Structural evolution of two-stage rifting in the northern East China Sea Shelf Basin

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This study focuses on the stratigraphic correlation and structural evolution of the leodo and Jeju basins in the northern East China Sea Shelf Basin (ECSSB), which are compared to the Changjiang and Xihu depressions, respectively. Based on multi-channel seismic reflection data, Cenozoic sedimentary successions resting on the acoustic basement in both basins can be divided into multiple syn- and post-rift units. Basement-involved structures exhibit different orientations, that is, E–W (ENE–WSW) and NE–SW trending structures in the leodo and Jeju basins, respectively. They represent the development of two-stage rifting. The first rift stage began in the Palaeocene and was only restricted to the leodo Basin located west of the Hupijiao Rise. The second rift stage subsequently occurred in the Jeju Basin located east of the Hupijiao Rise during the late Eocene to Miocene. The Eocene post-rift unit of the leodo Basin was uplifted while the Jeju Basin was subsided by bounding faults. The sequential development of rift structures in the basins suggests eastward migration of the Cenozoic rifting in the northern ECSSB. The NE-trending rift structure of the Jeju Basin parallel to the subduction zone of the Pacific Plate suggests that the second rift stage possibly evolved under the influence of the back-arc extensional regime. The Hupijiao Rise between the leodo and Jeju basins was possibly a geologic basement in the Palaeocene and was an uplifted remnant caused by footwall exhumation during the second rift stage of the Jeju Basin.

KEYWORDS
East China Sea Shelf Basin, Hupijiao Rise, leodo Basin, Jeju Basin, two-stage rifting

1 INTRODUCTION

Late Cretaceous–Cenozoic basins along the East Asian continental margin have attracted much attention for hydrocarbon exploration and evaluation over the past few decades (Gongcheng, Li, Lei, & Zhao, 2015; Jiang, Li, Chen, Zhang, & Wang, 2016; G. H. Lee, Kim, Shin, & Sunwoo, 2006; Pigott, Kang, & Han, 2013; Ye, Qing, Bend, & Gu, 2007; Zhou, Zhao, & Yin, 1989). East China Sea Basin (ECSB), one of the petroliferous sedimentary basins in the East Asia, is composed of elongated depressions aligned parallel to the subduction zone of the western Philippine Sea Plate with the Taiwan–Sinzi Belt and Ryukyu Arc (Figure 1; Wageman, Hilde, & Emery, 1970). Spatio-temporally, the ECSB has different generations and styles, showing the E–W zonation parallel to the subduction zone and N–S differentiation (Hsu, Sibuet, & Shyu, 2001; Lin, Sibuet, & Hsu, 2005; Sibuet & Hsu, 1997; Sibuet, Hsu, & Debayle, 2004; Su et al., 2014; Suo, Li, Yu, Somerville, & Liu, 2014; Suo et al., 2015; S. Yang et al., 2004; G. Zhang, Li, Suo, & Zhang, 2016).
In this study, we investigate the northern East China Sea Shelf Basin (ECSSB) consisting of the Ieodo and Jeju basins separated by the Hupijiao Rise, which is one of the representative uplifts (Figure 2). According to previous studies, both basins evolved from late Cretaceous to Miocene rifting and have undergone approximately coeval tectonic evolution (Cukur, Horozal, Kim, & Han, 2011; Koh 

![Topographic map of the East China marginal sea and adjacent trench-arc-basin region with the Ryukyu subduction zone](modified from Suo et al., 2015; Zhou et al., 1989). The contour map is extracted from data by Smith and Sandwell (1997). CJ: Changjiang Depression; DB: Diaobei Depression; DM: Domi Basin; FJ: Fujiang Depression; FZ: Fuzhou Rise; HJ: Haig//: Hupijiao Rise; ID: Ieodo Basin; JJ: Jeju Basin; SR: Sora Basin; TB: Taihei Depression; XH: Xihu Depression; YS: Yushan Rise [Colour figure can be viewed at wileyonlinelibrary.com]

![Stratigraphic correlations between the Ieodo and Jeju basins in the northern ECSSB](after Koh, Yoon, Lee, & Yoo, 2016; Lee et al., 2006; Su et al., 2014; J. Zhang et al., 2016)
et al., 2016; G. H. Lee et al., 2006). The Hupijiao Rise was regarded as a tectonic boundary, such as a transverse fault zone, separating the basins (Figure 2; Zhou et al., 1989). However, there have been few attempts to determine the structural linkage and stratigraphic differences between basins, or their relationship with adjacent basins (i.e., Changjiang and Xihu depressions) in the northern ECSSB.

This paper aims to examine the spatial and temporal distribution of the leodo and Jeju basins and the Hupijiao Rise in the northern ECSSB and provides refined seismic stratigraphy in comparison with other depressions of the ECSSB based on seismic interpretation.

2 | GEOLOGICAL SETTING

The NE trending ECSB along the East Asian continental margin is distributed between the East China mainland and the Ryukyu Trench (Figure 1; Q. L. Yang, 1992; Zhou et al., 1989). The ECSB is generally divided into the ECSSB landward and the Okinawa Trough seaward, which is separated by the Taiwan–Sinzi Belt (Figure 1; Q. L. Yang, 1992; Zhou et al., 1989). The ECSSB is located in the present-day continental shelf (Figure 1) and consists mainly of western and eastern depressions bounded by several different rises (the Hupijiao, Haijiao, Yushan, and Fuzhou rises; Q. L. Yang, 1992; Zhou et al., 1989).

The ECSSB formed as a result of rift process controlled by the back-arc extension or wrench tectonics related to the Indo–Asia collision (Allen, Macdonald, Xun, Vincent, & Brouet-Menzies, 1997; Li, Zhou, Ge, & Mao, 2009; Lin et al., 2005; Ren, Tamaki, Li, & Junxia, 2002; Sibuet et al., 2004; Sibuet & Hsu, 1997; Suo et al., 2014; Yin, 2010; J. Zhang, Li, & Suo, 2016). The basin subsequently experienced tectonic movements including the Oujiang, Yuquan, Huagang, and Longjing movements, related to the tectonic inversion in the ECSSB (Figure 2; Q. L. Yang, 1992; Zhou et al., 1989). The Oujiang Movement occurred in the late Palaeocene–early Eocene after deposition of synrift sediments in the western depressions (G. Zhang et al., 2016). The depocentre subsequently migrated into the eastern depressions during the Eocene, followed by regional deformation in the late Eocene–early Miocene, named the Yuquan and Huagang movements (J. Zhang et al., 2016). The outstanding structural deformation was the Longjing Movement representing reverse faults, folds, and regional uplifts with the unconformity in the late Miocene (Kong, Lawver, & Lee, 2000; Q. L. Yang, 1992; Zhou et al., 1989).

The northern ECSSB comprises the leodo (formerly known as Socotra), Jeju, Domi, and Sora basins (Figure 1; Oh, Park, & Park, 1997). These basins extend from the Changjiang, Xihu, and Fujiang depressions, respectively, which belong to the region of Chinese territorial waters (G. H. Lee et al., 2006). The Changjiang Depression is located between the western Zhemin and eastern central uplifts. It formed as isolated half-graben in the late Palaeocene (Su et al., 2014; Suo et al., 2015). The Xihu Depression is located between the western central uplifts and is commonly divided into the West Gentle Slope, Central Anticline Belt, and East Sharp Slope (Suo et al., 2015). It formed in the late Eocene, with relatively continuous full-graben geometry (Su et al., 2014; Suo et al., 2015).

The Jeju Basin, the largest basin in the northern ECSSB, has been coevally compared with the leodo Basin using seismic interpretation (Cukur et al., 2011; Koh et al., 2016; G. H. Lee et al., 2006). The lowermost sequence of the leodo Basin was interpreted to be the same stratigraphic level as the Jeju Basin (Cukur et al., 2011; Koh et al., 2016; G. H. Lee et al., 2006). According to the biostratigraphic study, the Jeju Basin was initiated in the late Eocene, and the tectonic evolution of the Jeju Basin was affected by that of the Xihu Depression (Yun et al., 1999). Basin-fills in the northern ECSSB were initially dominated by the fluvio-lacustrine deposits and subsequently by coastal plain to shallow marine deposits (KIGAM, 1997; G. H. Lee et al., 2006; Yun et al., 1999).

3 | STRUCTURE OF THE ACOUSTIC BASEMENT

In order to interpret the seismic stratigraphy and reveal the stratigraphic evolution of the northern part of the ECSSB where the leodo and Jeju basins are compartmentalized with the development of the Hupijiao Rise, we used multi-channel seismic reflection data acquired by the Korea Institute of Geoscience and Mineral Resources (KIGAM; Figure 3). Time structure and thickness maps are described to identify depocentres and structural styles and to constrain the stratigraphic level.

The leodo and Jeju basins represent normal fault-controlled depressions, showing growth faults and related half-graben fills.
The basin-fill successions resting on the acoustic basement in both basins are divided into syn- and post-rift units based on stratigraphic correlation and structural evolution. Four regional unconformities (early Eocene, early Oligocene, early Miocene, and late Miocene unconformities) are identified in the basins (Figures 4, 5, and 6).

The top of the acoustic basement is identified as mappable reflections that commonly separate pre-rift units from syn-rift units on seismic sections. The time structure map of the top acoustic basement shows that basement highs coincide with the area of the Hupijiao Rise and Taiwan–Sinzi Belt, and basement lows represent fault-controlled depressions around the rise (Figure 3a). The depressions reach a depth ranging in two-way travel time (TWT) from 1 to 5 s. A relatively deep basement occurs in the southern part of the study area between the Hupijiao Rise and the Taiwan–Sinzi Belt. This basement shows marginal geometry deepening into the Xihu and Changjiang depressions.

The Jeju Basin is generally identified as a NE–SW trending elongated depression along the Taiwan–Sinzi Belt (Figure 3). NE–SW trending faults are also dominant in the basins, with either normal or reverse offsets. These intrabasinal normal faults appear to have growth lengths of less than 60 km, forming isolated depressions. Some reverse faults are observed between the Hupijiao Rise and the Taiwan–Sinzi Belt, whose lengths appear to be generally longer than those of the normal faults and have a significant amount of vertical offset. The NE–SW trending Jeju Basin is offset by the NW–SE aligned steep fault system with upward-branching secondary faults (Figure 3a). This fault system is interpreted to affect the left-lateral movement of the Hupijiao Rise and the Taiwan–Sinzi Belt. Based on the left-lateral strike-slip fault system, the Jeju Basin can be divided into northern and southern Jeju basins (Figure 3b). There are several minor depressions either within or along the eastern margin of the Hupijiao Rise.

The Ieodo Basin is located along the western margin of the Hupijiao Rise and consists of a series of fault-controlled minor depressions and highs (Figure 3). E–W (ENE–WSW) trending normal faults are dominant in the Ieodo Basin. The structural geometry shows half-grabens dipping towards the south or the north, indicating different rift polarity. On the other hand, the Jeju Basin is characterized by NE–SW trending faults and NW-dipping rift polarity. In the northern area of the Jeju Basin, the rift polarity changes into the reversal (SE-dipping). The boundary between the Ieodo and Jeju basins is marked by south-dipping normal faults near the southern tip of the Hupijiao Rise (Figures 3a and 4a). The basin-bounding normal faults probably continue to the west where
the Changjiang Depression is located. The Ieodo and Jeju basins are structurally differentiated by the bounding fault; the basin-fills of the Ieodo Basin underlie the syn-rift unit of the Jeju Basin.

The acoustic basement is composed of Precambrian gneiss and Mesozoic granitoid (Su et al., 2014; Zhou et al., 1989). The Precambrian gneiss generally consists of Neoproterozoic rocks whose Cathaysia Block extended to the northern ECSSB of the basement (Su et al., 2014; Zhou et al., 1989). Depositional ages of the Ieodo Basin are not clearly defined due to the absence of wells in the basin. We infer that the pre-rift unit in the Ieodo Basin was formed in the late Cretaceous, based on the stratigraphic correlation of the nearby Changjiang Depression (Figure 2; Su et al., 2014).

4 | FIRST RIFT STAGE IN THE IEODO BASIN

4.1 | Syn-rift unit 1 (Palaeocene)

The syn-rift unit 1 is identified in the Ieodo Basin and overlain by the early Eocene unconformity (Figure 4a). The early Eocene unconformity only occurs in the Ieodo Basin and merges with the top of the acoustic basement near the western Hupijiao Rise (Figure 4b,c). Internal reflections in the syn-rift unit 1 are characterized by basinward pinch-out and onlapping patterns, forming a wedge-shaped geometry. The wedge-shaped half-graben fills are developed in the hanging wall of the E-W (ENE–WSW) trending normal faults (Figure 4a). The half-graben fills are isolated in the Ieodo Basin and mainly extend into the south-western areas where the Changjiang Depression occurs.

The fanning geometry and configuration of related reflections indicate a syn-rift stacking pattern (Nottvedt, Gabrielsen, & Steel, 1995; Schlische, 1991). The syn-rift phase in the Ieodo Basin occurred prior to the early Eocene, as indicated by the overlying early Eocene unconformity. The syn-rift unit in the Changjiang Depression, stratigraphically equivalent to the Ieodo Basin, was deposited in the Palaeocene (Su et al., 2014; J. Zhang et al., 2016). Hence, we suggest that the syn-rift unit 1 in the Ieodo Basin was most likely deposited in the Palaeocene.

4.2 | Post-rift unit 1 (early Eocene)

The post-rift unit 1 overlies the early Eocene unconformity and is identified in the Ieodo Basin (Figure 4). Internal reflections close to
the basin-bounding faults between the two basins exhibit upturned patterns and are truncated by the early Oligocene or early Miocene unconformity. The upturned strata are particularly identified in the footwall block of the bounding faults (Figure 5a). Internal reflections in the north-western area are onlapping against the top of the acoustic basement (Figure 4b,c).

The early Eocene unconformity marks the transition from the syn-to post-rift stage in the basin. It is a characteristic of a post-rift unconformity, indicating the onset of the post-rift stage (Withjack, Schlische, Olsen, Renault, & Ashley, 2002). According to the depositional age of the Changjiang Depression (Su et al., 2014), the post-rift unit 1 in the Ieodo Basin was deposited in the early Eocene (Figure 2).

5 | SECOND RIFT STAGE IN THE JEJU BASIN

5.1 | Syn-rift unit 2 (late Eocene to earliest Oligocene)

Regional cross-sections show that the syn-rift unit 2 is developed only in the Jeju Basin, and its thickness distribution is controlled by the NE–SW or E–W trending normal faults (Figure 5). The stratigraphic relationship between the syn-rift unit 1 and 2 is identified at the southern tip of the Hupijiao Rise where the south-dipping normal faults cut the pre-existing first rift units (Figures 4a and 5a). On the hanging-wall block of the basin-bounding fault, the syn-rift unit 2 unconformably overlies the early Eocene rift unit, forming wedge-shaped fills terminated by either the overlying early Oligocene or early Miocene unconformities (Figure 5b). The footwall block comprises the Eocene post-rift unit with contorted and tilted reflections. The syn-rift unit 2 relatively thickens south-eastward from the eastern margin of the Hupijiao Rise to the Taiwan–Sinzi Belt. The major syn-rift depressions are elongated with the NE–SW trending axis mostly parallel to the Taiwan–Sinzi Belt, whereas the minor depressions are localized in the eastern margin of the Hupijiao Rise. The second syn-rift fills are generally divided into lower and upper units. The former appears to dip towards the east and to onlap onto the top of the acoustic basement, whereas the latter shows distinct half-graben geometry controlled by the normal fault (Figure 5).

The second syn-rift stage commenced with the development of NE–SW or E–W trending normal faults in the Jeju Basin. These rift-related extensional faults stretched the basement highs in the east and the south of the Hupijiao Rise, forming the Juju Basin including the NE–SW trending major and minor depressions between the Hupijiao Rise and Taiwan–Sinzi Belt (Figure 5c). The microfossil biostratigraphy of exploration wells suggests that the second syn-rift deposits accumulated in coastal depositional environments during the late Eocene to earliest Oligocene (Yun et al., 1999).

5.2 | Post-rift unit 2 (Oligocene to Miocene)

The overlying post-rift unit 2 is regionally observed in the Ieodo and Jeju basins, whereas the post-rift unit 1 is confined to the Ieodo Basin (Figures 5 and 6a). The post-rift unit 2 consists of the lower and upper...
post-rift units (Figures 2 and 5). The former only rests on the early Oligocene unconformity in both basins and is terminated by the early Miocene unconformity (Figure 5). The latter rests on the early Miocene unconformity and is truncated by the late Miocene unconformity. Internal reflections show a concordant relationship between the upper and lower units, and they are onlapping against the Hupijiao Rise, while upturned reflections are observed near the Taiwan–Sinzi Belt (Figure 5b).

The distribution and geometry of the early Miocene unconformity are similar to the underlying early Oligocene unconformity (Figure 6b, c). The early Miocene unconformity drapes the early Oligocene unconformity and extends towards the Hupijiao Rise, while unconformities around the Taiwan–Sinzi Belt largely overlap, owing to the later uplift and erosion (Figure 7). The Oligocene lower post-rift unit thins towards the west (Figure 8a). The Miocene upper post-rift unit shows maximum thickness in the Jeju Basin (Figure 8b). The lower post-rift unit accumulated in the remnant topography and preceded the late post-rift unit widening in the rift basin (Figures 7 and 8; e.g., C. Lee, Shinn, & Ryu, 2016; Nottvedt et al., 1995).

SE-dipping reverse faults and fault-related folds are observed beneath the late Miocene unconformity in the Jeju Basin. The reverse faults and fault-related folds are offset by the left-lateral strike-slip fault which is the boundary between the southern and northern Jeju basins (Figure 3). The intensity of the deformation increases towards the Taiwan–Sinzi Belt and decreases towards the northern Jeju Basin (Figures 3 and 5). Such distinct deformation of the post-rift unit was likely caused by the compression of the late Miocene Longing Movement, resulting in thickening of the pre-existing unit and the stacked growth strata of the upper post-rift unit. Equivalent growth strata are also observed in the Xihu Depression (Li et al., 2009; Q. Wang, Li, Guo, Suo, & Dai, 2017). The deforming style of the reverse faults and fault-related folds is similar to that of the Xihu Depression, forming a fold belt, called the Central Anticline Belt (G. Zhang et al., 2016; J. Zhang et al., 2016). The left-lateral strike-slip fault separating the southern and northern Jeju basins was activated when the Okinawa Trough opened during the late Miocene and played a major role in the development of the transfer zone under the back-arc extension (Gungor et al., 2012).

5.3 Post-rift unit 3 (Pliocene to the present)
The post-rift unit 3 regionally rests on the late Miocene unconformity in the northern ECSSB including the leodo and Jeju basins. The unit vertically continues to the present seabed and laterally meets the western Okinawa Trough. The unit thins towards the west and thickens towards the east. Its thickness abruptly increases at the edge of the Taiwan–Sinzi Belt where the shelf break exists (Figure 5d). The shelf break is characterized by eastward-dipping clinoforms. The late Miocene unconformity is characterized by an angular unconformity in the eastern part of the Jeju Basin and merges into the planar top of the acoustic basement on the Taiwan–Sinzi Belt. On the other hand, the unconformity is poorly recognized in the leodo Basin.

The upper and lower reflections are bounded by the late Miocene unconformity in the leodo Basin and seem to progressively become concordant towards the west (Figure 5). The late Miocene unconformity in the Jeju Basin is relatively deeper than the leodo Basin and does not reflect the geometry of the Hupijiao Rise any longer (Figure 6d).

The clinoform geometry is indicative of deltaic, shallow marine environments and continental margin setting (Patruno, Hampson, & Jackson, 2015). The abrupt variation in thickness and stratigraphic dip towards the Okinawa Trough suggest that the post-rift unit 3 is closely associated with the opening of the Okinawa Trough (G. Zhang et al., 2016; J. Zhang et al., 2016).

6 TECTONIC EVOLUTION AND IMPLICATION

6.1 Structural evolution
The northern ECSSB evolved through two-stage rifting during the Palaeocene to Miocene period, resulting in the formation of the leodo
and Jeju basins. The first rift in the northern ECSSB began with the initiation of normal faults during the late Palaeocene. E–W (ENE–WSW) trending normal faults are dominant in the Ieodo Basin, west of the Hupijiao Rise, forming isolated half-grabens (Figure 9a). The orientation of the normal faults suggests that the Ieodo Basin was initiated by transtensional deformation related to dextral strike-slip movement (e.g., Suo et al., 2015). The transtension can possibly be attributed to the Indo–Asian collision in the Palaeocene to middle Eocene (Suo et al., 2014).

The Ieodo Basin continued to subside due to the post-rift thermal relaxation until the early Eocene. After the first rift stage, the Ieodo Basin experienced structural deformation compatible with the Oujiang Movement. This movement was typically identified in the west rift region of the ECSSB and caused inversion structures during the late Palaeocene to early Eocene period (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016; Zhou et al., 1989).

The subsequent extension, the second rift stage, was concentrated exclusively in the region of the east and the south of the Hupijiao Rise during the late Eocene (Figure 9b). The NE–SW trending normal faults controlled the syn-rift subsidence of the Jeju Basin during the late Eocene to earliest Oligocene, whereas the subsidence of the Ieodo Basin ceased at the same time. The Jeju Basin was progressively developed with a narrow width and an elongated length, showing NE–SW orientation parallel to the subduction of the Pacific Plate.

The lateral linkage between the depressions of the east rift region in the ECSSB is much better than that of the west rift region (Suo et al., 2015). At that time (Eocene), the rate of the Pacific–Eurasia convergence reached a minimum, indicating a widespread extension (Northrup, Royden, & Burchfiel, 1995). The NE-striking extensional structure parallel to the subduction zone further suggests that the second rift in the Jeju Basin was most likely related to back-arc extension due to roll-back of the subduction of the Pacific Plate (Li et al., 2009; Sibuet & Hsu, 1997).

The syn-rift unit in the Jeju Basin was affected by structural deformation, leading to the formation of the early Oligocene unconformity. The early Oligocene deformation is consistent with the Yuquan Movement, which has been well identified in the east rift region of the ECSSB, for example, the Xihu Depression (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016; Zhou et al., 1989). Following the Yuquan Movement, the Ieodo and Jeju basins underwent post-rift subsidence during the Oligocene to Miocene, forming the post-rift unit 2. This overall subsidence was temporarily interrupted by the early Miocene regional uplifting and folding.
resulting in the formation of the early Miocene unconformity. The unconformity corresponds to the tectonic event, named the Huagang Movement, that caused the regional deformation of the Xihu Depression (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016; Zhou et al., 1989) and is known to be the main cause of the uplift of the Taiwan–Sinzi Belt (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016; Zhou et al., 1989). In the Jeju Basin, however, it is not certain whether the movement affected the regional uplifting of the Taiwan–Sinzi Belt due to the structural overprint of the late Miocene deformation.

At the end of the Miocene post-rift subsidence, the entire region of the northern ECSSB was strongly deformed by regional contraction, as indicated by the late Miocene unconformity terminating fault-reactivated folds and tilted or upturned strata (Figure 9c). Such strong deformation was recorded not only in the Jeju Basin but also in the Xihu Depression, named the Longjing Movement (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016) or it resulted from the collision of the Luzon arc in the Philippines (Gungor et al., 2012; Ren et al., 2002; G. Zhang et al., 2016; J. Zhang et al., 2016). The Longjing Movement resulted from the back-arc opening of the Okinawa Trough by the subduction of the Philippine Sea Plate, forming the trench-arc-basin system in the middle Miocene (Gungor et al., 2012; Ren et al., 2002; G. Zhang et al., 2016; J. Zhang et al., 2016) or it resulted from the collision of the Luzon arc in the Philippines (Gungor et al., 2012; Ren et al., 2002; G. Zhang et al., 2016; J. Zhang et al., 2016).

The tectonic evolution of the Ieodo and Jeju basins in this study reveals the development of a two-stage rift in the northern ECSSB: the Palaeocene to early Eocene first rift in the Ieodo Basin, and the late Eocene to Miocene second rift in the Jeju Basin. We suggest the syn-rift depocentre in the northern ECSSB migrated from the Ieodo Basin to the Jeju Basin. This is supported by recent studies on the rift migration of the ECSSB from the western depressions (e.g., Changjiang Depression) to the eastern depressions (e.g., Xihu Depression; Su et al., 2014; Y. H. Suo et al., 2015; J. Zhang et al., 2016). The eastward rift migration of the ECSSB has been reported to result from the back-arc extension due to the subduction of the Pacific Plate beneath the Eurasian Plate (Hall, Ali, & Anderson, 1995; Northrup et al., 1995; Sibuet et al., 2004; Sibuet & Hsu, 1997; Su et al., 2014) or from extrusion tectonics due to the collision between the Eurasian and Indian plates (Liu, Cui, & Liu, 2004; Su et al., 2014; Suo et al., 2015). Alternatively, the interaction between the back-arc extension and the far-field effect of the Indo-Asian collision has been proposed as the source of the eastward rift migration (Ren et al., 2002; Su et al., 2014; J. Zhang et al., 2016).

In this study, although there is insufficient data to determine which force was the dominant factor controlling the overall evolution of the basin, the structural orientation and distribution of the second rifting, parallel to the subduction zone of the Pacific Plate, suggests that the second rifting was possibly developed under the influence of the back-arc extensional regime.

### 6.2 Role of the Hupijiao Rise between the Ieodo and Jeju basins

The Hupijiao Rise is a basement high between the Ieodo and Jeju basins (Han et al., 2015). It is one of the intra-basinal basement highs in the northern ECSSB, separating western depressions from eastern depressions (Figure 1). The basement highs have been interpreted as regional uplifts, tectonic boundaries, or relic arcs related to the development of NW trending transverse faults (Sibuet et al., 2004; Zhou et al., 1989). The uplift timing of the Hupijiao Rise was not defined but was probably constrained by the late Miocene unconformity (Han et al., 2015). In this study, we observe that the uplift caused upturned reflections in the pre-rift unit and post-rift unit 1 of the Ieodo Basin along the western margin of the Hupijiao Rise (Figure 4). In the pre-rift unit, the upturned reflections can be interpreted to be a consequence of uplifting due to the early Eocene tectonic inversion of the Oujiang Movement (Q. L. Yang, 1992; G. Zhang et al., 2016; J. Zhang et al., 2016; Zhou et al., 1989). In addition, the early Eocene
deformation in the Ieodo Basin was possibly associated with intrabasinal deformation related to igneous intrusion (Han et al., 2015). In the post-rift unit 1 of the Ieodo Basin, the upturned strata are identified in the footwalls of the basin-bounding normal faults between the Ieodo and Jeju basins, indicating the large amount of footwall uplift and erosion (Figure 4a). Footwall uplift with normal faulting commonly occurs under extension and records a significant amount of erosion due to exhumation (C. Lee et al., 2016; Wernicke & Axen, 1988). In the Changjiang Depression close to the north-western Xihu Depression, the folding of the Eocene strata was also affected by the extension (F. Wang, Zhu, Hu, Xu, & Zhao, 2005; G. Zhang et al., 2016).

We infer that the Hupijiao Rise was partly uplifted and eroded, owing to the isostatic adjustment in the late Eocene syn-rift stage. In addition, the positive anomaly of the footwall block is observed in a free-air gravity anomaly (Figure 10). In the gravity map (Sandwell & Smith, 2009), the positive anomaly locally coincides with the footwalls of basin-bounding faults. However, the anomaly in the Hupijiao Rise is not much stronger than that of the Taiwan–Sinzi Belt which exhibits a constant and strong positive anomaly, indicating regional uplift.

In the flattened surface of the early Miocene unconformity (Figure 11), there are few Oligocene and Miocene units on the Taiwan–Sinzi Belt, indicating exhumation during the late Miocene (Figure 7). We infer that a significant amount of the erosion of the Oligocene and Miocene units can be attributed to uplifting of the Taiwan–Sinzi Belt rather than the Hupijiao Rise during the late Miocene. Therefore, the tectonic subsidence in the Ieodo Basin ceased with the onset of the second rift stage in the Jeju Basin. In other words, the regions of the Ieodo Basin and the Hupijiao Rise were gently uplifted in response to the second rifting of the Juju Basin. We suggest that the Hupijiao Rise is not a regional uplift, but most likely is a geologic basement and was locally faulted and uplifted due to the isostatic rebound of the footwall during the late Eocene to earliest Oligocene subsidence of the Jeju Basin.

7 | CONCLUSIONS

Based on the stratigraphic correlation and structural evolution history, we reveal that the Ieodo and Jeju basins in the northern ECSSB underwent two different rift stages. The first rift with E–W (ENE–WSW) trending structures only occurred in the Ieodo Basin during the Palaeocene to early Eocene. The second rift showing NE–SW trending structures subsequently took place further east in the Jeju Basin during the late Eocene to Miocene. After the syn-rift phases, the basins experienced thermal contraction and multiple tectonic inversions, forming regional unconformities compatible with the Ouijiang, Yuquan, Huagang, and Longjing tectonic movements. The two-stage rift suggests that the depocentre of the northern ECSSB progressively became younger eastward from the Palaeocene to Miocene. The tectonic evolution of the Ieodo and Jeju basins mimics that of adjacent basins such as the Changjiang Depression in the western part and the Xihu Depression in the eastern part of the ECSSB, respectively.

E–W (ENE–WSW) trending normal faults are dominant in the Ieodo Basin, representing the first rift structures of isolated half-grabens. On the other hand, the NE–SW trending normal faults controlled the second syn-rift subsidence of the Jeju Basin. The different orientation and distribution of both basins suggest that the northern ECSSB evolved under the influence of different tectonic regimes, particularly the back-arc extensional regime in the second rift phase.

The Ieodo and Jeju basins are largely separated by basement highs, the Hupijiao Rise. The Hupijiao Rise was locally faulted and uplifted due to the isostatic rebound of the footwall during the late Eocene to earliest Oligocene subsidence of the Ieodo Basin, and then it remained stable while the Taiwan–Sinzi Belt was uplifted during the late Miocene. We suggest that the Hupijiao Rise is not a regional uplift zone inherited from the tectonic event but a basement high formed during the second syn-rift stage.

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