Journal of Himalayan Earth Sciences Volume 2026, No., 2026 pp. 1-14

Subsurface Geological Architecture of the Giant Jinding Zn-Pb Ore Deposit in the Meso-Cenozoic Lanping Basin, SW China: Insights from 2-D Shallow Seismic Reflection Survey

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Submitted Date:19/11/2025   Acceptance Date: 15/04/2026 Publication Date:

Abstract

The giant Jinding Zn-Pb deposit, located in the Meso-Cenozoic Lanping Basin, SW China, is structurally controlled by complex fault systems and evaporite-related deformation. However, the deep (>500 m) geological architecture remains poorly constrained. This study presents results from 2-D seismic reflection data processed using an enhanced workflow including coherent noise attenuation, surface-consistent amplitude compensation, detailed velocity analysis, and post-stack migration. Pre- and post-processing comparisons show significant improvement in reflector continuity and signal-to-noise ratio (SNR). Amplitude spectra analysis indicates suppression of low-frequency noise (<15 Hz) and preservation of structural frequencies between 20-45 Hz. Refined semblance analysis improved velocity picking stability, resulting in clearer imaging of reflections between 0.5-3.0 s TWT (approximately 500-3000 m depth). The processed sections reveal gently dipping stratigraphic reflections intersected by steep reverse and strike-slip faults. These structures correlate with known ore-controlling faults and suggest deep fluid migration pathways. Depth-converted sections and 3-D modeling highlight structural doming and fault intersections that likely controlled mineralization. The results refine the structural model of the Jinding deposit and demonstrate that optimized seismic processing can effectively image complex mineral systems in tectonically deformed basins.

Keywords**:** 2-D seismic reflection survey; Geological architecture; Stratigraphic system; Ore-controlling structure; Jinding Zn-Pb ore deposit.

1. Introduction

The giant Jinding sediment-hosted zinc-lead ore deposit located in the Meso-Cenozoic Lanping Basin in northwestern Yunnan Province, SW China. The Lanping Basin is located at the northern Indochina Block (Xue et al., 2006; Liang et al., 2022) and contains the Mesozoic to Early Cenozoic continental facies sedimentary sequence. The basin underwent three phases of tectonic evolution the basement formation, intracontinental basin filling, and the basin inversion under the orogenic settings (Tang et al., 2017). The Jinding Zn-Pb ore deposit is a world-class resource extensively explored using seismic, gravity, and geological surveys. All survey data are important for understanding subsurface geological formations and assessing deposit's potential. As such, notwithstanding its economic significance, the stratigraphic framework of the deposit is not fully comprehended owing to its intricate geological history. Detailed geological and geophysical studies have revealed the shallow geological structure and mineral potential of the Jinding ore deposit for over 60 years. It is known that NS- and NE-trending thrust faults and NW-trending strike-slip and inclined faults govern ore-hosting sedimentary sequences. However, the deep geological framework, ore-controlling mechanisms, and prospecting possibilities are unknown. A 2-D seismic reflection and gravity study defined the ore-hosting lithologies and deep ore-controlling structures to bridge the gap.

The seismic survey investigated the complex subsurface geological formations of the Jinding Zn-Pb ore deposit. The seismic survey consisted of four lines covering a total area of 25.5 km. The data is collected under the “Geophysical Exploration and 2-D Physical Structure in Jinding Ore Concentration Area” project sponsored by the National Key R&D Program. The data is processed with PROMAX and interpreted in Petrel based on surface geological conditions. The processed and interpreted 2-D seismic data results reveal ore-controlling features such as faults, fault planes, fractures, and folds and locate lithological contacts where mineral ore may accumulate.

The Jinding Zn-Pb ore deposit has recently uncovered shallow surface mineral deposits (Xue et al., 2006). Several attempts have been made to find the deep subsurface framework of this ore district. The results showed numerous mineral ores near the surface however, the deep structure framework, ore regulating structures, and deep ore potential remain unclear. As such, this shallow seismic near-surface research seeks to define the subsurface (500-3000m) geological structures of the massive Zn-Pb deposit.

Despite its low signal-to-noise ratio, the processing parameters used to analyze 2-D seismic data shows subsurface reflections. Various processing stages improved these reflections. These processing and interpretation methods have revealed subsurface geological structures that helped develop the deposit's geological model and find additional mineralization zones. This study develops and applies a novel analytical framework to improve the deposit area's stratigraphic correlation and lithological interpretation.

By addressing the obvious limitations of the seismic data and focusing on reconstructing subsurface geological events, this research advances the field of seismic data imaging in geologically complex areas. The results underscore the critical importance of a reconstructing subsurface geological architecture using seismic imaging and provide valuable insights of improving the architectural framework of the area. This study lays the groundwork for future research in this area, emphasizing the need for a better understanding of the seismic data for the architectural rebuilding using seismic data in geologically challenging terrains.

Although shallow mineralization has been extensively explored, the deep structural framework (500-3000 m) and its relationship to ore-controlling structures remain unclear. This study aims to (1) improve seismic imaging using optimized processing, (2) delineate deep fault systems, and (3) refine the structural model of the Jinding deposit.

2. Study Area

The Jinding Zn-Pb ore deposit lies in the Lanping Basin of the northern Lanping-Simao block in the eastern Himalayan-Tibetan orogenic belt, SW China (Song et al., 2020). The Jinding Zn-Pb ore deposit is located in Yunnan, SW China. It is a giant deposit with a total Pb and Zn reserves of 22 Mt, grading 6.08 % Zn and 1.29% Pb, with a Pb/Zn ratio of 1:4.7 (Xue et al., 2006). The Jinding Zn-Pb ore deposit is located in the Lanping Mesozoic-Early Cenozoic sedimentary basin in Yunnan Province, SW China, and ranks as the fourth largest zinc deposit in Asia, containing 200 million tons of metals with 6.1% zinc and 1.3% leadm (Huang et al., 2024; Leach et al., 2016). Characterized as a Mississippi Valley-Type (MVT) sub-type, it is hosted in a diapiric environment. Most of the ore is found in sandstone once evaporated glaciers, containing a mixture of extruded diapiric materials, including breccias, fluidized sand, and evaporites.

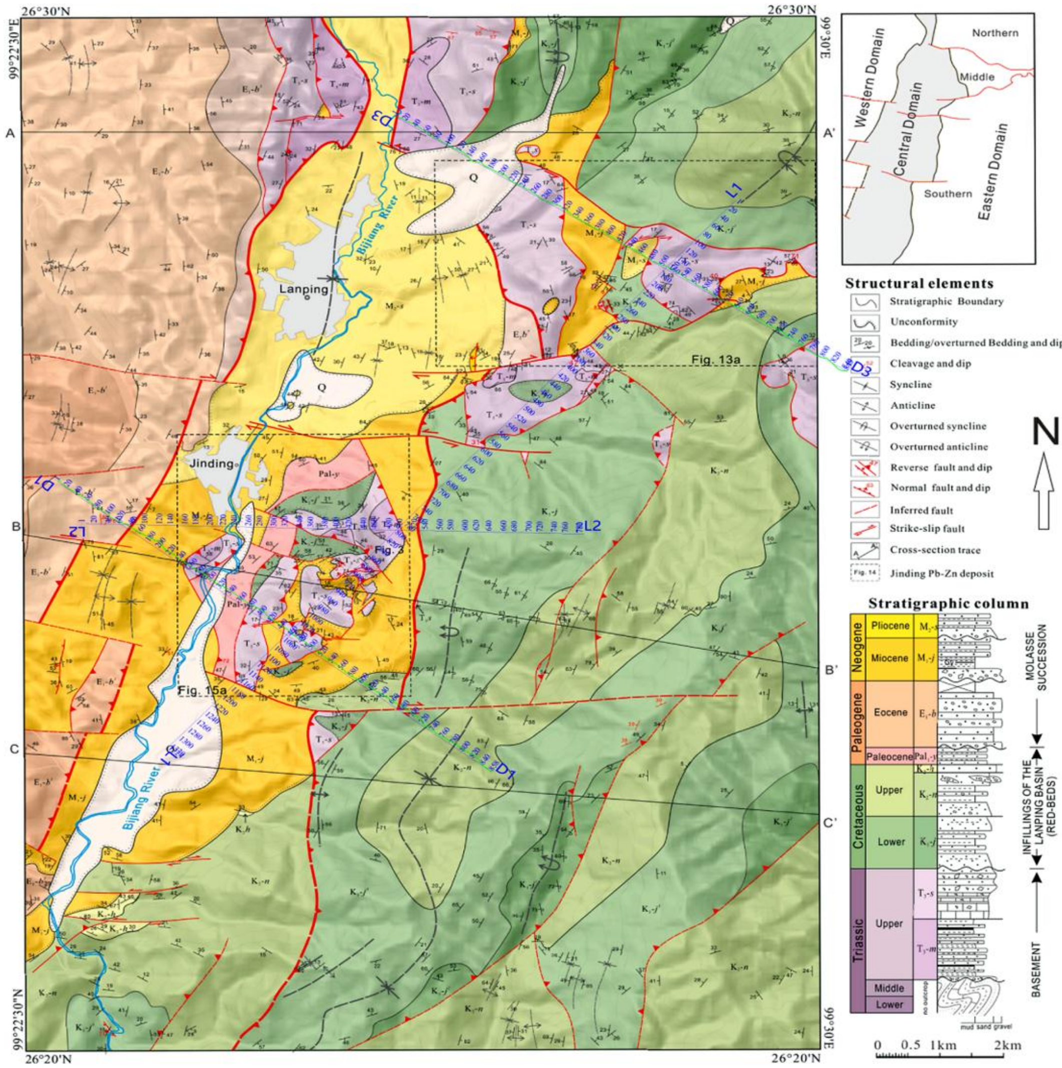

Fig. 1. Geological map of the Jinding Zn−Pbore deposit and its adjacent area in the Lanping basin. Upright inset: The structural framework of this map shows the subdivision of structural domains. Low right inset: Stratigraphic column of the Lanping Basin (Liang et al., 2022).

The presence of a dome structure with abundant gypsum and chaotic breccias within an evaporite-bearing sedimentary sequence indicates that the ore-hosting structures are related to halo kinesis (salt tectonics) and evaporite diapirism (Leach et al., 2016).

Figure 1 shows the Jinding deposit marked with black dashed lines in the central part. Upright inset is the structural framework map showing the subdivision of structural domains. The low right inset is the stratigraphic column of the Lanping Basin (Liang et al., 2022). Below the geological map is the geological cross-section illustrating the stratigraphic framework, structural features, and fault systems. Different lithological units are color-coded, with key faults and fold structures annotated according to the legend.

3. Materials and methodology

3.1 Seismic data acquisition

In this research, dynamite is used as the source. If dynamite is employed in the survey, the depth must be ascertained, the distance between the shot and reception points must be established, and the recording filters must be identified to mitigate extraneous signals.

The Jinding area is geologically complex. Innovative acquisition methodologies and advanced processing techniques, such as wide-azimuth or multi-azimuth acquisition, can improve image quality and subsurface imaging resolution in challenging geology environments. Pre-stack depth migration and other advanced processing methods can improve data interpretation and subsurface imaging (Chopra and Marfurt, 2007).

The seismic data acquired along four seismic lines, namely JD-2017-D1, JD-2017-D2, JD-2017-D3, and JD2017-L1. In this paper, only the lines JD-2017-L1 and JD-2017-D2 are processed and interpreted. The sampling interval is set to 1 millisecond to ensure high-resolution data capture. The shot interval is 80 meters, and the receiver interval is 20 meters to optimize spatial resolution. The record length was 5 seconds, providing enough subsurface imaging time. The coverage length was 150 seconds, split into three sets of 50 seconds each, which allowed for extensive data collection (Figs. 2 and 3). The survey lines cover 25 kilometers, with a maximum offset of 3990 meters. Data is recorded in SEG-D format, which makes it compatible with standard processing workflows.

3.2 Seismic data processing

Advanced processing strategies are implemented to mitigate noise and improve signal clarity. Techniques such as filtering, deconvolution, and velocity analysis are applied iteratively to enhance the signal-to-noise ratio (SNR).

The seismic data processing workflow using PROMAX follows a structured sequence to ensure high-quality imaging of the subsurface. The process begins with data input, followed by assigning geometry to map the acquisition parameters correctly. First break picking is conducted to identify the initial arrivals of seismic waves, which is essential for further processing. Tomography static correction is then applied to account for variations in near-surface velocities, improving data accuracy (Yilmaz, 2001). To enhance signal clarity, noise attenuation techniques are implemented, followed by deconvolution, which sharpens the seismic signal by removing distortions. Subsequently, velocity analysis, normal move-out (NMO) correction, and residual statics adjustments are performed to refine seismic velocities and align reflections properly. Once these corrections are in place, the data undergoes final stacking, combining multiple seismic traces to improve signal-to-noise ratio. The final step involves migration, which correctly positions seismic events in their actual subsurface locations, leading to an accurate geological interpretation.

Migration refines the subsurface image, aligning geological structures more accurately. By integrating these steps with auxiliary data, the workflow ensures meaningful interpretation, even with limited data quality, aiding in the achievement of the study's goals.

4. Results

Due to the study area's highly deformed complex subsurface geology, the seismic imaging reveals a complex subsurface geological architecture. It has been a challenge to see the reflections throughout the sections. However, the seismic lines JD-2017-D2 and JD-201-L1 showed useful reflections within depths 500-3000 meters (shown in Fig. 2-4). The analyzed seismic sections reveal significant faults. These faults produce reflections that serve as indicators for identifying significant ore-controlling structures. Seismic reflection interfaces are present between the ore-bearing strata and the surrounding rocks in this area, and the considerable scale of major ore-controlling faults facilitates the reflection of seismic waves. This makes using reflection signals to detect key ore-controlling structures and strata feasible.

4.1 Stratigraphy and lithological units

The survey results indicate a stratigraphic sequence featuring notable lithological changes throughout the studied area. Key marker horizons are essential reference sites for lithostratigraphic correlation. The research identified variations in lithological properties between structural discontinuities, including faults and folds.

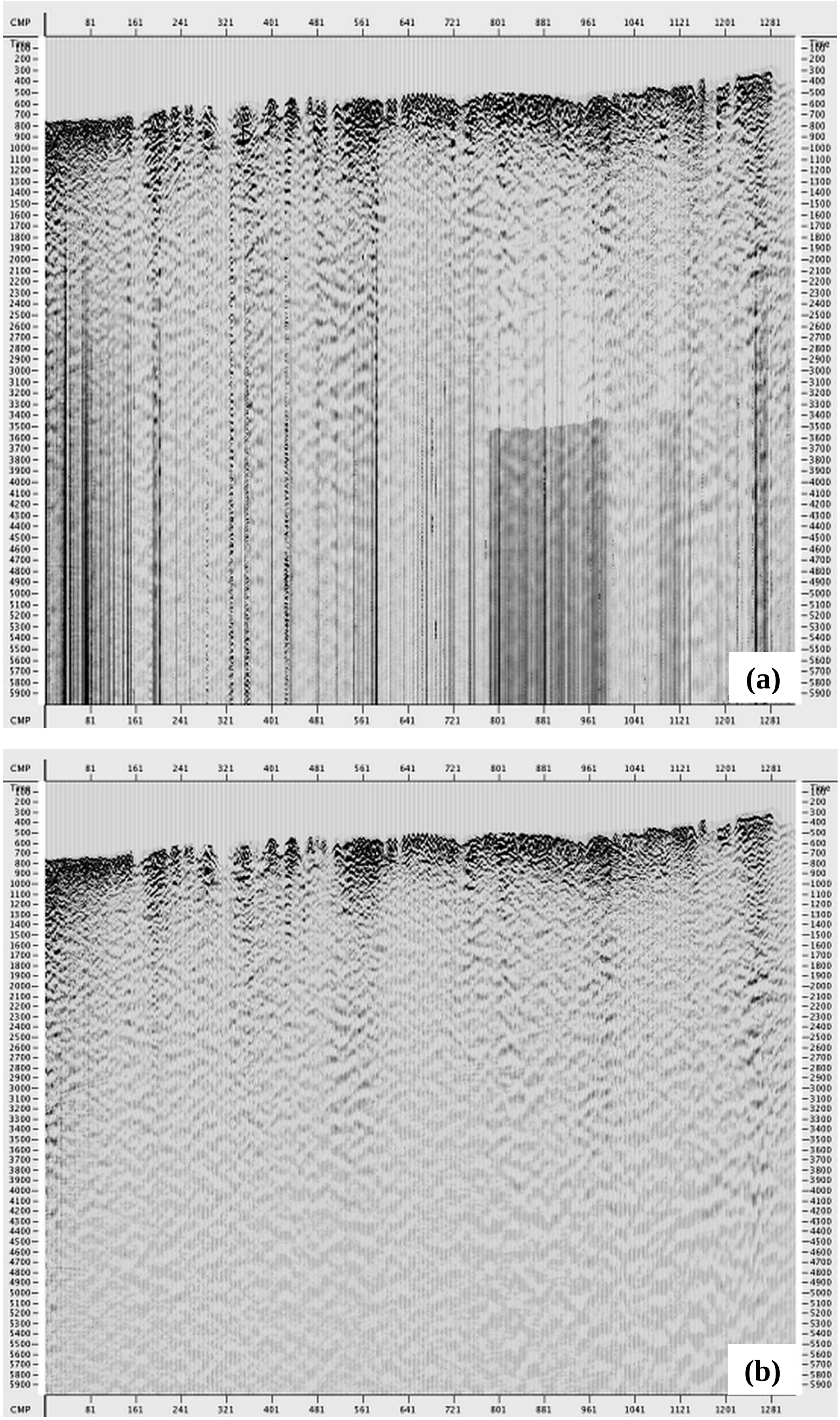

Fig 2. a) JD-2017-L1-Stack before wild amplitude recovery, showing extreme amplitude variations b) Stack after wild amplitude recovery. Amplitude values have been normalized, enhancing the visibility of subsurface reflectors and structural features

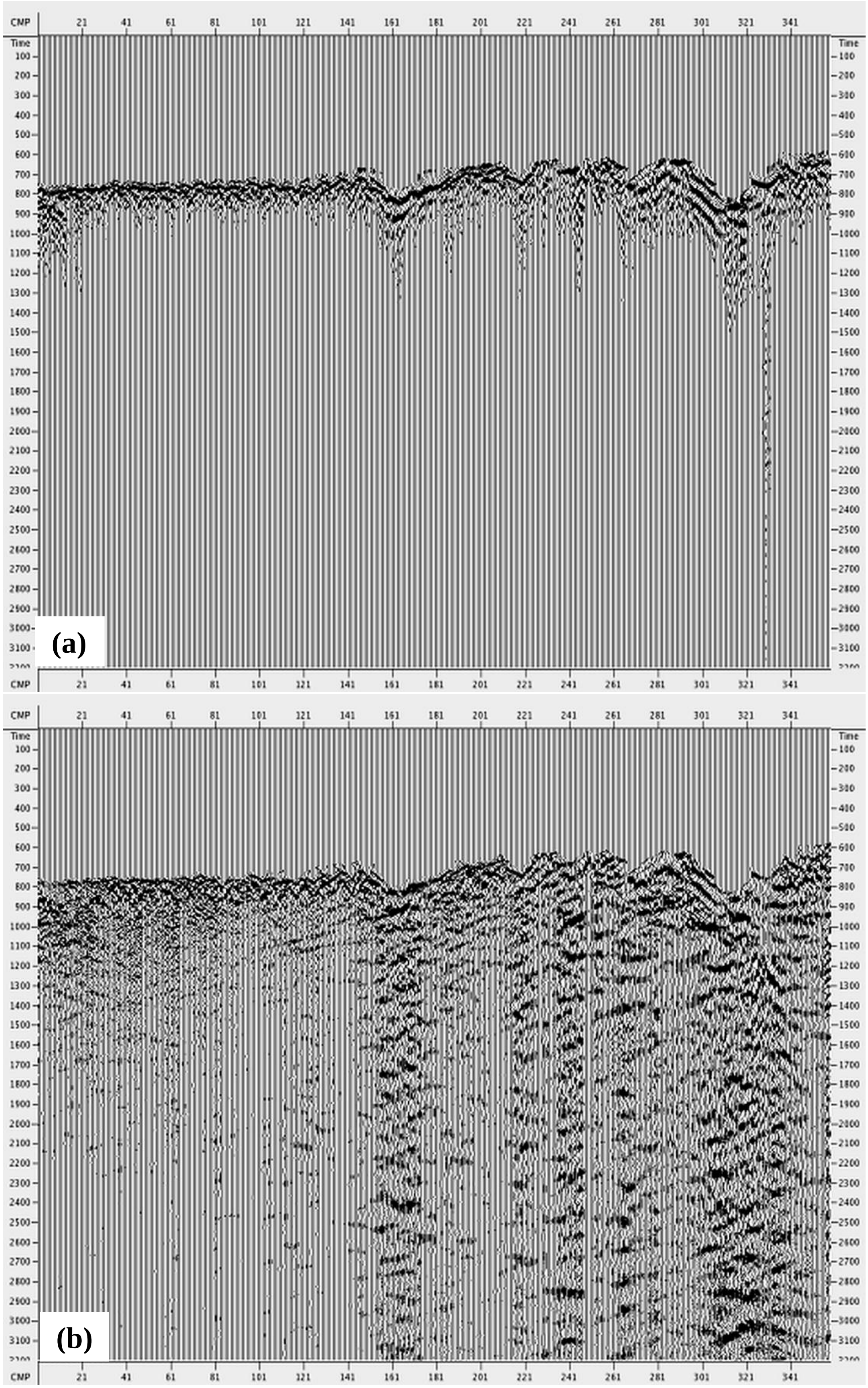

Fig 3. (a) Brute-stack data, displaying raw seismic reflections with significant noise and amplitude variations. (b) Processed seismic section after applying a sequence of corrections, including geometrical spreading compensation, wild amplitude recovery, coherent noise attenuation, and surface-consistent amplitude compensation.

The seismic reflection method improves comprehension of the geological framework of the Jinding Zn−Pb ore deposit and establishes a significant basis for recognizing new exploration possibilities. The interpretation reveals several stratigraphic units, fault structures, and notable geological features, which are color-coded and labeled in Figures 5 and 6. The black lines passing vertically through the section are major reverse faults, and the red vertical lines are strike-slip sub-faults. In Figure 5, the faults F1 and F2 marked with black vertical lines crossing the seismic sections are considered to be the main faults. These faults may act as conduits for mineralizing fluids. Figure 6 shows that the blind faults observed during the interpretation are marked as green, yellow, orange, and pink in color.

The highlighted yellow vertical rectangle runs from CDP 350 to CDP 550, which is the location of the Jinding Zn-Pb ore deposit area. Most of the mineralization seems to occur here.

4.2 Horizon interpretation

The identification of horizons is the most critical step during the interpretation. From the top, five horizons N_1J (white) lower Miocene Jinding formation, the upper Triassic unit is divided into two units T_3s and T_3m in the interpretation T_3s (light-blue) upper Triassic Sanhedong Formation, T_3m (orange) Upper Triassic Maichuqing Formation, K_1j(Green) Lower Cretaceous Jinxing Formation, $T_{1\text{-}2}p$ (blue) lower-to-middle Triassic paleo-soil and pale-oxidized zone along the unconformity surface are marked.

The section also shows the folding effect caused by the tectonic forces in the area. The anticlines and synclines could be judged from the curvatures in the layers due to compression.

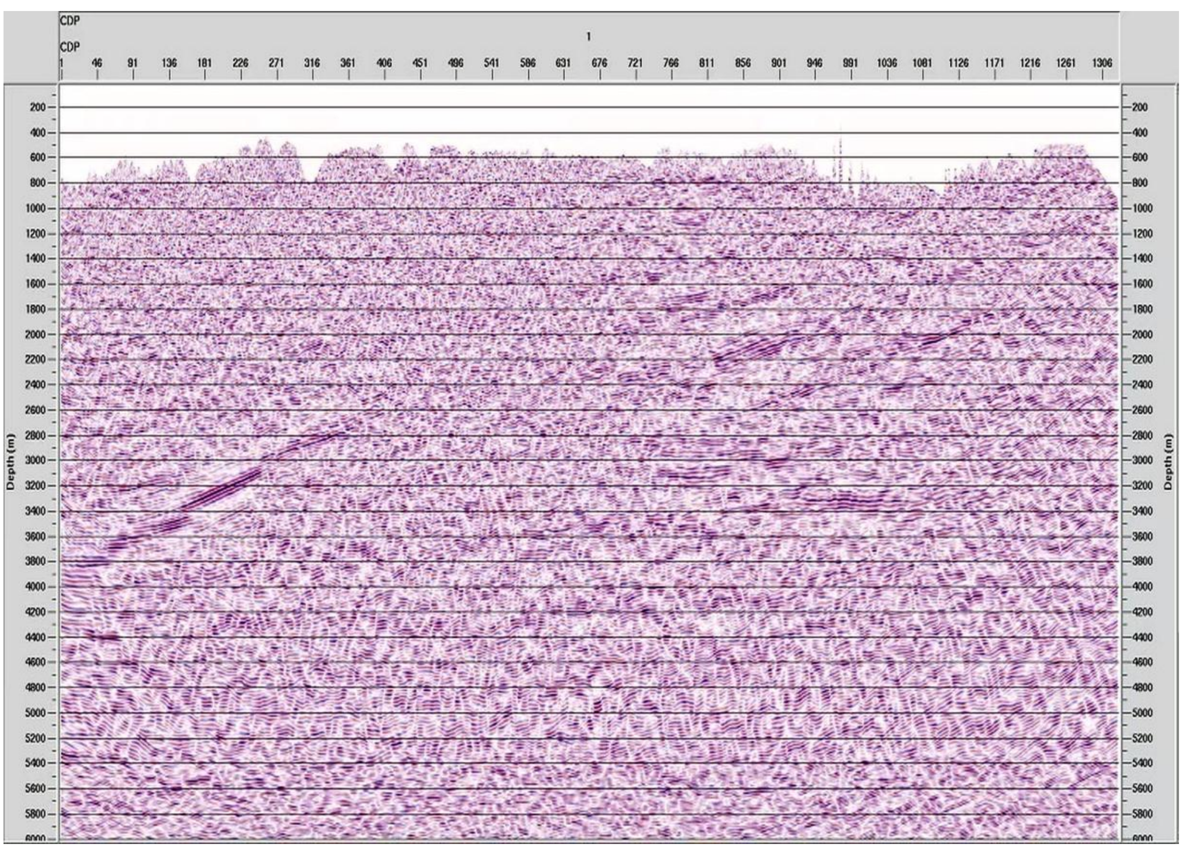

Fig. 4. Depth map of seismic section JD-2017-L1. The depth map in meters highlights the depth distribution of seismic reflectors, structural features such as faults and folds, and stratigraphic boundaries (shown in interpreted section)

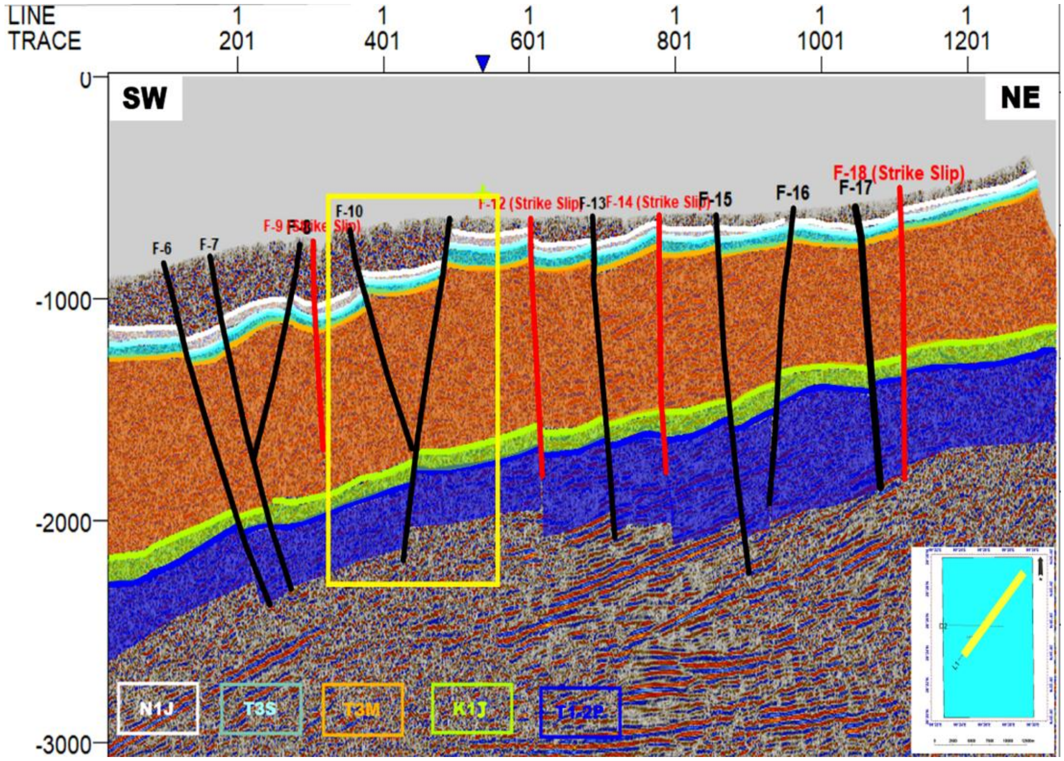

Fig. 5. The seismic section (in TWT) is the interpretation of Seismic Line JD-2017-L1, spanning from the southwest (SW) to the northeast (NE). The horizontal axis is CDPs and the vertical axis shows TWT (Two Way Time) in milliseconds.

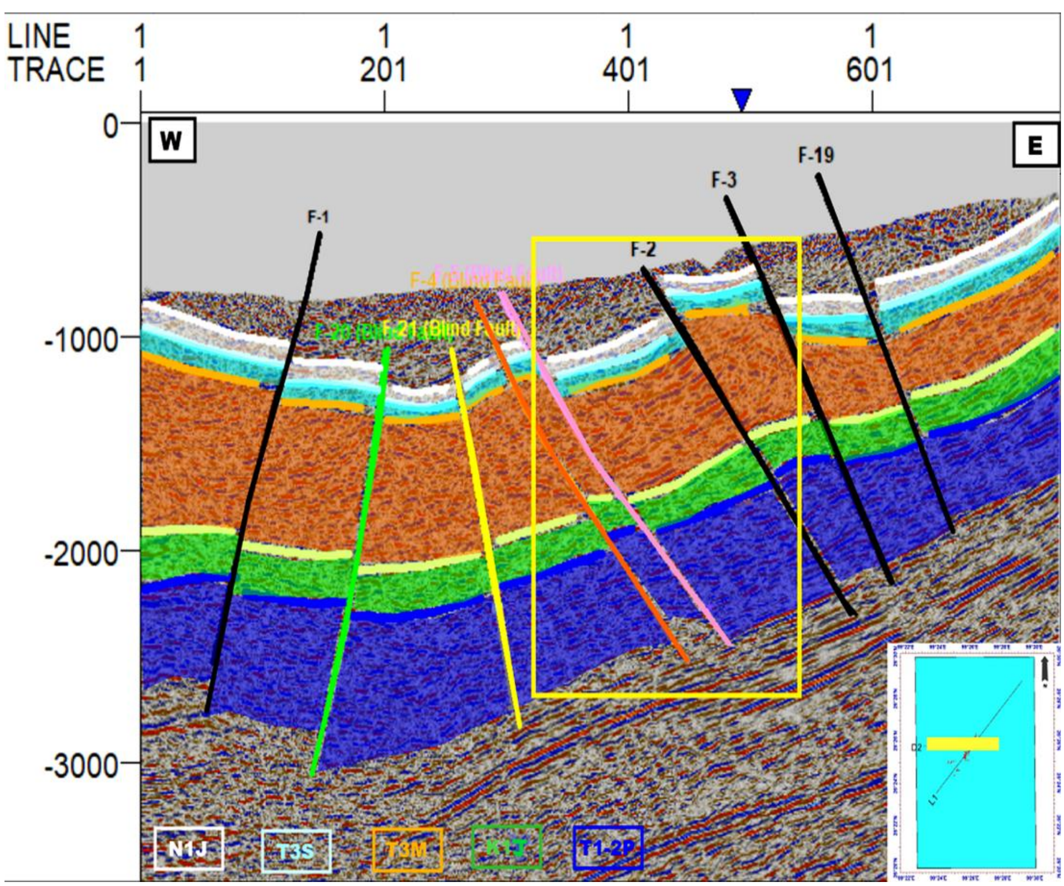

Fig. 6. The seismic section (in TWT) is the interpretation of Seismic Line JD-2017-D2, spanning from the southwest (W) to the northeast (E). The horizontal axis are CDPs and the vertical axis shows TWT (Two Way Time) in milliseconds

The seismic section indicates that the reflection interfaces between the ore-bearing strata and adjacent rocks, along with the significant scale of major ore-controlling faults, establish optimal conditions for the reflection of seismic waves, facilitating the identification of ore-controlling structures and strata through reflection signals. Moreover, small-scale, high-density lenticular ore bodies may induce scattering interference, so interpretation is complicated. This region's intricate, deep seismic geological characteristic need sophisticated techniques for efficient exploration. The observed seismic amplitude fluctuations in reflection patterns support this explanation. Regions with high-density mineralization show elevated reflection amplitudes, indicating significant impedance differences between ore-bearing zones and adjacent host rocks.

4.3 Depth contour maps

These contour clusters can be interpreted as subsurface lows or highs based on increasing or decreasing contouring values. In the case of the Earth's surface, if the cluster's contours show an increase in values, it shows an elevated part, and if it decreases, it will show depression, but for subsurface as in time (TWT) and the depth contours the situation is reversed if the contours of the cluster show increasing order values, then it will show depression, and if decreasing order values, it will show elevation. Therefore, these contours give us succinct information about the slope/dip of the formations' structural relief (faulting or folding or both) created by that formation.

The fault polygons in Figure 7 are assigned in the study area based on the different faults marked on the given seismic sections after that contour maps are generated. Fault polygons are usually in NW−SE to NE−SW direction as we proceed from west to east.

4.4 3D geological model

From the interpretation, it is known that the study has several faults, including complex geometries. Figures 5 and 6 also show thrust, normal, and strike-slip faults with a few buried faults. The 3-D geological model shown in Figure 8 is a subsurface representation of the Jinding deposit area.

The 3-D geological model was generated using the Petrel platform and the 2-D seismic lines overlying the Jinding Zn-Pb ore deposit area. The model visually represents the study area's subsurface stratigraphic, structural, and fault distribution.

The model reveals a complex and deformed sedimentary sequence consistent with a transpersonal tectonic regime, perhaps due to the study being in the deformed zone of the India-Eurasia collision. The area shows crustal shortening, uplift, and formation of fault-controlled basins and domes.

Five formations were shown in Figure 8 with N_1J (Miocene deposits) at the top and $T_{1\text{-}2}p$ (Lower to Middle Permian) at the bottom, each with a different color code. Faults were also indicated in the above geological model with NW-SE and NE-SW directions. As previously explained, the area is intensely deformed with both thrust (reverse) and strike-slip faults. These faults acted as fluid conduits, channeling Zn-Pb-bearing hydrothermal fluids into receptive carbonate hosts from deeper sources. The fault planes in the study area are crucial for understanding tectonic activity, fluid activity, and ore localization. Moreover, the fault intersection and terminations usually form traps for ore deposition.

Based on the geological history of the ore deposit area, the mineralization is mainly hosted by north-trending thrust faults in the Triassic-hosted rocks. This model justifies that the faults and folded stratigraphy control the ore distribution.

In conclusion, this conceptual model represents a 3-D visualization of the subsurface setting of the rock formations, faults, folds, and potential ore-hosting structures. This model can be useful for exploration, mining planning, and geophysical interpretation of the Jinding ore district.

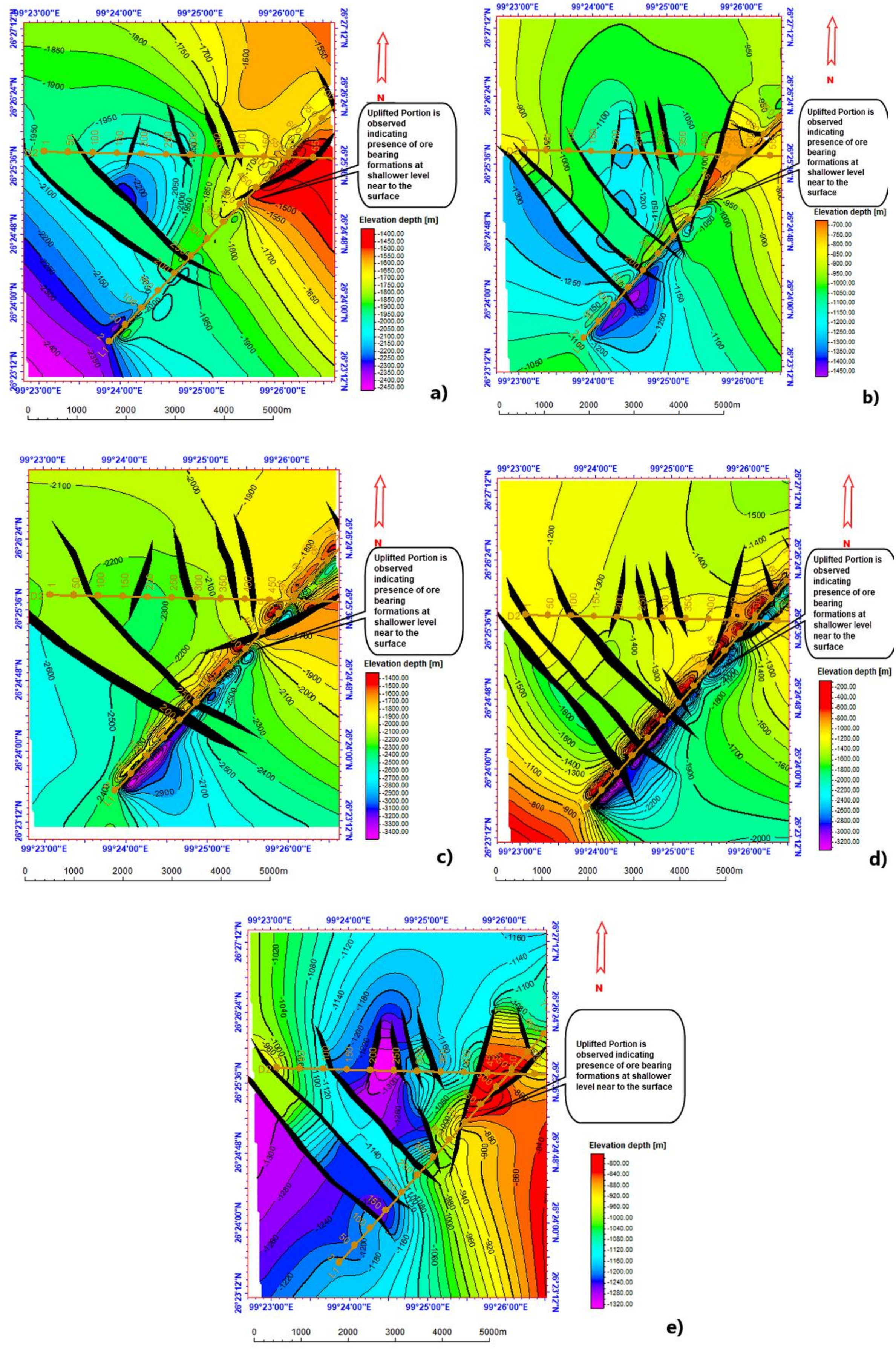

Fig. 7. a) and b) depth contour map of K_1j (left) and N_1J (right), c) and d) the depth contour map of $T_{1\text{-}2}p$ (left) and T_3m (right), e) is the depth contour maps of T_3s.

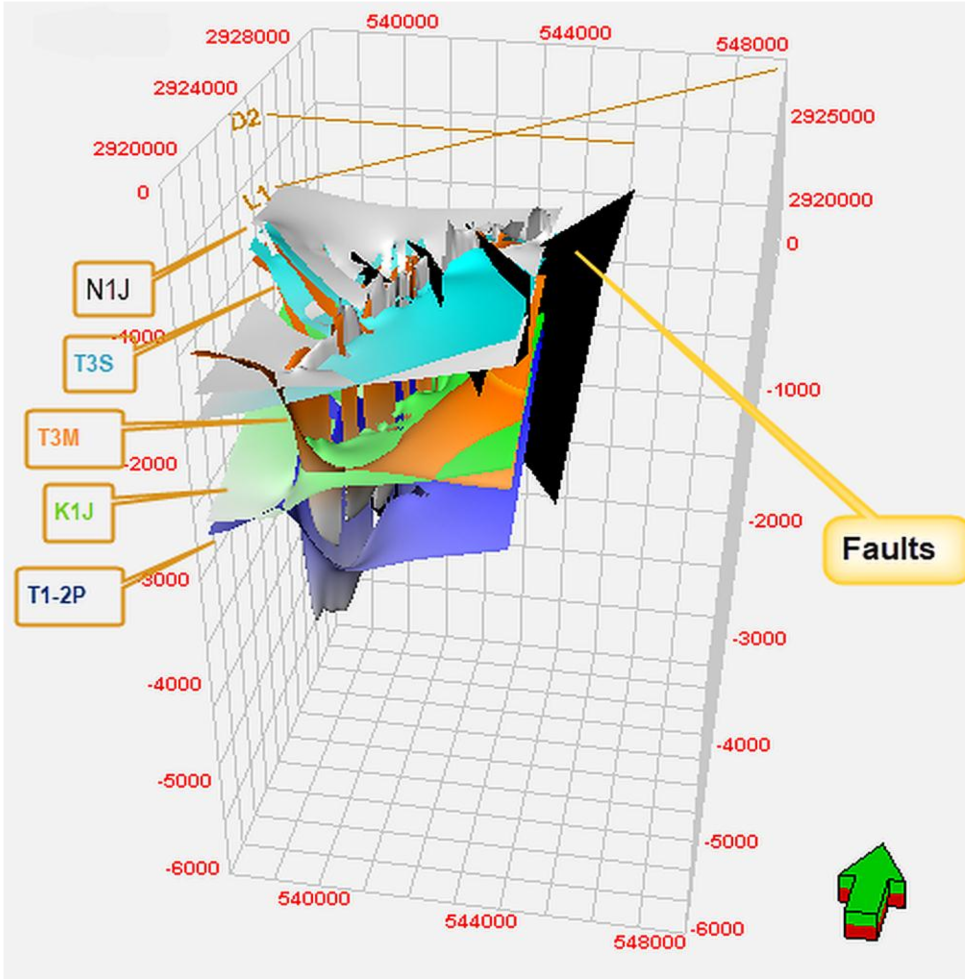

Fig. 8. Subsurface 3D Geological model of the Jinding Zn−Pb deposit are. The X-axis and Y-axis are horizontal coordinates in UTM. Z-axis represents depth in meters.

Since the mining industries primarily focused on the extraction of minerals near the surface with minimum economic constraints, the areas bearing shallower depths would be the No.1 priority for extraction keeping the host formations, which are shallower and have some potential of minerals.

4.5 Interpretation

A large number of geophysical methods have been used to explore the subsurface. The seismic method is the only method that is used for hydrocarbon exploration as it facilitates us in mapping the subsurface with accurate information and high resolution. The 2-D seismic method provides complete knowledge/subsurface information on where stratigraphy, structure, and rock properties of the Earth are identified. 2-D seismic data interpretation is suitable for the subsurface geological structural architecture. It can also be used to obtain general information about an area, to locate a zone of interest for exploration drilling, and to plan 3-D surveys in field already discovered.

The seismic data interpreted in Petrel is based on surface geological information. The key reflection horizons were interpreted. Reflections from sedimentary layers and structural features, including faults and folds, were seen although with diminished lateral continuity. The data shows many central fault systems and thrust structures. These structural characteristics are likely to be the main ore-controlling structures.

5. Discussion

The 2-D seismic reflection profiles acquired in the Jinding Zn-Pb ore district provide new insights into the subsurface structural framework and stratigraphic configuration of the central Lanping Basin.

The findings underscore the significance of combining 2D seismic reflection methods with the geological data, enabled a comprehensive interpretation of subsurface structures and mineralization processes.

Although the seismic records were affected by a relatively low signal-to-noise ratio due to complex near-surface conditions and strong scattering from fault zones, but the processing techniques in PROMAX including detailed velocity analysis and targeted noise attenuation allowed the recovery of key reflection events essential for geological interpretation. Interpretation in Petrel helped Identifying marker horizons and lithological variations within the stratigraphic sequences has contributed to a clearer understanding of the ore deposit's geological framework. These marker horizons serve as critical indicators for recognizing areas of potential mineralization, particularly in deep or poorly explored regions. The improved comprehension of subsurface stratigraphy has enhanced our understanding of the ore-hosting environment and provided valuable insights into the regional geological evolution.

5.1 Ore Formation Controlled by the Major Geological Structures

From the figures 5, 6 are processed and interpreted sections which reveal a network of faults, with several extending from near-surface to deeper levels, suggesting that these faults act as primary ore-controlling structures. In particular, the continuous, gently dipping reflections intersected by steep fault planes correspond well with mapped surface structures and with fault zones.

5.2 Stratigraphic Sequences observed in Seismic Sections

The seismic profiles clearly distinguish stratigraphic packages within the Meso-Cenozoic fill of the Lanping Basin. The relatively continuous, subparallel reflectors in the upper sequences are interpreted as sedimentary layers deposited during basin subsidence, whereas deeper, more discontinuous reflectors may correspond to older, deformed strata and possible evaporite horizons. The identification of such units is significant because evaporites and related ductile layers may have influenced both fault kinematics and ore fluid focusing.

This study highlights the significance of the structural evolution of ore-controlling components, including faults, non-integrated surfaces, and ore seams, and their influence on the spatial distribution of mineralization. The observed structural disruptions, including faults and folds, significantly influence the continuity of the stratigraphic layers and play a central role in shaping the formation of the ore deposit. These disruptions are essential for understanding the localization of mineralized zones, as they can create pathways for hydrothermal fluids and facilitate the concentration of metals.

Additionally, integrating geophysical and geological data has enabled the development of a more accurate model of the region's tectonic evolution. This model suggests that the Jinding Zn-Pb deposit was influenced by a combination of factors, including the regional tectonic setting, fluid migration patterns, and the interaction between different lithological units. These findings align with previous studies on ore deposits in similar tectonic settings, reinforcing that regional tectonics play a significant role in determining ore-forming processes.

While this study provides valuable insights into the Jinding Zn-Pb deposit, it also highlights several areas for further investigation. Future studies could focus on refining the understanding of the fluid-rock interactions that led to mineralization, primarily through detailed geochemical analysis and the application of isotope tracers. Additionally, more detailed seismic imaging and deeper drilling campaigns could provide further insights into the deep geological structures that remain poorly understood.

The methodological innovations introduced in this study offer significant potential for advancing future exploration efforts. By applying a multi-method approach that combines geophysical data with geological surveys, exploration teams can achieve more accurate models of subsurface conditions, particularly in complex and deep-seated ore deposits. This integrated approach could be applied to other regional mining districts, helping to identify new mineralization zones and improve the efficiency of resource exploration.

In conclusion, this study's findings significantly contribute to the understanding of the geological architecture of the Jinding Zn-Pb ore deposit. Integrating advanced geophysical techniques with geological data provides a powerful framework for future exploration, offering new opportunities for discovering mineral deposits and advancing exploration methodologies.

6. Conclusions

This study represents a detailed analysis of the deep geological architecture of the Jinding Zn-Pb ore deposit in the Lanping basin. This study applied 2-D shallow seismic reflection surveying to investigate the subsurface geological architecture of the Jinding Zn-Pb ore deposit in the central Lanping Basin, SW China. Advanced processing workflows, including detailed velocity analysis and targeted noise attenuation, were implemented to overcome the challenges posed by strong near-surface noise and complex stratigraphy. The processed seismic sections reveal well-defined fault systems extending from shallow to deeper levels, in agreement with the known ore-controlling structures in the Jinding district. Clear stratigraphic layering is observed within the Meso-Cenozoic basin fill, with variations in reflector continuity that appear to be related to structural deformation and the presence of possible evaporite horizons. Compared to conventional processing results, the improved reflector continuity and clarity achieved in this study enable a more confident and detailed geological interpretation.

It demonstrates the integration of seismic reflection data and geological survey data, and the results have revealed a detailed deep geological architecture (500-3000m) of the giant Jinding Zn-Pb ore deposit area. By examining the spatial distribution and structural evolution of ore-controlling elements, as well as associated metallogenic bodies, significant progress has been made in understanding the complex subsurface structures of the region. Identifying key marker horizons, lithological variations, and structural disruptions, such as faults and folds, provides crucial insights into the tectonic evolution and mineralization processes governing the deposit.

The new findings provide substantial insights into the stratigraphic and structural architecture of the Jinding Zn-Pb ore deposit. Identifying marker horizons and lithological differences improves the comprehension of subsurface stratigraphy and underscores regions with mineralization potential. Observations of structural disruptions, including faults and folds, demonstrate their impact on stratigraphic continuity, highlighting their significance in forming ore-hosting settings.

The results of this study not only enhance the understanding of the stratigraphic and structural framework of the Jinding ore deposit but also emphasize the importance of methodological innovation in geological research. The approach developed here is a robust foundation for future exploration efforts, offering new strategies for identifying mineralization potential and refining ore-hosting models. Ultimately, the findings contribute to a more refined understanding of the geological factors that control the formation of the Jinding Zn-Pb deposit and provide a solid basis for further advancements in exploration and resource management within the Lanping Basin.

This study emphasizes the significance of methodological innovation in geological research. This comprehensive approach enhances understanding of the Jinding Zn-Pb ore deposit and establishes a foundation for future exploration and methodological progress.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Acknowledgments

This research was financially supported by the Natural Sciences Foundation of China (42163007), the Ministry of Sciences and Technology of China (2021QZKK0301, 2016YFC0600306). We appreciate Prof. Tiannan Yang for his helpful discussions. The authors are thankful to the editor and reviewers for their valuable comments and suggestions which helped to improve the paper.

Authors' Contribution

The author carried out the overall study, including data processing, analysis, interpretation, and manuscript preparation. The data collection was conducted under the supervision of Prof. Yu Changqing. Mohammad Kamal and Li Hao assisted with data processing. Prof. Xue Chuandong and Prof. Yu Changqing contributed to the development of the key concept and provided valuable guidance. All remaining aspects of the work were completed by the author independently.

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