Research Article

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Structural deformation characteristics of the Lower Yangtze area in South China and its structural physical simulation experiments

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Abstract: The analysis of structural deformation characteristics in the Lower Yangtze area of South China is of great significance to petroleum exploration and development in this area. Based on the geological and geophysical data, the structural deformation characteristics of the Lower Yangtze area are systematically discussed. Structural physical simulation experiments are further conducted to model the typical structural deformation systems and to discuss their dynamic mechanism. The results show that the hedging system is characterized by “asymmetric opposite hedging in the south and north” of the study area. The structural deformation on the northwest of the hedging system mainly occurred in the Middle-Late Triassic and was controlled by southeaster compression in the Indo-Chinese Period. The deformation of southeastern side of the hedging system mainly occurred in Middle-Late Jurassic and was controlled by northwester strong compression in the early period of the Yanshanian Movement. According to the development and evolution sequence of the hedging structure system in the Lower Yangtze area, Wuxi area has weak structural deformation and has not undergone intensive transformation in later periods. Also, the other factors of petroleum accumulation, including the source rock, reservoir, and sealing conditions, are superior, which make a potential area for exploration.

Keywords: Lower Yangtze area, structural deformation characteristics, structural physical simulation, forming mechanisms, petroleum exploration

1 Introduction

The Lower Yangtze area is an important part of the Eastern Yangtze paraplatform. Affected by multiphase tectonic events such as the movement of the North China Plate, South China Plate, and Pacific Plate, it has been a hot subject for tectonics studies [1–4]. Meanwhile, with well source rock conditions, the Lower Yangtze area is considered to be a potential area for petroleum exploration. However, large-scale petroleum exploration and development activities have not yet been carried out due to limited understanding of its tectonic setting. In the study area, the multi-stage structural movement occurred and strongly transforms primary oil and gas reservoir and hence, the complexity of hydrocarbon accumulation in marine Mesozoic and Paleozoic [5,6]. Many studies have focused on the tectonic framework and evolution of the Lower Yangtze area and showed that north margin of the area had undergone three stages of evolution: passive continental margin, transformation from marine foreland basin to continental foreland basin, and intra-continental foreland basin. Ancient buried hills were widely developed in the stable uplift area, deep thrust and subsidence area, and deep paleo-involved subsidence area of each basin. The Mesozoic and Paleozoic strata in the basins of this area were rich in shale gases [7–9]. However, it is still controversial about the formation time of the thrust nappe zone and the hedge zone and deformation mechanisms within the plates, and hence, the comprehensive research on this subject is needed.

In this article, based on the multiple geological and geophysical data, four typical regional geological sections are established, and the typical structural deformation characteristics are analyzed in the Lower Yangtze area.

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Structural physical simulation experiments are used to simulate the typical structural deformation systems in the study area and to discuss its dynamic mechanisms. With the aforementioned analysis of tectonic setting, we try to provide a strong basis for petroleum exploration in the Lower Yangtze area.

2 Geological setting

The Lower Yangtze area, located in the eastern part of the Yangtze paraplatform, is bounded by the Dabie-Sulu orogenic belt to the north, the Jiang-Shao fault zone to the south, the Tanlu fault zone to the west, and the South Yellow Sea to the east. It is a SW-NE oriented horn-shaped area, with its mouth opening to the northeast (see Figure 1). Geographically, it can be defined as a large marine sedimentary area bounded by the Tanlu fault zone and the Jiangshao fault zone [10–12]. Based on the basement faults and structural deformation characteristics, the Lower Yangtze area can be subdivided into five first-order tectonic units from north to south: the Subei

Thrust area, the north-south Hedge Belt, the Sunan Thrust area, the Zhebei Thrust Belt, and the Jiangnan Orogenic Belt. From bottom to top, there are Meso-Neoproterozoic metamorphic rocks, Upper Sinian-Middle Triassic marine carbonate and clastic rocks, Upper Triassic-Quaternary terrestrial strata, and volcanic rocks in the Lower Yangtze area [13]. The Mesozoic and Paleozoic source rocks in the Lower Yangtze area are well developed, which is a prospective area for oil and gas resource exploration. There are three sets of main source rocks in the study area: the Lower Cambrian, the Upper Ordovician-Lower Silurian, and the Upper Permian. Among them, organic-rich marine shale is widely distributed in the Lower Paleozoic. Affected by Indosinian compressional nappe and Yanshanian and Himalayan extensional tectonic movements, the previous oil and gas reservoirs are often damaged. However, there are multiple complete depressions in local area, where the Upper Paleozoic is covered with a large set of Triassic limestone and has good conditions for petroleum preservation and accumulation. The distribution of cap rocks for petroleum accumulation in the study area is stable, while the basement varies from rock types to the degree of

Figure 1: Regional tectonic background of the Lower Yangtze area.

Geological age			Age (Ma)	Tectonic episode	Lithologic column	Lithological description	Geological events	Magmatic activity	source- reservoir -cap combination		
Era	Period	Epoch									
Cenozoic	Neogene	N ₂	24.6	Himalayan		sand-conglomerate	rise	eruption of basic magma			
		N ₁				fine-sandstone	sedimentation	eruption of basic magma			
	Paleogene	E ₂	53			interbedded strata	sedimentation-rise	eruption of basic magma			
		E ₁				sandstone and shale and coal line	fault-subsidence	eruption of basic magma			
Mesozoic	Cretaceous	K ₂	100	Yanshanian		interbedded strata	rise	intermediate-acid magmatic intrusion,eruption	Cap		
		K ₁				muddy limestone, shale and siltstone	sedimentation thrust	intermediate-acid magmatic intrusion,eruption			
	Jurassic	J	200		Indosinian		trachyte coarse andesite	fold		intermediate-acid magmatic intrusion,eruption	
		T ₃					shale	regression			
	Triassic	T ₂	248			fine-sandstone	rise		source rock		
		T ₁				argillaceous limestone dolomite	fold				
	Paleozoic	Permian	P ₂	286	Hercynian		shale	oscillation		cap	
			P ₁				fine-sandstone				
Carboniferous		C ₂	300			argillaceous limestone					reservoir
		C ₁				dolomite					
Devonian		D ₃	400	Caledonian		dolomitic limestone	ridge		reservoir		
						shale					source rock
Silurian		S ₁₊₂	438			sand-conglomerate	regression		reservoir		
						interbedded strata shale and siltstone					source rock
Ordovician		O ₃	500			argillaceous limestone	transgression		reservoir		
		O ₂				dolomite					source rock
Cambrian	O ₁	505		dolomitic limestone			reservoir				
	Є			dolomite					source rock		
Late Proterozoic	Sinian	Z	600	Caledonian		shale	regression			reservoir	
			700			dolomite dolomitic limestone					
			800			limestone					
Middle Proterozoic Era			850			argillaceous limestone		intermediate-acid intrusive			
					silty mudstone						
						limestone					
						argillaceous limestone					

Figure 2: Synthetic stratigraphy of the Lower Yangtze area.

metamorphism (see Figure 2). In addition, the Paleozoic source rocks, including Lower Cambrian, Upper Ordovician-

Lower Silurian, and Upper Permian source rock, develop well.

3 Structural deformation characteristics of the Lower Yangtze area

The main regional structural trend of the Lower Yangtze area is along the NE direction and gradually turns northward to a near-NEE direction. Based on a field geological survey and geophysical exploration, four typical geological sections, being perpendicular to the regional structural trend, are established from north to south: the A-A' (NNW direction), the B-B' (NW direction), the C-C' (NW direction), and the D-D' (NW direction). They are used to understand the regional structural deformation characteristics of the study area (see Figure 1).

3.1 The Jinniu Mountain–Mufu Mountain–Lishui geological section (AA')

The Jinniu Mountain–Mufu Mountain–Lishui geological section (AA') is a NNW section perpendicular to the northern structural trend of the study area, passing through structural units of the Subei Basin and Jurong Basin from north to south and passing through Jinniu

Mountain, Mufu Mountain, and Qixia Mountain, while extending south to Lishui (see Figure 3). This section exhibits an overall hedging structure centered on the Baohua Mountain anticline. While it shows a SE trending compressional thrust in the north side and shows a NW trending thrust nappe deformation in the south side. Subei Basin, located in the northernmost part of this section, is a typical semi-graben basin in deep layers. The boundary fault of the basin started to form in the Late Triassic Period and experienced a strong reversal in the Late Cretaceous-Eocene Period, finally forming a semi-graben basin with the boundary fault on the north side. In the south part of the Subei Basin, there are three arc-shaped EW trending fold-thrust belts, including the Mufu Mountain, the Qixia Mountain, and the Baohua Mountain. The two wings of these threefold thrust belts are steep, and the thrust faults are extremely developed. The fault surfaces are NW dipping, indicating thrust from the SE direction. The wings of synclines held by the three anticlines are gentle (see Figure 3). Field surveys show that the Lower Cambrian source rocks in this area are well developed. Lower Cambrian (ϵ_1) black carbonaceous shales interbedded with siliceous shales are observed near the Nanjing Mufu Mountain (32.13°N, 118.79°E). The outcrop is weathered, and the rocks are extremely brittle (see Figure 3a). The section (AA') extends south to the Jurong Basin, which is a semi-graben basin formed in

Figure 3: The Jinniu Mountain–Mufu Mountain–Lishui geological section (AA'). (a) Lower Cambrian black carbonaceous shale in Mufu Mountain. (b) Tectonic characteristics of Qixia Mountain. (c) Tectonic characteristics of Zijin Mountain. (d) Tectonic characteristics of Baohua Mountain. (e) Tectonic characteristics of Tangshan Mountain. Ar = Archean formation; Pt = Proterozoic formation; Pz = Paleozoic formation; Mz = Mesozoic formation; Cz = Cenozoic formation; ϵ = Cambrian formation; D-P = Devonian-Permian formation; S = Silurian formation; ϵ -O = Cambrian-Ordovician formation; K-E = Cretaceous-Paleogene formation; J₁₋₂ = lower-middle Jurassic formation; P₂₋₃ = middle-upper Permian formation; K₁ = upper Cretaceous formation; Q = Quaternary formation; T₂ = middle Triassic formation; T₃ = upper Triassic formation; C-P₁ = Carboniferous-lower Permian formation; D₃ = upper Devonian formation.

the Late Cretaceous Period. Regional seismic data showed that the Silurian-Jurassic strata in the basin formed a NW trending thrust imbricate structure, and the lower part converged to the detachment layer at the bottom of the Silurian strata [3].

The Jinniu Mountain–Mufu Mountain–Lishui geological section (AA') reveals that the northern part of the Lower Yangtze area is centered on the Baohua Mountain anticline, the north and south wings are opposed to the NNW–SSE direction, and experience differing degrees of extensional rifting in the later stages.

3.2 The Maoshan Mountain–Zhangzhu–Changxing geological section (BB')

The Maoshan Mountain–Zhangzhu–Changxing geological section (BB') starts in the west of the Maoshan Mountain in the north, passing through the Changzhou–Xuancheng Basin, the Zhangzhu syncline, and the Meishan syncline to the SE, and extends to the Changxing, the Huzhou, in the south, with a total length of 100 km (see Figure 4). The Maoshan Mountain is elongated and NNE trending. Lower Silurian black shales are observed near the Maoshan Mountain Palace (31.79°N, 119.31°E), which is a set of good source rocks that have developed in this

area (see Figure 4a). The Maoxi fault, developed on the west side of the Maoshan Mountain, is a low-angle thrust nappe fault with Silurian-Triassic outcropping on the hanging wall. Strong deformation is observed inside the thrust nappe, and a large number of inverted fold structures are developed. The Dinggong anticline, the Qingshan syncline, and the Quanshuidong-Banshan anticline are developed from NW to SE. The cores of the anticlines are mainly Lower Silurian (S_1), with steep wings on both sides. The cores of the synclines are the Middle-Lower Triassic (T_{1-2}), of which the axial surface is dipping toward the SE, and the top of the folds are all strongly denuded. The Maodong Fault is a SE-dipping steep normal fault developed on the east side of the Maoshan Mountain (see Figure 4), demonstrating a structural reversal on the basis of earlier thrusts. The Zhangzhu syncline in the middle of the section is a typical monocline dipping toward the center of the basin with a gentle dip angle of about 25°. The structures in this area are relatively simple, dominated by small gentle folds, without the development of typical faults (see Figure 4). There are many basement-involved syncline folds that have developed in Changxing County to the southeast of the section (BB'). The core of the syncline is the Middle-Lower Triassic (T_{1-2}), and the orientation of the fold axis changes from SE to NW. Based on the field survey, Lower Cambrian (C_1) black carbonaceous mud shales, well-developed source

Figure 4: The Maoshan Mountain–Zhangzhu–Changxing geological section (BB'). (a) Lower Silurian black shale in Nanjing. (b) Lower Cambrian black carbonaceous shale in Anjiluo village, Huzhou. $\epsilon-O$ = Cambrian-Ordovician formation; S_1 = upper Silurian formation; S_{2-3} = middle-upper Silurian formation; D-P = Devonian-Permian formation; T_{1-2} = upper-middle Triassic formation; K-Q = Cretaceous-Quaternary formation; C = Carboniferous formation; P = Permian formation; D_3 = upper Devonian formation; K_2 = middle Cretaceous formation.

rocks in this area, are observed near the Anjiluo Village in Huzhou (30.63°N, 119.67°E; see Figure 4b). On the whole, in the Maoshan Mountain–Zhangzhu–Changxing geological section, except for the Lower Silurian detachment layer existing on the bottom of the Zhangzhu syncline, the other basement-involved deformed strata are generally deeper, reaching to the Cambrian or even older strata.

The Maoshan Mountain–Zhangzhu–Changxing geological section (BB') demonstrates that the central part of the Lower Yangtze area has experienced a change in the thrust direction from NW to SE, the dynamics of which are mainly derived from the merger of the Yangtze Plate and North China Plate from north to south in the late Indo-Chinese epoch in the Mesozoic era.

3.3 The Qianshan area–Huaining–Dongzhi geological section (CC')

The Qianshan area–Huaining–Dongzhi geological section starts from the Yuexi County and the Anqing City in Anhui Province in the northwest and extends SE through the Qianshan area, Huaining, and the Wangjiang Basins to the Dongzhi County and the Chizhou City in Anhui Province, with a total distance of 120 km (see Figure 5). This section is a NW–SE trending hedging structure on the whole, with the Qianshan Basin on the north side and the Wangjiang Basin on the south side. Both of them are NE trending basins developed from the Late Crataceous–Paleogene period [14]. Overall, it is a thrust nappe structure system with SE trending foreland thrust deformation on the west of Changjiang Fault and NW trending thrust on the east side. It can be inferred that the deformation dynamics of the NW part of the section is mainly derived from the thrust of the collision between the North China plate and Yangtze plate in the late period of the Indo-Chinese movement, while the dynamics of the SE part are mainly from intraplate thrust in the early period of the Yanshanian Movement.

3.4 The Taizhou–Wuxi–Jiaxing geological section (DD')

The Taizhou–Wuxi–Jiaxing geological section starts from Taizhou, Jiangsu Province in the NW. It passes through Jiangyin, Huashan area, Shashan area, Wuxi, Suzhou, and Jiaxing, terminating in Zhejiang Province to the SE, with a total length of about 180 km. Fold structures are widely distributed from the Upper Paleozoic Period to the Triassic Period in this section, presenting a closed anticline and open syncline alternately arranged as a combination of compartments. The true thickness of the same rock layer remains almost constant throughout the folds, showing the typical characteristics of parallel folds (see Figure 6). The NW wing of the anticline is steeper, with a dip angle of more than 60°, while the SE wing is gentler with dip angle of about 45°. Thrust faults are widely distributed along the steeper wing of the folds, with the fault surface dipping to SE. The structure deformation system has changed significantly to the south of Suzhou, with a large number of fault-extended folds developing. In addition, inverted folds are developed in many places in this section, such as the inverted anticline with a SE axial plane in the Shashan area, and the inverted steering inclined syncline with a SE axial plane in Jiaxing area, which further reflects the SE–NW compression in the study area.

As a whole, the Lower Yangtze area has developed a typical hedging structural system, and the overall structural deformation is not completely symmetrical. Taking the Jinniu Mountain–Mufu Mountain–Lishui geological section and the Qianshan area–Huaining–Dongzhi geological section as examples to illustrate the details. Jinniu Mountain–Mufu Mountain–Lishui geological section is characterized by the thrusting deformation centered on the Baohua Mountain anticline, while the north side shows the SE trending compressional thrust and the south side shows the NW trending thrust nappe deformation. Similarly, Qianshan area–Huaining–Dongzhi geological section shows the hedging structure deformation centered on the Yangtze River fault, while the western trending thrust toward the SE and the eastern trending

Figure 5: The Qianshan–Huaining–Dongzhi geological section (CC'). Ar = Archean formation; Pt = Proterozoic formation; Pz = Paleozoic formation; Mz = Mesozoic formation; Cz = Cenozoic formation.

Figure 6: The Taizhou–Wuxi–Jiaxing geological section (DD'). €-O = Cambrian-Ordovician formation; S = Silurian formation; J = Jurassic formation; T = Triassic formation; K-Q = Cretaceous-Quaternary formation; Pz₂ = middle Paleozoic formation; Z = Sinian formation.

thrust toward the NW, showing the evident opposing structure.

4 Structural physical simulation experiment

As mentioned earlier, the hedging system in the typical profile of the study area is distinct: the structure background is relatively stable before the Late Triassic, the boundary fault developed from the Late Triassic and reversed in the Late Cretaceous-Eocene. In terms of the formation mechanism, the hedging system began to develop in the late Indosinian movement and was strongly affected by the Indosinian plate collision and the Yanshan intraplate thrust. A typical hedging structure system is proposed in the Lower Yangtze area, starting from the late Indo-Chinese movement. The structure system is strongly affected by the Indo-China plate collision and the Yanshanian intraplate thrust. The evolution process of typical profiles in the study area is reconstructed by structural physical simulation experiments, and the dynamic evolution mechanism of the study area is further probed. To study the structural deformation characteristics and evolution mechanism of the Lower Yangtze area further, structural physical simulation experiments are used. The NNW–SSE trending Jinniu Mountain–Mufu Mountain–Lishui geological section (AA') is selected as the experiment object to illustrate the process of structural evolution within the study area since the Middle Triassic (T₂) Period. The experiment details are discussed in the following sections.

4.1 Principles of experimental design

The basic principle of the experiments under laboratory conditions is the principle of similarity, which means the

experimental model and the geological prototype should conform to the principle. The indicators of similarity include similar model sizes, similar experimental materials, similar experimental time, and similar boundary conditions [15–17].

4.2 Experimental model and experimental materials

The length and depth of the NNW–SSE trending Jinniu Mountain–Mufu Mountain–Lishui geological section is about 120 km/15 km, respectively, and the experimental model is set to be 100 cm and 12.5 cm, with a similarity coefficient of 1.20×10^{-5} . To facilitate the observation of the experimental deformation results, 80–100 mesh fine-grained loose colored quartz sand was selected as the experimental material, and the friction coefficient of the substrate was less than 3. A 6 cm thick polystyrene foam substrate (pave a certain angle on both sides to achieve thrust napping in deep layers) and 6.5 cm thick quartz sand on the upper part were preinstalled (see Figure 7), with a similarity coefficient of formation thickness of 1.31×10^{-5} (see Table 1). To avoid the influence of personnel operating proficiency and instrument system error on the experimental accuracy during the experiment, the physical simulation experiment was divided into multiple groups, and cyclic rolling was conducted. The sand-to-mud ratio, stress duration, and rate were all processed differently. The average results of multiple experiments were evaluated [18,19].

4.3 Boundary conditions and loading methods

This structural physical simulation experiment used double-sided extrusion to simulate the compression

Figure 7: Map showing physical modeling simulation experiment for structural evolution.

Table 1: Stratum thickness parameters in the structural physical simulation experiment

Ordinal number of stratum	Geological age	Stratum thickness (cm)	Special processes
1	Pt	7.2	
2	Pz	4.5	
3	Mz	4	Adding 2% vaseline
4	Cz	4.3	Adding 2% vaseline

Pt = Proterozoic; Pz = Paleozoic; Mz = Mesozoic; Cz = Cenozoic.

stress generated by plate activities, orogenic activities, and boundary fault activities. The compression stresses were provided by advection pumps on both sides. The extrusion stress was applied in the SSE direction to simulate the geological period from the Middle Triassic to early Jurassic (T_2 – J_1), and the extrusion stress was applied in the NNW direction to simulate the stress since the Middle Jurassic (J_2) period. The magnitude of extrusion stress was controlled by the flowrate of the advection pump. The experiment lasted for 74.2 min, and the time similarity coefficient was 1.86 Ma/min. The advancing speeds of the advection pumps on both sides were 0.25 cm/min (0–4.3 min), 0.27 cm/min (4.3–17.7 min), 0.28 cm/min (17.7–31.1 min), 0.30 cm/min (31.1–39.2 min), and 0.50 cm/min (39.2–74.2 min).

4.4 Experimental process and result analysis

The experiment lasted for 74.2 min and was carried out in two stages.

Stage 1: The polystyrene foam substrate in the experimental container was preinstalled, the quartz sand layer was evenly lay, the right side of the container with a baffle was fixed, and the advancing speed of the left drive unit to 0.25 cm/min was set. When the experiment has run for 4.3 min, the advancing speed was adjusted to

0.27 cm/min. During operation, the SSE-direction extrusion force was generated, and the experimental model began to deform under the stress of the SSE-direction extrusion.

Figure 8a shows the initial state of the experiment. In the unstressed state, the sand body maintained its original state. Under the continuous compression stress from the left side, the left side of the sand body presented a large uplift when the experiment ran for 4.3 min, forming a wide and gentle anticline. Also, the bottom of the right side of the sand body was slightly bent and deformed (see Figure 8b). At 17.7 min, a fault dipping to the NW appeared, named Fault 1, which was a reverse fault, corresponding to the thrust fault at Qixia Mountain in the Jinniu Mountain–Mufu Mountain–Lishui geological section.

Stage 2: The left side of the container with a baffle was fixed, and the advancing speed of the right drive unit to 0.28 cm/min was set. The advancing speed of the driving was accelerated unit at 31.1 and 39.2 min. NNW compression stress was generated during the process, and the experimental model continued to deform under the NNW extrusion.

When the experiment had run for 31.1 min, the sand body on the right side uplifted rapidly, and Fault 2 began to develop, which was a SE dipping reverse fault. Meanwhile, Fault 1 continued to thrust, and the central sand body subsided relatively. The hedge structure has miniature (see Figure 8d). At 39.2 min, as the compression

Figure 8: Physical simulation experiment processes and interpretations of the hedging structure in the Lower Yangtze area. (a) Initial stage of the experiment. (b–f) Experiments at 4.3 min, 17.7 min, 31.1 min, 39.2 min, 47.3 min, respectively. (g) The final stage of the experiment at 74.2 min. Pt = Proterozoic formation; Pz = Paleozoic formation; Mz = Mesozoic formation; Cz = Cenozoic formation.

stress was increased, the deformation of the sand body increased, forming an apparent hedging structure (see

Figure 8e). When the experiment had run for 47.3 min, Faults 3 and 4 occurred successively on the hanging

wall of Fault 2 on the right side of the sand body. Faults 3 and 4 were also reverse faults dipping to SE, forming an imbricate structure (see Figure 8f). When the experiment had run for 74.2 min, the hedging structure was stable (see Figure 8g). The result of the physical simulation experiment has good correspondence with the structural system of the Jurong Basin in the Jinni Mountain–Mufu Mountain–Lishui geological section.

5 Analysis of formation mechanism

Based on the analysis of the formation and evolution of the hedging tectonic system in the Lower Yangtze area, the study area undergone two periods of tectonic movement: the Middle-Late Triassic (T_{2-3}) and the Middle-Late Jurassic (J_{2-3}) [20–22]. However, there is rarely systemic and detailed research about the development sequence of the thrust deformation of the hedging structure on both sides in the study area. Based on the geological survey, geophysical exploration, and structural physical simulation experiments, this article study the development and evolution mechanism of the hedge structure since Middle Triassic in the study area. Since the Jin-Ning movement, the Lower Yangtze area has experienced multiple tectonic movements and shaped a typical hedging system. The Indosinian movement, the key tectonic event, changes the tectonic framework of the study area. During the end of the Middle Triassic (T_2), the Yangtze plate collided and spliced with the North China plate. With the formation of the Sulu orogenic belt, the Yangtze platform moved northward and presented an “A” type subduction toward the Dabie-Sulu orogenic belt [23]. As a result, the Lower Yangtze area had a strongly SE compression, which was the dynamic source for the formation of the hedging system in the study area. The Lower Yangtze area has experienced multiple periods of the tectonic movement since the Jinning Movement, forming a typical hedging structure. Of all those movements, the Indo-Chinese Movement was a key tectonic movement that has changed the tectonic system in the study area [23]. At the end of the Middle Triassic (T_2) era, the Yangtze plate converged and collided with the North China plate. With the formation of the Sulu orogenic belt, the Lower Yangtze area was strongly compressed from the SE direction [24], providing dynamic drives for the formation of the hedging tectonic system. The field data provide strong evidence for the importance of the Indo-Chinese Movement on the deformation of the study area. The anticline at the Qixia Mountain (32.15°N, 118.95°E) in Nanjing is well developed, with a strongly deformed Silurian-

Triassic core and steep wings. In contrast, the overlying rock (J) is gentle and without strong deformation. Typical unconformity can be observed between these two layers (see Figure 6). There is a parallel unconformity between the overlying J_{1-2} and the underlying T_3 from Qixia Mountain to Zijin Mountain (32.07°N, 118.83°E), with uniform deformation characteristics (see Figure 3b). In Huaining, which is the west of the study area, the overlying J_1 and the underlying T_{2-3} also have a significant shift from angle unconformity to parallel unconformity [25]. All of these indicate that the Indo-Chinese Movement has an evident controlling on the NW side of the hedging structure, while the controlling on the SE side is relatively weak. Meanwhile, structural physical simulation experiments indicate that the Lower Yangtze area has been continuously compressed in the SSE direction since the Middle Triassic era [26]. Until 200 Ma, corresponding to the end of the Late Triassic, anticline and thrust faults developed on the NW side, while the SE side was relatively stable without significant deformation (see Figure 8a–c). This is verified by the field data, which further confirm that the structural deformation in the Indo-Chinese period in the study area mainly occurs on the NW side of the hedging structure system.

Since the Middle Jurassic (J_2) era, the Yanshanian Movement has become another important tectonic event that has changed the structural framework of the study area. During this period, the Pacific plate subducted in the NW direction under the Eurasian continent. The subduction was quite active in the Late Jurassic Period, which induced large-scale magma activities. At the same time, restricted by the mid-Pacific ridge, the Pacific subduction in eastern part of China transformed into a left-lateral transpression [26]. In this dynamic environment, the Lower Yangtze area was strongly compressed in the NW direction, and the hedging system continued to develop. The field data provide strong evidence for the development of the hedging structure of the study area. Middle Triassic (T_2) breccia limestone was widely exposed on the NW wing of the anticline on Baohua Mountain (32.14°N, 119.09°E) in Jurong City. The high angle breccia limestone thrusts above the Lower-Middle Jurassic (J_{1-2}) sandstone at a high angle in the NW direction (see Figure 3i). Southeastward to the Tangshan area (32.06°N, 119.05°E), the Upper Sinian and Paleozoic (Pz) thrusts onto the Lower-Middle Jurassic (J_{1-2}) and the Middle-Upper Triassic (T_{2-3}), while thrust faults on the NNW side developed to Lower-Middle Jurassic and was underlid by Lower Cretaceous (K_1) angle unconformity (see Figure 3d). Therefore, the southern thrust structure of the hedging system mainly developed in the Middle-Late Jurassic period. In addition, the results

of the structural physical simulation experiments showed that since 175 Ma (the beginning of the Middle Jurassic era), the SE side of the section was influenced by the continuously influence of the NNW compression and that it deformed significantly. In the Middle-Late Jurassic era, three steep thrust faults developed successively, showing a typical “up-stack” development sequence. However, the NW side of the study area was relatively stable and the deformation was not evident. The hedging structure of the study area was formed (see Figure 8d–j). This was verified by the field data, which further confirm that the structural deformation in the SE of the hedging system mainly occurred in the Mid-Late Jurassic era.

6 The implications for petroleum exploration

In the Cretaceous era, with the terminal of the large-scale magmatic activity, the compressive structural deformation of the Lower Yangtze area was replaced by regional extension. Influenced by the Cenozoic tectonic activities, the north and south sides of the Mesozoic hedging system show significant differences. On the NW side of the hedging system, the basins are semi-graben controlled by the north fault (the Qianshan Basin and the Subei Basin), whereas on the SE side of the hedging system, the basins are semi-graben controlled by the south fault (the Wangjiang Basin and the Jurong Basin) [27–29].

The Lower Yangtze area is a favorable place for hydrocarbon production and has great exploration potential in the Paleozoic-Mesozoic stratum. However, the Lower Yangtze area has been affected by multiple stages of reconstruction and destruction, and the preservation conditions are poor. Hydrocarbon reservoirs in good conditions have not been discovered yet. According to our detailed analysis of the deformation characteristics in this article, with many parts of the Upper Paleozoic being exposed to the surface through structural deformation, there are poor petroleum preservation conditions in the study area. Therefore, the key for a breakthrough in petroleum exploration of this area is to find weak structural deformation and transformation play. Taking the Taizhou–Wuxi–Jiaying geological survey as an example to illustrate the detail. The Lower Paleozoic stratum in the Wuxi area is weakly affected by structural deformation and is well preserved. The deformation characteristics of the Upper Paleozoic stratum are consistent with the Lower Paleozoic, showing a stable distribution of parallel folds, which might therefore be a favorable exploration area.

In addition, the source rocks are well developed in the Wuxi area. The Lower Cambrian (C_1) stratum, the Upper Ordovician Wufeng Formation (O_3w), the Lower Silurian stratum (S_1), and Lower Permian stratum (P_1) are the main source rocks in the region. These source rocks, characterized by mature to over-mature, have abundant total organic carbon and good organic types and have great potential for oil generation. Meanwhile, the source rocks are thick and widely distributed, which could also act as good reservoirs [30,31]. The results of this study suggest that the source-reservoir-seal conditions are superior, and structural conditions are relatively stable in the Wuxi area of the Lower Yangtze area, which might be a potential exploration zone in the study area.

7 Conclusion

- (1) Based on the geological survey, geophysical exploration, and structural physical simulations experiments, there is a typical hedging system in the Lower Yangtze area, which is characterized by “asymmetric hedging in the South and North.” The overall structure is a two-sided opposing structure, with the southern thrust belt thrusting toward the NW and the northern thrust belt thrusting towards the SE.
- (2) The hedging structural framework in the Lower Yangtze area was formed from two tectonic movements: the Middle-Late Triassic (T_{2-3}) movement and the Middle-Late Jurassic (J_{2-3}) movement. The structural deformation in the NW part of the hedging system, controlled by SE compression in the Indo-Chinese period, mainly occurred in the Middle-Late Triassic. While the deformation of SE side of the hedging system, controlled by NW strong compression in the early period of the Yanshanian Movement, mainly happened in the Middle-Late Jurassic.
- (3) The deformation is weak in the Wuxi area, and the petroleum preservation condition is preferable because this area has not been intensively modified in later periods. Besides, other factors of petroleum accumulation, including the source rocks, reservoirs, and sealing conditions, are superior, making this area potential for petroleum exploration.

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