Late Mesozoic transition from Andean-type to Western Pacific-type of the East China continental margin—Is the East China Sea basement an allochthonous terrain?

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Funding information
Dream Project of MOST of China, Grant/Award Number: 2016YFC0600402; National Natural Science Foundation of China, Grant/Award Number: 41676027,41376066 and 41676027; National Programme on Global Change and Air-Sea Interaction, SOA, Grant/Award Number: GASI-GEOGE-01; NSFC-Shandong Joint Fund for Marine Science Research Centres, Grant/Award Number: U1606401

Handling Editor: I. Somerville

1 INTRODUCTION

Previous studies on the southeastern margin of the South China Block have revealed the following three facts: (a) a broad continental magmatic arc developed from the Jurassic to the Middle Cretaceous (190 to 90 Ma), traditionally indicating the existence of an Andean-type active continental margin (i.e., Li & Li, 2007; Li, Santosh, Zhao, Zhang, & Jin, 2012; Niu et al., 2015; Zhou & Li, 2000); (b) magmatic activities ceased since 90 Ma and the magmatic gap continued to 60–50 Ma (Li et al., 2012; Niu et al., 2015; Niu & Tang, 2016); and (c) the eastern continental margin of the South China Block experienced bimodal magmatism and back-arc rifting related to the subduction of the Pacific and the Philippine Sea plates after 60–50 Ma, illustrating a Western Pacific-type continental margin (Chen et al., 2010; Chung, Sun, Tu, Chen, & Lee, 1994; Chung, Yang, Lee, & Chen, 1995; Li et al., 2012; Lin, Watts, & Hesselbo, 2003; Niu et al., 2015; Niu & Tang, 2016; Luo et al., 2015; Zhou et al., 2009; Zhu et al., 2004). However, how and when the Andean-type continental margin switched into a Western Pacific-type remains unclear. Li and Li (2007) and Li et al. (2012) proposed that a new continental arc was initiated after 280 Ma along the coast after a magmatic gap owing to flat-slab subduction, which persisted until 90 Ma. After 90 Ma, a slab rollback of the Mesozoic Palaeo-Pacific subduction zone caused a retreat of the arc system and a back-arc rifting. However, those researchers did not provide...
further discussion about the magmatism gap between 90 and 50 Ma, or a retreat process of the subduction zone.

Studies on the Mesozoic Palaeo-Pacific subduction zone before a slab rollback began in the late 20th century, but the location of this zone is still in doubt. Guo, Shi, and Ma (1983) argued that the suture, as a relic of this Mesozoic subduction zone, is generally along the 40-m-depth contour offshore of East China. With geophysical studies on the Taiwan Straits, Wang, Chen, Cao, Pan, and Wang (1993) confirmed this opinion and pointed out that the Coastal Fault Zone is the southward extension of the suture. Studies related to metamorphic rocks within the Tananao Basement Complex in the eastern Taiwan Central Range, however, have suggested that this complex belt is the suture (Cao & Zhu, 1990; Lo & Yui, 1996). Despite arguments about the position of the Mesozoic subduction zone, few works have focused on the time-space relationship of the East China Sea (ECS) and the Mesozoic subduction zone, and what kind of role this relationship played during the transition from Andean-type to Western Pacific-type of the eastern margin of the South China Block. In this study, we try to reveal the crustal structure and nature of the ECS basement since the Mesozoic and to constrain the transition from Andean-type to Western Pacific type continental margins to the east of the South China Block.

2 GEOLOGICAL SETTING

The ECS is a 1300-km-long, nearly 740-km-wide sea distributed between 21°54′N and 33°17′N and 117°05′ and 131°03′E, with a total area of 770,000 km² (Figure 1). The average water depth is 370 m, but reaches 2,322 m in the Okinawa Trough. The ECS contains two major tectonic units: the continental shelf basin in the west and the Okinawa Trough in the east, separated by a narrow continental slope. Some linear sand ridges are well developed on the continental shelf. To the east, the Ryukyu Arc serves as the tectonic boundary between the ECS and the Philippine Sea. It is generally accepted that the ECS is a part of the South China Block, which has experienced episodic rifting since the Late Cretaceous, owing to rollback of the subducted Mesozoic Palaeo-Pacific slab. The Okinawa Trough is a back-arc basin related to the subduction of the Philippine Sea under Eurasia since 2 Ma (J. B. Li, 2008a; X. Li, 2008b; Liu et al., 2016).

Research on the ECS basement started in the 1980s, and geophysical and geological data have dramatically increased in the past three decades with more exploration efforts, especially from drilling. There are currently more than 70 drilling sites in the ECS, one third of which penetrated into the pre-Cenozoic basement (J. B. Li, 2008a; X. Li, 2008b). Drilling results show that the basement of the Zheming volcanic belt is mainly composed of pre-Sinian metamorphic rocks and well-developed Yanshanian intrusive and volcanic rocks, broadly consistent with the Cathaysia basement rock in the South China Block (Li et al., 2012; Wang et al., 2015). The pre-Cenozoic basement of the continental shelf basin is mainly composed of Mesozoic terrestrial sediments, volcanic rocks, and pre-Sinian metamorphic rock (J. B. Li, 2008a; X. Li, 2008b). The Diaoyu Island uplift-fold belt was connected with the Ryukyu Arc before the opening of the Okinawa Trough and shares a similar basement with Late Paleozoic, Mesozoic, and Paleogene metamorphic sediments (J. B. Li, 2008a; X. Li, 2008b). The basement of the Okinawa Trough includes Paleogene, Mesozoic sedimentary, and metamorphic rocks, with volcanic intrusions and seamounts (J. B. Li, 2008a; X. Li, 2008b).

The ECS is subdivided into five tectonic units, including the Zheming Volcanic Belt, the continental shelf basin, the Diaoyu Island uplift-fold Belt, the Okinawa Trough, and the Ryukyu Arc (Suo et al., 2014; Suo et al., 2015; Zhang, Li, & Suo, 2016, Zhang, Li, Suo, & Zhang, 2016). The Zheming Volcanic Belt is similar to the East China Granite Belt, characterized by Yanshanian intermediate-acid intrusive and eruptive rocks (Li & Li, 2007; Niu et al., 2015; Zhou & Li, 2000). The continental shelf basin covers most of the ECS and is further divided into the West Depression, the Central Uplift, and the East Depression (Zhang, Li, & Suo, 2016; Zhang, Li, Suo, & Zhang, 2016). The sediments in the West Depression are mainly Paleogene. The East Depression is characterized by larger sags and thicker sediments than those of the West Depression. The sediments are mainly Miocene. The Central Uplift is absent of Mesozoic and Paleogene sediments and covered with sparse, thin Neogene sediments. In the shallow Diaoyu Island uplift-fold Belt, the basement is covered with Pliocene and Quaternary sediments. The Okinawa Trough is moon-shaped, with negative topography elongating in a various NNE-, NE- to ENE orientation. It is mainly composed of very thick Neogene sediments that can reach 10 to 12 km. The deposition age in the ECS gets younger from north to south and from west to east (Liu et al., 2016).
3 | DATA AND METHODS

3.1 | Data

Gravity and magnetic data were collected by the 1:500000 Scaling Gravity, Magnetic, and Bathymetric Survey in 2005, the 1:250000-scale Gravity, Magnetic, and Bathymetric Survey in 2000 to 2002, and the Near Shore 1:250000-scale Gravity, Magnetic, and Bathymetric Survey in 2007 to 2010. All these surveys were carried out by the Second Institute of Oceanography, State Oceanic Administration, China. The total length of surveying lines in the study area is about 141,000 km. The mean square roots of intersection for the gravity and magnetic surveying lines are more than $\pm 1.47 \times 10^{-5}$ m/s$^2$ and $\pm 6.69$ nT, respectively. Blank areas are interpolated with a satellite-derived gravity model (Sandwell et al., 2013) and Earth Magnetic Anomaly Grid 2 data (Maus et al., 2009). We normalized the data sets and generated gravity grid data and magnetic grid data with 1′ × 1′ spatial resolution. The gravity and magnetic anomaly maps are shown in Figure 2. The depths of the sediment basement were compiled from seismic imagery from Shanghai Offshore Petroleum (Lin, Sibuet, & Hsu, 2005) and a Cenozoic sediment isopach map (Liu, 1992). The grid was produced in a Mercator projection referenced to WGS84 with central longitude at 125°E and central latitude at 29°N.

3.2 | Methods

3.2.1 | Upward continuation and reduction-to-the-pole (RTP) of magnetic anomaly

The computation of upward continuation of a magnetic anomaly reduces local magnetic disturbances and reveals deeper anomalies in the lithosphere. In this study, variable inclination RTP is employed (Li & Olderburg, 2001; Li J.B., 2008a; Li X., 2008b), in which we divide the study area into 10 zones (3° per zone) with corresponding inclination and deflection. The inclination ranges from 60.6° to 16.8°, and the deflection ranges from −6.9° to −1.2° from north to south during the process.

To standardize resolution of magnetic grid data in the continental and oceanic regions, we further upward continued the data set and reduced some high-frequency parts in the oceanic region. The upward continuation equation is:

$$e^{2\pi n(u^2+v^2)^{1/2}z}.$$

Where $u$ and $v$ are the wave number in two directions, and $z$ is the latitude. The result of 5 km upward continuation is shown in Figure 3.

3.2.2 | Calculation of crustal thickness

Sediment thickness is an important factor in the calculation of Moho depth and crustal thickness. Deposition on the continental shelf of the ECS is generally more than 2 km thick and can reach more than 10 km in some areas (Zhu, Mi, & Zhang, 2010). Correction for the effect of sediments is essential when calculating the Moho depth and crustal thickness of the ECS. By using a variable density correction formula for fan blocks in a spherical coordinate system, we reduced the gravity effect on sediments and obtained the residual gravity anomaly, which reflects the surface of the density contrast between the crust and mantle. The inversion is conducted based on the 3D Parker inversion method (Oldenburg, 2012), with constraints from multichannel seismic data (Zhou et al., 2013). The density contrast is calculated as $0.44 \times 10^{-3}$ kg/m$^3$. The recovered crustal thickness is shown in Figure 4.

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FIGURE 2  Gravity anomaly (a to the left) and magnetic anomaly (b to the right) of the East China Sea and adjacent regions. Thick broken lines are the northern and southern basin boundaries of the East China Sea. Thin dashed lines are the boundaries of major geological units [Colour figure can be viewed at wileyonlinelibrary.com]
RESULTS: GEOPHYSICAL CHARACTERISTICS AND CRUSTAL THICKNESS

Based on RTP gravity and magnetic anomalies and the crustal thickness, we divided the ECS into five geological units, including the Zhemin Volcanic Belt, the West Depression-Central Uplift, the East Depression, the Diaoyu Island Uplift-Fold Belt, and the Okinawa Trough, from west to east (Figures 2, 3, and 4). The boundaries of all these units fit well with sharp geophysical field changes. The West Depression and the Central Uplift show similar geophysical features and crustal thickness, so we treat them as one unit.

The RTP magnetic anomaly map shows that the Zhemin Volcanic Belt is characterized by high frequency, high-amplitude anomalies, which are believed to be the result of strong magmatic activities (Figure 3). The West Depression-Central Uplift is characterized by low frequency, low-amplitude anomalies, indicating a different basement composition. The Zhemin Volcanic Belt and the West Depression-Central Uplift were generally separated by the 0 nT contour, which is 100 km away from the coastline (Figure 3). The Zhemin Volcanic Belt has distinct differences in crustal thickness from the West Depression-Central Uplift, which is more than 25 km, but drops sharply to nearly 20 km in the latter region (Figure 4).

The magnetic anomalies in the East Depression generally range from 0 to 100 nT at low frequencies similar to those in the West Depression-Central Uplift. Isolated island-shaped positive anomalies appear occasionally, caused by magmatic intrusions. The crustal thickness of the East Depression is less than 20 km, and even reduces to 15 km (Figure 4). These data indicate that the basement composition of the East Depression is similar to that of the West Depression-Central Uplift, but experienced stronger extensive rifting.

The Okinawa Trough is a back-arc basin with large-scale, low-amplitude, wide, negative magnetic anomalies. The crustal thickness is less than 20 km and can be as little as 15 km. It is thinner than those of typical continental crust and is thicker than those of normal oceanic crust. Initial seafloor spreading might have occurred in the south with minimum crustal thickness (Sibuet & Hsu, 1997).

DISCUSSION

5.1 The East China Sea basement as an allochthonous terrain

The distance between a trench and a volcanic arc cannot be unlimited and is controlled by the subduction angle, the water, and volatile contents within the subducted materials (Stern, 2002, 2004). Recent
studies on the active Western Pacific, such as the Okinawa Trough in the initial seafloor-spreading stage, or the Lau Basin and Mariana Trough that have mature oceanic basins, show that the distance between the subduction zone and the arc/back-arc basin is generally between 150 and 350 km (Li, Ding, & Li, 2011).

The Zhemin Volcanic Belt is mainly composed of Late Jurassic–Early Cretaceous intermediate-acid intrusive and eruptive volcanic rocks with ages ranging between ~190 and ~88 Ma, getting younger seaward (Li & Li, 2007; Niu et al., 2015; Zhou & Li, 2000). Considering the regular distance between the volcanic arc and the trench, that is, 150 to 300 km, the related Mesozoic Palaeo-Pacific Subduction zone should not be far from the Zhemin Volcanic Belt and may lie within the present ECS continental shelf area.

Remarkable differences in geophysical features between the ECS continental shelf basin and the Zhemin Volcanic Belt indicate that the ECS basement might not be an offshore part of the continental lithosphere of the South China Block. We hypothesize an allochthonous origin for the ECS basement, which was originally a thinned continental block within the Palaeo-Pacific Plate and moved westward with it. In the Late Cretaceous, this thinned continental block collided with the South China Block. This thinned continental block was too buoyant to be subducted and thus caused the cessation of Mesozoic subduction, jammed the trench, and ceased the extensive magma activities in East China. The suture (i.e., the jammed trench) lies possibly between the West Depression and the Zhemin Volcanic Belt. Fission track thermochronology on the Linfeng and Yandang uplifts within the West Depression of the ECS (Tang, Seward, Wilson, Sewell, & Carter, 2014), and on the Chencai region of the onshore Jiangshan–Shaoxing Fault Zone (Wang et al., 2015), suggests that all of these regions experienced rapid uplifting in this stage, which might have resulted from the collision of the ECS basement with the South China Block.

The history of the Nansha Block in the South China Sea provides a convincing case for the buoyant and unsubductable properties of the ECS allochthon. It has been generally accepted that the South China Sea opened in response to slab pull during subduction of proto-South China Sea oceanic crust beneath NW Borneo (e.g., Cullen, 2010; Franke et al., 2014). With the opening of the South China Sea, the Nansha Block, which is similar in size to the ECS, broke off from the South China Block after 32 Ma, and moved southward for hundreds of kilometres before finally colliding with Borneo (Ding, Franke, Li, & Steuer, 2013). The collision jammed the trench caused by the subduction of the Proto-South China Sea beneath Borneo and halted the seafloor spreading of the present-day South China Sea (Cullen, 2010; Ding & Li, 2016).

5.2 Dynamic mechanism of the magma gap-trench jam?

Limited volcanic activities related to subduction were observed in East China between ~90 and ~50 Ma (Li & Li, 2007; Niu et al., 2015). The eastern continental margin of the South China Block and the collided ECS were both controlled by transensional stress fields. The faults in the continental shelf basin are characterized by transensional faulting and show extensional structures in seismic profiles (Suo et al., 2014; Suo et al., 2015). The sedimentary formations are mainly Palaeocene in the West Depression (Figure 5), which are dominated by Eocene–Oligocene in the East Depression (Figure 6), indicating eastward propagation of the sedimentary basins and tectonics migration. The typical Andean-type continental margin likely terminated at around 90 Ma. Li et al. (2012) argued that this dramatic tectonic transition was due to the rollback of the old and heavy oceanic slabs in the Western Palaeo-Pacific Ocean. Zhang, Li, and Suo (2016) suggested this transition of tectonic regime was related to the composite actions of the passive retreat of the subduction zone of the Palaeo-Pacific Plate and the far-field effect of the convergence between the Indian–Australian and Eurasian plates. We cannot exclude all of these possibilities. Although considering the opinion that the ECS basement is an allochthonous terrain, the collision between the ECS basement and the South China Block might give more details about why the retreat of the Palaeo-Pacific Plate occurred at 90 Ma.
Niu, O’Hara, and Pearce (2003) demonstrated that subduction cannot stop once initiated and that the only cause of subduction cessation is trench jamming. The arrival of the buoyant ECS at the trench would jam the trench because it is too buoyant to subduct. The Palaeo-Pacific Plate continued its north–north-west (NNW)-trending motion, but the convergence rate of the Palaeo-Pacific Plate reduced from 130 to 75 mm/a (Zhang, Li, & Suo, 2016). Both the eastern continent margin of the South China Block and the ECS basement were controlled by right lateral tension-shear stress fields, characterized by well-developed wedge-shaped faulted sags and limited magmatic activities.

This dextral transtension dominated not only the eastern margin of the South China Block and the ECS basement but also the southern margin of the South China Block. Since the Late Cretaceous prototypical margin of the South China Sea also experienced episodic rifting between the Late Cretaceous and the Oligocene and formed numerous NE-SW-trending half-grabens, and finally resulted in the seafloor spreading between 32 and 16 Ma (Li et al., 2014).

6 | MESO-CENOZOIC RECONSTRUCTION OF THE EAST CHINA SEA EVOLUTION

Most previous attempts at an evolutionary model treated the ECS as part of the continental lithosphere of East China, which was first an Andean-type active margin caused by the subduction of the Palaeo-Pacific Plate; eastward migrating rifting then occurred, caused by slab rollback of the subduction zone (e.g., Chen et al., 2010; Chung, Sun, et al., 1994; Chung, Yang, et al., 1995; Li et al., 2012; Lin et al., 2003; Suo et al., 2014; Suo et al., 2015; Yang et al., 2016; Zhu et al., 2004). However, by accepting the notion that the ECS is an allochthonous terrain and that there was a passive margin stage before the development of the Western Pacific-type continental margin, the whole evolution model should be reconstructed as follows.

Between the Late Jurassic and Early Cretaceous, the Palaeo-Pacific Plate subducted under the Eurasian Plate at a low angle. The eastern continental margin of the South China Block was an Andean-type active margin (i.e., Li & Li, 2007; Niu et al., 2015; Zhou & Li, 2000). The extensive Zhemin Volcanic Belt formed (i.e., Li & Li, 2007; Sun, Ding, & Hu, 2007) and the ECS basement was a continental block in the Palaeo-Pacific Plate that moved westward (Figure 7a).

In the Late Cretaceous, the buoyant ECS basement began to collide with the South China Block, jamming the trench instead of subduction. This terminated the subduction of the Palaeo-Pacific Plate and the related volcanic activities. The collision zone, or the suture, generally lies along the boundary between the Zhemin Volcanic Belt and the West Depression, about 100 km from the coastline. The continental margin of the South China Block and the collided ECS basement were dominated by dextral transtension, which led to the formation of NE-SW-trending wedge-shaped faulted sags, such as the faulted sags in the onshore Zhejiang and Fujian provinces and the offshore West Depression in the ECS (Figure 7b). The rifting and cessation of subduction-related volcanic activities continued until the Early Eocene.

**FIGURE 7** Conceptional tectonic model showing the evolutionary reconstruction of the East China Sea basement since the Mesozoic. (a) Between Late Jurassic and Early Cretaceous, the eastern continental margin of the South China Block was an Andean-type active margin with giant granitoid magmatism. The ECS basement was a continental block in the Palaeo-Pacific Plate and moved westward; (b) In the Late Cretaceous, the East China Sea basement collided with the South China Block, terminated the subduction and related magmatism. The ECS was dominated by right lateral tension-shear stress field, developing wedge-shape rifts, including the West Depression; (c) Renewed westward subduction of the present-day Pacific since the Middle Eocene triggered the development of the pro-Ryukyu Arc and the back-arc rifting in the East Depression. The ECS basement was a Western Pacific-type continual margin; (d) Since the Middle Miocene the ECS basement experienced thermal subsidence; (e) At 5 Ma, the Philippine Sea Plate began its subduction under Eurasia. The Okinawa Trough began the back-arc spreading; ZMVB = Zhemin Volcanic Belt; ECSB = East China Sea basement; SCB = South China Block; WD = West Depression; ED = East Depression; CU = Central Uplift; DUPB = Diaoyu Island Uplift-Fold Belt; OT = Okinawa Trough; RA = Ryukyu Arc [Colour figure can be viewed at wileyonlinelibrary.com]
Since the Middle Eocene (~50 Ma), the present-day Pacific Plate began its subduction under the Eurasian Plate (Wu, Suppe, Lu, & Kanda, 2016). The old and cold Pacific oceanic lithosphere of about 50 Ma began its initial subduction and resulted in a high subduction angle, forming the Western Pacific-type continental margin (Figure 7c). It is also consistent with less than 20 Myr stagnant slab age by Liu, Zhao, Li, and Wei (2017). The Central Uplift separated from the proto-Ryukyu Arc, and the East Depression that developed between them acted as a back-arc basin. Upper Eocene–Middle Miocene deposits more than 10 km thick developed in these faulted sags, with structural patterns that differed obviously from those of the West Depression (Figure 6). During this stage, the West Depression experienced long-term uplifting (about 30 Myr), and the Middle Eocene–Early Miocene deposits were eroded. This tectonic inversion might have been caused by clockwise rotation of the faulted blocks; that is, the rift shoulders, including the Central Uplift and the West Depression, experienced uplifting whereas the East Depression was subsiding (Suo et al., 2014; Suo et al., 2015; Zhang, Li, & Suo, 2016, Zhang, Li, Suo, & Zhang, 2016).

After the Middle Miocene, the ECS was dominated by regional thermal subsidence (Figure 7d). The Philippine Sea finally began its subduction under the ECS along the Ryukyu Trench after long-term NNW-trending movements. The proto-Ryukyu Arc was broken up by back-arc seafloor spreading. The Okinawa Trough began spreading, which separated the modern Ryukyu Arc in the east and the Diaoyu Island Uplift-Fold Belt in the west (Figure 7e).

7 | CONCLUSIONS

Geophysical inversion analysis based on recent gravity and magnetic data reveals significant differences between the continental shelf basin of the ECS and the coastal regions of the South China Block in geophysical features, as well as crustal structures. The former is characterized by low-frequency, low-amplitude magnetic anomalies, and thinner crustal thickness (generally between 15 and 20 km), and the latter is characterized by high-frequency and high-amplitude anomalies, and thicker crustal thickness (generally higher than 25 km). These facts make us doubt that the ECS basement is an offshore extension of the South China Block covered with land-derived sediments. We have presented a hypothesis that the basement of the ECS is a buoyant, allochthonous terrain unrelated to the continental lithosphere of East China. With this notion, we try to explain two mysteries of western Pacific geodynamics, that is, how did the eastern continental margin of South China Block transform from Andean-type to Western Pacific-type in the late Mesozoic, and why was there a granitoid magmatism gap that lasted ~40 Myr since then?

Reconstruction of the Meso-Cenozoic ECS tectonic models with geophysical and geological constraints suggests that during the entire Mesozoic, the westward subduction of the Palaeo-Pacific Plate under Eurasia created extensive magmatism in East China and formed a broad continental magmatic arc. The ECS basement was a continent block on the Palaeo-Pacific Plate and moved westward. It finally collided with the South China Block in the late Mesozoic (~90 Ma) and jammed the proto-trench because it was too buoyant to subduct, thus terminating the subduction of the Palaeo-Pacific Plate and the related volcanic activities. The suture generally lies along the boundary between the Zhemin Volcanic Belt and the West Depression, approximately 100 km from the coastline, as implied by sharp changes in gravity and magnetic anomalies and crustal thicknesses. The NNW-orientation motion of the Palaeo-Pacific Plate and the reduced convergence rate with the Eurasia Plate made the eastern continental margins of the South China Block and the collided ECS basement be dominated by dextral tension-shear stress fields without granitoid magmatism.

Further efforts with respect to the ECS Mesozoic sedimentary provenance, the nature and origin of the ECS basement, and lithospheric structure are needed to test the hypothesis that the ECS basement is an allochthonous terrain and to provide solid constraints on the Late Mesozoic evolution of the East China continental margin.

ACKNOWLEDGEMENTS

We want to thank Prof. Ian Somerville and another anonymous reviewer for their comments. This work was financially supported by the Dream Project of MOST of China (Grant 2016YFC0600402), the NSFC-Shandong Joint Fund for Marine Science Research Centres (Grant U1606401), the National Programme on Global Change and Air-Sea Interaction, SOA (Grant GASI-GEOGE-01), and the National Natural Science Foundation of China (Grants 41676027 and 41376066).

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How to cite this article: Ding W, Li J, Wu Z, Li S, Lin X. Late Mesozoic transition from Andean-type to Western Pacific-type of the East China continental margin—Is the East China Sea basement an allochthonous terrain?. Geological Journal. 2018;53:1994–2002. https://doi.org/10.1002/gj.3029