Mesozoic basin evolution of the East China Sea Shelf and tectonic system transition in Southeast China

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Abstract
The East China Sea Shelf Basin (ECSSB) is located on the south-eastern edge of the Eurasian Plate. The tectono-evolution and dynamic mechanism of the ECSSB are related to the collision of the Pacific Plate with the Eurasian Plate, and the remote pushing effect of the Indo-Australian Plate remains a hot topic of debate. Based on the latest survey data, this paper mainly focuses on the evolution of the Mesozoic basin in the East China Sea Shelf by means of assessing the regional tectonic background, conducting structural physical simulation experiments, and applying balanced geological section recovery technology to discuss the processes of dynamic transition in Southeast China. Our data suggest that the ECSSB experienced an evolutionary sequence involving the pre-Late Triassic passive continental margin; the Late Triassic–Middle Jurassic active continental margin extrusion–depression; the extrusional stress from the low-angle subduction of the Izanaki Plate under the Eurasian Plate; the late Early Cretaceous to Late Cretaceous active continental marginal extension faulted basin, during which the extensional stress originated from the lithospheric thinning and palaeoenvironment resulting from the subduction of the Palaeo-Pacific Plate under the Eurasian Plate; and the Palaeogene back-arc extension faulted sags. The transition time from the E-W-trending Palaeo-Tethys tectonic system to the NE-trending Palaeo-Pacific tectonic system in Southeast China occurred at the end of the Middle Triassic. The low-angle subduction and withdrawal of subduction of the Palaeo-Pacific Plate probably represented the deep geological processes of the Mesozoic in Southeast China.

KEYWORDS
basin evolution, East China Sea Shelf Basin (ECSSB), Mesozoic, Southeast China, structural physical simulation experiment, transition process of tectonic system

1 INTRODUCTION

The ECSSB is located at the south-eastern margin of the Eurasian Plate and is a Mesozoic–Cenozoic superimposed basin that developed on the pre-Mesozoic craton. The basin area is $26.7 \times 10^4 \text{ km}^2$. According to existing geological and geophysical data, the East China Sea Shelf from west to the east in sequence is the Zhejiang-Fujian Uplift Belt, the ECSSB, the Diaoyu Islands Uplift Belt, the Okinawa Trough Basin, and the Ryukyu Upfold Belt. The structural trend is NE-trending, which is basically the same as the coastline and shelf. Over recent decades, many geologists and geophysicists have presented in-depth discussions on many key issues in this region, such as the tectonic evolution and dynamic mechanisms in Southeast China using different technical methods (mainly from geology, geophysics, and geochemistry) and from different perspectives (Bao, Guo, Zhang, & Huang, 2013; Cai, Zhu, & Cao, 2003; Cukur et al.,...
2 | GEOLOGICAL SETTING

The ECSSB is located in a major area of convergence and lithospheric thinning among the Indo-Australian Plate, the Pacific Plate, and the Eurasian Plate. It is located at the centre of global convergence (Li et al., 2013; Maruyama, Isozaki, Kimura, & Terabayashi, 1997). The east and west sides of the East China Sea are separately related to the evolution of the western Pacific tectonic domain and Tethys tectonic domain, which are important parts of the western Pacific continental margin system (Figure 1).

Regionally, the ECSSB is located at the south-eastern edge of the South China Block. Its basement is an extension of the Cathaysian Block on the East China Sea Continental Shelf (Li et al., 2013; Zhang, Zhang, & Tang, 2014).

In the Mesozoic, the basement strata, the depression strata, and the faulted strata are divided from bottom to top in the ECSSB. Each stratum is bounded by regional unconformity. The basal structural strata refers to the various rocks and structural deformations before the formation of the basin. It mainly includes Proterozoic-Palaeozoic metamorphic rock series and is a metamorphic crystalline basement from the west-Early Indosinian period of the South China Sea with multiple layers in a longitudinal direction (Li & Zhu, 1992; Yang & Li, 2003). There are deep metamorphic rock series in both the Lower Proterozoic and the Upper Proterozoic and Palaeo-metamorphic rock series in the Palaeozoic. The LF-1 well and the WZ6 well in the Oujiang faulted sag revealed a gneiss section with a thickness of over 300 m. The depression strata include the Upper Triassic-Middle Jurassic Fuzhou Formation, which is distributed from Guangdong, Fujian, Southwest Japan, to the Okinawa Islands (Yang, Li, & Dai, 2011; Yang, Li, Gong, & Yang, 2015). Examining material from drilling in the East China Sea, the lower section is grey, black mudstone and grey sandstone sandwiching a thin coal seam; the bottom (not in) for the thick sandstone with thin mudstone; the upper is grey sandstone, brown and tan mudstone, and light grey-grey mudstone in unequal interlayers (Figure 2), containing coccoliths, cyanobacteria, and sponge spicule nanofossils. The internal reflected energy is medium–weak, and its continuity is normal–poor on seismic profiles. The profiles show a relatively uniform lithological depositional environment with a set of parallel-like dense reflections (200 ms) at the bottom, and the internal composition is parallel-like to parallel-messy from blank reflections (Figure 3). The faulted strata represent the late Early Cretaceous-Late Cretaceous sediments, including those from the Xiamen Formation to the Shimentan Formation, mainly consisting of red clastic rock in the inland basin, and parts of volcanic clastic rock, gypsum and halite (Jin et al., 2015). The Southwest Taiwan Basin deposits are mostly littoral and shallow marine or interactive marine-terrestrial sandstone, mudstone, and shale. From the perspective of seismic reflection characteristics, it has a layered reflection with a medium-strong amplitude and a good continuity. The top is truncated, showing an angular unconformity contact with the overlying Cenozoic strata.

According to the existing literature, the tectonic evolution of the ECSSB is very complicated. In the Mesozoic, at least three structural movements, Keelung, Yushan, and Yandang, were experienced by the ECSSB (Yang et al., 2012). During the Early and Middle Triassic, the regional tectonic stress was mainly characterized by tensile (NW–SE), and the large-scale extensional activity of the pre-Mesozoic basement, such as the occurrence of fault activity in the basement of the Keelung Sag and the Minjiang Slope, mainly forming NE-trending and ENE-trending faults. The Late Triassic-Middle Jurassic sedimentary structures of the ECSSB show large uplifts and depressions, and sedimentation is almost uncontrolled by faults (Yang et al., 2012). In the Late Jurassic-early Early Cretaceous, the rudimentary Wuyi Tectonic Belt and Taipei Transition Zone formed on the Minjiang Slope, forming a positive tectonic belt from the south to the north, and the Southwest Taiwan Basin and the Chaoshan Basin reversed to form central uplift in the middle of the basin because of the stretching and thinning of the crust and the combination of many fault fractures, the upwelling process of magma and the development of large-scale volcanic-intrusive complexes are activated (Liu et al., 2018). In the late Early Cretaceous-Late Cretaceous period, mainly due to strong post-arc expansion caused by the large-scale back-subduction of the Pacific Plate under the Eurasian Plate, the western Pacific active continental margin is formed in the eastern part of South China, and the volcanic activity is significantly weakened. During this period, the ECSSB generally experienced torsional stress, forming a series of faulted sags in the east-faulted and west-overlapping areas, such as the Oujiang faulted sag, which is small in scale and has a small settling amplitude. In addition, the period ended with the reversal of the Yandang movement, except for the unconformity between the Palaeocene and the Upper Cretaceous in some areas, no regional structural changes were observed.
TECHNICAL METHODS AND DATA

3.1 Using sandstone and trace elements to identify tectonic background

3.1.1 Sandstone elements used to identify the tectonic background of Source Area

Plate tectonics control the development and distribution of various types of sandstones and sedimentary rocks. The composition of sandstones is directly affected by the source area, while the type and pattern of sedimentary rocks between sources and sedimentary basins are controlled by tectonism. Dickinson and Suczek (1979) analysed and quantified the composition of sandstones in nearly 100 regions of the world and produced ternary diagrams based on the composition of endmembers. Four types of source areas can be distinguished: stable cratons, basement uplifts, Magmatic arcs, and rerotations back to the orogen.

Using the results of core sample identification from the FZ13 Minjiang Formation by the China University of Geoscience (Beijing; Hu, 2012) and pyroclastic rock and tuffaceous sandstone samples from the Shipu Formation in Xiangshan, Zhejiang Province by the Southwest Petroleum University (Chen & Hu, 2017), it is shown that the sedimentary-geotectonic background in the Cretaceous is mainly that of an island arc transition zone (island arc or continental arc; Figure 4).

3.1.2 Trace elements used to discriminate the tectonic setting of the source area

The trace elements in terrigenous clastic rock, especially including La, Th, Zr, and Sc have greater stability (Bhatia, 1983). In the process of weathering, transportation, and deposition, it is seldom affected by...
FIGURE 2 Mesozoic integrated bar chart in the East China Sea Shelf Basin [Colour figure can be viewed at wileyonlinelibrary.com]

The Pacific Plate movement shifted from NW to NNW, and the Marine China Sea shelf developed a series of

Due to the subduction of the Paleo-Pacific Plate to the Eurasian continent, large-scale volcanic eruptions and pyroclastic accumulations occurred in the Southeast China in the late Jurassic-early Cretaceous. The West Taiwang Basin and the ECSSB remained on the land. The Plates of the Paleo-Pacific Plate dive into Eurasian are pulled back to the ocean due to too steep inclination in the Late Early Cretaceous, and the regional stress changed from pressure to twisting. The Keelung Sag and the Minjiang Slope are firstly formed in the the ECSSB by the NW-SE extensional stress, and then the Oujiang Faulted-sag formed under the effect of the detach-fault.

The Late Triassic was the peak period of the Indo-China movement and Paleo-Tethys gradually closed. The outer margin in the eastern part of the ECSSB developed folds and uplifts, and formed a continental marginal uplift zone under the NNW oblique subduction of the Izu Peninsula Plate; the Zhejiang-Fujian Uplift in the western part of the ECSSB slowly ascended and suffered from erosion under regional compression. The ECSSB began to settle and received a set of sand-shale interbeds deposited in the Late Triassic-Middle Jurassic.

It was influenced by the Indian Movement after the Middle Triassic. The tectonic trend changed from EW or ENE to NE, and the basin entered the stage of paleo-Pacific active continental margin. The Pre-Mesozoic was characterized by passive continental margin basin.
other geological processes. The content change and trace element ratio can be used to discriminate the tectonic setting and tectonic evolution of the source area. Figure 5 shows the discriminant figure of the trace elements in the core samples from the FZ13 Minjiang Formation by the China University of Geoscience (Beijing; Hu, 2012). The provenance and tectonic background of the area is mainly characterized by the junction of the continental arc and the oceanic island arc.

3.2 | Balanced geological section recovery technology

The restoration of balanced geologic section is used to test the rationality of the interpreted seismic section (Gibbs, 1983). By restoring the section to its original state, the processes of stretching and compressing the basin are visually displayed, and the structural deformation and distribution characteristics of each stage in the structural evolution of the section are obtained. According to the rigidity of the Mesozoic in the ECSSB, many balanced geological profiles are drawn using the law of conservation of strata length based on seismic profile interpretation from the ECSSB (Figure 6). The geologic profiles of various tectonic units during different geological times were restored, and the main structural styles of the tectonic units were reversed in the Mesozoic.

From the perspective of the restored geological profile, in the Late Triassic–Middle Jurassic, the Minjiang Slope and the Keelung Sag have a complex depression, and the Taipei Transition Zone develops small underwater-uplift. The maximum thickness of the centre of the Minjiang Slope is nearly 2,200 m. The maximum thickness of the sedimentary unit in the Keelung Sag is nearly 2,500 m. There are several local westward-dipping small-sized faults, and the western Oujiang faulted sag has not yet received sedimentation. In the Cretaceous, the Oujiang faulted sag is a compound faulted sag consisting of two small faulted rifts. The western part is a graben faulted sag, and a double graben is developed in the east. In the section of the Minjiang Slope, it shows a structural style similar to that of a dustpan faulted sag. The formation gradually thinned westward and thickened eastward, and igneous rock intrusion in the eastern part of the Minjiang Slope was observed.

3.3 | Structural physics simulation experiment

3.3.1 | Structural physical simulation methods and materials

The structural physical simulation experiment is used to reproduce the structural deformation process and study the deformation behaviour of the structure. A large number of simulation experiments show that the process of structural deformation is mainly controlled by geometric conditions and has little relationship with rock mechanical properties and stress magnitude (Braun, Batt, Scott, Mcqueen, & Beasley, 1994; McClay & White, 1995). The boundary conditions and deformation models of the physical simulation are usually obtained according to the actual deformation mode of the study area. Through the study of the compositional characteristics of the research section using similar conditions to select experimental materials, the deformation characteristics and evolution processes of the model with increasing corresponding variables can be studied (Zhou, Qi, & Tong, 1999).
As the structural physical simulation is mainly confined to studying the macro-deformation phenomena and deformation processes such as buckling and fracture of the crustal rock, it does not aim to examine the microscopic processes studied by petrological methods (Heuret, Funicello, Faccenna, & Lallemand, 2007; Isozaki, Akoik, Nakama, & Yanai, 2010). Therefore, in the actual simulation process, we mainly consider the principles of similar boundary conditions, similar stress conditions, similar basal conditions, similar pre-existing structural conditions, similar deposition thickness, similar model proportions, and similar deformation time, and adopt a step-by-step approach for simulation studies.

Although the method for determining similar conditions is derived from the mathematical equations of rock deformation (Table 1), there are still many uncertainties about the mechanical properties of rock under long-term high temperature and low strain rate deformation conditions. Therefore, the current relative conditions are summarized by experimental experience. The general similarity conditions are used as a general reference in the selection of experimental materials. Finally, the structural morphological changes of the model are approximated to the actual structural phenomena as the main criteria.

According to the principle of material similarity (Table 1), soft materials such as clay, petrolatum, silica gel, and raw rubber in the experimental materials can be appropriately formulated to obtain the corresponding experimental parameters, and are the preferred soft materials that meet similar conditions. The tensile strength of loose quartz sand is close to zero, and its deformation characteristics are in line with the Coulomb failure criterion. It is the same as the deformation characteristics of shallow rock in the crust. Loose quartz sand is a material that mimics the deformation of shallow crust. The density of materials such as honey and syrup is similar to that of the asthenosphere, and they are common materials for the simulation of the asthenosphere (Faccenna et al., 1996; Faccenna, Giardini, Davy, & Argenti, 1999). According to the principle of material similarity, the simulation experiment in this paper uses loose, dry quartz sand to represent sandstone, conglomerate, and other rock formations with strong deformability to verify the previous generation of mantle plume genetic models and rifting genetic models in the East China Sea Basin. Balloon expansion and magmatic upper arch models were used for simulation-based research. Central magmatic intrusion, fissure-type magmatic intrusion, and superimposed simulation experiments with extension were also conducted. By comparison, the simulation experiment on the uplift boundary double extrusion and superimposed bilateral extension (Figure 7) is closest to the present structural deformation characteristics of the basin (Figures 8 and 9).

On the right side of the model seen in Figure 7, the right subduction boundary is made according to the similarity of the Ryukyu trench pattern (scale: $1.0 \times 10^{-6}$, model 1 cm represents an actual 10 km). A plastic mat is placed on the lower part of the steel plate on the right side of the model, and its shape is similar to that of the right side. Three protrusions are made of foam on the left side of the model.

### Table 1: Simulated material similar parameters of structural physical simulation

| Parameters                        | Time       | Elastic modulus (MPa) | Shear strength (MPa) | Viscosity (p) | Length (km) | Density (kg/cm³) | Gravity acceleration |
|-----------------------------------|------------|-----------------------|----------------------|---------------|-------------|------------------|---------------------|
| Similar boundary condition expression | $C_t$      | $C_G = C_pC_pC_L$   | $C_D = C_pC_L$     | $C_H = C_pC_T$ | $C_L$       | $C_p$            | $C_g$               |
| Rock parameters                   | 10–100 Ma  | $10^6$–$10^5$         | 1–50                 | $10^{17}$–$10^{22}$ |             |                  |                     |
| Simulated material parameters     | 1 min      | $10^{-2}$–1           | $10^{-4}$–$10^{-5}$  | $10^2$–$10^3$  | 80 cm       |                  |                     |
| Similarity factors               | $10^{-11}$–$10^{-13}$ | $10^{-4}$–$10^{-6}$  | $10^{-4}$–$10^{-6}$  | $10^{-15}$–$10^{-19}$ | $10^{-4}$–$10^{-6}$ | 0.5               | 1                   |

FIGURE 6 Equilibrium geological profile in the East China Sea Shelf Basin [Colour figure can be viewed at wileyonlinelibrary.com]
and the thickness of the bottom of the protrusion is gradually thinned and connected with the left side baffle to represent the Fujian-Zhejiang Uplift. Three plastic mats are placed on the upper and lower sides of the three projections for later extension. The experimental materials selected include quartz sand to represent the Jurassic and Cretaceous units and silicone (viscosity 2 × 10⁴ Pas) selected to represent plastic material, similar to the lower crustal material. In the early stage of the experiment, the motors on both sides were squeezed at the same time, and in the late stage of the experiment, the motors on both sides pulled the plastic seat to represent simultaneous compression and stretching, respectively.

4 | RESULTS: MESOZOIC BASIN EVOLUTION

There are two main perspectives on the evolution of the ECSSB during the Mesozoic: back-arc extensions and fore-arc extrusion, such as the simple shear model (Okada & Sakai, 1993; Zhou, Zhao, & Yin, 1990), the back-arc basin model (Wang, 1987) and the back-arc rift model (Zhao, Wang, Qi, & Guo, 2016), the residual back-arc basin model (Sun, 2004), the mantle plume model (Wu, Zhang, Zhou, Jia, & Liu, 1999), the fore-arc model (Feng, Cai, Wang, & Gao, 2003; Yang et al., 2012), and other genetic composite models (Cui et al., 2017). Their disagreement focused on whether the tectonic setting of the basin during the Mesozoic was an extruding or a stretching environment. According to plate tectonics, a trench-arc-basin system can be

FIGURE 7 Simulation experiment model of double-extrusion and double-side stretching for pre-existing uplift boundary [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Comparison of experimental simulation results (a) with the structural pattern (b) in the East China Sea shelf [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 9 Comparison between the interpretation section of the East China Sea Shelf Basin (BB') and results of the experimental simulation (GH) [Colour figure can be viewed at wileyonlinelibrary.com]
created during the subduction of oceanic plate into the continental plate. The structure of the ECSSB shows that, from west to east across the ECSSB, the Diaoyu Islands Upfold Belt, the Okinawa Trough Basin, the Ryukyu Upfold, and the Ryukyu Trench, the crust thickness gradually reduced to the east. From the combinations of aspects of sedimentary characteristics, age of volcanic rocks, and crust thickness, the Okinawa Trough Basin began to develop in the Miocene and is in a stage of rapid expansion (Gao et al., 2009). The nature of the crust still retains the characteristics of continental crust. However, the thickness of the crust is only between 15 and 24 km (Jin & Yu, 1987), which shows that the evolution of the basin is already at the highest stage of continental crust and fracture (Zhou, Liao, Jin, & Jia, 2001). This is the result of the back-arc expansion effect produced by plate subduction. This evidence indicates that the Ryukyu Upfold and the Diaoyu Islands Upfold Belt are the uplifted edge of the ancient East China Sea Shelf as a geological unit before the formation of the Okinawa Trough Basin. This uplift zone is mainly composed of Palaeozoic, Mesozoic, and Cenozoic materials and displays volcanic activity during different periods of the Cenozoic. It can also be considered that the marginal uplift zone has now developed into an arc zone. The nature of the ECSSB at the trailing edge is a back-arc rift basin (the crust should be continental crust). The marginal uplift zone that formed by the Ryukyu Upfold and the Diaoyu Islands Upfold belt is always connected with the tidal subduction zone and is caused by the subduction of the trench. However, in different stages of development, it has different controlling effects on the ECSSB, which in turn determines the nature (genetic type) of the ECSSB.

Based on the comprehensive analysis of sedimentary stratigraphy, volcanic age, and results of structural physical simulation etc., the Mesozoic evolution model of the ECSSB was constructed (Figure 10). It is believed that the ECSSB has experienced three stages since the Mesozoic: active continental margin squeezing depression, active continental margin extensional faulted depression, and back-arc extensional rift depression. The ECSSB is a multistage complex basin formed in a background of regional tectonic evolution of plates with continuous subduction.

### 4.1 Extrusional depression of the active continental margin in the Late Triassic–Middle Jurassic

In the Late Triassic–Middle Jurassic, the Izanaki Plate began to subduct at a low angle under the Eurasian Continental Plate. Under the influence of this subduction, the basement strata in the eastern margin...
of the ECSSB suffered compression and began to develop low uplift. (Epicontinental Uplift Zone). In addition, it suffered denudation and formed a depression at the trailing edge of the uplift belt, forming a subsidence zone and receiving the Late Triassic to Middle Jurassic deposition. At the same time, due to the uplift caused by the long-range effect of plate subduction in the Zhejiang-Fujian Uplift, the west side of the ECSSB is higher than the east side, forming tectonic-sedimentary units with geographically higher elevation in the west, lower elevation in the east, and unit thinning to the west. At this time, no obvious fracture or magmatic activity occurred in this area. Sedimentation and filling are not significantly controlled by faults. The sedimentary sequence is overlaid on both sides, and it appears as a superimposed form. The nature of the basin should belong to an extrusional depression (Figure 10a). In the process of structural physical simulation, under the boundary conditions of the precipitating plate boundary and the marginal uplift boundary, the double-side extrusion model (Figure 7) is used to realize the structural reconstruction process (Figures 8,9). The results of the simulation are similar to the results of seismic section restoration. The interpretation of the seismic profile and the results of structural physical simulation is insufficient evidence to show that the sediments in this period were controlled by thrust faults.

4.2 Extensional faulted basins of the active continental margin in the late Early Cretaceous–Late Cretaceous

In the late Early Cretaceous to Late Cretaceous, the speed and angle of the Pacific Plate subduction towards the NW increased. Affected by the retreat subduction of the Pacific Plate into the Eurasian Plate, there was extensive deformation, forming a combination of graben and semi-graben structures controlling the late Early Cretaceous–Late Cretaceous sedimentary stratigraphy, with local magmatic intrusion in the ECSSB located on the epicontinental marginal uplift belt. The result of seismic section interpretation and structural physical simulation showed that the depositional centre is located in the Keelung Sag, the Minjiang Slope is overlaiding from east to west, and multiple secondary graben and semi-graben constructions have been developed in its interior. In this period, the Oujiang faulted sag began to develop. Its structure was a west-fault east-overlap semi-graben with three faults in an echelon arrangement. The main boundary fault appeared as a moderately steep profile, and its downward extension may be detached into the weak layer between the crust and mantle, showing transtensional characteristics. During the structural physical simulation, a two-sided stratified differential stretching model was adopted. First, the Keelung Sag and the Minjiang Slope (representing the Early Cretaceous stratigraphic sediments) were generated in which the lower plastic mats were used to drive the stretch of silica gel, and both sides were simultaneously stretched. Then, the differential stretching pattern of the upper plastic sheet was used to realize the development of the Oujiang faulted sag (representing Late Cretaceous deposition). The experimental results show that the detachment faults produced by the upper plastic mats can form a semi-graben structure, and the differential stretching can result in NW-trending converted faults. The results of seismic data interpretation and experiments clearly demonstrate that the late Early Cretaceous–Late Cretaceous basin was a stratified and stretched faulted basin under bilateral tensile stress (Figure 10b).

4.3 The Palaeogene back-arc extensional faulted basin

After the Cretaceous sedimentation, the study area may have undergone temporary uplift and erosion. The truncation phenomenon can be seen on the top of the Cretaceous unit in the Minjiang Slope and the Yandang Low Uplift.

Since the Palaeogene, due to the outer continental shelf-generated volcanic eruptions forming a volcanic arc at the continental margin, the ECSSB is located in a back-arc stretch environment, meanwhile, the subduction of the Pacific Plate continued to enhance and the subduction angle of the Pacific Plate to the European Continental Plate changed (at 42.5 Ma, the direction of the subduction has changed from NNW to WNW). Under the effect of continuous tensile stress, the faulting intensity in the Keelung Sag increased, and the sedimentary strata became more inclined towards the southeast. At the same time, the Yandang Low Uplift was increased by the detached fault, and the top was subjected to erosion. The settlement amplitude also increased in the upper faulted plate of the Oujiang faulted sag. Due to the intense extension, a newly developed faulted sag began to form on the eastern continental margin uplift zone, and the new island arc zone (Ryukyu Island Arc) began to grow (Figure 10c) because of strong volcanic activity near the plate subduction zone in the southeast.

5 DISCUSSION: MESOZOIC DYNAMIC CONVERSION PROCESS

The ECSSB is a Mesozoic and Cenozoic superimposed basin that developed on the craton. Its evolutionary geodynamic background is due to the combination of the formation of the ancient Asian continent, the subduction of the Pacific Plate under the Eurasian continent since the Late Triassic, and the long-range effect of the Indian Plate’s subduction under the Eurasian Continent. The tectonic system underwent a major transformation during the Mesozoic, this area experienced a system transformation from the E-W-trending Tethys system to the NE or NNE-trending Western Pacific system, and the dynamic system changed significantly (Table 2) (Huan, Shi, & Yan, 1982; Li, Zhang, Dong, & Johnston, 2014; Shu et al., 2004). However, the start-up time and the process of dynamic conversion have always been the issues of concern and controversy (Li, Santosh, et al., 2012; Li, Jahn, et al., 2017; Sun, 2004; Sun et al., 2016). However, due to the differences in the study area, research objectives, and research methods, there are differences in the start-up time for inferred tectonic transformation. Ren (1984) and Ren, Chen, Niu, Liu, and Liu (1990) believed that starting in the Triassic, South China began to receive the joint action of the Palaeo-Tethys and Palaeo-Pacific Plate, and some of the E-W-trending belts were reconstructed. According to the analysis of deep geophysical characteristics and
TABLE 2 Mesozoic tectonic evolution and dynamics in the East China Sea Shelf Basin

| Period             | Basin evolution | Structural features                              | Fracture development | Tectonic stress field                                      | Plate tectonic background                              | Affiliated domain          |
|--------------------|-----------------|--------------------------------------------------|-----------------------|-----------------------------------------------------------|--------------------------------------------------------|-----------------------------|
| Palaeogene         | Back-arc faulted basin | The mantle is arched and the upper part of the crust is fractured, with the Oujialiang faulted-sag being the most obvious. The late Palaeogene rift moved from west to east | NE normal fault       | NE-SW extension or stretching                            | The Pacific Plate dives and the Indian Plate pushes remotely | Pacific domain              |
| Late Cretaceous    | Extrusion reversal, local uplift and erosion | Intracontinental tectonic system, crust extension and detachment, lithospheric thinning | Local reversal of NE-NNE fault to faulted period | NE-SW extrusion | The Izanaki Plate dives to the edge of the Eurasian continent | palaeo-Pacific domain Pacific domain |
| Late Jurassic–early Early Cretaceous | Biaxial stretching, large-area volcanic activity | Extrusion structure to extension structure conversion | NE-SW extrusions or stretches | Izanaki Plate NNW subduction | palaeo-Pacific domain |
| Late Triassic-Middle Jurassic (T₃–J₂) | Extrusion depression | Pacific Plate moving to the West | NE, NNE-oriented, few NW-regulatory faults | NW extrusion | Izanaki Plate NNW dive towards low angle | palaeo-Pacific domain |
| Middle Triassic    | Pushing and sieving by thrusting, collage of collision between North China Block and Yangtze Block | E-W or NEE is mainly NE-NNE | NW extrusion | Tethys closes, North China-Huaxia Block fits together | Palaeo-Tethys converted to Palaeo-Pacific domain |
| Early Mesozoic     | Passive continental margin | Multi-block convergence, collision between Sibumasu block and Indo-South China block | Mainly E-W or ENE | S-N horizontal extrusion | Andean edge | Palaeo-Tethyan domain |

lithofacies palaeogeography in southwest Fujian Province, Wu et al. (2000) believed that the Middle Triassic is an important transition stage, as in the Southeast China, there was a transition from the Palaeo-Tethys tectonic system to the Palaeo-Pacific tectonic systems in the Late Indosinian to early Yanshanian. According to the folds and faults developing in the Xuefengshan area, Li, Jahn, et al. (2017) thought that the conversion of the tectonic direction was completed in the Late or Middle Triassic. Based on zircon dating clastic rocks from the eastern Guangdong Province of South China, Yang and He (2013) speculated that the transition from the Palaeo-Tethys to the Palaeo-Pacific tectonics has been completed in the end of the Late Jurassic (180 Ma). Liu and Ma (1997), based on the end of the Middle Jurassic tectonic mélange of East Asia, and Zhao, Yang, and Ma (1994), based on palaeomagnetism, geochronology, and palaeontology, suggested that the initiation time of Palaeo-Pacific Plate subduction was at the end of the Middle Jurassic.

The previous argument shows that there were three stages of evolutionary characteristics, and each stage had a different deep dynamic background in the Mesozoic in the ECSSB. The structural patterns of active continental margin depression by NNW-trending subduction at low angles of the Izanaki Plate in the Late Triassic–Middle Jurassic; of active continental marginal tectonic styles by NNW-trending drawdown subduction of the Izanaki Plate in the late Early Cretaceous–Late Cretaceous; and of the left-sliding of Tancheng–Lujiang faults in the Late Cretaceous, resulted in the distribution of faulted sags and basin structures that indicated the existence of strike-slip-pulling of NNE-to-basal faults and back-arc rift.

Tectonic styles in the end of Late Cretaceous–Cenozoic were mainly characterized by the subduction of the Pacific Plate and the Indian Plate pushing remotely.

The basement of the ECSSB, revealed through drilling, is very close to the South China Block. The 1600 Ma ancient gneiss was drilled in the MRF-1 well. Geochemical data and the study of granite genesis in Taiwan revealed that there were 1700–2000 Ma Precambrian strata in the ancient basement of Taiwan. In addition, the age of the Dahan’ao Group in Taiwan was 240–200 Ma, and coral and other fossils were found in the crystalline limestone, indicating that the middle-upper strata included Early Permian strata (Ma, 1992). However, there is no evidence that there was a subduction zone in the Indosinian in the eastern part of South China. Therefore, it was inferred that this may be a passive continental margin facing the Palaeo-Pacific (Pan-Ocean).

In the Early Triassic, the eastern margin of the Palaeo-Tethys extended eastward into southern China, and most of Guangdong, Guangxi, Southwest Yunnan, and Southeast Yunnan developed marine
sedimentary environments (Li, 2008). During the Middle Triassic, the Indosinian Movement began to affect South China. The lithofacies palaeogeography is divided by east and west as roughly the boundary of Yunkai ancient land. Yunnan continues to be controlled by the Tethys domain, extensive transgression has occurred, and semideep marine environments have appeared in the Nanpanjiang area of Guizhou and southwest Guangxi. In the Southeast China, the seawater receded to Yangshan, North Guangdong. The direction of the tectonics also changed from E-W-trending and NE-ENE-trending to NE-NNE-trending and gradually set the stage for the Palaeo-Pacific Plate active continental margin (Li, Santosh, et al., 2012; Yang et al., 2012).

The Late Triassic was the peak of the Indochina Movement. In the western South China Sea, when the Palaeo-Tethys gradually closed, the Indochina Block and the China–Myanmar Block collided and sutured, and a huge tin-bearing granite belt was formed due to deep melting along the suture zone (Li, 2008); in the eastern part of South China, transgression began in the Middle-Late Carnian, Triassic (T₃⁻¹). The East Guangdong Sea Basin formed in the Southwest in East Yunnan and North Central Guangdong, and the East China Sea Basin formed in the East China Sea Shelf. There was shallow marine carbonate and clastic rock formation and marine-continent interaction coal-bearing debris construction, which deposited hundreds of metres to nearly 3,000 m of material. A brief regression occurred after the Norian (T₃⁻²). However, a greater transgression occurred in the Early Jurassic, a semideep sea environment existed in East Guangdong and the East China Sea, and a semideep marine facies flysch formation was developed in the Nantang Group with a thickness of 2,300 m in the land area. Coal-bearing detritus has been deposited in other areas. The changing characteristics of lithofacies indicated that the transgression was apparently from the southeast or east, and there should be a marginal sea that was related to the Palaeo-Pacific subduction under Eurasia or to Palaeo-Pacific sea level rise. At the same time, a series of NNE–NE-trending faulted sags also formed within the South China Block. The intensity of fault activity shows an increasing eastward trend. It also shows the effect on the Palaeo-Pacific Plate subduction. The East China Sea Basin found Pacific Rim biota in the Upper Triassic. However, the Lower Jurassic contained Tethys fauna, probably because of the increase of global sea level in the Early Jurassic, which led to the large amount of seawater in Tethys entering this area, showing the combined effects of the two major tectonic domains. During the Middle Jurassic, most parts of South China and the Indochina peninsula were land, developed by red layers of lacustrine material, and the tectonic movement was relatively calm.

The Late Jurassic-Early Cretaceous, West China, was land. The clastic deposition of continental fluvial and lacustrine facies was dominant, and both unconformable contact with the underlying strata and volcanic activity were rare. The eastern part of South China was the upsurge of the Yanshan movement. Due to the subduction of the Palaeo-Pacific Plate under the Eurasian Plate, large-scale volcanic eruptions and pyroclastic accumulations occurred. Volcanic activity was especially common in the diamond-shaped region, east of the Zhenghe-Dapu-Haifeng Fault, where acid-acidic volcanic rocks are mainly distributed (He & Xu, 2012; Xu, Zhang, Jia, Shu, & Wang, 2009; Zhou & Li, 2000). This indicates that it has been subjected to uplift and erosion at the active continental margins of the Palaeo-Pacific Ocean and that the southwest Taiwan Basin develops deep-sea shale of several hundred metres thick in the Lower-Middle Jurassic, and the Upper Jurassic is generally absent.

In the Early Cretaceous, significant tectonic conversion took place at the continental margin of East Asia. The subduction plate sheets from the Palaeo-Pacific Plate under the Eurasian Plate retreated to the ocean due to too high slope, thus ending the hyperplasia of the Eurasian continent. The continental margin of East Asia began to enter the expansion period of the continental margin. The regional stress field changed from extrusion to stretching (Niu, 2015). The large-scale splitting eventually formed a series of Cenozoic sedimentary basins from the Yuandong in Russia to the north and to the south through the East China Sea and the South China Sea to the Gulf of Thailand.

According to subduction-forming 80–90 Ma blue chronosphere belts in Taiwan and Japan (Ma, 1992), indicating that there is a subduction active continental margin along the East Asian continent in the early Late Cretaceous. Through the restoration of its structural features (Sengor & Natalin, 1996), it was thought that the continental margin was still an Andean-type active continental margin (James & Sacks, 1999).

However, due to the combined effect of Pacific Plate subduction and western Indo-Eurasian Plate collision, the continental margin was in the background of the right-handed shear stretch for the East Asian continent and brought about a series of pull-basins that were mainly controlled by NE-trending strike-slip faults along the continental margin and the inland region in the Late Cretaceous to the Eocene.

The Cenozoic basin evolution has obvious stages under the control of the regional stress field. During the Palaeocene-Eocene Period, the direction of Pacific Plate movement shifted from WNW-trending to NNW-trending, subjecting the entire East China Sea Shelf to a single main shear stress field. This led to a series of verrucous faulted depressions in the basin and two regional tectonic events that are directly related to the formation of the faulted depression structure in the basin, namely, the early Palaeocene Yandang movement and the early Eocene Oujiang movement. The Palaeocene-Eocene Epoch is the main development period of each depression in the ECSSB, and it is the main basin-forming period of the Cenozoic basin in the East China Sea continental shelf. The Palaeocene and Eocene are the main developmental periods of western and eastern depressions.

6 | CONCLUSIONS

Based on summarizing and analysing previous research on the Mesozoic tectonic evolution and tectonic system transformation of the ECSSB, the combined analysis of the regional tectonic background, of structural physical simulation experiments and of balanced geological profiles, the evolution processes of the Mesozoic basin in the East China Sea Shelf were analysed, and the process of basin dynamics transitions were discussed. We reached the following conclusions:
1. The Late Triassic–Middle Jurassic is the stage of an extrusion-depression basin of active continental margin, and the compressive stress is derived from the low-angle subduction of the Izanagi Plate under the Eurasian Plate. The basement strata in the eastern margin of the East China Sea Continental Shelf suffer from extrusional low uplift (uplift in the continental margin) and are subject to denudation. A depression formed at the trailing edge of the uplift belt and a subsidence belt, which is subject to Late Triassic to Middle Jurassic deposition.

2. The late Early Cretaceous–Early Cretaceous is the stage of extension faulted basins of the active continental margin. The stress originates from the thinning effect of the lithosphere caused by the subduction of the Palaeo-Pacific Plate under the Eurasian Plate, resulting in extensional deformation, forming a combination of graben and semi-graben structures and controlling late Early Cretaceous–Late Cretaceous stratigraphic deposition. The Oujiang faulted sag was a semi-graben basin formed by the double-stretched lithosphere.

3. The transition time from the Palaeo-Tethys tectonic domain to the Palaeo-Pacific tectonic domain in the ECSSSB occurred in the Late Triassic. That is, the Palaeo-Pacific Plate began to subduct during the Late Triassic. The low-angle subduction and withdrawal of the Palaeo-Pacific Plate may be more representative of the deep Mesozoic geological processes in southern China. Before the Middle Jurassic, the subduction was low angle. After the Early Cretaceous, the subduction plates were turned from low angle to high angle, and the subduction relented.

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