Structural Characteristics and Tectonic Evolution of the Wunansha Uplift in the South Yellow Sea Basin, China

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By selecting typical seismic sections to carry out detailed structural interpretation, the structural style features of the Wunansha Uplift in the South Yellow Sea basin were systematically combined, and the compressional structures (imbricate, opposite/back thrust, and Y-shaped structures), strike-slip faults (positive flower-shaped faults), and extensional normal faults (listric-shaped normal faults) were identified. On this basis, combined with the characteristics of the regional stress field and the background of deep geodynamics, the genetic mechanism and structural evolution of the structural style in the Wunansha Uplift were defined. The stress mechanism of the compressional structures originated from the initial high-speed and low-angle NW subduction of the paleo-Pacific plate during the early Yanshanian movement in the Early Jurassic. The regional strike-slip fault was mainly a positive flower structure with compression and torsion characteristics, and its stress mechanism originated from sinistral shear caused by the Early Cretaceous low-angle NNW subduction of the paleo-Pacific plate. The Tan-Lu fault in eastern China also had sinistral shear characteristics in this period. The extensional normal fault was characterized by a listric shape, which developed along the northern boundary of the Wunansha Uplift, that is, the connection between the Wunansha Uplift and the Southern Depression of the South Yellow Sea basin. The stress mechanism was derived from the transition of the paleo-Pacific plate from low-angle to high-angle subduction during the late Yanshanian movement in the Late Cretaceous. Simultaneously, the tectonic stress system in eastern China also changed from compressional to tensional.

1. Introduction

The South Yellow Sea basin is located in the central paleo-Asian and circum-Pacific tectonic domains [1] and in the northeastern margin of the lower Yangtze plate [2, 3]. It is a basin containing Mesozoic-Cenozoic continental deposits superimposed on Mesozoic-Paleozoic marine carbonate rocks [4], and has experienced superimposed transformation because of multistage tectonic movement, such as the Caledonian movement at the end of the Silurian, the Indosinian movement in the Late Triassic and the Yanshanian episodic movement since the Early Jurassic; in addition, a tectonic framework of North-South two-directional enclosed extrusion has formed in the South Yellow Sea basin [5–13].

The Wunansha Uplift is located in the southernmost part of the South Yellow Sea basin. Its structural characteristics have been mainly controlled by the convergence of the lower Yangtze plate and Cathaysian plate in the Caledonian movement at the end of the Silurian and the multistage subduction of the paleo-Pacific plate in the Yanshanian episodic movement since the Early Jurassic. The collisional orogeny of the North China plate and the lower Yangtze plate in the Late Triassic Indosinian movement was mainly concentrated in the northern part of the South Yellow Sea basin, and its control on the Wunansha Uplift was relatively weak. At present, only the CZ35-2-1 well, which was drilled in December 2000, exists in the Wunansha Uplift; it revealed the Quaternary to Permian Qixia Formation but showed no oil and gas. Since then, there have been few reports on the Wunansha Uplift [14], and research on the structural features of the Wunansha Uplift has been stagnant for a long time. Therefore, a systematic analysis of the relationship between the structural characteristics and multistage tectonic movements of the Wunansha Uplift is helpful for a
more comprehensive understanding of the Mesozoic-Paleozoic tectonic deformational history in the South Yellow Sea basin.

In this study, we selected typical seismic sections of the Wunansha Uplift in the South Yellow Sea basin to carry out detailed structural interpretation and systematically sort the structural style characteristics of the Wunansha Uplift. Then, in combination with the characteristics of the regional stress field and dynamic background, the genetic mechanism and tectonic evolution of the structures in the Wunansha Uplift were clarified. This paper fills in the research gap on the structural characteristics of the Wunansha Uplift in the South Yellow Sea basin and establishes a solid data foundation for further study on the Mesozoic-Paleozoic structural characteristics in the South Yellow Sea basin.

2. Geological Setting

Geographically, the South Yellow Sea lies between the Chinese mainland and the Korean Peninsula. The northern part of the South Yellow Sea basin is connected to the North Yellow Sea by a line between Chengshanjiao on the Shandong Peninsula and Bailing Island off the Korean Peninsula, and the southern part is connected to the East China Sea by a line between Qidongjiao in Jiangsu Province and Jeju Island off the Korean Peninsula. The South Yellow Sea basin extends to the coasts of Shandong and Jiangsu Provinces in the west and to the west coast of the Korean Peninsula in the east. The area of the South Yellow Sea basin is approximately $30 \times 10^4$ $\text{km}^2$ [15].

Tectonically, the South Yellow Sea basin is mainly located on the Yangtze platform, which is an extension of the lower Yangtze platform in the northeast direction [7]. The northern boundary of the South Yellow Sea basin is adjacent to the North China plate at the Qianliyan Uplift north fault, the southern boundary is connected with the Cathaysian plate at the Jiangshan-Shaoxing fault, the western boundary is connected with the Subei basin at the Subei-Binhai fault, and the eastern boundary is the eastern margin fault of the Yellow Sea. It should be pointed out that the northern and southern boundaries of the South Yellow Sea basin are the products of two stages of collisional orogeny belts (the collisional orogeny between the North China and lower Yangtze plates and the convergence of the lower Yangtze and Cathaysian plates), which are characterized by complex thrust fault zones [16–18]. The western and eastern boundaries are controlled by the multistage subduction of the paleo-Pacific plate since the late Mesozoic and are mainly characterized by regional strike-slip faults [19–21].

From north to south, the South Yellow Sea basin can be divided into the Qianliyan Uplift, Northern Depression, Central Uplift, Southern Depression and Wunansha Uplift, which forms a structural pattern of “three uplifts and two depressions”. Among them, the Southern Depression can be regarded as the offshore extension of the Subei basin, while the Wunansha Uplift, which is a positive structural unit of the Mesozoic-Paleozoic, is located at the southernmost end of the South Yellow Sea basin (Figure 1).

As a typical superimposed basin that is the combination of a Mesozoic-Paleozoic marine residual basin and a Mesozoic-Cenozoic continental faulted basin, the South Yellow Sea basin can be divided into two sets of structural layers. One set is a marine Mesozoic-Paleozoic structural layer that has Sinian to Early-Middle Triassic marine strata that are part of a stable platformal-type basin sedimentary assemblage. The second set is a continental facies Mesozoic-Cenozoic structural layer, which is composed of a Late Jurassic to Quaternary dustpan fault depression and lake basin sedimentary combination, a depression basin fluvial facies and a marine-land transitional clastic sedimentary facies [22]. The Wunansha Uplift in the South Yellow Sea basin mainly contains thick marine Mesozoic-Paleozoic strata. The Indosinian movement at the end of the Triassic resulted in uplift and erosion of the Wunansha Uplift and corresponding missing upper Triassic, Jurassic and Cretaceous strata. Cenozoic sediments directly cover the Middle Triassic Zhouchongcun Formation.

3. Data and Methods

The seismic sections acquisition of the Wunansha Uplift was concentrated in the 1990s. In this study, eight typical seismic sections (A-A’, B-B’, C-C’, D-D’, E-E’, F-F’, G-G’, H-H’) of the Wunansha uplift are collected, which are shown in Figure 1. The total length of these seismic sections is about 980 km, and the spacing distance between each seismic section is 10-20 km. The seismic reflection data of them were acquired by air gun, recorded for 5 s, and sampled at 2 ms. The shots distance and the receivers distance are both 25 m. According to the wave impedance reflection characteristics of these typical seismic sections, seven seismic reflection interfaces are identified in the Mesozoic-Paleozoic strata of the Wunansha Uplift in the South Yellow Sea basin: T8, T9, T10, T11, T12, T13 and Tg. The characteristics of each reflection interface are as follows (Figure 2). The T8 reflection interface is equivalent to the seismic reflection at the bottom of Cenozoic and has a clear reflection interface, a strong amplitude, good continuity and an angular unconformity with the underlying strata. The T9 reflection interface is equivalent to the seismic reflection at the bottom of Qinglong Formation of Lower Triassic and has a clear reflection interface, a moderately strong amplitude and a continuous reflection. The T10 reflection interface is equivalent to the seismic reflection at the bottom boundary of lower Permian Qixia Formation and has a clear reflection interface, a moderately strong amplitude and a relatively continuous reflection. The T11 reflection interface is equivalent to the seismic reflection at the bottom of the Upper Devonian Wutong Formation and has a clear reflection interface, a moderately strong amplitude and a continuous reflection, and an angular unconformity with the underlying strata. The T12 reflection interface is equivalent to the seismic reflection at the bottom boundary of the lower Silurian Gaojiabian Formation and shows a medium-strong amplitude and relatively poor continuity. The T13 reflection interface is equivalent to the bottom boundary of the Cambrian system and has a weak amplitude and poor continuity. The Tg reflection interface is equivalent to the bottom Sinian boundary and has a weak amplitude and poor continuity.
In this study, the balanced profile restoration technology is mainly used to analyze the structural evolution characteristics of the Wunansha Uplift. This technology follows the principle of conservation of area and layer length. Since the Wunansha Uplift mainly develops rigid strata, the principle of layer length conservation is adopted, that is, assuming that the thickness of the stratum is unchanged, the length of the stratum after deformation is the same as that during original deposition [23]. After the restoration of stratigraphic deformation and expansion characteristics of the current profile, the structural evolution profiles of different stages in the Wunansha Uplift can be obtained. Due to the lack of drilling disclosure in the deep strata of the Wunansha Uplift, the erosion data at each stage are mainly obtained by the formation trend method. See Figures 3 and 4 in “Analysis of the genetic mechanism” for detailed structural evolution profiles.

4. Structural Style Features

In this paper, typical seismic sections in the Wunansha Uplift are selected to carry out detailed structural interpretation, and a variety of combination structural styles, such as compressional structures (imbricate, opposite/back thrust, and Y-shaped structures), strike-slip faults (positive flower-shaped faults), and extensional normal faults (listric-shaped normal faults), are identified.

The most important structural features of the Wunansha Uplift are the compression structural styles, which vary and are widely distributed in the Wunansha Uplift. Among them, the most typical compression structural styles are imbricate structures, opposite/back thrusts and Y-shaped structures (Figure 5).

Imbricate structures refer to a series of reverse fault combinations with the same tendency. The hanging wall of each
fault uplifts relative to the next block and successively overlaps the next to form a succession similar to roof shingles or scales; thus, it is called an imbricate structure, also known as an imbricate fault. The imbalanced structure developed in the Wunansha Uplift is characterized by an en echelon distribution in plane view, a steep fault dip angle and a long vertical extensional distance in profile; some faults extend down to the Tg plane.

Opposite thrusts occur when two thrust faults are opposite and their respective hanging wall fault blocks are thrust onto their mutual footwall fault block by compression displacement, which causes the common footwall fault block in the middle to sink relative to the hanging wall fault blocks. This process results in an opposite thrust. However, if the two faults are face-to-face, compressional displacement causes their common hanging wall fault block in the middle to uplift relative to the footwall blocks. This process results in a back thrust structure.

Y-shaped structures are composed of a main thrust fault and a branch reverse fault, and structural deformation is mainly developed in the hanging wall of the main fault. According to the combined characteristics of the main fault and branch fault, the fault can be further divided into a positive Y-shaped structural style and an anti-Y-shaped structural style.

The strike-slip structures developed in the Wunansha Uplift are mainly positive flower structures (Figure 6). In a positive flower structural style, the fracture zone composed
of the main strike-slip fault and the associated branch faults is called the flower structure, which has a "flower" shape that is wide at the top and narrow at the bottom. Among this type of structure, a normal flower structure is produced under the action of compression and torsion, and most of its faults have reverse fault displacements. A positive flower structure indicates that the fault was formed due to strike-slip action and local compression or due to oblique convergence and strike-slip action. The positive flower structure developed in the Wunansha Uplift is a back thrust structure...
composed of a steep strike-slip fault and associated thrust faults. The cutoff stratum is an anticline (Figure 6), with sinistral shear strike-slip properties and NNW-SSE strikes (see Figure 1 for the location of the strike-slip fault). It is speculated that the formation mechanism of this strike-slip fault is similar to that of the NNW-SSE-trending boundary strike-slip fault (the Subei-Binhai fault) [20] between the Subei basin and the Southern Depression of the South Yellow Sea basin; this formation mechanism needs more in-depth comparative study.

Figure 4: NE-SW-trending tectonic evolution section of the Wunansha Uplift, South Yellow Sea basin (see Figure 1 for profile location).
The extension in the Wunansha Uplift is relatively weak. The extensional structure, as the boundary fault between the Wunansha Uplift and Southern Depression, has the characteristics of a normal listric-shaped fault with a steep top and gentle bottom, which indicates that the Southern Depression of the South Yellow Sea basin began to form and accept sedimentation afterwards. In addition, local extensional structural assemblages are visible in residual sub-depressions, which were developed locally in the Wunansha Uplift.

5. Analysis of the Genetic Mechanism

Based on the study of the structural styles of the Wunansha Uplift in the South Yellow Sea basin combined with the...
characteristics of the regional stress field and the deep geodynamic background, the genetic mechanism of the structural style of the Wunansha Uplift is clarified (Figure 7) and the tectonic evolution process of the Wunansha Uplift in the South Yellow Sea basin is systematically sorted (Figures 3 and 4). There is a good correlation between the multistage tectonic movement and the spatial-temporal distribution, development stages and genetic mechanism of structural styles in the Wunansha Uplift in the South Yellow Sea basin. The details are as follows.

*The Caledonian movement at the end of Silurian.* During the early Paleozoic, the Cathaysian plate subducted under the Yangtze plate, and the South China Ocean contracted in a pulsating mode, leading to the Caledonian movement at the end of the Silurian. After the disappearance of the South China Ocean, the Yangtze plate and the Cathaysian
The early Yanshanian movement in the Late Triassic. The Indosinian movement at the end of the Triassic was an important turning point in the tectonic framework of eastern China. Since then, eastern China has shifted from the paleo-Asian tectonic domain to the circum-Pacific tectonic domain [25, 26]. Due to the closure of the Qinling Ocean in the late Early Triassic, the Yangtze plate moved northward rapidly and collided with the North China plate at the end of the Triassic, forming the Qinling-Dabiesulu orogenic belt [27, 28]. The Indosinian movement completely changed the development of the Paleozoic basins in eastern China, causing the early prototypes of the basins to undergo great changes.

Under the influence of collisional orogeny between the Yangtze and North China plates during the Indosinian movement at the end of the Triassic, a complete foreland basin system formed in the northern part of the South Yellow Sea basin that included the wedge top zone of the Qianliyan Uplift, the foredeep zone of the Northern Depression, and the foreland belt of the Central Uplift [29]. The compressive strength gradually decreased from north to south. There was no obvious compression structural style in the southern part of the South Yellow Sea basin, which showed only a certain degree of strata uplift and erosion in the Wunansha Uplift (Figures 3(b) and 4(b)).

The early Yanshanian movement in the Early Jurassic. In the Early Jurassic, the deep geodynamic background and the characteristics of the regional stress field in eastern China changed greatly. The paleo-Pacific plate began to subduct relative to the Eurasian plate in the NW direction at a high speed and low angle [30], indicating that the beginning of the early Yanshanian movement was dominated by compression and thickening in eastern China [31]. At this time, the South Yellow Sea basin experienced NW-SE compressional stress, and imbricate structures, opposite/back thrusts and Y-shaped structures widely developed in the Wunansha Uplift (Figures 3(c) and 4(c)).

Sinistral shear movement in the Early Cretaceous. During the Early Cretaceous, the low-angle subduction direction of the paleo-Pacific plate changed from NW to NNW, which resulted in strong sinistral shear transformation in eastern China. At this time, the Tan-Lu fault zone experienced strong left-lateral translation [30]. In the seismic section of the Wunansha Uplift in the South Yellow Sea basin, a positive flower structure composed of a main strike-slip fault and associated branch faults is shown. The strike-slip fault developed in the Wunansha Uplift had a formation mechanism similar to that of the NNW-SSE-trending boundary strike-slip fault (Subei-Binhai fault) between the Subei basin and Southern Depression of the South Yellow Sea basin (Figure 4(d)).

The late Yanshanian movement in the late Cretaceous. In the Late Cretaceous, the subduction angle of the paleo-Pacific plate gradually became steeper, resulting in mantle upwelling and plate retreat. The tectonic stress system in eastern China changed fundamentally from a NNW-SSE compressive stress environment to a NNW-SSE regional tensile stress environment, indicating that the late Yanshanian movement was dominated by extensional thinning in eastern China [31]. At the northern boundary of the Wunansha Uplift in the South Yellow Sea basin, a listric-type normal fault developed, which was steep in the upper part and gentle in the lower part (Figure 3(d)). At this time, the Southern Depression of the South Yellow Sea basin formed and began to accept sedimentation, which also marked the beginning of the Cenozoic evolution of the South Yellow Sea basin.
6. Conclusions

In the Wunansha Uplift of the South Yellow Sea basin, there have been many structural combination styles, such as compressive structures (imbricate, opposite/back thrust, and Y-shaped structures), strike-slip faults (positive flower-shaped faults), and extensional structures (listric-shaped normal faults).

The stress mechanism of the compressional structures was derived from the early Yanshanian movement in the Early Jurassic and the initial high-speed and low-angle NW subduction of the paleo-Pacific plate relative to the Eurasian plate.

The strike-slip fault is mainly characterized by a positive flower structure with compression and torsion, which corresponds to sinistral shearing caused by the low-angle subduction of the paleo-Pacific plate from NW to NNW in the Early Cretaceous; the Tan-Lu fault in eastern China also shows sinistral shear characteristics during this period.

The extensional normal fault is a listric-shaped normal fault and is developed at the northern boundary of the Wunansha Uplift, that is, at the connection between the Wunansha Uplift and the Southern Depression of the South Yellow Sea basin. Corresponding to the late Yanshanian movement in the Late Cretaceous, the paleo-Pacific plate changed from low-angle subduction to high-angle subduction, and the tectonic stress system in eastern China experienced a transformation from compression to extension.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


