Mesozoic Thrust-Nappe and Extensional Structure Frameworks in the East Segment of Southeast Yangtze Block, Southeast China

Xinqi Yu†1, Ziwei Chen2, Jun Hu1, Yan Zeng1, Xiu Liu1, Yu He1, Zishen Wang1, Linghui Meng1
1. School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
2. Chongqing Institute of Geology & Mineral Resources, Chongqing 400042, China
@Xinqi Yu: https://orcid.org/0000-0001-7566-6091

ABSTRACT: Multi-stage Mesozoic thrust-nappe and extensional structures are distributed in the east segment of the Southeast Yangtze Block situated in the junction region of Zhejiang-Jiangxi-Anhui provinces. The features and genetic mechanism of the deformations were analyzed after a detailed field observation of their distribution, geometry, and kinematics. In addition, the time sequences of the thrust and extensional structures were determined by combining the results of the comparative analysis with the chronological evidence of strata and magmatic rocks cut by a fault or formed after a fault according to field facts. This study identified three stages of the nappe structures and at least two stages of the extensional structures during the Mesozoic. The geotectonic setting of the nappe and extensional structures was considered to be related to the different geodynamics in the study area including the Early Mesozoic geological event, i.e., N-S compression, forming Lantian fault, etc.; the Late Mesozoic flat-slab subduction, forming Xiaoxi thrust fault and tectonic window; and the roll-back of the paleo-Pacific Plate, forming extensional structures like basin marginal fault; the last compression, forming Wucheng-Shenxian fault. These findings provide additional evidence for remodeling the tectonic and geodynamic evolution of Southeast China.

KEY WORDS: Mesozoic, nappe structure, extensional structure, time sequence, east segment of the Southeast Yangtze Block.

0 INTRODUCTION

The east segment of the Southeast Yangtze Block (ESSYB) occupies a large area of the junction region of Zhejiang, Jiangxi, and Anhui provinces (Fig. 1). This area has attracted increasing attention in recent decades because its tectonic settings and long-term evolution history remains in debate which has dampened the enthusiasm for the research on Paleozoic and Mesozoic geological characteristics and evolution. To determine the mutual sequences and evolutionary history of deposition events, magmatism, and tectonic action during the Neoproterozoic, numerous studies have been focused on the precise dating of epi-metamorphic rock series with stratigraphic comparisons and magmatic rocks. Significant progress has been achieved in this research field (Liu et al., 2013; Yao et al., 2013; Guan et al., 2010; Zhang et al., 2010; Wang et al., 2008; Li, 2003; and references therein). By contrast, few studies have been conducted on Mesozoic thrust-nappe and extensional structures, which are overprinted on the southeast part of the Yangtze Block.

* Corresponding author: yuxinqi@cugb.edu.cn
© China University of Geosciences (Wuhan) and Springer-Verlag GmbH Germany, Part of Springer Nature 2020

Manuscript received January 1, 2020.
Manuscript accepted March 15, 2020.

Extant literature mainly highlights the central area of the Yangtze Block (such as the areas of Hunan, Jiangxi, Guangdong, and Fujian provinces) rather than ESSYB (Li S Z et al., 2017; Suo et al., 2017; Shu et al., 2015; Li J H et al., 2014; Li Z L et al., 2013; Yang and He, 2013; Zhang et al., 2011; and references therein). Zhang et al. (2012, 2011) summarized the five-stage tectonic stress evolutionary history from the Late Mesozoic to Early Cenozoic in whole South China (including ESSYB), and Li J H et al. (2014, 2015) presented a three-stage tectono-thermal evolutionary history during the Cretaceous (145–137 Ma NW-SE compressional setting, 136–86 Ma alternate extensional and shortening events, and 107–86 Ma WNW-ESE extensional regime). Dong et al. (2015) and Shi et al. (2015) proposed a two-stage tectono-thermal evolutionary history of East Asia during the Late Middle Jurassic and Early Cretaceous (approximately 170–120 Ma). Li et al. (2017) examined the Mesozoic transition from the E-W-trending Tethys to the NE-trending palaeo-Pacific tectonic systems and further into the initiation of the palaeo-Pacific subduction (Li et al., 2017; Suo et al., 2017). Thus, the Mesozoic tectonic transition from the E-W palaeo-Tethyan tectonic domain into the NE-NNE West Pacific domain had an important effect on the evolution of the whole South China (Yang and He, 2013; Yu et al., 2006); as a result, the South China Plate exhibited polyphase intensive intracontinental deformation during the Mesozoic (Dong et al., 2020).
Mesozoic Thrust-Nappe and Extensional Structure Frameworks in the East Segment of Southeast Yangtze Block 773

2015; Shi et al., 2015). By comparison, there is relatively scarce literature on the Mesozoic tectonic-magmatic events and their sequence in ESSYB. Deficient and incomplete outcrops along the fault belts increase the difficulty in conducting research. Many geologists cannot perform geological mapping at certain scales in such a large study area and thus cannot successfully observe all the structures. Thus, ESSYB has been overlooked by geological research. A few investigations have been recently focused on regional structures by analyzing the identified faults (Jiang et al., 2016; Song et al., 2010) or local tectonic stress fields synthetically by observing the rapidly facies-changed terrestrial deposits in the Jurassic–Cretaceous red basin (such as the Huangshan Basin) (Xu et al., 2016; Pan et al., 2014). However, problems remain unsolved in the research on their attribution and the features of tectonic-magmatism-metallization events. Thrust-nappe and extensional faults must be distinguished among all identified faults. The number of stages that these Mesozoic nappe structures and extensional-sliding faults have in ESSYB and their thrust distance and mechanism must be determined.

This predicament has seriously affected ore deposit prospecting. The newly found large or medium copper (Cu)-tungsten (W)-molybdenum (Mo) deposits in North Jiangxi and South Anhui are all located in a thrust-nappe structure (Chen et al., 2015; and oral discussion). The cataclasite (from the Late Paleozoic beds) inside this fault is the material basis of mineralization, and the Neoproterozoic epimetamorphic rock series constitutes the hanging and foot walls of the thrust-nappe structure (Chen et al., 2015). Ore bodies are distributed within the fault zone. Enlightened by such examples, geologists have focused on the nappe structures and the outcrops of the Upper Carboniferous (Chen et al., 2015). The Cretaceous red beds in South Anhui and Northeast Jiangxi contain substantial limestone gravel and even a thick layered basal conglomerate from the Upper Carboniferous. Evidently, the present scattered outcrops of the Upper Carboniferous cannot sufficiently support the

Figure 1. Geological sketch map of the eastern segment of the Southeast Yangtze Block (revised after 1:500,000-scale geological maps of Zhejiang-Jiangxi-Anhui provinces). (a) Geological sketch map of the Southeast Yangtze Block; (b) geological sketch map of the eastern segment of the Southeast Yangtze Block; (c) section shows ramp-type thrust faults in ESSYB.
large erosion source. This condition indicates that these Late Paleozoic strata have been exposed over a large area through their geological history. Whether these Late Paleozoic strata also exist in the thrust-nappe structure beside the eroded ones must be explored. The presence of ore deposits beneath the nappe must be determined. If such an ore body is covered by a thrust fault, then the distance covered from the tip of the nappe to the ore body must be measured. A synthetic analysis and examination of these structures in ESSYB will not only facilitate the exploration of potential targets but also help reconstruct the tectonic-magmatic evolution history. Ultimately, the reconstruction of a continental dynamics model for South China Plate can be supported.

In addition, this study regards granitic rocks and Mesozoic red beds as important indicators for understanding the tectonic-magmatic relationship. Accordingly, we attempt to redefine the intersecting relations of different structural features, analyze the associations and sequential relationships between tectonic and magmatic activities, and explore the dynamic background of the tectonic-magmatic events in ESSYB.

1 GEOLOGICAL SETTINGS

The study area ESSYB is in the north of the Jiangshan-Shaoxing fault zone and the Cathaysian Block (Fig. 1a).

The Neoproterozoic epimetamorphic basement rock series in ESSYB is well cropped out and forms the major part of the east section of the Jiangnan orogenic belt. These basement rocks are divisible into the south and north regions using the Qimen-Shexian fault zone (Fault 1 in Fig. 1b) (Yu et al., 2020). The south area of the basement rocks includes the Neoproterozoic Xikou Group (Pt3X) and the cover Jingtan Formation (Qn1) volcanic bed (Fig. 1b), which have been deformed and are nearly entirely subjected to structural transposition. The strata in the north area sequentially expose the Neoproterozoic Shangxi Group (Pt3S) and Likou Group (Pt3L) (Fig. 1b), which experience slight metamorphism and deformation and have a well-preserved fabric, a clear basic sequence, and a recoverable stratigraphic sequence (Yu et al., 2020).

The first cover strata upon the Neoproterozoic basement rocks are Nanhua (Ediacaran–Early Silurian) (Yu et al., 2020). These strata are distributed on the south and north sides in ESSYB. The bottom beds of the Lower Nanhua System at the north margin unconformably overlie the Neoproterozoic epimetamorphic series and the approximately 830 Ma granodiorite plutons (Fig. 1b) (Yu et al., 2020). At the south (southeast) margin, the Lower Nanhua System unconformably overlies the Neoproterozoic metamorphic clastic rocks. The study area lacks Late Silurian–Early Carboniferous marine deposit. The gradual transgression starting from the Lower Yangtze region to the study area in Late Devonian and the Upper Paleozoic sedimentary strata overlies the Neoproterozoic metamorphic basement rocks; thus, it covers the top of the epimetamorphic rock series and the Nanhua–Cambrian folded strata. The outcrops of the Carboniferous–Early Triassic strata within this area are sporadic and unconformably overlie the Neoproterozoic epimetamorphic phyllite series directly (Yu et al., 2020).

Intrusive rocks from two periods are present in ESSYB. The first-stage intrusive bodies are Neoproterozoic granodiorites and granites (porphyry), and the second-stage bodies entail Late Mesozoic granitic rocks (porphyry) (Fig. 1b). Such rocks were likely affected by the Mesozoic nappe and extensional structures (Yu et al., 2020).

The orientation of structures in the study area exhibits a clear regularity. The faults in its midwest are mainly trending near the E-W and NNE directions and are cut by the late NE-trending faults. In the southeast, the orientation of structures is mainly along NE-NNE. The NNE-trending Wucheng-Shexian-Ningguo fault (Fault 6 in Fig. 1b) is the main fault zone in the area. Its north section is the Shexian-Ningguo fault zone, and its south section is the Wucheng fault zone. The NE-NNE-trending faults include the Shexian-Sanyang fault zone (Fault 3 in Fig. 1b) and the nappe structures along the border of Anhui and Jiangxi provinces, including the Wucheng-Xiaoxi thrust-nappe structure (Fault 4 in Fig. 1b).

2 FIELD GEOLOGY

A 1 : 50 000-scale regional geological map shows concentrated fault zones in ESSYB. According to the orientation, these faults can be divided into four groups: (1) north-northeast (NEN), (2) northeast (NE) and northeast-east (NEE), (3) near east-west (EW), and (4) northwest (NW) directions. The main NEE and EW direction faults are mostly distributed in the basement rock series, including the Early Paleozoic Qimen-Shexian fault (Fault 1 in Fig. 1b). The Early Paleozoic Qimen-Shexian fault was reactivated during the Late Mesozoic as the boundary fault of the Jurassic–Cretaceous basin.

The major faults in the study area include multi-stage thrust-nappe structures (Zhang Y J et al., 2013; Yu et al., 2011), such as the Mesozoic reactivated Northeast Jiangxi fault zone and other faults (Xiao et al., 1998). Branches or secondary faults are also present along the edges. The Mesozoic Northeast Jiangxi fault zone (Fault 2 in Fig. 1b), which was reactivated from the Neoproterozoic Northeast Jiangxi fault, is also called the Wan-Zhe-Gan (Anhui, Zhejiang, and Jiangxi) fault, and its north section is the Shexian-Ningguo fault (Yu et al., 2011).

Several ductile shear zones are present in the Neoproterozoic epimetamorphic basement rock series. The south part of the southeast wall of the Wucheng-Shexian fault zone (Fault 6 in Fig. 1b) is the front edge of the nappe and includes several small ductile shear zones. Yu et al. (2011) obtained the 40Ar/39Ar age of 429 Ma for sericite from one shearing zone belonging to the Early Paleozoic. Xu et al. (2015) identified the synchronous 40Ar/39Ar ages of 449±4 and 429±3 Ma for the shearing zones. These ductile shear zones were produced by the same stress field as the nappe structure during the Late Mesozoic, and they have merely been uplifted by the Late Mesozoic nappe structure. Therefore, these ductile shear zones formed much earlier than the Mesozoic and are thus excluded from the scope of this study.

2.1 Folds in Strata from Late Carboniferous to Early Triassic and Early Mesozoic Faults

As indicated in Fig. 1b, the Late Carboniferous–Early Triassic strata are sporadically distributed on the epimetamorphic basement rock series in South Anhui and Northeast Jiangxi and scattered in Northwest Zhejiang. In Liutang of South
Mesozoic Thrust-Nappe and Extensional Structure Frameworks in the East Segment of Southeast Yangtze Block

Anhui (Fig. 2), the Late Triassic coal-bearing Anyuan Formation is angular and unconformably covers the limestone of the Early Triassic Qinglong Formation. Moreover, the Carboniferous–Lower Triassic strata developed an asymmetric fold that thrusts from the southeast toward the northwest (Fig. 2) (Zhou et al., 2015). This fold has been covered by the Upper Triassic and the Jurassic System. Thus, this fold can be posited as a response to Early Mesozoic tectonic events (Zhou et al., 2015). The NE-trending Lantian fault (Fault 2 in Fig. 1b) and the parallel faults that cut the Lantian relict syncline and are covered by the Huangshan Basin (the bottom bed of this basin is Lower Jurassic) probably formed during the Early Mesozoic. In addition, Liu et al. (2016) ascertained an age of 245.2 Ma for quartz porphyry near Xucun Town (central area in Fig. 1b), and Yu et al. (2011) obtained the 40Ar/39Ar age of 230.5±2.3 Ma for sericite from the Shexian-Sanyang fault (Fault 3 in Fig. 1). Thus, Early Mesozoic tectonic events created several deformation-magmatism features in the study area.

Geometrically, the strikes of the Early Mesozoic faults are present in the NE and W-E directions. The NE extending faults (such as the Lantian fault) mainly have vertical or steeply dipping surfaces toward the northwest and climb the southeast wall and have a left strike-slip (Fig. 3). The near W-E trending Sanyang fault dipping toward south was reformed by quite a few small N-S trending faults and changed its direction from W-E trending to ENE trending. As for the regional stress field (Fig. 3), \( \sigma_1 \) should be in the N-S direction, as deduced from the sinistral-oblique-thrust of the NEN Lantian fault (Fault 3 in Fig. 1b) and the Liutan fold (Fig. 2).

2.2 Nappe Structures with Middle Jurassic Foot Wall of Hongqin Formation

NE-trending nappe structures in the junction region of the Zhejiang, Jiangxi, and Anhui Provinces have been reported in previous works (Yu et al., 2011). Several nappe structures have also been discovered by prospecting efforts during the last few years (Chen et al., 2015). The Zhuxi Cu and W ore deposits (near the south edge of Fig. 1b) in Northeast Jiangxi are found within an NE-trending fault zone (Chen et al., 2015). Moreover, the Late Paleozoic Huanglong Formation and the Chuanshan Formation in the fault zone are the host rocks for mineralization (Fig. 4b). The hanging and foot walls of the Zhuxi nappe structure (Fig. 4a) comprised the Neoproterozoic epimetamorphic series, and mineralization and alteration occurred at the contact zone between the granite porphyry and Huanglong and Chuanshan formations (Chen et al., 2015; Liu et al., 2014; Huang et al., 2013). The data from drilling observations at the Wucheng gold mine in South Anhui Province confirmed that the Neoproterozoic granitic batholiths are rootless and thrust toward the north on the Middle Jurassic red beds (Figs. 5a and 5b). In Xiaoxi Village, a small tectonic window was developed by the Neoproterozoic epimetamorphic rock series that thrust upon the Middle Jurassic red beds (Fig. 5b) (Yu et al., 2011) with a noticeable contact surface (Figs. 6c and 6d). In Shangling Mountain (central area in Fig. 6a), an undeformed granite porphyry body is covered by the Xiaoxi nappe structure. This condition indicates that the Shangling granite porphyry body was formed before the nappe structure. In Taoxi Village, a granite porphyry vein cuts the Xiaoxi nappe structure (central area in Fig. 6a, this study). Therefore, the Taoxi vein was formed later than the nappe structure. The nappe structure extending northeastward from Wucheng to Xiaoxi shows that the high mountains in the south wall (which are formed by the Neoproterozoic epimetamorphic series and the Neoproterozoic granite batholiths) are allochthons resulting from the thrust sheet extending for more than 5 km from the south.

The field features of the nappe structure in Mengkeng (Fig. 7; location in Fig. 1b) have been used to demonstrate similar characteristics to those in the Zhuxi Cu and W ore deposits in

**Figure 2.** (a) Geological map of Liutang area, Xiuning County, South Anhui (mapping by the authors during 1994–1998; stratigraphic codes are the same as Fig. 1b); (b) a sketch showing the nappe fold in Liutang area (drawn by the authors during 1994–1998).
Northeast Jiangxi Province. Field outcrop observations have indicated that the gravel corroded from the Carboniferous Huanglong and Chuanshan formations formed the vast and thick basal conglomerate of the Middle Jurassic Hongqin Formation near the area without any sporadic outcropping of the Carboniferous and Permian systems in its surroundings. This condition reveals that the Paleozoic strata once occurred on a large scale. The Late Paleozoic strata probably exist in the nappe structure (Fig. 7, dipping 48° toward 130°) or under the nappe plates aside from the eroded parts.

A common feature of these nappe structures is that their foot walls belong to the Middle Jurassic Hongqin Formation and the lower beds they cover. A Cretaceous red bed is not found from the foot wall in the field and the drilling core. These fault series cannot be tracked in the south of Huangshan City as they go through the Cretaceous red beds (central area in Fig. 6) and are assumed covered by the red beds.

As for the thrust direction of the nappe structures, the Anhui and Zhejiang regions in the east mainly display thrusting from southeast to northwest (Figs. 4 and 5); in addition, the border of Anhui and Jiangxi in the west occur from the northwest to the southeast direction thrust (Figs. 3 and 8, Chen et al., 2015; Zhang Y J et al., 2013). Between them, the NE-trending fault zone of Anhui, Zhejiang, and Jiangxi (i.e., the Wucheng-Shexian-Ningguo fault zone (Fault 2 in Fig. 1)) is regarded as an approximate boundary. The faults of this group are mainly distributed southeast of ESSYB, extend to an average of N50°E orientation, and dip toward the southeast at an angle of 40°–35°. Thus, \( \sigma_1 \) should be in the NW-SE direction. Clear outcrops can be observed in the Xiaoxi Window (Fig. 6c) and south of Shaolian (Fig. 6d). Essentially, the fractured rocks in the fault zone range from minimal to none. In addition, no apparent superposed relationship exists between this group of faults and the discovered Early Mesozoic faults.

Figures 4, 5, and 6 show a ramp structure in the NW-SE-trending section (Fig. 1c), which is across Zhanggongshan Mountain. This ramp structure is separated by Zhanggongshan Mountain, and the rock bodies in the northwest part in this section thrust toward southeast, and the southeast part thrusts in reverse direction.

2.3 Nappe Structures with Cretaceous Foot Wall

As shown in Fig. 6, a northeast-trending nappe structure (F5) is distributed along the belt from Shaolian to Xiaozi and Taoli and obliquely cuts the Xixi nappe structure (F4) near Xiaozi Village (Figs. 6a–6d). The hanging wall of F5 (southeast side, metarhyolite of the Neoproterozoic Jingtan Formation) thrusts northwestward on the slightly older Neoproterozoic epimetamorphic series. A clear outcrop in the nappe structural section can be observed in the south of Shaolian and extends along the fault with significant landform features (Fig. 6d).

The geological features of the southeast wall that thrust northwestward on the Cretaceous red beds occur at various sites along the Wucheng NE-trending fault zone (Fault 6 in Fig. 1). The Neoproterozoic Shexian granodiorite thrusts from the southeast to the northwest on the Cretaceous red beds (K1\(_h\) to K2\(_q\), Fig. 8a). Moreover, in Northeast Jixi County (Fig. 1), the slates of the Neoproterozoic Niuwu Formation (Pt3\(_n\)) thrust northwestward on the Early Cretaceous red beds of the Huizhou Formation (K1\(_h\)). A clear fault surface inclines 125° southeastward, and the dip angle is 35° (Fig. 8b). Although several geological outcrops show that the foot wall is composed of Lower Cretaceous beds, the nappe structures with the Cretaceous foot wall must have developed after the sedimentation of the Late Cretaceous because all the Cretaceous red beds are continuous in stratigraphy.
Figure 4. Geological map of Zhuxi area (a) and sections near Fuchun (I–I’) and across the Zhuxi Cu-deposit (II–II’), Northeast Jiangxi (modified after Chen et al., 2015).

Figure 5. Drilling profile of the Tianjingshan (Wucheng) gold deposit (geological prospecting memoir from 332 Team of Anhui Bureau of Metallurgy and Geology).
This group of faults is widely distributed in the junction region of Zhejiang, Jiangxi, and Anhui provinces; extends in approximately 25°N–40°E orientation; and dips toward the southeast at an angle of 20°–35°. In certain areas, 5–10 cm fault gouges are present (Fig. 8b). This group of faults cuts the W-E and NEE faults. A N40°E fault (F5) cuts the N50°E fault (F4) (Fig. 6) near southeast Shaolian. The Wucheng-Shenxian fault (F6) cuts the Xiaoxi nappe structure (F4) in the Wucheng area, the Zhukou-Qimen-Shexian fault (F1), the Sanyang fault (F3) in the Shexian area, and the surroundings (Fig. 1b).
Figure 7. Bottom conglomerate of the Middle Jurassic Hongqin Formation near Mengkeng Village, Shenxian County, South Anhui. Location see Fig. 1.

Figure 8. Nappe structures with foot wall of Cretaceous. (a) Photos showing the Neoproterozoic Shexian granodiorite (γδ 2) and Xicun Formation (Pt 3) thrust northwestward upon Late Cretaceous red beds ((a1) the areas 2 kilometers northeast to Shexian downtown; (a2) 5 kilometers east to Shexian downtown); (b) section of the Wucheng-NE-trending fault zone (location see Fig. 1b).
2.4 Extensional-Sliding Structure

Regionally, the reactivation of the Early Paleozoic Qimen-Shexian boundary fault (Fault 1 in Fig. 1) during the Early Cretaceous became a south-dipping normal fault with the hanging wall of the Jurassic–Cretaceous Huangshan Basin. A clear normal fault surface (growth fault) along the north basin boundary can be observed in Chenshan Village (Figs. 9a and 9b). In the south of the basin, the Cretaceous red bed unconformably covers the Jurassic, Upper Paleozoic, and Neoproterozoic epimetamorphic series and forms a half-graben basin.

In the area around Chenshan Village in South Anhui, the north margin of the Cretaceous red basin has an extensional fault filled with quartz and felsic veins (Fig. 9a). The drilling of an ore prospecting project reveals that the Chenshan pluton in the northeast of Chenshan Mountains has developed a suite of detachment faults from north to south (Fig. 9b).

The Late Cretaceous Xiaoyan Formation has a basalt bed. Meanwhile, the study area is intruded by ultramafic picrite and mafic hornblende-andesites, which represent the intrusion or eruption of mantle-derived magma under an extension environment.

2.5 NW-Trending Faults

Several NW-trending faults are distributed in the area. This group of faults clearly cuts all other faults; therefore, they were formed during approximately the Early Cenozoic at the latest (Fig. 6). These fault surfaces primarily dip toward the northeast at a medium to a large angle, and the hanging wall relatively glides downward. That is, most of the surfaces belong to normal faults and a few normal faults with strike sliding.

Figure 9. Basin margin fracture and extensional sliding structure in Jiangcun and Chenshan area (3.5 km north to Shexian downtown). (a) Geological sketch of Chenshan area, Shexian County; (b) extensional sliding structural section in Chenshan area, Shexian County.
2.6 Mesozoic Three-Stage Intrusive Bodies

Investigations on the Mesozoic structural-magmatic activity and tectonic settings in ESSYB, as a part of the research achievements related to Southeast China, have achieved considerable progress in the last few years. Geologists and project team members have classified the magmatic activity at ESSYB into two stages: the 180–160 and 145–120 Ma periods (He and Xu, 2012; Li H et al., 2012; Yang et al., 2012; Jiang et al., 2011, 2005; Zhao et al., 2010; Zhou et al., 2004). The petrography of the first stage mainly consists of granodiorite, which first appeared at approximately 180 Ma from Northeast Jiangxi (Yang et al., 2011; Wang et al., 2004). A recent discovery has indicated that the granodiorite expanded to the west of Zhejiang and South Anhui at approximately 167–155 Ma (Qiu et al., 2013; Wang et al., 2010). The first-stage magma activities in several areas lasted until 146 Ma (Li P J et al., 2013; Wang et al., 2011; Zhou et al., 2011; Xue et al., 2009). This granitic zone, which is slightly older than both of its side regions, could have been formed by ridge subduction (Yang et al., 2012) and slab tearing (Wu et al., 2012). Subsequently, the study area experienced a series of tectonic domain transition processes from the active continental margin before approximately 145 Ma to the thinning of the continental lithosphere and the regional extensional environment after 145 Ma (possibly until 140 Ma) (Li Z L et al., 2013; Qiu et al., 2013). The second stage focuses on granite, which was chiefly formed during the Early Cretaceous, primarily at 135–120 Ma (He and Xu, 2012; Jiang et al., 2011, 2009; Zhao et al., 2010; Weng et al., 2009; Xue et al., 2009; Zhang et al., 2007). The second-stage granites are distributed as several near-EW-trending zones in ESSYB according to regional geological mapping, and all plutons in each zone generally present a northeast direction (Fig. 10).

A third-stage (110–95 Ma) magmatic activity in ESSYB has been found recently. An ultrabasic limburgite was discovered at the center area between Lantian and Xucun (Fig. 1) in South Anhui and in the north of Longtoushan Town in Dexing County, Northeast Jiangxi (Lou et al., 2001). At least three hornblende andesite stocks also intruded the Early Cretaceous Huizhou Formation around the Huangshan areas. Accordingly, the Huizhou Formation sandstone around the hornblende andesite exhibited siliconization and hornfelsic alteration to form a thin outside contact zone near Huangshan City, similar to the Xiaolongshang body (Fig 11a, location see Fig. 6). Thus, the formation time should be at least later than the Early Cretaceous. Given the difficulty in using zircon for dating from ultramafic rocks, the formation time of these mafic to ultra-mafic

![Figure 10. Four E-W trending Cretaceous A-type granite belts in the Southeast China.](image-url)
Figure 11. Characteristics of some granitic rocks dealing with thrust faults. (a) The siliconization and hornfelsic alteration of the Cretaceous Huizhou Formation sandstone around the Xiaolongshan hornblende andesite; (b)–(e) features of the Taoxi granite vein, Xiuning County. (a) The Taoxi granite vein across the thrust fault; (b) contact surface between granite vein (γπ) and hanging wall Pt3 epimetamorphic rock series of the fault; (d) petrologic feature of granite vein under microscope; Kfs. K-feldspar; Pl. plagioclase; Qtz. quartz; Bt. biotite; Py. Pyrite; (f) Guzhu granitic body; (g) Shimen granitic body ((f), (g) show different degrees of deformation on different granitic bodies along NE fault; locations of granite body see Fig. 6).
stocks is estimated to be approximately the same as the formation time of the basalt layer near the bottom of the Late Cretaceous Xiaoyan Formation. The resulting age is near or younger than those of the Late Cretaceous basalt in Northwest Zhejiang (bulk rock K-Ar dating age is 98–105 Ma, Yu et al., 2001) and the alkali basalt in Northeast Jiangxi (K-Ar method age is 98–102 Ma, Wang et al., 2002).

This study considers these three-stage intrusive bodies as important indicators of the tectonic background and the signs of fault displacement. Many geologists have believed that the tectonic transition from the EW-trending paleo-Tethyan tectonic domain to the NE-NNE West Pacific domain in Southeast China occurred during the end of the Early–Middle Jurassic and ended during Early Cretaceous, and the geodynamics of Southeast China then changed from a compressional system to an extensional system (Li et al., 2017; Yu et al., 2006; Sun, 2005; Shu and Zhou, 2002). That is, the first-stage granitic rocks may be intruded in a compressional background, and the second- and third-stage ones intruded in an extensional background.

2.7 Jurassic–Cretaceous Beds with Three-Stage Volcanic Rocks

Several Mesozoic intermountain basins are distributed in ESSYB (Fig. 1b). A typical example is the Huangshan Basin in South Anhui. The development of the terrestrial red bed is complete from the Yuetang Formation of the Early Jurassic to the Late Cretaceous Xiaoyan Formation (Fig. 12), including the Jurassic Yuetang, Hongquin, Bingqu, and Shiling formations and the Cretaceous Yantang, Huizhou/Huangjian, Qiyunshan, and Xiaoyan formations.

The bottom bed pure quartzose conglomerate of the Early Jurassic Yuetang Formation unconformably covers the Neo-proterozoic basement rock series. The area above the conglomerate chiefly contains mudstone with thin coal interbeds. This formation belongs to the coal-bearing formation within intermountain basins. The Middle Jurassic Hongquin Formation mainly consists of purple and daffodil-yellow medium-fine sandstones, which generally overlie the basement rocks and constitute the inland river red bed formation. The Late Jurassic–Early Cretaceous Shiling Formation (in Huangshan City and its surrounding areas, Yu et al., 2016) and the Early Cretaceous Huangjian Formation (in the Qingliangfeng region at the border of the Zhejiang and Anhui provinces, Wang et al., 2014; Li P J et al., 2013) are of the intermountain basin volcanoclastic formation. The Bingqu Formation underlies the Shiling Formation, and the Huangjian Formation underlies the Laocun Formation fluvial sediment conglomerate. The thickness of the overlying Yantang Formation is less than 100 m, and this formation is of lacustrine fine clastic calcium deposit that contains rich biological fossils and belongs to an intermountain basin melanocratic formation. Moreover, the Middle and Late Early Cretaceous Huizhou formations (including the Laocun Formation in Qingliangfeng) unconformably cover various layers of the underlying strata. Given the regional compression at the end of the Cretaceous, the basin formed an incomplete series from the lower molasses-like formation to the middle red bed formation and the upper molasses-like formation that overlies the Jurassic series, with a basalt bed in the Xiaoyan Formation.

The deposit facies of the terrestrial red beds usually rapidly change from one to another. An angular unconformity in the Huangshan Basin between the upper conglomerates and lower sandstones may be a disastrous alluvial fan or the overlap unconformity produced by enlarging or reducing the basin area. Their depocenter remains unchanged, and the sedimentation is continuous. Thus, this small angular unconformity within a formation is barely equal to a tectonic event. Accordingly, the sedimentation during the Jurassic and the Cretaceous is a consecutive process. If the sedimentation is disturbed by a tectonic or magmatic event, then the sedimentation center would have shown a remarkable migration. Figure 1b illustrates that the Cretaceous center of sedimentation migrated slightly to the north relative to the former Jurassic depocenter.

The three-stage (interbeds) volcanic rocks within the Jurassic–Cretaceous beds (Fig. 12) represent additional evidence of an extensional mechanism and indicate fault displacement. The lower bed volcanic rock within the Huangshan Basin is called the Shiling Formation, and its major lithology involves rhyolite and tuff. Recently, Yu et al. (2016) first obtained the LA-ICPMS zircon U-Pb weighted average age of 154.7±2.5 Ma for rhyolite from the Huangshan area (Fig. 1b). This result implies that the volcanic rocks of the Shiling Formation formed during the Late Jurassic (older than 145 Ma) and not in the Early Cretaceous, as asserted by a prior 1:50 000-scale regional geological survey.

The middle bed volcanic rock in Qingliangfeng Mountain at the border of Zhejiang and Anhui Provinces is called the Huangjian Formation with a major lithology of bulb-shaped rhyolite. The recently obtained LA-ICPMS zircon U-Pb age of rhyolite is approximately 133 Ma (Wang et al., 2014; Li P J et al., 2013), and it belongs to the Early Cretaceous. Therefore, the Shiling Formation in the Huangshan Basin and the Huangjian Formation in the Qingliangfeng region cannot be compared horizontally.

The upper bed volcanic rock in the bottom layer of the Late Cretaceous Xiaoyan Formation is an 8–12 m-thick basalt layer. The occurrence of these basalts is estimated to be near or later than those of the Late Cretaceous basalt in Longyou City, Zhejiang (whole rock K-Ar dating method age 98–105 Ma, Yu et al., 2001) and the alkali basalt in Yushan in Northeast Jiangxi (K-Ar method age 92–111 Ma, Wang et al., 2002).

3 LA-ICPMS ZIRCON DATING OF GRANITIC ROCKS

Many new fault-dating methods have been applied in the last few years. These methods have significantly enhanced the possibility of determining fault time and redefining structural sequence (Wang, 2004). Besides using sensitive high-resolution ion microprobe (SHRIMP) for zircon and monazite dating in felsic veins in certain fault zones (particularly the syn-deformational granites) (Zhao et al., 2006; Liu et al., 2004), the ⁴⁰Ar/³⁹Ar age dating for potashium feldspar from the veins, neogenic sericite, muscovite, or deformed biotite in the fault zone is the most common method mastered by researchers and has garnered numerous achievements (Scharf et al., 2016; Idelman et al., 2014; Schneider et al., 2013; Yu et al., 2011; Zhang et al., 2008, 2004; Deng et al., 2006). However, collecting
and sorting dating samples from the fault surface is extremely difficult. Such difficulty arises from the rarity of the outcrops of the fault surfaces and the absence of neogenic minerals on the surfaces for dating. At present, syn-tectonic granite has not yet been identified in the relevant faults in the study area. Only granitic vein bodies and small stocks have been ascertained to intrude into the nappe structures or be covered by nappe structural slices. This study conducted laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) zircon uranium-lead (U-Pb) dating for this type of granitic vein bodies and stocks as one of the referential bases for determining fault sequence.

3.1 Sampling

The intersecting relationship between intrusive bodies and faults has just been identified in one case in Taoxi Village (Fig. 6). This porphyry granite vein was found to cut the Xiaoxi nappe structure, indicating that it was formed after the fault.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Formation</th>
<th>Thick (m)</th>
<th>Geological column</th>
<th>Lithology</th>
<th>Geological setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous</td>
<td>Xiaoyan Fm.</td>
<td>K_a x</td>
<td>267.6</td>
<td>Red conglomerate with sandstone</td>
<td>Compression (thrust nappe structure)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_a y</td>
<td>&gt;95.9</td>
<td>Red conglomerate with sandstone and silty mudstones</td>
<td>Extension (105–98 Ma for basalt from Xiaoyan Fm.)</td>
</tr>
<tr>
<td></td>
<td>Qiyunshan Fm.</td>
<td>K_a y</td>
<td>413.2</td>
<td>Red conglomerate with sandstone and growth strata</td>
<td>Struck-slip fault (?)</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Huazhao Fm.</td>
<td>K_h y</td>
<td>371.4</td>
<td>Red sandstone and silty mudstones</td>
<td>Extension (-133 Ma for rhyolite from Huangian Fm.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_h x</td>
<td>97</td>
<td>Arenaceous shale and sandstone</td>
<td>Unconformity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_h j</td>
<td>122</td>
<td>Fluvial sediment conglomerate</td>
<td>Compression (Thrust nappe structure)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_h i</td>
<td>221.2</td>
<td>Volcanic tuff, rhyolitic tuff with basal sandstone</td>
<td>Unconformity (139.7 ± 1.5 Ma for rhyolite from J_s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J_s x</td>
<td>294.6</td>
<td>Rhyolite and rhyolitic tuff</td>
<td>Compression (154.7 ± 2.5 Ma for rhyolite from J_s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J_s y</td>
<td>190.9</td>
<td>Conglomerate with sandstone</td>
<td>Unconformity</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Hongai Fm.</td>
<td>J_s x</td>
<td>754.5</td>
<td>Purple and daffodilyellow medium-fine sandstones</td>
<td>Extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J_s y</td>
<td>42.0</td>
<td>The upper bed is mudstone within coal interbeds</td>
<td>Unconformity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The lower bed is pure quartzose conglomerate</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12. The Jurassic–Cretaceous depositional system within the Huangshan Basin.
The contact surface is clear in the field, and the potash feldspar phenocrysts have not undergone metamorphism and deformation (Figs. 11b, 11c, 11d and 11e). Another porphyry granite vein covered by the Xiaoxi nappe structure is found in Shanglingtou area (north of Taoxi) (center area in Fig. 6). This intersecting relationship indicates that the Shanglingtou granite vein was formed before the fault. Moreover, the granitic stocks along or near the Xiaoxi nappe structure in the region exhibit considerable differences in deformation, which suggests that they experienced variable structural actions. Several granitic stocks are distributed from the southwest and toward the northeast in Shimen, Guzhu, and Changgai area (Fig. 6). The orientations of these stocks are related to the semi-concealed fault (or blind fault) zone (as indicated in unpublished geophysical prospecting data on the local unit of geology and mineral resources). As observed, outcrops include granite porphyry, and the phenocryst consists of anorthite, quartz, and hornblende. The phenocryst content is 10%~15%, and the base materials are anorthite (50%~55%), potassium feldspar (15%~20%), and quartz (10%~15%). The deformation of the Guzhu stock is stronger than that of the Shimen rock mass (Figs. 11f and 11g). The former has a strip shape and multi-stage joints. The latter has a nearly oval shape, and its joints are rare. These stocks should exhibit differences in formation, and they underwent different change times.

This study selected three samples from the Guzhu stock (D030), the Taoxi vein (D208), and the Shimen stock (D251) in Shexian County for conducting zircon LA-ICPMS U-Pb isotopic dating.

### 3.2 Analytical Method

Zircon extraction from the bulk-rock samples was conducted at the Hebei Institute of Regional Geology and Mineral Resources Survey, China. Zircons were mounted on an epoxy disk, carefully polished until their cores were exposed, and photographed via transmitted light, reflected light, and cathodoluminescence (CL). LA-ICPMS U-Pb zircon geochronological analysis was performed at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. Laser sampling was conducted with a GeoLas2005 System, and the ICPMS with the Agilent 7500a. Helium was used as the carrier gas, and argon was employed as the complementary air plasma central gas stream (Ar+He) to improve the sensitivity of the instrument, decrease the detection limit, and enhance the plasma precision for the laser ablation system and for the ICPMS instrument and data reduction are similar to those described by Liu Y S et al. (2010a, b, 2008).

Transmitted light, reflected light, and CL images (Fig. 13) were used, and zircons with obvious rims, bright surfaces, and no cracks and inclusions were employed for analysis. The laser ablation diameter was approximately 30 μm, and the measured 206Pb content was utilized for common lead deduction. Test results revealed that the error of a single data point was 1σ, and the weighted average error was 2σ.

### 3.3 Zircon U-Pb Dating Results

Figure 16 shows the CL images of zircons from three granite stocks and veins. Table S1 and Fig. 14 show the zircon U-Pb isotopic dating results of three samples.

The dating confirms that the Guzhu stock (D030) was formed at 146.7±4.3 Ma (MSWD=8.3) and the Shimen stock (D251) at 127.6±1.5 Ma (MSWD=5.1). The formation time of the Guzhu stock occurred 20 Ma before the Shimen stock. In addition, zircons from sample D208 yielded a mean U-Pb age of 141.0±6.7 Ma (MSWD=29), and sample D089, 149.1±1.17 Ma (MSWD=1.01). All these ages can help estimate the activation time of the Xiaoxi nappe structure (with footwall belonging to the Middle Jurassic Hongqin Formation, Jsh).

### 4 DISCUSSION

#### 4.1 Time Sequence of Nappe and Extensional Structures in ESSYB

Four groups of Mesozoic faults formed during different times in ESSYB, extending in the NEN, NE or ENE, near-EW, and NW directions. They were mainly nappe structures and extensional-sliding faults. The indicators of magmatic rocks, red beds (which are cutting faults or had been cut by faults), and intercrossing faults can be used to establish the time sequence of the thrust-nappe and extensional structures in ESSYB.

Distinct features were used to identify the three tectonic compression events in the study area from the Middle Triassic to the end of the Late Cretaceous. The first tectonic compression event during the Middle Triassic (Early Mesozoic) caused strong folding in the strata lower than the Early Triassic, particularly the folding in the Carboniferous–Permian strata, which covered the Precambrian epimetamorphic basement rock series. The asymmetrical fold axial are trending in the near EW direction with a south-dipping axial plane, and the south wing of the fold thrust from south to north in Liutang Village (Fig. 2), south of Anhui Province. These folds were covered by an essentially undeformed Late Triassic Anyuan Formation coal-bearing series and Jurassic–Cretaceous beds (Zhou et al., 2015). Coevally, the NEN-trending strike-slip faults (such as the NEN-trending left lateral movement and thrusting Fault 2 in Fig. 1b in the Lantian area of South Anhui) cut the Early Paleozoic Lantan residual syncline (Zhou et al., 2015; Yu et al., 2005) and was in turn covered by the Jurassic–Cretaceous beds. The second tectonic compression event in the study area may have occurred in the period of 146.7±4.3 to 127.6±1.5 Ma. The Xiaoxi nappe structure (with a footwall belonging to the Middle Jurassic Hongqin Formation), as a representative, occurred between 146.7±4.3 and 141.0±6.7 Ma, that is, during the transition from Jurassic to Cretaceous (Qiu et al., 2013). This phenomenon occurred because the Taoxi 141.0±6.7 Ma granite vein cut the Xiaoxi nappe structure, and the fault covered the Shanglingtou 149.1±1.2 Ma granite vein in turn. In the west of the Huangshan Basin and across Zhanggongshan Mountain, a ramp structure is distributed in the NE-SW direction (Fig. 1c). The
rock bodies in the northwest part of this section thrust toward southeast, and the southeast part thrusts in the opposite direction.

The last tectonic compression event must have occurred during the end of the Late Cretaceous. Age data of the nappe structures have not yet been obtained, and the forming time can only be estimated at the Late Cretaceous or during the transition

Figure 13. Zircon CL images of Guzhu (a), Shimen (b) and Taoxi (c) granite stocks from Shexian County (locations see Fig. 6), South Anhui.
between the Mesozoic and Cenozoic. At the southeast margin of the Huangshan Basin (similar to Shexian in Fig. 8a) along the Shexian-Ningguo fault zone, the Neoproterozoic basement rock series and the Neoproterozoic Shexian pluton thrust northwestward onto the Late Cretaceous red beds (Fault 6 in Fig. 1b), meaning that the last event was active after the sedimentation of the Late Cretaceous red beds.

In the durations among the three compression events, the geological background in ESSYB should entail mainly extension environments. During the tectonic transition from the EW-trending paleo-Tethyan tectonic domain to the NE-NNE West Pacific domain in Southeast China, magmatic rocks were

Figure 14. Zircon U-Pb Concordia diagrams of Guzhu (a), Shimen (b) and Taoxi (c) granite stocks (locations see Fig. 6), South Anhui.
scarcey present in the study area until approximately 180 Ma (in North Jiangxi) or approximately 167 Ma (in Northwest Zhejiang). The compressional background lasted from the Middle to the Late Jurassic and was accompanied by granitic or dioritic rocks, but no coeval compressive folds and faults were identified in the study area and/or reported in literature. This outcome means that the surface response of the tectonic clearly occurred later than the magmatism. Thus, many granodiorites aged approximately 180–146 Ma and volcanic rocks aged approximately 154 Ma in the region were interpreted by numerous geologists as representing an extension regime (Yu et al., 2016; Qiu et al., 2013; He and Xu, 2012; Li H et al., 2012; Wu et al., 2012; Yang et al., 2012; Jiang et al., 2011, 2005; Wang et al., 2010; Zhao et al., 2010; Zhou et al., 2004). Following the duration from Early Cretaceous to the end of Cretaceous, the presence of 135–120 Ma granites (Li P J et al., 2013; Qiu et al., 2013), volcanic rocks (Wang et al., 2014), approximately 125–120 Ma A-type granites (Yang et al., 2012; Jiang et al., 2011; Wong et al., 2009), and 98–105 Ma basalts (and intrusive hornblende andesite) imply the long-term existence of an extension environment in the region. Several geologists (Xu et al., 2016; Pan et al., 2014) have established eight paleo-stress stages (at least five stages from Jurassic to Cretaceous) in the Jurassic–Cretaceous Huangshan Basin through fault-slip analysis and age estimation. However, the terrestrial deposit facies of red beds in the Huangshan Basin changed rapidly, and several angular unconformities between the upper conglomerates and lower sandstones within a single formation could indicate a disastrous alluvial fan or an overlapping unconformity caused by the enlargement or reduction of the basin area. Thus, this small angular unconformity can barely equal a tectonic event. Given the lack of age dating, the extension and strike-slip faults from Early Cretaceous to the end of Cretaceous cannot be correctly positioned into the sequence framework. The basement boundary and normal faults at the north margin of the Huangshan Basin in Chenshan Village (Fig. 9) are posited in this research to have been formed during the Early Cretaceous after or at the same time as the sedimentation of the Huizhou Formation (K_{h}).

Observations and analyses in the field have revealed that the sequence of the Mesozoic nappe and extensional structures in ESSYB are as follows: the first compression event during the Middle Triassic, the first extension event in the Jurassic, the second compression in the Late Jurassic (or the transitional period between Jurassic and Cretaceous), the second extension in Early to Middle Cretaceous, the strike-slip in Middle to Late Cretaceous, and the last compression at the end of Late Cretaceous. Each stage is related to the occurrence of structural or magmatic events. Their cutting of all faults above them indicates that the NW-trending faults may have been formed after the transitional period between Cretaceous and Cenozoic and probably during Early Cenozoic.

Regarding the specific time sequence of the different orientation faults under the compressive background, the first faults formed are the near EW-trending faults (including the NE-trending Lantian fault), followed by the NE- and NEE-trending faults, the NEN-trending faults, and the NW-trending faults.

### 4.2 Sequential Relationship between Tectonic Action and Magmatism in ESSYB

Previous studies have theorized that the asthenosphere upwelling during the Early Mesozoic and the Pacific plate subduction during the Late Mesozoic elicited a strong response from Southeast China (Xiao et al., 2006). This response is characterized by large-scale magmatic rocks and a series of extensional faults, folds, and nappe structures. Li (2000) verified the close association between the Cretaceous granitic magmatic activity and lithosphere extension in South China. Wang et al. (2005) claimed that A-type granite and alkali intrusive rocks can be classified into three stages, namely, Jurassic (184–152 Ma), Early Cretaceous (139–123 Ma), and Late Cretaceous (101–86 Ma); therefore, multiple stages of extensional action occurred in the lithosphere in South China. Shen et al. (2008) asserted that the lithosphere in South China became thinner than before and developed multiple metamorphic core complexes between 140 and 120 Ma. Moreover, many geologists have started investigating mafic dikes and alkali rocks to explore whether these materials caused the breakup of the South China Block since the Mesozoic Period (Zhang and He, 2020; Lou et al., 2011; Xie G Q et al., 2006). Li S Z et al. (2013, 2012) believed that the continental margin of East Asia was passive before the Triassic, the Andean-type active continental margin was based on the continental magmatic arc during the Late Triassic–Early Cretaceous, the Andean-type continental margin was based on the strike-slip pull-apart basin during the late period of the Early Cretaceous–Eocene, and the West Pacific-type active continental margin occurred after the Oligocene.

Three stages of intrusive and volcanic activities were identified in the study area, which are similar to those reported by Wang et al. (2005). Reminiscent of the case in Southeast China, the Mesozoic nappe and extensional structures in the study area are closely related to magmatism. Among the three stages of intrusive and extrusive rocks, the intrusive rocks of the first stage (180–146 Ma) and the Shiling Formation rhyolite (154 Ma) essentially have the same formation period as the Guzhu granite porphyry (Fig. 6). Such materials could have been formed during the post-transition period from the Tethys to the Pacific domain (nearly an extensional setting) stage before the Late Jurassic compression. For the second-stage intrusive bodies (Early–Middle Cretaceous), the Huangjian Formation rhyolite in the Qingjiangfeng area at the border of Zhejiang and Anhui provinces and the third-stage Late Cretaceous Xiaoyan Formation basalts are not directly related to the faults. However, the Cretaceous red beds are covered by the last nappe structure. This condition indicates that Cretaceous magmatism occurred during the extensional period between the two compressions formed in Late Jurassic and at the end of Cretaceous.

### 4.3 Background of Tectonic-Magmatism in ESSYB

For over 20 years, a long-running debate has involved the Mesozoic dynamic background of the large-scale multi-stage tectonic-magmatism in South China. Several theories have been proposed, such as lithosphere extension and asthenosphere mantle upwelling (Wang et al., 2005; Zhu et al., 2005; Li, 2000), an extensive rift system in East Asia and large-scale lithosphere delamination and thinning (Cai et al., 2002), a rift
in the entire east coast of China that has existed since the Mesozoic Era (Gilder et al., 1996), the subduction of the paleo-Pacific Plate beneath the Eurasian Plate (Li et al., 2017; Suo et al., 2017; Li and Li, 2007; Zhou et al., 2006; Shu et al., 2002; Niu, 2005; Zhou and Li, 2000; Jahn et al., 1990, 1976), and the mantle plume that rose in South China during the Mesozoic (Deng et al., 2004; Xie et al., 2001). East China is currently situated in the west coast of the Pacific Ocean. Thus, many geologists in China and abroad have believed that the Mesozoic lithosphere evolution in East China is related to the subduction of the Pacific Plate beneath the Eurasian Continent. This finding is supported by numerous studies (Li S Z et al., 2017; Suo et al., 2017; Tao et al., 2017; Dong et al., 2015; Li J H et al., 2015, 2014; Shu et al., 2015; Li Z L et al., 2013; Yang and He, 2013; Zhang et al., 2011; Zhou and Li, 2000; Jahn et al., 1990, 1976; Hide, 1977). The most accepted theories are the low-angle subduction model (Zhou and Li, 2000) and the flat-slab subduction model (Li and Li, 2007) of the Pacific Plate, which have been paid close attention (Li et al., 2017; Suo et al., 2017; Tao et al., 2017). Recently, a ridge subduction model was suggested and applied to partly explain the magmatism that occurred on the coast during the Early Mesozoic, the large-scale magmatism in the Nanling region during the Jurassic, and the magmatic zoning in the Middle and Late Cretaceous in South China (Wu et al., 2012; Sun et al., 2008, 2007).

ESSYB, as a part of the South China Plate, has been substantially influenced by low-angle and flat-slab subductions but exhibit unique phenomena that slightly differ from those of the South China Block. After the Early Mesozoic tectonic event that caused the collision between the North and South China blocks and produced folds in the study area (such as the Liutang fold in Fig. 2 and the stress field in Fig. 3), the entire Mesozoic geological and thermochronological records in Southeast China can be optimally interpreted with the flat-slab subduction, tearing, delamination, and roll-back of the paleo-Pacific Plate (Li et al., 2017; Tao et al., 2017; Li and Li, 2007) (Fig. 15). The model accounts for the advance of the mountain front and its foreland basin during the Early Mesozoic collision. The eclogitization of the oceanic crust occurred during subduction. Once a sufficient proportion of the oceanic slab had been converted to denser eclogite, the oceanic slab became depressed at the center and dragged the overriding Southeast China downward (Wang et al., 2018; Li et al., 2017; Tao et al., 2017). This gravitational pull led to the formation of a gentle depression atop the continental lithosphere and thus created the sag basin on the surface during Late Triassic to Early Jurassic (Li et al., 2017; Tao et al., 2017; Fig. 15a). The stress field of the Early Mesozoic structural deformation was inferred from the Liutang folds and the Lantian faults (Fig. 3). When the delamination and break-up of the flat-subducted and eclogitized oceanic lithosphere occurred during the Middle-Late Jurassic, the burial in the sag basin was substituted by lithospheric rebounding and rifting with magmatic emplacements (Li et al., 2017; Tao et al., 2017).

The Jurassic granites and volcanoes in South China have been described as elements of the delamination-related magmatism in an extensional tectonic setting (Fig. 15b) (Tao et al., 2017; He et al., 2012; Yu et al., 2010; Li and Li, 2007; Li et al., 2007; Zhou et al., 2006; Chen et al., 2005). The southeastward retreat of the Pacific flat-slab during the Cretaceous would have generated intraplate lithospheric extensions (Fig. 15c) (Li and Li, 2007). Moreover, the subduction zone and its related arc had migrated to the south of the present continental margin of South China by approximately 90 Ma (Fig. 15c) (Li J H et al., 2012; Lapierre et al., 1997). This phenomenon accounted for the observed shift in intensive Late Cretaceous volcanic activity into the coastal areas of South China at present (Meng et al., 2012). As to their compressional tectonic backgrounds, the South China Block and ESSYB are highly similar but not the same. At the gap between the extensional actions, many folds and nappe structures emerged in the entire South China (Li S Z et al., 2013, 2011; Li J H et al., 2012; Zhang Y Q et al., 2012; Lin et al., 2011; Li and Li, 2007; Wang et al., 2005). Li et al. (2011) revealed four types of contact interfaces of the unconformities between the Triassic and Jurassic in the Xuefengshan tectonic system (high-angle unconformity, low-angle unconformity, disconformity, and conformity) that have become increasingly younger westward. The characteristics of Early Mesozoic folds are also subdivided into two directions of fold axial traces in South China, namely, the northeast and northwest striking folds, which were superimposed by the N-S-trending nappe structures. As such, Li et al. (2011) proposed that the longitudinal arcuate and northeastward structures in the Xuefengshan intracratonic tectonic system resulted from the control of different block borders under the same stress field as the previous one. On the basis of the field analysis of fault kinematics affecting the different lithostratigraphic units of the Yuanma basin in central South China, Zhang Q Y et al. (2012) established a five-stage tectonic stress evolution history from Late Mesozoic to Early Cenozoic. This history included the Middle-Late Jurassic E-W compression, the Early Cretaceous NW-SE extension, the Early Cretaceous NW-SE compression, the Late Cretaceous N-S extension, and the Paleogene NE-SW compression. The change in tectonic stress directions was interpreted in terms of the change in either the plate tectonic settings or the deep-seated crustal process. Zhang G W et al. (2013) regarded the east of the South China Continent as having been overprinted by various compressional and extensional structures of the continental margin because of the subduction of the West Pacific Ocean with varied subduction directions, angles, and speeds in different periods. In particular, the authors contended that the intense multi-phase volcanic intrusion magmatic activities and deformation that have occurred since Middle-Late Jurassic formed a basin and ridge-type tectonic zone on the continental margin. Moreover, the surface has developed a considerable amount of nappe structures (Zhang et al., 2012), including synorogenic granites (Yang et al., 2003; Xie, 2002). At approximately 125 Ma, the intracontinental compression transformed from relaxation to extension (Mao et al., 2014, 2012; Sun et al., 2008, 2007) under the rotation of the subduction direction of the paleo-Pacific Plate. In summary, multi-stage compression-tectonic events appear to have been identified in central South China than in ESSYB. Several geological phenomena in ESSYB might be difficult to identify or might be concealed.

Given the analysis above, the background of the tectonic-magmatism in ESSYB should be similar to that of the South...
China Block. That is, after the Early Mesozoic movement, the Late Mesozoic nappe and extensional structures in the study area might be related to the flat-slab subduction, tearing, delamination, and roll-back of the palaeo-Pacific Plate (Wu and Suppe, 2018; Li and Li, 2007). A response relation also existed between the magmatism and the Pacific Plate subduction during the Mesozoic. However, the response of each stage of the background remains a special feature and is not uniformly similar to that of the South China Block.

5 CONCLUSIONS
The ESSYB developed three stages of nappe structures and two stages of extensional structures during the Mesozoic. These stages were the first compression in the Middle Triassic, the first extension in Middle–Late Jurassic, the second compression in Late Jurassic, the second extension in Early Cretaceous, and the last compression at the end of Late Cretaceous, followed by the Early Cenozoic extension. All the structural features are related to the Early Mesozoic movement; Late Mesozoic flat-slab subduction, tearing, and delamination; and
the roll-back of the palaeo-Pacific Plate. The research results provide additional evidence for remodeling the tectonic and geodynamic evolution of Southeast China.

ACKNOWLEDGMENTS
This work was supported by the NSFC (No. 41872201). The LA-ICPMS U-Pb zircon geochronological analysis was performed at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Two anonyims have provided constructive suggestion and significantly improved the manuscript. We appreciate the 332 Geological Team of Anhui Bureau of Geology and Mineral Resources for their enthusiastic help. The final publication is available at Springer via https://doi.org/10.1007/s12583-020-1292-z.

Electronic Supplementary Material: Supplementary material (Table S1) is available in the online version of this article at https://doi.org/10.1007/s12583-020-1292-z.

REFERENCES CITED