | Basalt accuracy                                     | 78.3%                            | 23 intervals                                | Well LT1              |
|                                               | Coal-bearing accuracy                               | 80.0%                            | 15 intervals                                | Well LT1              |

## 5. Conclusions

(1) Based on seismic, geological, and well log data, we applied gravity anomaly separation and integrated gravity–magnetic–electrical–seismic joint inversion to extract the gravity responses of target formation and delineate the deep architecture of the basin at uplift resolution. Resistivity logs were used to calibrate electrical stratigraphic units, providing a reliable basis for stratigraphic interpretation. Despite volcanic masking and poor seismic imaging, this integrated workflow successfully resolved the deep structure of the Gaolihan Sag. Quantitative validation against wells GC1 and LT1 yielded interface depth errors of 5–8% (averaging 6.2%, based on 6 validation points across three interfaces), resistivity deviations of <12% ( $r = 0.84$ ,  $n = 150$  depth samples), and an overall lithology prediction accuracy of 85.0% (based on 153 intervals from well LT1). These results confirm that multi-geophysical integration offers a viable pathway for deep exploration in tectonically complex, low-seismicity basins where conventional methods reach their limits.

(2) Structural interpretation reveals 12 faults, predominantly NE–NNE-trending (75%), defining a “three sags and three uplifts” framework. The NE-striking fault system (espe-

cially Hegenshan branches F2 and F3) correlates strongly with basement relief ( $r = 0.67$ ) and controls both sag subsidence and eastern uplift. These extensional faults not only created accommodation but also segmented the basin into depocenters with contrasting subsidence rates. The southern Gaolihan Sag subsided 20–30% more than the northern sector during the Jurassic–Cretaceous, as shown by southward burial gradients (Cretaceous: 18 m/km; Jurassic: 25 m/km; Carboniferous–Permian: 22 m/km). This differential subsidence has critical implications for hydrocarbon maturation: the southern deep kitchens (Jurassic >4600 m; C–P >6700 m) likely entered the oil and wet-gas windows earlier and more extensively. Integrated analyses confirm Upper Paleozoic formation and resolve the deep framework with overall consistency exceeding 85%.

(3) The integrated gravity–magnetic–electrical–seismic inversion method is well-suited for complex, volcanic-covered basins with deep targets (>3 km) and low exploration maturity. However, key uncertainties stem from physical property inaccuracies ( $\pm 3$ –5% to interface depth), inversion non-uniqueness, and stripping errors ( $\pm 2$ –3% per step). In addition, TFEM resolution declines below 3 km, and resistivity–lithology ambiguity complicates interpretation. These issues can be reduced via high-density acquisition, seismic constraints, and well calibration. Future work should employ Bayesian or Monte Carlo methods for probabilistic uncertainty quantification in data-sparse frontier areas.

Layer stripping confirms widespread pre-Cretaceous formation, with the C–P basement averaging 6580 m ( $\pm 390$  m). The pre-Cretaceous section (Jurassic + C–P) constitutes ~55% (3.4 km) of the 6.2 km total fill. The strong correlation between C–P basement depth and surface topography ( $r = 0.58$ ) indicates that the present-day structure largely inherits the Mesozoic extensional framework, with persistent fault control on sedimentation. Three Jurassic electrical layers—high-resistivity basalt (8–25  $\Omega \cdot \text{m}$ ), sub-uplift resistivity sandstone (5–15  $\Omega \cdot \text{m}$ ), and low-resistivity coal-bearing mudstone (2–6  $\Omega \cdot \text{m}$ )—reveal a volcanic–sedimentary cycle: basalt extrusion, fluvial–lacustrine deposition, and swampy coal formation. This upward-fining succession, combined with uplift thermal maturity, points to both source rocks and potential coal-measure gas plays—a previously unrecognized exploration target in the GLH Sag.

(4) For broader application, the workflow requires careful evaluation of basin tectonics, target depth, volcanic cover, drilling density, and seismic quality. Procedures should be adapted to each basin’s geological similarity with the Gaolihan Sag, with inversion strategies optimized accordingly. Drilling verification remains essential.

The workflow is best suited for complex, volcanic-covered basins with deep targets (>3 km) and low exploration maturity. Success depends on three prerequisites: (a) at least one calibration well for density and resistivity constraints; (b) sufficient contrasts (density > 0.3 g/cm<sup>3</sup>, resistivity > 3-fold); and (c) 2.5D geometry with strike length  $\geq 5 \times$  target depth. Key uncertainties—property variations ( $\pm 3$ –5% to depth), inversion non-uniqueness, and stripping errors ( $\pm 2$ –3% per step)—can be reduced by high-density acquisition, seismic constraints, and multi-well calibration.

The southern Gaolihan Sag, where the C–P basement exceeds 6.7 km and the Jurassic hosts both source and reservoir facies, is the most promising deep target. The successful LT1 well, guided by TFEM predictions, validates the workflow and suggests similar integrated approaches could accelerate exploration in other volcanic-covered rift basins of NE China (e.g., Hailar, Songliao) where conventional seismic faces pre-Cretaceous imaging challenges.

## 6. Discussion

### 6.1. Geological Implications of the Results

The integrated geophysical interpretation presented in this study provides new insights into the deep geological framework of the Gaolihan Sag and its hydrocarbon potential.

**Tectonic implications:** The identified “three sags and three uplifts” structural pattern, controlled by NE–NNE-trending faults, confirms that the Mesozoic tectonic framework of the eastern Erlian Basin is predominantly governed by extensional faulting related to the Paleo–Asian Ocean closure and subsequent intracontinental rifting. The interpreted fault system, particularly the Hegenshan Fault and its branches (F2 and F3), appears to have played a dual role: (1) controlling the subsidence of the Gaolihan and Bayanhua sags during the Early Cretaceous, and (2) providing potential pathways for deep hydrocarbon migration. The NW-trending faults, although less prominent, may have acted as later-stage transverse adjustments that locally modified the structural geometry and potentially influenced hydrocarbon trapping.

**Stratigraphic distribution and deep source rock potential:** The burial depth maps (Figures 8, 11 and 19) reveal that the pre-Cretaceous formation (Jurassic and Carboniferous–Permian) are widely distributed across the Gaolihan Sag, with maximum burial depths reaching 4400–4600 m for the Jurassic and 6500–6700 m for the Carboniferous–Permian. These depth ranges coincide with the oil and condensate wet gas windows previously established for the Erlian Basin [17]. The presence of three electrical layers within the Jurassic succession—high-resistivity basalt intervals, sub-uplift resistivity clastic rocks, and low-resistivity coal-bearing formation—suggests a complex sedimentary and volcanic evolution. The lower low-resistivity layer, inferred as the Lower Jurassic Hongqi coal-bearing formation, is particularly significant as it indicates the presence of potential source rocks and possible coal-measure gas accumulations.

**Lithology prediction and reservoir potential:** The resistivity-based lithology identification criteria established in this study (sandstone/siltstone:  $>10 \Omega \cdot \text{m}$  + low GR; mudstone/carbonaceous mudstone:  $<5 \Omega \cdot \text{m}$  + upliftGR) provide a practical tool for deep lithology prediction in areas with limited drilling. The uplift prediction accuracy for sandstone/siltstone (88%) suggests that resistivity and dual-frequency phase attributes are effective for identifying potential reservoir lithologies. The high-resistivity layers interpreted as basalt may also indicate volcanic rock reservoirs, which have been recognized as important exploration targets in the Erlian Basin. However, the distribution of favorable reservoir lithologies appears to be laterally variable, with better-developed sandstone intervals in the central and southern parts of the sag, as suggested by the resistivity patterns in Figure 17.

### 6.2. Applicability of the Proposed Workflow

The integrated geophysical workflow is particularly suitable for basins with (1) complex tectonic settings where seismic imaging is poor due to volcanic rock shielding or structural complexity, (2) deep exploration targets ( $>3 \text{ km}$ ) with significant density and resistivity contrasts ( $>0.3 \text{ g/cm}^3$  and  $>3$ -fold, respectively), and (3) low exploration maturity with limited drilling. The Erlian Basin shares these characteristics with other Mesozoic–Cenozoic rift basins in Northeastern China, such as the Hailar and Songliao basins.

As summarized in Table 5, the integrated workflow combines the strengths of individual methods while mitigating their respective limitations. Although 2D seismic offers vertical uplift resolution, its performance deteriorates significantly under volcanic cover. Gravity and magnetic methods are cost-effective but suffer from non-uniqueness and limited target specificity. TFEM provides moderate resolution but loses sensitivity below 3 km.

The integrated workflow, by contrast, achieves high-resolution multi-property characterization at moderate cost, with the only prerequisite being the availability of calibration wells.

**Table 5.** Performance comparison of different geophysical methods for deep target characterization.

| Geophysical Method  | Primary Target        | Depth Range | Resolution        | Cost     | Key Limitation                    |
|---------------------|-----------------------|-------------|-------------------|----------|-----------------------------------|
| 2D Seismic          | Structural geometry   | 0–10 km     | uplift (vertical) | High     | Poor imaging under volcanic cover |
| Gravity             | density interface     | 0–10 km     | Low (lateral)     | Low      | Non-uniqueness                    |
| Magnetic            | Magnetic basement     | 0–5 km      | Low               | Low      | Limited to magnetic formations    |
| TFEM                | Resistivity structure | 0–8 km      | Moderate          | Moderate | Resolution decreases below 3 km   |
| Integrated workflow | Multi-property        | 0–10 km     | High              | Moderate | Requires calibration wells        |

The successful application of this workflow requires high-quality gravity, magnetic, and TFEM data with appropriate coverage and resolution, as well as at least one or two calibration wells to constrain density and resistivity parameters. In areas lacking well control, the reliability of inversion results would decrease. The 1:50,000 scale survey and targeted TFEM profiling represent a moderate investment compared to extensive 3D seismic acquisition, making this workflow a cost-effective screening tool for identifying priority zones for subsequent seismic and drilling deployment.

### 6.3. Summary of Uncertainties

While the integrated workflow has been validated with drilling data, several uncertainties should be considered:

(1) Physical property uncertainties: The density and magnetic susceptibility values used in the inversion are based on 790 specimens from 15 stratigraphic units. Although this dataset is statistically significant, spatial variability in physical properties—particularly in volcanic rocks and structurally complex zones—may not be fully captured. The estimated contribution of physical property inaccuracies to interface depth is  $\pm 3\text{--}5\%$ .

(2) Non-uniqueness of inversion: Both gravity and electromagnetic inversions are inherently non-unique. The gravity interface inversion may produce alternative depth solutions that yield similar gravity anomalies. The seismic horizon constraints and well calibration used in this study mitigate but do not eliminate this non-uniqueness.

(3) Cumulative stripping errors: The layer-stripping procedure introduces cumulative errors at each step. With two stripping steps applied in this study (Cretaceous removal, followed by Jurassic removal), the cumulative error in Carboniferous–Permian basement depth is estimated at approximately  $\pm 4\text{--}6\%$ . This is consistent with the 6% deviation observed at well GC1.

(4) TFEM resolution limitations: The TFEM method exhibits limited sensitivity to low-resistivity formations below 3 km depth, as indicated by the  $>12\%$  relative error for resistivities above  $5\ \Omega\cdot\text{m}$ . This limitation should be considered when interpreting deep lithology, particularly in zones where resistivity contrasts are subtle.

(5) Drilling calibration bias: The validation results are based on only two wells (GC1 and LT1). Although the consistency is uplift ( $>85\%$ ), the limited number of calibration points may introduce bias in areas with different geological conditions. Additional drilling will be required to further validate and refine the interpretation.

Despite these uncertainties, the consistency between multiple independent methods provides strong confidence in the main conclusions.

#### 6.4. Sensitivity Analysis and Uncertainty Quantification

To assess the robustness of the inversion results, we conducted a sensitivity analysis by perturbing key input parameters within their physically plausible ranges and quantifying the corresponding changes in the output model parameters.

**Density perturbation:** The density values used in forward modeling were derived from 790 rock specimens ( $2.10\text{--}2.85\text{ g/cm}^3$ ). We perturbed the density of each stratigraphic unit by  $\pm 5\%$  ( $\pm 0.10\text{--}0.15\text{ g/cm}^3$ ), which represents the typical measurement uncertainty of core samples. The results show that a  $\pm 5\%$  density change leads to an interface depth variation of approximately  $\pm 3\text{--}4\%$  for the Cretaceous basement and  $\pm 4\text{--}5\%$  for the Carboniferous–Permian basement. This sensitivity is lower than the  $5\text{--}8\%$  relative error validated against well data, confirming that density uncertainty is not the dominant source of error.

**Magnetic susceptibility perturbation:** Magnetic susceptibility values range from  $50 \times 10^{-5}\text{ SI}$  to  $3200 \times 10^{-5}\text{ SI}$ . A  $\pm 10\%$  perturbation in susceptibility yields a magnetic anomaly variation of  $<2\%$ , which has negligible impact on gravity-derived interface depths.

**Resistivity perturbation:** For TFEM inversion, we evaluated the effect of  $\pm 20\%$  variation in the initial resistivity model. The inverted resistivity values show a corresponding change of  $\pm 8\text{--}12\%$ , with the highest sensitivity observed in the  $3\text{--}5\text{ km}$  depth interval; this is consistent with the  $<12\%$  relative error reported in Section 4.4. This indicates that the TFEM inversion results are moderately sensitive to initial model selection, but the well-calibrated results remain within acceptable tolerances.

**Frequency sampling sensitivity:** We compared the inversion results using the conventional 10-frequency acquisition versus the targeted 36-frequency acquisition. The 36-frequency scheme reduces the resistivity uncertainty from  $\pm 15\%$  to  $\pm 8\%$  in the deep target interval ( $3\text{--}6\text{ km}$ ), confirming the effectiveness of the frequency densification strategy (Figure 14).

**Implications for uncertainty quantification:** The sensitivity analysis confirms that the deterministic inversion results are stable within the range of parameter uncertainties expected from the measured petrophysical data. The major uncertainty contributors are resistivity initial model selection ( $\pm 8\text{--}12\%$  in inverted resistivity) and density perturbation ( $\pm 3\text{--}5\%$  in interface depth). Future work should consider Bayesian inversion or Monte Carlo-based uncertainty quantification to provide probabilistic estimates of model parameters and their confidence intervals, particularly in areas lacking drilling calibration.

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**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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