

# Seismic Forward Modeling of the Lower Ordovician in the Northwestern Sichuan Basin

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## Abstract

The Ordovician strata in the northwestern Sichuan Basin comprise a mixed sedimentary succession of clastic and carbonate rocks, the primary target strata are thin and exhibit significant variations in seismic reflections, complicating the interpretation of seismic strata. Consequently, precise well-to-seismic calibration is essential for accurately understanding stratigraphic architecture. Utilizing well logging, mud logging and seismic data from the Ordovician in this region, this study establishes geological models for various stratum interfaces within the mixed sedimentary sequence. Lithological seismic wave velocities are derived through logging analysis, leading to the establishment of a velocity model. Seismic forward modeling was then conducted to elucidate the seismic reflection characteristics and lateral variation responses of stratum interfaces under different lithological and thickness conditions. The findings indicate that the seismic response evolves from a double-peak to a composite wave and ultimately to a single peak as the stratigraphic thickness decreases. Moreover, an increase in the dominant frequency of seismic waves enhances the identification accuracy of thin layers. Specifically, frequencies below 15 Hz are insufficient to resolve layers thinner than 6 meters in the study area. The seismic forward modeling results provide a robust basis for seismic horizon interpretation and enhanced geological understanding in the study area.

## Keywords

Seismic Forward Modeling, Mixed Sedimentation, Model, Ordovician System

## 1. Introduction

The northwest Sichuan region, situated in the northwest of the Sichuan Basin and falling under the administrative jurisdiction of Mianyang and Guangyuan regions, spans a southwest-northeast zone, geotectonically, it lies on the northwest periph-

ery of the Yangtze Platform (Luo, 2021), hosting various geological units like the Deyang-Mianyang Depression, the Tianjingshan Ancient Uplift, and the Central Sichuan Ancient Uplift. The Ordovician system, around the margins of these ancient uplifts and depressions, provides favorable conditions for large-scale shoal bodies development, serving as a crucial target for the exploration of hydrocarbon accumulations. Nevertheless, exploration efforts in the northwest of Sichuan Province remain relatively limited, with uncertainties persisting regarding the stratigraphic development, as well as the distribution of large-scale shoals, which hinders advancements in risk exploration and the discovery of significant resources in the region. The Ordovician strata in the study area, exhibit a mixed sedimentary succession of clastic and carbonate rocks. The primary target layers are thin, exhibit significant variation in seismic reflections, and pose challenges in seismic stratigraphic interpretation. Consequently, precise well-seismic calibration is crucial to comprehend the characteristics of stratum development accurately.

Furthermore, the mixed clastic-carbonate succession presents specific geological challenges. These include difficulties in lithology identification and the evaluation of reservoir effectiveness, increased complexity in selecting optimal exploration targets and deploying well locations, as well as intricate seismic responses that result in reduced prediction accuracy.

Traditional sedimentology theory holds significant differences in the developmental backgrounds of sedimentary facies zones between terrigenous clastic rocks and carbonate rocks. Since the 1950s, the recurring discovery of mixed sediments in stratigraphic sections has increasingly garnered the attention of geologists (Wu et al., 2020). Mount was the first to propose the concept of mixed sedimentation, classifying it primarily as the sedimentary mixing of terrigenous siliceous debris and carbonates during deposition. In this article, mixed sedimentation refers to the incorporation of terrigenous clastic and carbonate components within the same rock layer, as well as the formation of alternating interlayers or intercalations of the two (Ma et al., 2012).

The fundamental characteristics of seismic waves, including amplitude and frequency, are closely linked to the lithology and physical properties of geological strata (Jing et al., 2020; Zhang et al., 2013). Seismic forward modeling technology plays a crucial role in elucidating the seismic response characteristics of geological formations, such as rock masses and structures (Cao et al., 2013; Dai et al., 2023; Huang et al., 2011; Huang et al., 2012), thereby enhancing the accuracy and efficiency of seismic interpretation (Bi et al., 2020). By constructing underground geological models and simulating the propagation of seismic waves through various media, this technology can forecast the seismic wave field responses under diverse geological conditions. This provides a theoretical foundation for interpreting seismic data and aids in optimizing exploration design strategies, representing a key method for overcoming bottlenecks in exploring mixed sedimentary strata. This study focuses on the Ordovician strata in the northwestern Sichuan region. By

utilizing well logging, mud logging and seismic data from the region, it aims to emphasize the seismic response mechanisms at the interfaces of mixed sedimentary sequences and seek to overcome the limitations of traditional exploration methods for these strata.

Current research on mixed sedimentary rock layers in seismic exploration has several limitations: traditional studies often concentrate on the seismic response of a single lithology and pay insufficient attention to mixed sequences of alternating sand-mudstone and carbonate rock; constructed geological models frequently neglect lateral lithologic variation and thickness heterogeneity, which produces discrepancies between forward-modeling results and actual subsurface conditions; and some forward modeling studies of mixed sediments are confined to one-dimensional single-well simulations, lacking two-dimensional profile-scale analysis of lateral responses, which limits insight into the spatial variability of formation interfaces.

At the methodological level, existing research often relies on empirical formulas to estimate velocity parameters for mixed sedimentary rocks. In contrast, this study directly extracts lithology-based velocities from acoustic logging curves, which markedly improves parameter accuracy. Moreover, traditional forward modeling results are rarely compared with actual seismic data, in this study, the forward modeling outputs are overlaid and analyzed alongside real seismic profiles from northwest Sichuan Province to strengthen their reliability and practical applicability. Overall, for the interfaces within the Ordovician mixed sedimentary strata of northwestern Sichuan, there is a lack of integrated systematic research combining “geological modeling—velocity acquisition—forward modeling—real-data verification.” This study intends to explore and contribute specifically in this aspect. The specific research contents are as follows:

- 1) Establish geological models of mixed sedimentary rocks, including one-dimensional geological models of different lithological interfaces and two-dimensional geological models of lateral variations in stratigraphic thickness.
- 2) Utilize acoustic logging to obtain velocities of different lithologies and construct a velocity model.
- 3) Perform seismic forward modeling of geological models, including one-dimensional stratigraphic forward simulation and two-dimensional profile seismic reflection forward modeling.
- 4) Analyze the forward-modeling results in comparison with observed seismic reflection characteristics, and apply the modeling outcomes to seismic interpretation in the study area.

## 2. Methods and Data

### 2.1. Methods

Forward modeling serves as the basis of seismic exploration methods and in seismic data interpretation, it primarily used to validate interpretation schemes and to identify anomalous geological bodies. When real seismic data are ambiguities,

forward modeling technology provides an intuitive and effective tool to support interpretation and to help resolve difficult problems in seismic exploration (Wang & Zhu, 2009).

Seismic forward modeling technology involves constructing geological models that reflect actual underground geological features and simulating these models to generate synthetic seismic records, and then inferring geological conditions by analyzing the response characteristics of these synthetic records (Wang, Qu, & Li, 2014). In geophysics, forward modeling primarily encompasses two methods: the physical modeling method and the numerical modeling method (Bi et al., 2020). This method relies on the assumption that the medium structure and rock physical parameters of underground geological bodies are known. The numerical modeling calculations utilize mathematical techniques. Within a computer environment, researchers design a suitable observation system based on the characteristics of the target body and derive the propagation characteristics of seismic waves in underground media through numerical modeling. Subsequently, the numerical seismic records are computed at predetermined observation points, and these records undergo routine processing and interpretation to yield a specific numerical modeling result of the seismic response profile (Bi et al., 2020). The essence of this approach lies in the numerical simulation of the established geological model. Numerical modeling offers advantages such as flexibility, simplicity, speed, and cost-effectiveness, making it highly significant for interpreting actual seismic data and characterizing underground structures and lithology. Based on the given conditions and comprehensive considerations, the numerical modeling method is adopted in this study for investigation.

The quality monitoring procedure in seismic data processing has reached a relatively advanced stage. Commonly used one-dimensional forward modeling primarily simulates the single seismic record channel of underground horizontal strata at zero offset, with artificial synthetic seismic records serving as the representative (Huang et al., 2012). The artificial synthetic seismic record method is currently the predominant approach for layer calibration, and the creation of high-precision synthetic seismic records is a prerequisite for the calibration of these artificial synthetic records (Mu et al., 2024). This method constructs the seismic response at the wellbore through theoretical simulation, subsequently comparing it with the actual ground seismic profile to achieve alignment of geological layers and the seismic events. Essentially, it employs well logging data to deduce theoretical seismic signals, and then adjust parameters to ensure that the theoretical signals correspond with the actual ones, thereby elucidating the relationship between layers. In this study, one-dimensional forward modeling was conducted to analyze the seismic reflection characteristics of various lithological interfaces.

In contrast to one-dimensional seismic forward modeling, two-dimensional seismic forward modeling employs two-dimensional geological models to simulate the propagation of seismic waves through subsurface media and to generate corresponding seismic responses. This method emphasizes geological features at

the “planar section” scale, wherein underground strata exhibit not only vertical lithological and thickness variations but also lateral distribution differences, such as variations in strata thickness, lateral lithological phase transitions, and structural forms like faults, folds, and spicules. By simulating seismic wave propagation within these two-dimensional models, the resulting seismic responses can reflect lateral variations more accurately, thereby aligning more closely with actual subsurface geological conditions. SMI (Seismic Meme Inversion, Beijing Zhongheng Lihua Petroleum Technology Research Institute, version 4.5) offers an integrated workflow that effectively combines structural and property modeling with seismic simulation, achieving high efficiency. So this paper employed the SMI software to develop a two-dimensional geological model that incorporates lateral variations and generated two-dimensional seismic profiles, thereby providing a theoretical foundation for interpreting real seismic data.

The Ricker wavelet is selected for the subsequent forward modeling in this study, considering its close approximation to actual seismic sources, distinct advantages in mathematics and signal processing, good stability, and its established role as a standard test wavelet in the field of seismic exploration.

## 2.2. Date

The research scope of this study encompasses the Paleo-Uplift in the northwestern and central regions of Sichuan Province, as well as the Deyang-Mianyang Depression (**Figure 1**). Well Pengshen 6, Well Pengshen 2, and Well Longtan 1 were selected for detailed analysis. The target formation for this research is the Ordovician System (**Figure 2**). It can be observed that the Ordovician System in the study area is characterized by mixed sedimentation of both clastic and carbonate rocks. The data utilized primarily consist of well logging, mud logging, and seismic data from the Ordovician system in the study area, allowing for the acquisition of lithology, lithology thickness, velocity, and other relevant data for each well (**Tables 1-3**).

**Table 1.** Statistical summary of petrophysical parameters in Well Pengshen 6.

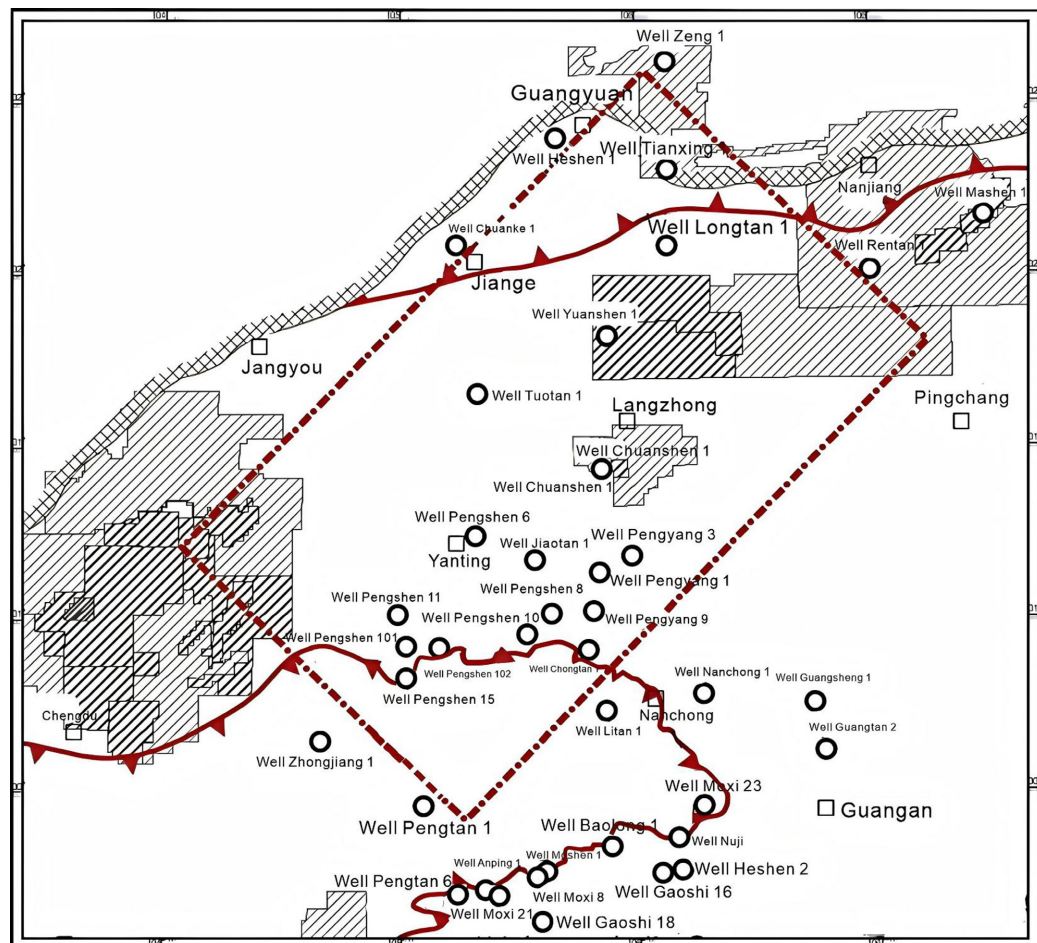
Lithology	Velocity (m/s)	Density (g/cm <sup>3</sup> )	Thickness (m)
Shale	3600	2.4	7
Limestone	5750	2.7	36
Calcareous Mustone	4600	2.55	14
Mudstone	3880	2.45	47
Limestone	5450	2.66	22
Dolomite	5760	2.7	12
Mudstone	3500	2.38	6
Argillaceous Dolomite	5680	2.69	14

**Table 2.** Statistical summary of petrophysical parameters in Well Pengshen 2.

Lithology	Velocity(m/s)	Density(g/cm <sup>3</sup> )	Thickness(m)
Shale	3990	2.46	3
Limestone	5840	2.71	42
Mudstone	4100	2.48	40
Dolomite	6000	2.73	16
Argillaceous Dolomite	5600	2.68	15
Dolomite	6300	2.76	11

**Table 3.** Statistical summary of petrophysical parameters in Well Longtan 1.

Lithology	Velocity(m/s)	Density(g/cm <sup>3</sup> )	Thickness(m)
Shale	4400	2.52	6
Limestone	5900	2.72	47
Mudstone	3900	2.45	11
Dolomite	6200	2.75	7
Argillaceous Dolomite	4600	2.55	14



**Figure 1.** Location map of the study area.

system	series	Formation		
Silurian System	Lower	Longmaxi Formation		
		Wufeng Formation		
Ordovician System	Upper	Baota Formation		
		Shizipu Formation		
	Middle	Meitan Formation		
		Lower	Honghuayuan Formation	
			Tongzi Formation	
	Cambrian System	Upper	Xixiangchi Formation	
		Middle	Gaotai Formation	
			Longwangmiao Formation	
		Lower	Canglangpu Formation	
			Qiongzhusi Formation	
Sinian System	Upper	Dengying Formation		
	Lower	Doushantuo Formation		
Pre-Cambrian				

**Figure 2.** Stratigraphic column of the Sinian Ordovician in the Sichuan Basin.

### 3. Results and Discussion

#### 3.1. One-Dimensional Geological Model and Its Seismic Responses

Based on the data from the Ordovician system in northwest Sichuan Province, Wells Pengshen 2, Pengshen 6, and Longtan 1 were selected for detailed analysis. Accordingly, a one-dimensional geological model was constructed to represent the various lithological interfaces within the mixed sedimentary rock layers of the Ordovician system in the study area. The analysis reveals that in Well Pengshen 6, the Wufeng Formation consists of shale, the Linxiang Formation through to the Shizipu Formation comprises limestone, the Meitan Formation is calcareous mudstone and mudstone, the Honghuayuan Formation is limestone, and the Tongzi Formation includes dolomite, mudstone, and argillaceous dolomite. In Well Pengshen 2, the Wufeng Formation to Linxiang Formation is composed of shale, the Linxiang Formation to Shizipu Formation consists of limestone, the Meitan Formation is mudstone, the Honghuayuan Formation is dolomite, and the Tongzi Formation consists of argillaceous dolomite and dolomite. In Well Longtan 1, the Wufeng Formation is shale, the Linxiang Formation to the Shizipu Formation comprises limestone, the Shizipu Formation to the Meitan Formation consists of mudstone, the Honghuayuan Formation is dolomite, and the Tongzi Formation is argillaceous dolomite.

Using logging data, the seismic responses in underground strata were simulated

with software. The synthetic seismic records were then aligned with the actual seismic profile adjacent to the well. By adjusting parameters such as the wavelet phase and local velocity, the reflection events (e.g., strong peaks and troughs) of the synthetic records were matched with those of the actual seismic data in terms of phase and amplitude as closely as possible. When the synthetic record aligns with the actual seismic profile, the geological layer positions identified in the logging can be directly correlated with specific reflection events on the actual seismic profile.

Through one-dimensional seismic forward simulation (Figures 3-5), the following seismic responses were determined: The top of the Ordovician at Well Pengshen 6 exhibits a peak reflection, while the Lower Ordovician, with a thickness of 54 meters, displays a double-peak reflection. Both the Tongzi Formation and the Meitan Formation are characterized by peak reflections. In Well Pengshen 2, the top of the Ordovician also shows a peak reflection. However, the lower Ordovician, with a thickness of 42 meters, presents a composite wave reflection. The Meitan Formation exhibits peak reflections, whereas the Tongzi Formation is in a near-zero phase. In Well Longtan 1, the top of the Ordovician system reveals a slightly upward reflection of the wave peak, while the lower Ordovician system, with a thickness of 19 meters, demonstrates a semi-peak reflection. The Meitan Formation shows a zero phase, and the Tongzi Formation reflects slightly below a wave peak.

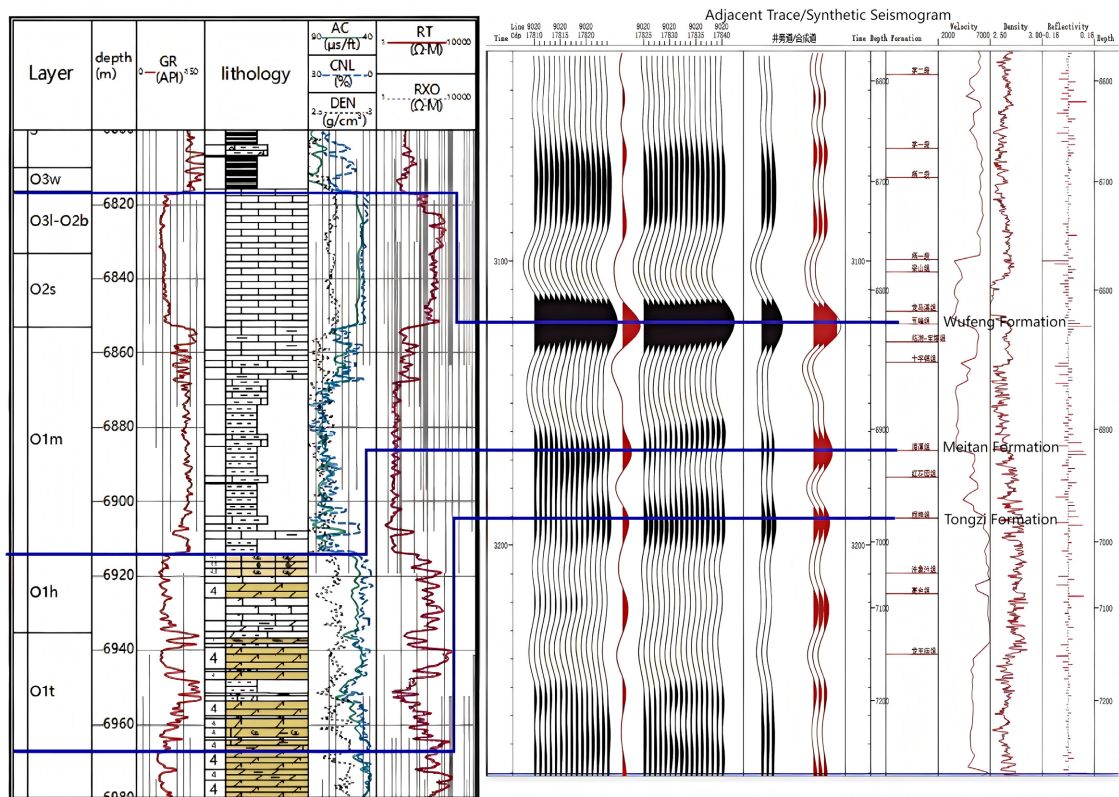


Figure 3. Well to seismic calibration for Well Pengshen 6.

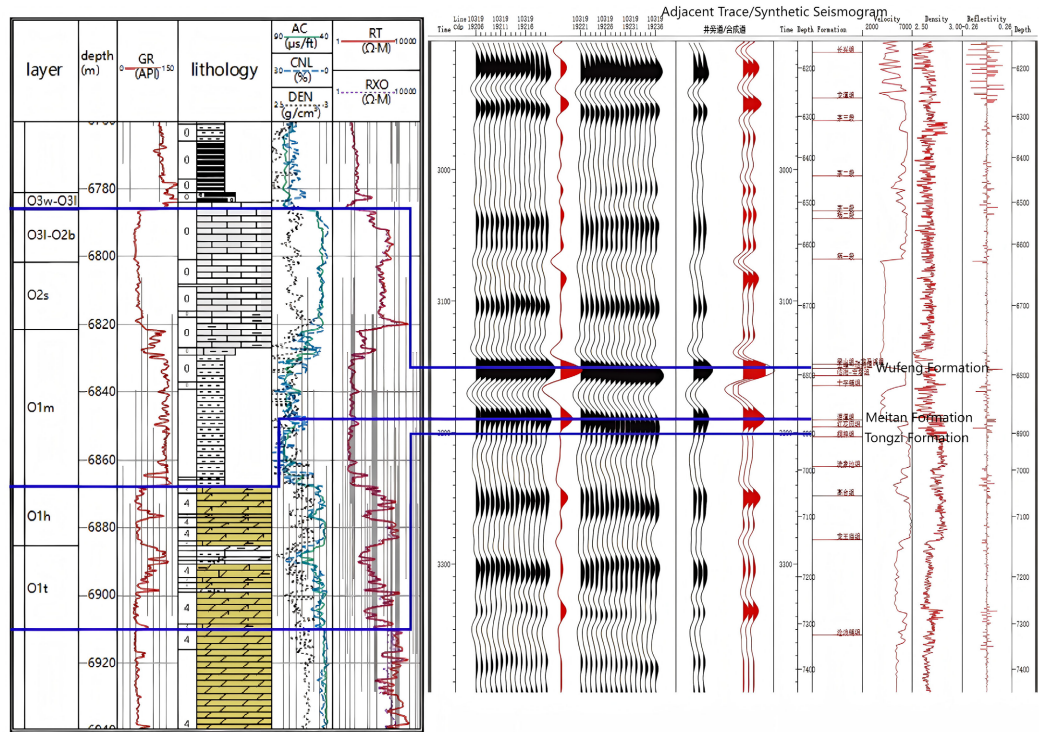


Figure 4. Well to seismic calibration for Well Pengshen 2.

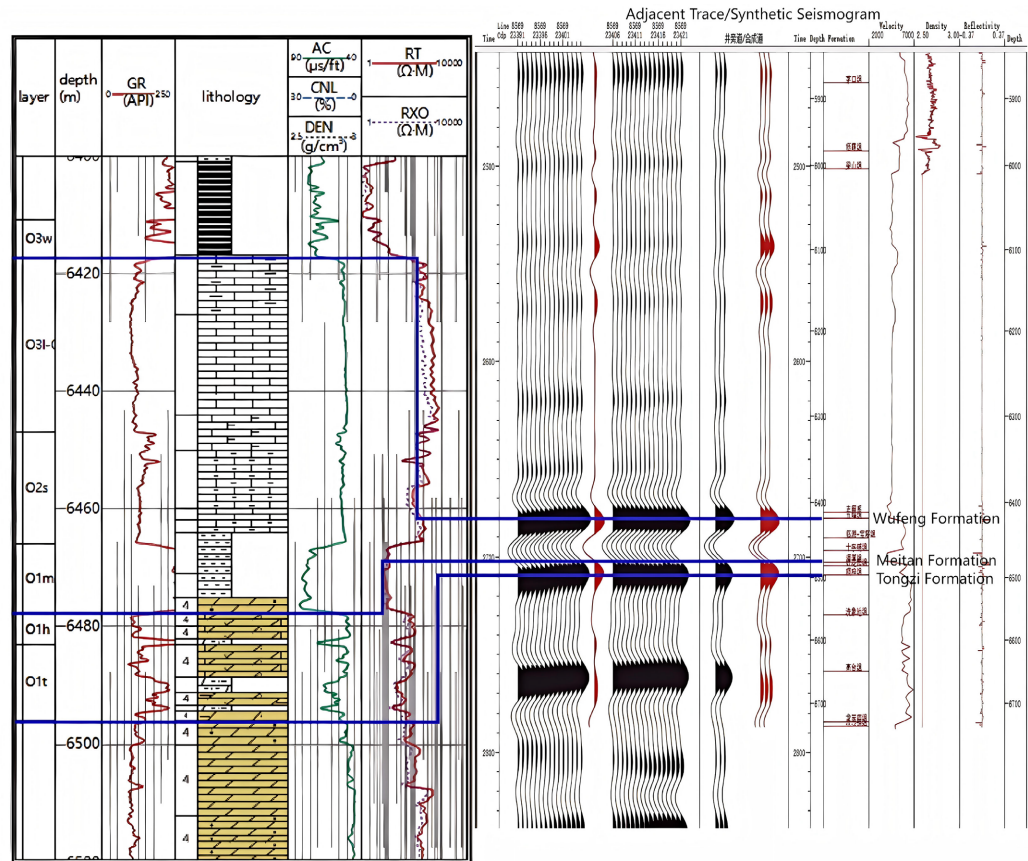


Figure 5. Well to seismic calibration for Well Longtan 1.

Based on the summary of the three selected wells (**Table 4**) and analysis of the one-dimensional forward modeling results, it can be concluded that strata thicker than 45 meters exhibit a double-peak reflection with both the top and base interfaces as peaks. For thicknesses between 25 and 45 meters, the response is a composite wave, with the top as a peak and the base near zero-phase. When the thickness is less than 25 meters, the response becomes a single to semi-peak reflection, where the top is at zero-phase and the base is reflected slightly below a peak.

**Table 4.** Summary of 1D forward modeling results.

Well	Reflection at Top Ordovician	Thickness of Lower Ordovician (m)	Seismic Response of Lower Ordovician	Response of Tongzi Formation (Lower Ordovician top)	Response of Meitan Formation (Lower Ordovician base)
Pengshen 6	Peak reflection	54	Double-peak reflection	Peak reflection	Peak reflection
Pengshen 2	Peak reflection	42	Composite wave reflection	Near-zero phase	Peak reflection
Longtan 1	Reflection slightly above a peak	19	Semi-peak reflection	slightly below a peak.	Zero-phase

## 3.2. Two-Dimensional Geological Model and Seismic Forward Modeling

### 3.2.1. Two-Dimensional Geological Model

Utilizing the one-dimensional geological models of the Ordovician formations from Well Pengshen 6, Well Pengshen 2, and Well Longtan 1, along with the lithological velocities derived from logging data (**Tables 1-3**), two two-dimensional geological models were ultimately developed using SMI software. The model's horizontal extent measures 1000 meters, while the vertical dimension corresponds to the actual depth. In **Figure 6**, Well Pengshen 2 is characterized by a lateral width ranging from 0 to 300 meters. The lithological sequence, from top to bottom, consists of the following layers: the first layer is shale; the second layer is limestone, with a thickness of 42 meters; the third layer is mudstone, with a thickness of 40 meters; the fourth layer is dolomite, with a thickness of 16 meters; the fifth layer is argillaceous dolomite, with a thickness of 15 meters; the sixth layer is dolomite, with a thickness of 11 meters; and the seventh layer is limestone from the Cambrian Xixiangchi Formation. In the horizontal width range of 700 to 1000 meters, Well Pengshen 6 exhibits a different lithological composition, which, from top to bottom, includes: the first layer is shale; the second layer is limestone, with a thickness of 36 meters; the third layer is gray mudstone, with a thickness of 14 meters; the fourth layer is mudstone, with a thickness of 47 meters; the fifth layer is limestone, with a thickness of 22 meters; the sixth layer is dolomite, with a thickness of 12 meters; the seventh layer is mudstone, with a thickness of 6 meters; the

eighth layer is argillaceous dolomite, with a thickness of 14 meters; and the ninth layer is limestone from the Cambrian Xixiangchi Formation. The lithology between 300 and 700 meters in lateral width represents a transitional zone from Well Pengshen 2 to Well Pengshen 6. In Figure 7, Well Longtan 1 is located within the model's lateral width ranging from 0 to 300 meters. The lithological sequence, from top to bottom, consists of the following layers: the first layer is shale; the second layer is limestone, with a thickness of 47 meters; the third layer is mudstone, with a thickness of 11 meters; the fourth layer is dolomite, with a thickness of 7 meters; the fifth layer is argillaceous dolomite, with a thickness of 12 meters; and the sixth layer is limestone from the Xixiangchi Formation of the Cambrian period. Within the horizontal width range of 700 to 1000 meters lies Well Pengshen 6. The lithology within the lateral width range of 300 to 700 meters represents a transitional zone from Well Longtan 1 to Well Pengshen 6.

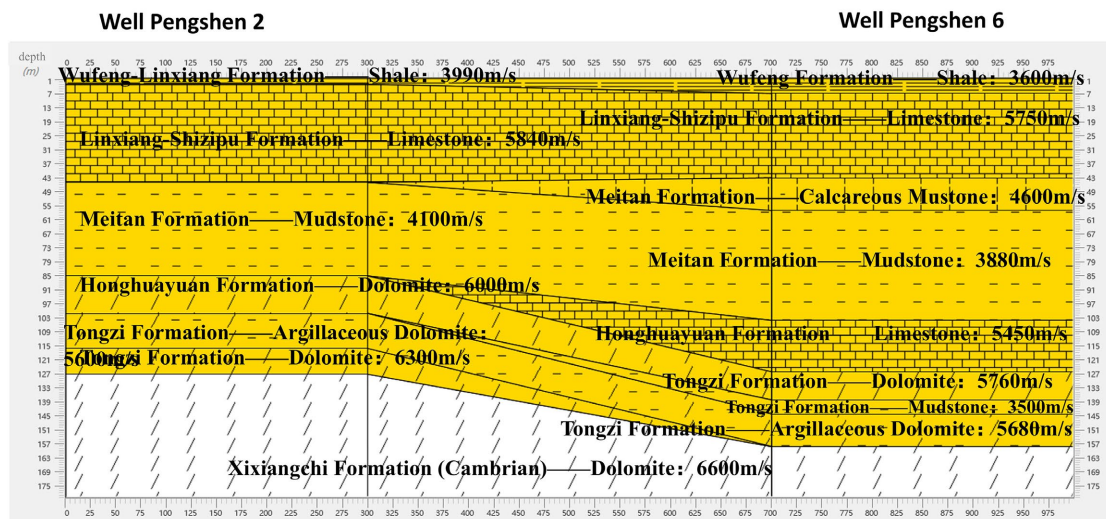


Figure 6. Two dimensional geological model between Wells Pengshen 2 and Pengshen 6.

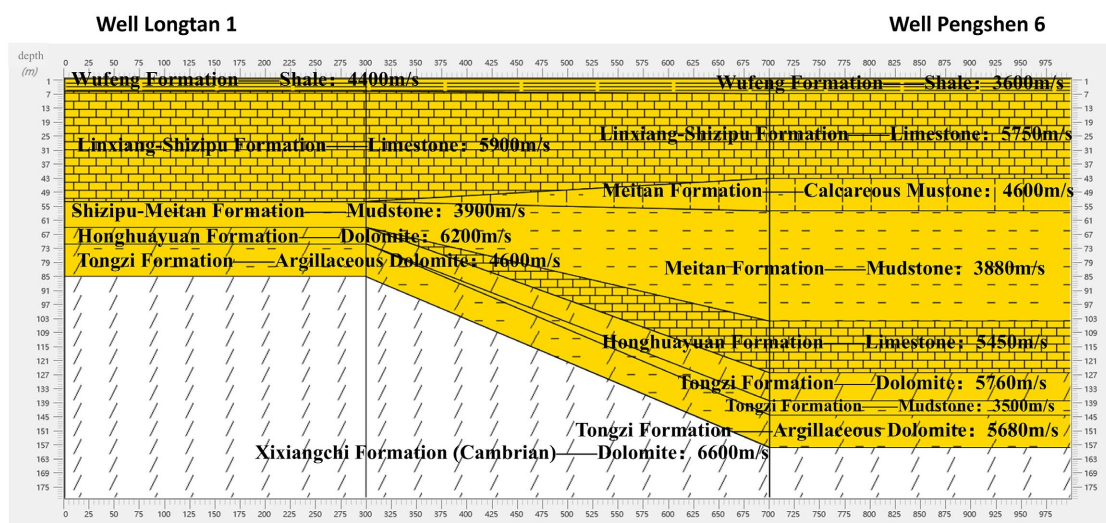


Figure 7. Two dimensional geological model between Wells Longtan 1 and Pengshen 6.

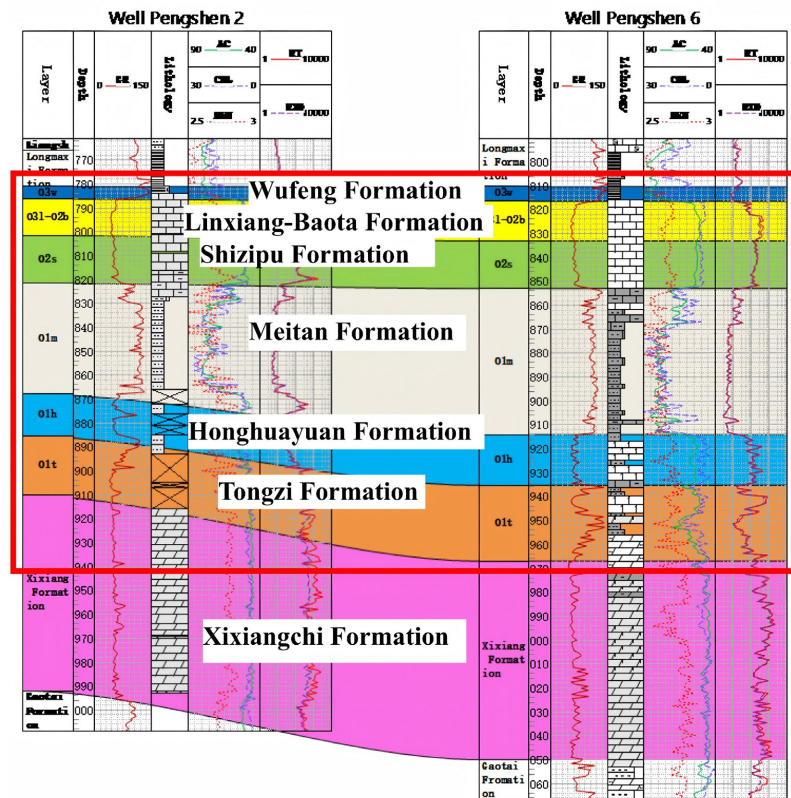


Figure 8. Well correlation profile between Wells Pengshen 2 and Pengshen 6.

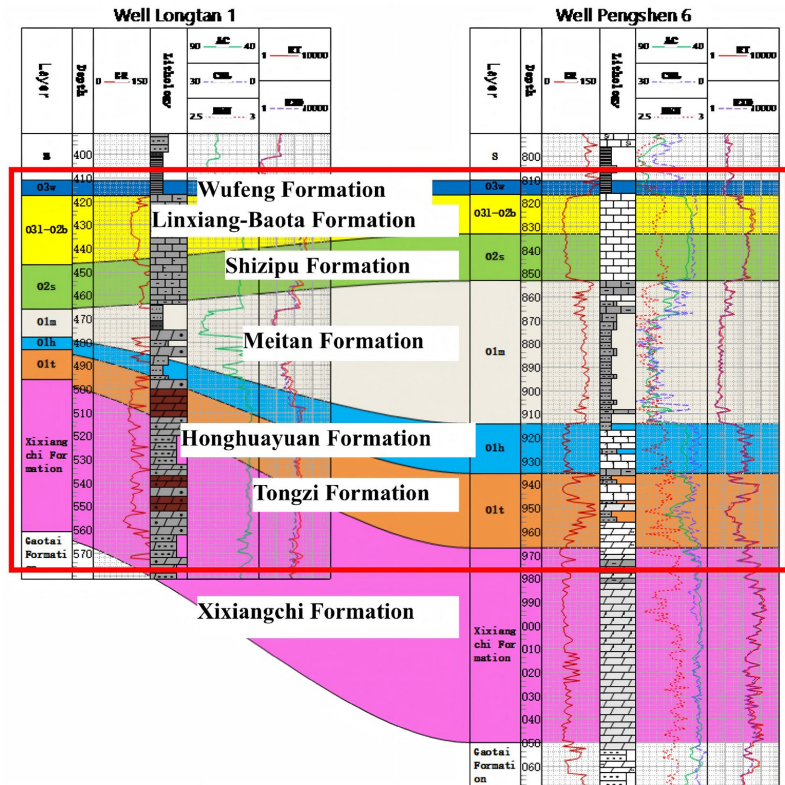
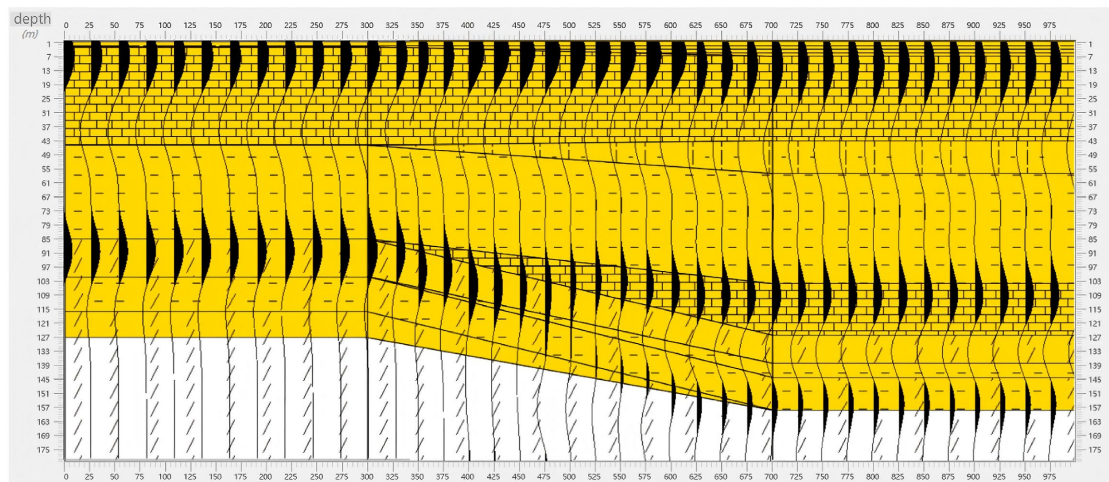


Figure 9. Well correlation profile between Wells Longtan 1 and Pengshen 6.

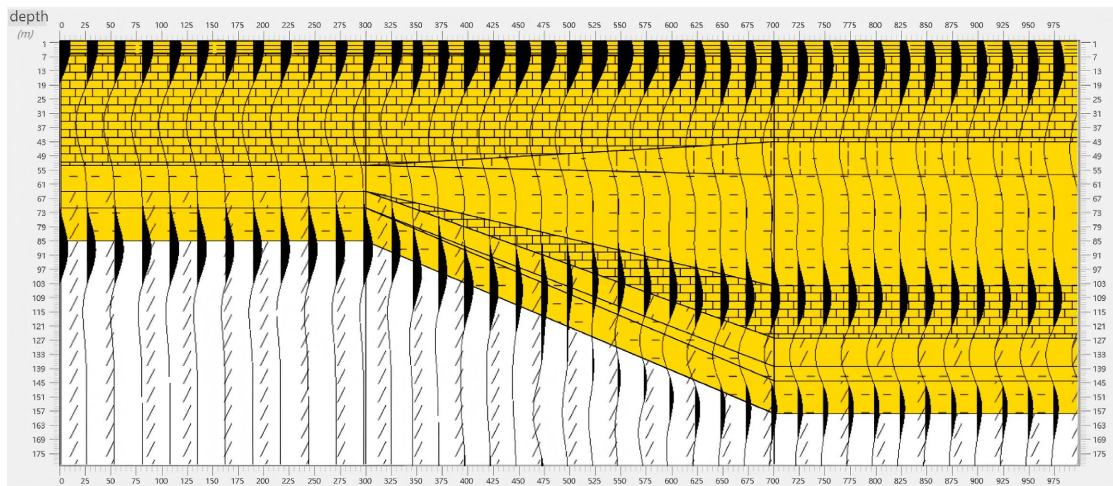
Subsequently, the actual well connection profiles of Wells Pengshen 2-Pengshen 6 and Longtan 1-Pengshen 6, illustrated in **Figure 8** and **Figure 9**, were compared with the established two-dimensional geological model to assess the validity of the model.

### 3.2.2. Two-Dimensional Seismic Forward Modeling

Forward modeling of the two distinct two-dimensional geological models was conducted using the SMI software, resulting in synthetic seismic profiles for the geological models of Well Pengshen 2-Well Pengshen 6 and Well Longtan 1-Well Pengshen 6 (**Figure 10**, **Figure 11**).



**Figure 10.** Synthetic seismic section between Wells Pengshen 2 and Pengshen 6.



**Figure 11.** Synthetic seismic section between Wells Longtan 1 and Pengshen 6.

The synthetic seismic profiles reveal pronounced wave peaks at the stratum interfaces where significant differences in wave impedance exist. The seismic responses of Well Pengshen 2, Well Pengshen 6, and Well Longtan 1 align with the results from one-dimensional seismic forward modeling. As the transition occurs

from Well Pengshen 6 to Well Longtan 1, where some lithological units gradually pinch out and bed thickness decreases, the seismic response evolves from a double-peak to a composite wave and then to a single peak. This finding is similarly reflected in the composite seismic profile of Wells Pengshen 2 to Pengshen 6. Comparison with the actual seismic profiles (Figure 12, Figure 13) reveals that the phenomenon of double peaks transitioning to single peaks is also evident in the real seismic data.

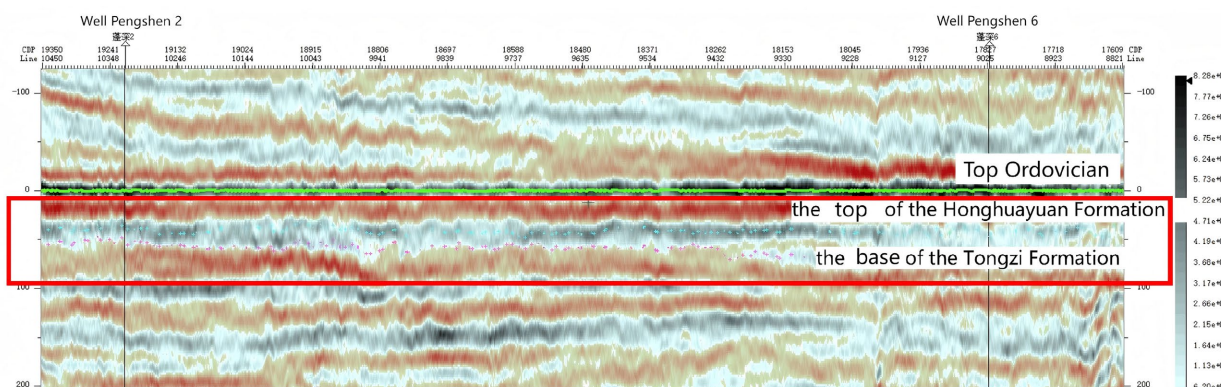


Figure 12. Actual seismic section between Wells Pengshen 2 and Pengshen 6.

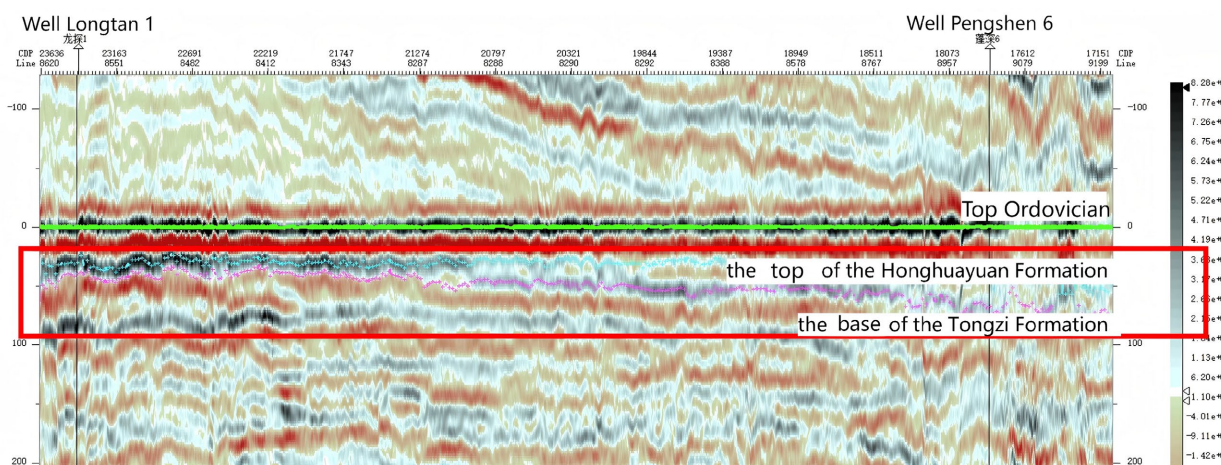
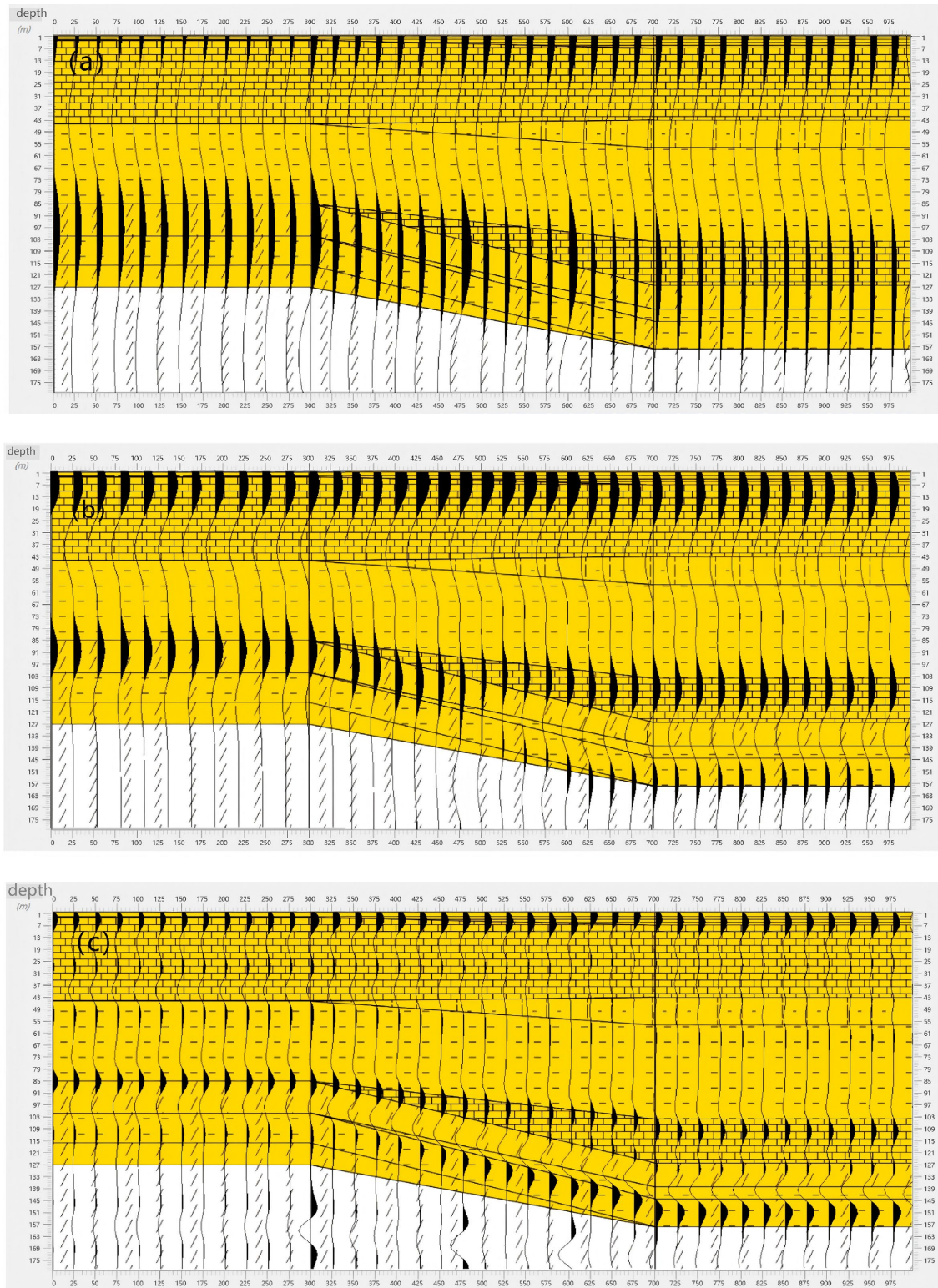
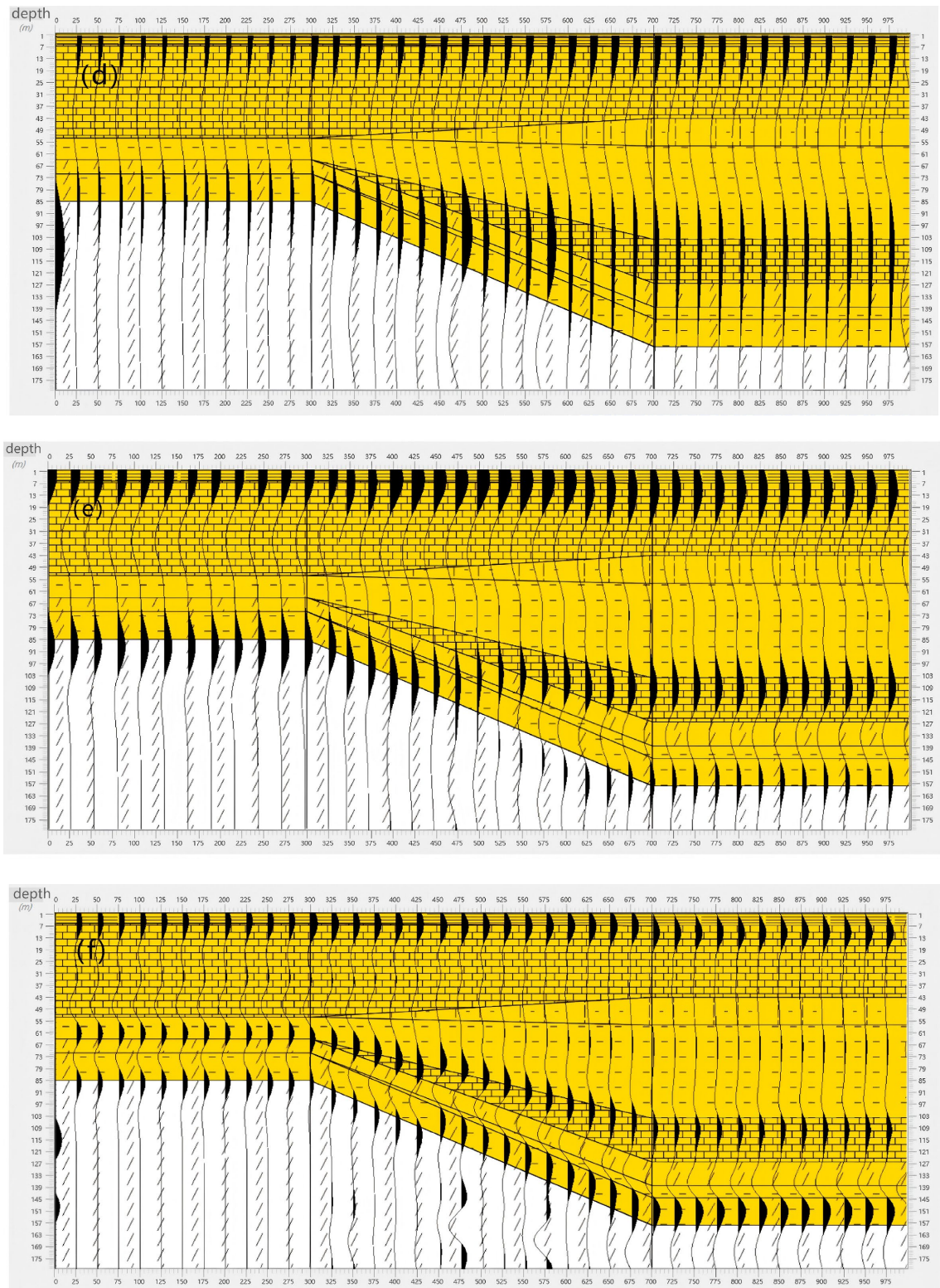


Figure 13. Actual seismic section between Wells Longtan 1 and Pengshen 6.

Two-dimensional seismic forward modeling using a Ricker wavelet observed that the magnitude of the seismic dominant frequency significantly influences the identification capability of thin layers. In the Pengshen 2-Pengshen 6 well model, the results indicate that when the selected seismic dominant frequency is 15 Hz, a 6-meter-thick mudstone layer is not discernible in the synthesized seismic profile (Figure 14(a)). In contrast, it became clearly identifiable at 35 Hz and above (Figure 14(b)). Even at 80 Hz, thin-layer interfaces with subtle impedance contrasts were detected (Figure 14(c)). Similarly, two-dimensional forward modeling was executed on the Longtan 1-Pengshen 6 well model, low dominant frequencies failed to clearly delineate several thin layers and interfaces near Well Pengshen-6

(Figure 14(d)). However, as the dominant frequency increased, the responses of all interfaces became distinctly observable (Figure 14(e), Figure 14(f)). Consequently, it can be concluded that an increase in the dominant frequency of seismic waves correlates with enhanced identification accuracy of thin layers.





**Figure 14.** Synthetic seismic sections at different dominant frequencies. (a) Synthetic seismic section between Wells Pengshen 2 and Pengshen 6 at 15 Hz; (b) Synthetic seismic section between Wells Pengshen 2 and Pengshen 6 at 35 Hz; (c) Synthetic seismic section between Wells Pengshen 2 and Pengshen 6 at 80 Hz; (d) Synthetic seismic section between Wells Longtan 1 and Pengshen 6 at 15 Hz; (e) Synthetic seismic section between Wells Longtan 1 and Pengshen 6 at 40 Hz; (f) Synthetic seismic section between Wells Longtan 1 and Pengshen 6 at 60 Hz.

## 4. Conclusion

This study successfully delineated the seismic response characteristics of lithological interfaces and their lateral variations within the Ordovician sequence through the construction of geological models and subsequent seismic forward modeling. The findings provide a crucial foundation for seismic-geological interpretation and enhance the resolution and accuracy of seismic exploration in this region. The key conclusions derived from this work are summarized as follows:

1) Within the study area, the top of the Ordovician is consistently characterized by a peak reflection. Analysis of the three selected wells reveals that as the stratigraphic thickness decreases laterally, the corresponding seismic response transitions from a double-peak through a composite wave to a single peak. Specifically, strata thicker than 45 meters exhibit a double-peak reflection with both the top and base interfaces as peaks. For thicknesses between 25 and 45 meters, the response is a composite wave, with the top as a peak and the base near zero-phase. When the thickness is less than 25 meters, the response becomes a single to semi-peak reflection, where the top is at zero-phase and the base is reflected slightly below a peak.

2) Seismic forward modeling using a Ricker wavelet established that thin-bed resolution improves with higher dominant frequencies, with the 6-meter layer in the study area can not be resolved at frequencies below 15 Hz.

3) The seismic forward modeling results provide an effective guide for seismic horizon interpretation in the study area. Specifically, different interfacial reflection characteristics should be selected for interpretation in zones with varying stratigraphic thicknesses. This work establishes a solid foundation for reservoir prediction and the selection of favorable exploration targets in the study area.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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