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Geochronological, Sedimentary, Structural, and Metallogenic Characteristics of Southeast China during the Mesozoic: A General Review

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Abstract

The tectonic evolution of Southeast China during Late Mesozoic is a prominent topic. Numerous tectonic models on Late Mesozoic evolution of Southeast China have been published in the past 50 years. We synthesized many up-to-date and precise zircon U-Pb ages, sedimentary strata, and regional structures and discussed the oxygen fugacity of magmas and related ore deposits. We also analyzed the most current tectonic models published by some scholars. A multistage tectonic stress evolution history during Late Mesozoic was constructed, which included the following stages: 1) Early-Middle Jurassic (196 - 175 Ma) extension, in which many bimodal volcanics formed; 2) Middle-Late Jurassic (165 - 140 Ma) compression, which generated largescale gneissic granites, garnet-bearing granites, stratigraphic hiatus, and nappe structures; 3) Early Cretaceous (140 ± 5 - 120 Ma) extension, which formed weakly deformed or undeformed granites, alkali granites, metamorphic core complexes, graben basins, and basic dike swarms; 4) Early Cretaceous (120 - 110 Ma) compression, which generated nappe structures, volcanic hiatuses, and garnet-bearing granites; and 5) Early-Late Cretaceous (110 - 80 Ma) extension, which generated largescale bimodal volcanics, basic dike swarms, alkali granites, and graben basins. The Late Mesozoic tectonic evolution of Southeast China may be attributed to the drifting history of the Paleo-Pacific plate. The drifting direction of the Paleo-Pacific plate has changed several times since 140 Ma, which led to major changes in the tectonicphenomena from Jurassic to Cretaceous and to the formation of Late Mesozoic mineral deposits.

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Keywords

Tectonic Evolution, Late Mesozoic, Zircon U-Pb Age, Regional Structures, SE China

1. Introduction

The tectonic evolution of Southeast China during Late Mesozoic is a prominent topic. For more than half a century, geologists worldwide have undertaken studies on igneous rocks in Southeast China, and numerous tectonic models on Late Mesozoic evolution of the region were published. These models can be mainly divided into four categories: an active continental margin related to the subduction of the Paleo-Pacific plate, with flat subduction [1] or with a low-angle to a medium-angle subduction [2] [3]; a composite of orogenic belts formed due to continental collisions within the South China block during the Mesozoic period [4]-[6]; rifting along the entire eastern margin of China that commenced in the Middle Mesozoic [7]; and a hot mantle plume in South China block during Mesozoic [8]. Despite the number of studies on this problem, this issue remains unresolved. The reasons for this research gap may be attributed to the use of outdated equipment or the lack of comprehensive study on multiple geological elements. Some traditional dating methods, such as K-Ar and Rb-Sr systems, can be easily disturbed by subsequent hydrothermal events or cannot obtain the exact ages of geologic events. Therefore, a precise and accurate determination of the temporal-spatial distribution of igneous rocks is essential to explore the tectonic evolution of Southeast China. Furthermore, the analysis of sediment and regional structure is required.

This study synthesizes the up-to-date and precise zircon U-Pb ages on the basis of recent studies by our team and other groups. This study also discusses the geological features of Mesozoic basins, nappe structures, angular unconformity, and the oxygen fugacity of magmas and related ore deposits to analyze the plate tectonic setting and petrogenesis of Late Mesozoic igneous rocks. Subsequently, this study reveals the tectonic evolution history of Southeast China during Late Mesozoic.

2. Temporal-Spatial Distribution of Igneous Rocks

Igneous rocks are often emphasized by researchers. Zhou and Li [2] suggested that the magmatic activity of the Southeast China continental margin migrated oceanward to the southeast because the slab dip angle of the Paleo-Pacific plate subduction underneath Southeast China increased from low angle to medium angle. Li and Li [1] proposed that the ages of synorogenic magmatism, thrusting, and metamorphism showed a trend of younging toward the cratonic interior during the Permian-Triassic orogeny. They then put forward a flat-slab subduction model. The age of igneous rocks is one of the most critical factors in determining the tectonic evolution of Southeast China. However, some disagreements exist among the ages obtained via different dating methods. Currently, U-Pb dating is accepted as the most accurate dating method available. Therefore, we consulted approximately 1000 papers and collected hundreds of up-to-date U-Pb dating data [87] to reveal the temporal-spatial distribution of igneous rocks during Late Mesozoic. As shown in **Figure 1**, we conducted statistics on most zircon U-Pb ages of igneous rocks in Southeast China. Basing on the temporal-spatial distribution of these rocks, we did not observe obvious tendency for igneous rocks to grow younger from inland areas toward the coastal areas. Specifically, Jurassic orogeny igneous rocks are distributed throughout both the coastal areas and inland areas (**Figure 1**), and younger rocks coexist with the older rocks in many areas [9]-[12].

Table 1 and **Figure 2** show that the ages of these Yanshanian intrusive rocks can be grouped into four episodes: 196 - 175 Ma (formed diabases, granites and diorite porphyry scattered across Eastern China), 165 - 136 Ma (formed largescale gneissic granites, garnet-bearing granites, and granodiorite), 135 - 120 Ma (formed weakly deformed and undeformed granites, alkali granites, metamorphic core complexes, and some basic dike swarms), and 110 - 80 Ma (formed largescale basic dike swarms, alkali granites, and syenites). The ages of extrusive rocks can be grouped into three episodes: 195 - 177 Ma (formed bimodal volcanics), 145 - 120 Ma (formed felsic volcanics and intermediate-acid volcanics), and 110 - 80 Ma (formed largescale bimodal volcanics).

Magmatic rocks can be used to indicate the setting [46]-[50], such as bimodal volcanics that are generally formed in an extensional tectonic regime. Large-scale volcanic sequences, alkali granites, metamorphic core

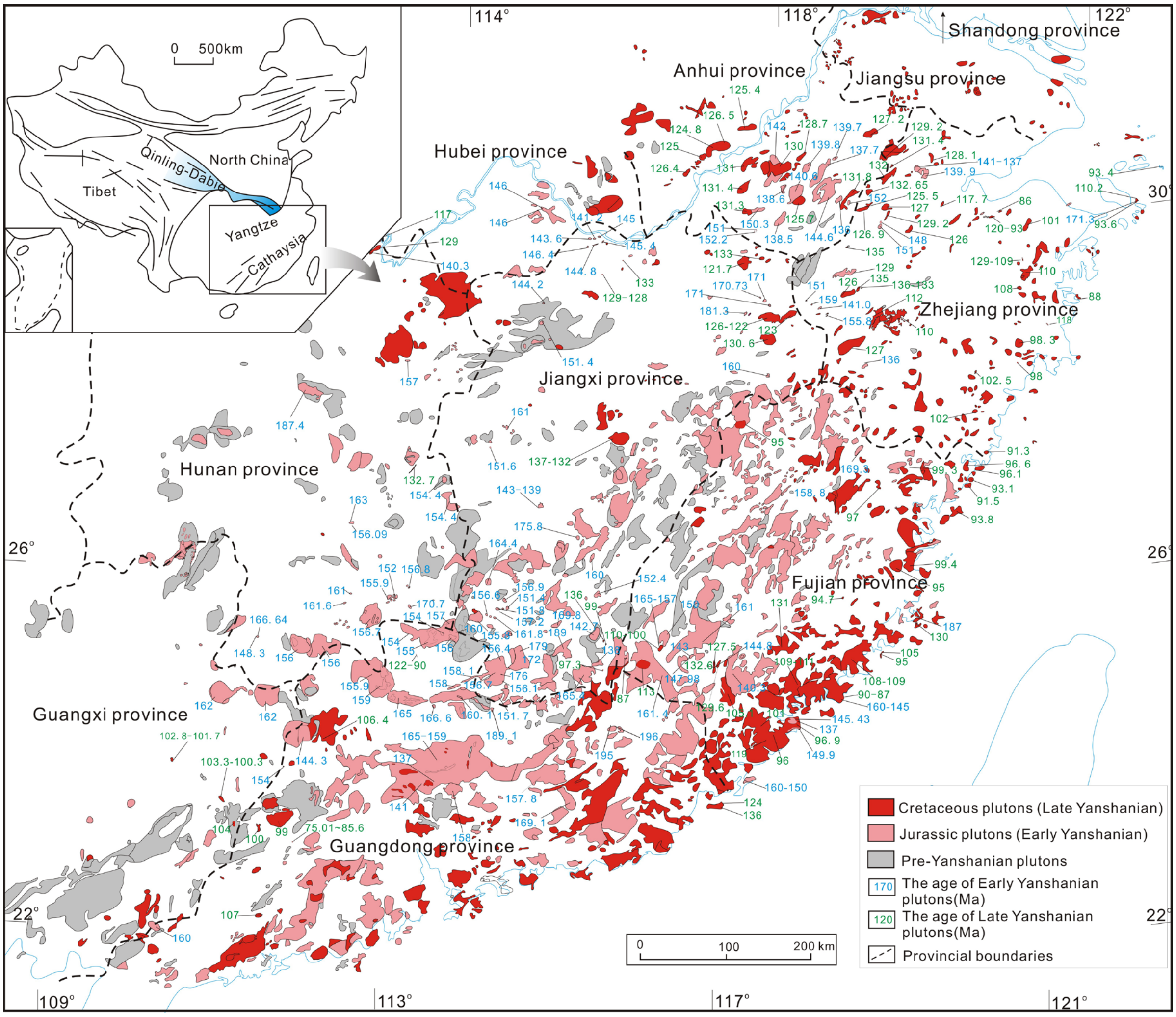


Figure 1. Age distribution of the Yanshanian (200 - 80 Ma) plutons in SE China (The details are shown in [87]).

complexes, and basic dike swarms are the typical products of extensional tectonics [48]. Muscovite, cordierite, garnet-bearing granites, and gneissic granites generally form in syn-orogenic settings [29] [49].

We preliminarily conclude that two compressional and three extensional tectonic events occurred during Yanshanian (200 - 80 Ma): 1) Early-Middle Jurassic (196 - 175 Ma) extension, featured by bimodal volcanics; 2) Middle-Late Jurassic (165 - 140 ± 5 Ma) compression, represented by largescale gneissic granites and garnet-bearing granites; 3) Early Cretaceous (140 ± 5 - 120 Ma) extension, characterized by weakly deformed or undeformed granites, alkali granites, metamorphic core complexes, and some basic dike swarms; 4) Early Cretaceous (120 - 110 Ma) compression, evidenced by volcanic hiatuses during 120 - 110 Ma; and 5) Early-Late Cretaceous (110 - 80 Ma) extension, evidenced by largescale bimodal volcanics, basic dike swarms, and alkali granites.

3. Stratigraphic Analyses

Each tectonic event is accompanied by corresponding sediments. The Late Mesozoic stratigraphic sequences in Southeast China show an angular unconformity between Middle Jurassic (J_2) and overlying Early Cretaceous (K_1) (**Figure 3**). Thus, the hiatus of Late Jurassic (J_3) is general in the study area. The hiatus indicates that Southeast China underwent an intense tectonic event in Late Jurassic when the crust was lifted and eroded. This phenomenon also exists in the adjacent areas, such as Qinling region in North China. This finding suggests that the acme of compression in Eastern China occurred during Late Jurassic. Another angular unconformity occurred between Early Cretaceous (K_1) and the overlying Late Cretaceous (K_2) in Southeast China (**Figure 3**).

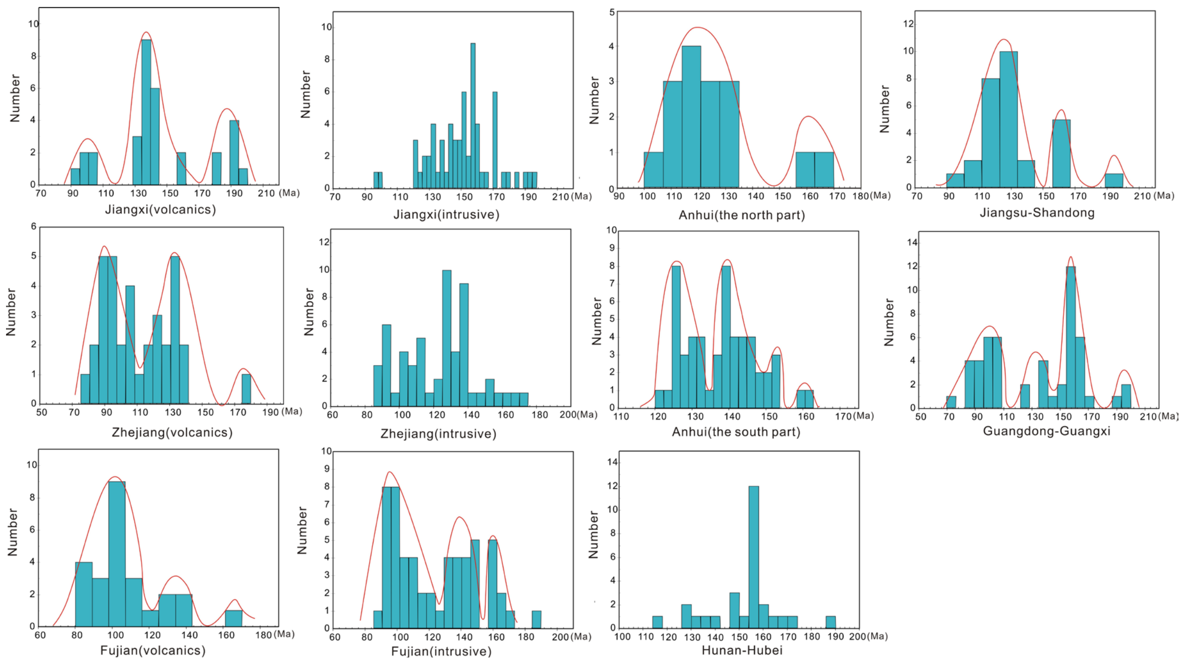


Figure 2. Cumulative diagram of all ages of Yanshanian plutons in ten eastern provinces of China; the diagrams are plotted by CGDK software [13].

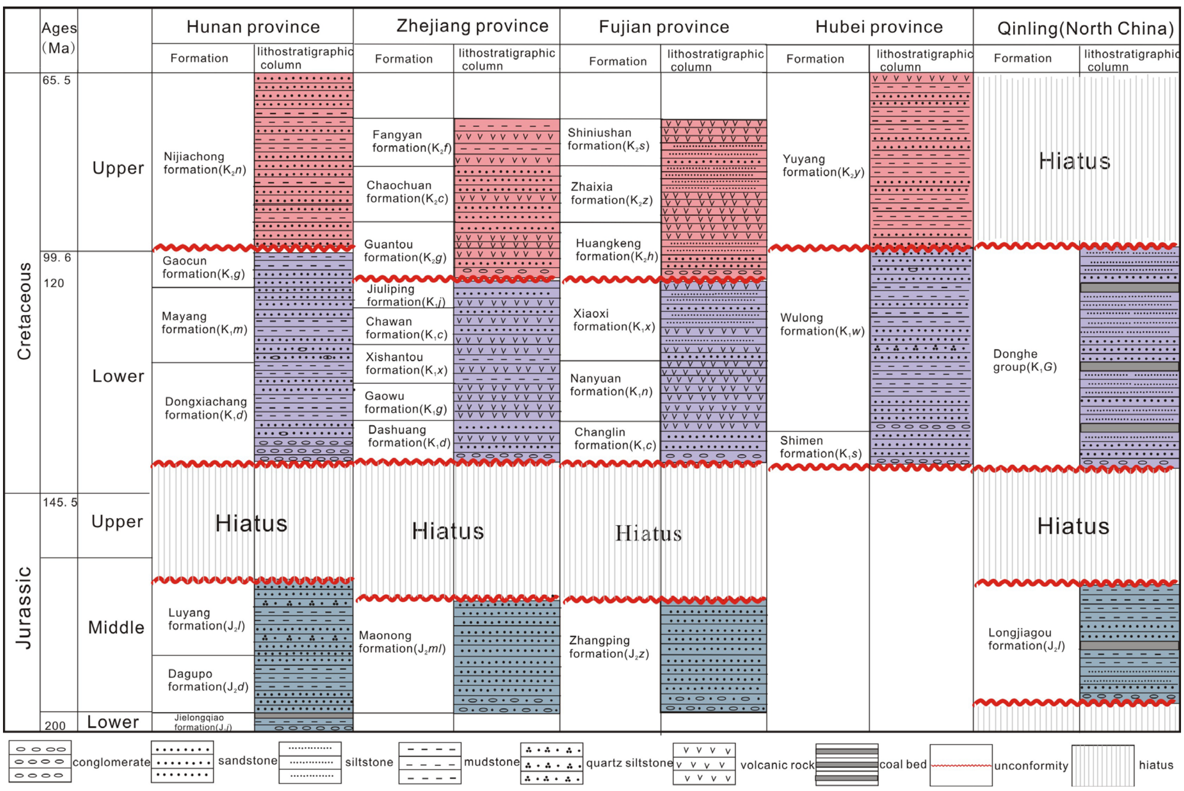


Figure 3. Late Mesozoic regional stratigraphic column in SE China (Stratigraphic column of Hunan and Hubei province from [51]; Fujian province from [43]; Zhejiang province from [36]; Qinling region from [52]).

Compared with the Late Jurassic tectonic movement, the unconformity in Early Cretaceous was smaller. A brief hiatus was identified at 120 - 110 Ma between the lower and upper sedimentary series [36].

Table 1. Ages of Yanshanian plutons in Eastern China (The details are shown in [87]).

Province	Rock types	Typical lithology	Age-bracket	Reference
Jiangsu-Shandong	Intrusive rocks	Diorite porphyry	191 Ma	[14]
		Gneissic granite; Monzogranite	160 - 156.9 Ma	[9] [15]
		Weakly deformed granite; Undeformed granite; Alkali granite	135 - 90 Ma	[9]
Anhui (the north part)	Intrusive rocks	Gneissic granite; Garnet-bearing granite	165 - 159 Ma	[16]
		Granite	130.1 - 103 Ma	[17]
	Extrusive rocks	Intermediate-acid volcanics	132 - 116 Ma	[18]
Anhui (the south part)	Intrusive rocks	Granodiorite	161.2 - 139 Ma	[10] [19]
		Alkali granite	136 - 121.8 Ma	[20]
	Metamorphic core complexes	Granodiorite	126.4 Ma	[20] [21]
Jiangxi	Intrusive rocks	Diabase; Granite	196 - 175 Ma	[1] [22]
		Granodiorite porphyry	170 - 144 Ma	[12] [23]
		Syenogranite	138 - 121.7 Ma	[24]
	Extrusive rocks	Bimodal volcanics	195 - 178.2 Ma	[25]
		Felsic volcanics	145 - 128 Ma	[25]
		Bimodal volcanics	105 - 93 Ma	[26]
	Metamorphic core complexes	Granite	133 Ma	[27]
		Muscovite in the ductile shear zone	140.4 Ma	[27]
Guangdong-Guangxi	Intrusive rocks	Granite	196 - 189.1 Ma	[28]
		Gneissic granite	169.1 - 136 Ma	[29]
		Weakly deformed granite	137 - 100 Ma	[29]
	Extrusive rocks	Layered Mafic-Ultramafic rocks	195 Ma	[28]
		Trachyte	135.4 Ma	[30]
		Rhyolite	103 - 83.4 Ma	[31]
Hunan-Hubei	Intrusive rocks	Granite	187.4 Ma	[32]
		Granodiorite	170 - 146 Ma	[33]
		Monzogranite	134 - 117 Ma	[34]
	Extrusive rocks	Basalt; Dacite	132 - 128 Ma	[35]
Zhejiang	Intrusive rocks	Granodiorite	171 - 139 Ma	[10]
		Syenogranite; Monzogranite	136 - 86 Ma	[20]
	Extrusive rocks	Tuff	180 - 177 Ma	[36]
		Tuff; Basalt	140 - 120 Ma	[36]
		Bimodal volcanic; Basic dike swarm	110 - 83 Ma	[37]
	Basic dike swarm	Mafic rocks	135 Ma	[38]
		Mafic rocks	93.4 Ma	[39]
Fujian	Intrusive rocks	Granite	187 Ma	[40]
		Gneissic granite	169 - 137 Ma	[29]
		Fine-grained granite; alkali-feldspar granite; syenite	132 - 87 Ma	[41]
	Extrusive rocks	Basic-acid volcanics	170 - 162 Ma	[42]
		Basic-acid volcanics	134 - 120 Ma	[43]
		Bimodal volcanic; Basic dike swarm	111 - 80.7 Ma	[11]
	Basic dike swarm	Mafic rocks	96 - 87 Ma	[44]
		Mafic rocks	90 - 87 Ma	[45]

4. Regional Structures

Regional structures are the intuitive feature of the tectonic movement. The nappes or thrusts are an indicator of compressional setting. During fieldwork, we found a nappe structure in Xiaohe gold mines, Anhui Province. This nappe structure is parallel to the NE-trending Jiangshan-Shaoxing fault zone and thrusts from SE to NW, leading to the Neoproterozoic Jingtan formation (Pt_3j) overlaying the Middle Jurassic Hongqin formation(J_2h). Granites formed during the Proterozoic Eon were cut and transported to the present location, in which the root can no longer be seen nowadays. This finding denotes that the nappe structure was large-scale. Late Jurassic thrust structures also outcrop in Jiangxi Province (**Figure 4**). The NE-trending thrust structure in Lengshuikeng deposit thrusts from NW to SE. Therefore, the Jurassic Daguding (J_3d) formation was overlaid by the Proterozoic Laohutang formation (Pt_3l), and synchronous granitic rocks formed (**Figure 4**). The U-Pb ages of 160.8 Ma for the Daguding formation and 154.3 Ma for the granitic rocks [53] indicate that this thrust structure formed at or after 154.3 Ma. As shown in **Figure 5**, largescale thrust structures formed in the whole South China during Late Jurassic. Examples of thrust structures include Xiaoxi thrusts in Anhui, Shuikoushan thrusts in Hunan, and Jinzhukeng thrusts in Fujian. These thrust structures indicate that South China underwent an intense compression in late Jurassic.

Metamorphic core complexes, granitic dome structures and graben basins are always related to the extensional settings [54]-[56]. Wugongshan in Jiangxi Province was a Mesozoic granitic dome-type extensional structure (**Figure 6(A)**) that is composed of metamorphic core complexes [54], the youngest Zircon U-Pb age of Wugongshan granitic dome constrain the final formation time of these metamorphic core complexes at 126.3 Ma [57]. Many other metamorphic core complexes, such as Lushan metamorphic core complex in Jiangxi Province (**Figure 6(B)**), developed in South China during Early Cretaceous. Zircon U-Pb ages constrain the formation time of these metamorphic core complexes between 133 and 123 Ma [27] [58]. Graben basin is commonly seen in South China during Early Cretaceous, filled by Lower Cretaceous-Upper Cretaceous sediments (**Figure 6(C)**). This observation indicates that Early Cretaceous was a significant extensional stage in South China, and the zenith of extension was between 135 Ma to 120 Ma.

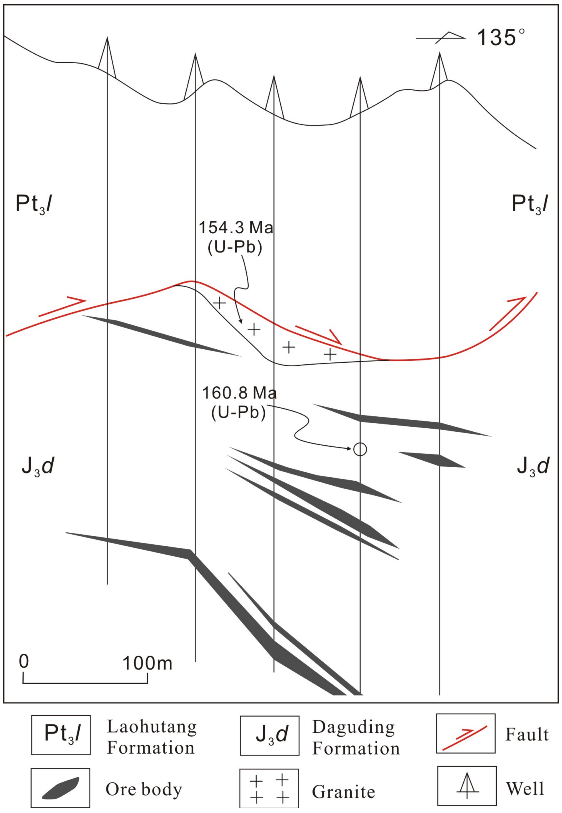


Figure 4. Profile of nappe structure in the Lengshuikeng deposit, Jiangxi province [53].

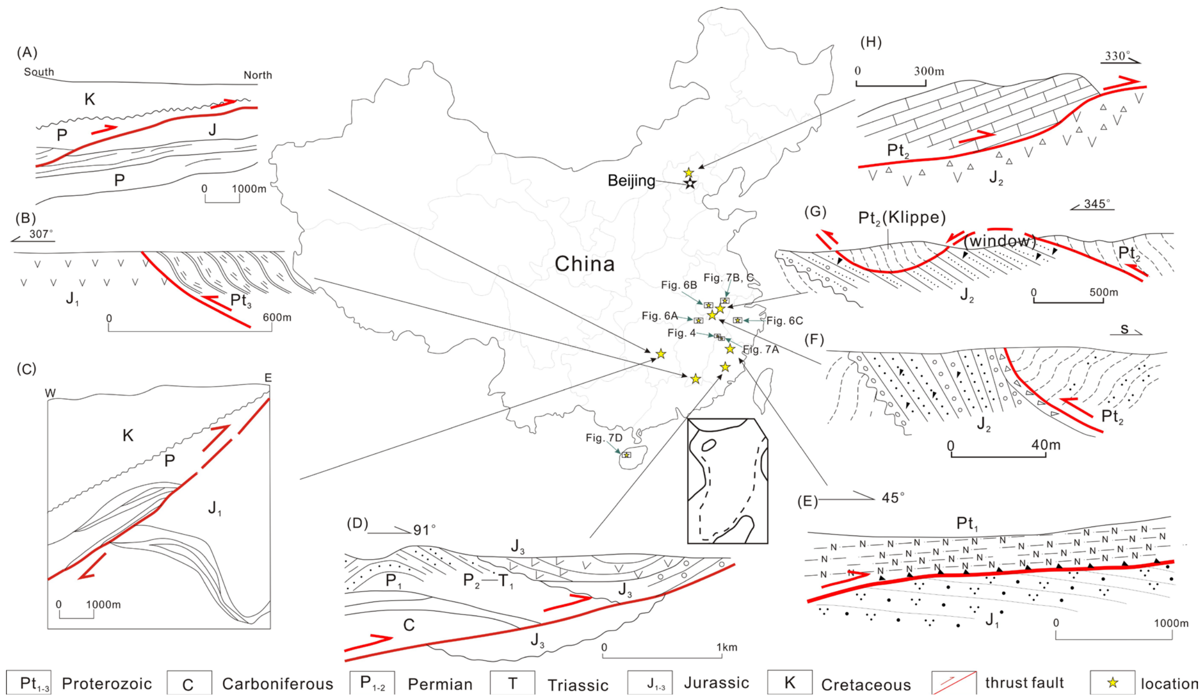


Figure 5. (A) The thrust structure of Shuikoushan deposit, Hunan province [59]; (B) Geological section of Liren to Hangang in Longnan basin, Jiangxi province [25]; (C) The thrust structure of Kangjiawan deposit, Hunan province [59]; (D) Sketch map of the thrust structure in Huangli, Yongan City, Fujian province [60]; (E) The thrust structure of the Jinzhukeng deposit, pucheng county, Fujian province [61]; (F) The thrust structure in Jinzhu village, Xiuning county, Anhui province [62]; (G) Structural window in Xiaoxi Village, Shexian County, Anhui province [63]; (H) Shisanling thrust faulting of Xiyu village, Beijing [48].

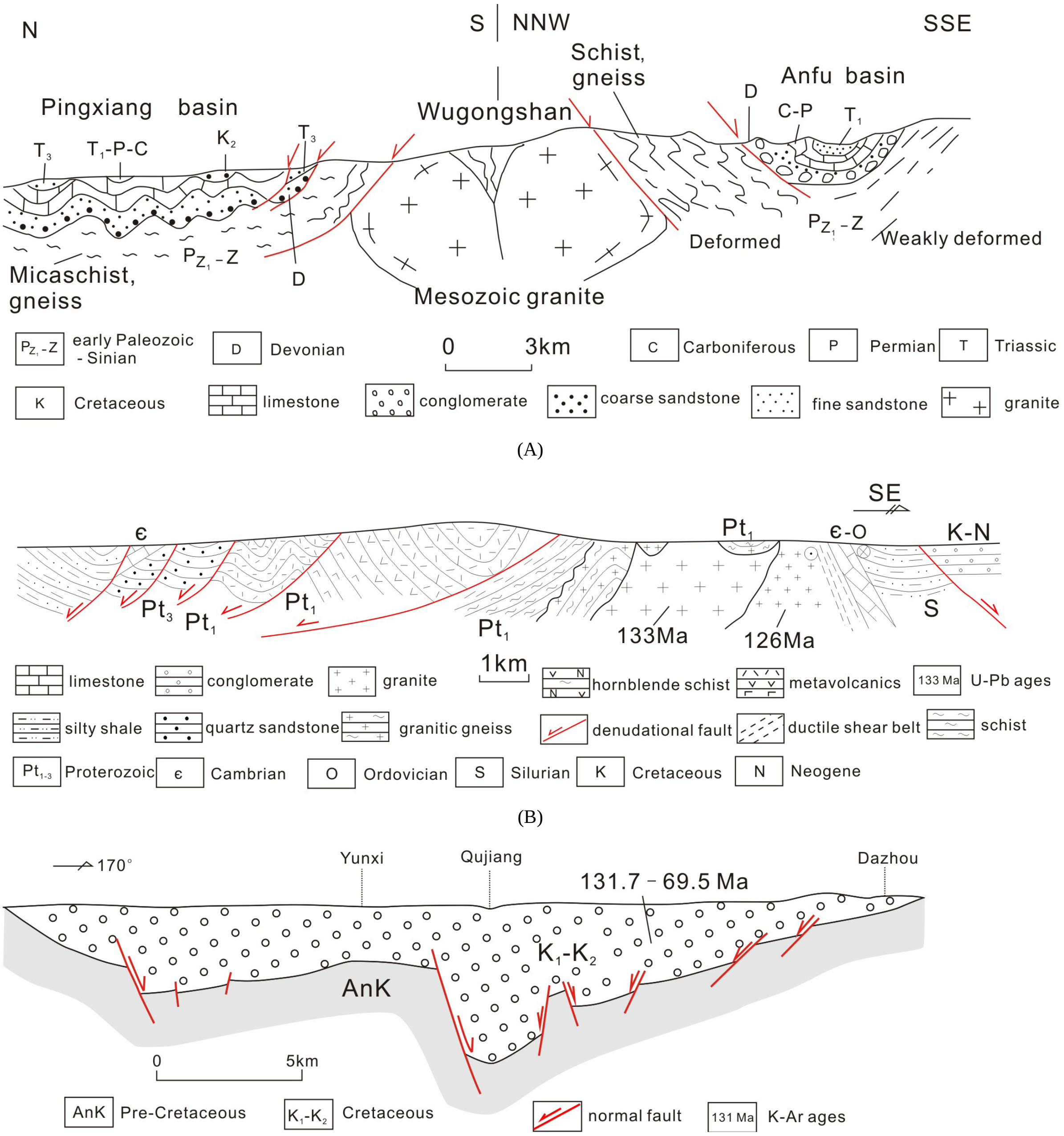
Another series of thrusts formed between Early to Late Cretaceous in Southeast China. For example, Mesoproterozoic strata thrust over Jurassic strata in Huangbi, Jiangxi Province, during Middle-Late Jurassic (**Figure 7(A)**). By contrast, in Early-Late Cretaceous, the Mesoproterozic and Jurassic strata overlay the Early Cretaceous Ehuling formation (K_1e) (**Figure 7(A)**). The same phenomenon can be seen in Anhui and Hainan Provinces, where the Mesoproterozoic and Paleozoic overlay the Lower Cretaceous (**Figures 7(B)-(D)**). Compared with the Late Jurassic thrust structures, the thrust structures formed in Early-Late Cretaceous are smaller in scale.

Basing on the temporal-spatial distribution of igneous rocks, stratigraphic sequence, and regional structures (**Figure 9**), we can infer that two compressional and three extensional events happened in Southeast China during Late Mesozoic (200 - 80 Ma).

5. Distribution of Mineral Deposits and Magmatic Oxygen Fugacity

One of the most important mineralization events occurred in the Mid-Late Jurassic in Southeast China. Numerous Cu-Au-Mo deposits, which are associated with I-type granites, formed during this period [66]. In addition, these ore deposits distributed widely from coastal areas to inland (**Figure 8**) were probably caused by the subduction of the Paleo-Pacific plate on the Pacific margin [67]-[69]. The Early Cretaceous is also an important metallogenic epoch in which many Cu-Au-Mo deposits formed. For example, the famous Zijinshan Cu-Au deposit formed during 110 Ma to 100 Ma [11]. However, the Early Cretaceous Cu-Au deposits differ from the Late Jurassic deposits because the former deposits are distributed only along the coastal areas (**Figure 8**). Both the Jurassic and Cretaceous Cu-Au deposits are featured by extremely high magmatic oxygen fugacity [67] [70] [71].

Studies on controlling factors of high fo2 have received much attention for a long time [74] [75]. Ballard *et al*. [76] reported that the Chuquicamata calc-alkaline intrusions of northern Chile had high magmatic oxygen fugacity, which is probably associated with subduction of plates. Lee *et al*. [74] found that the oxygen fugacity of arc-related magmas is higher than that formed in other tectonic environments. Wang *et al*. [75] stressed the influence of subducting oceanic sediments and slab dehydration fluids on magmatic oxygen fugacity through the



(C)

Figure 6. (A) Geological section through the Wugongshan granitic dome [54]; (B) Cross-sections through the Lushan metamorphic core complex, Jiangxi province [27]; (C) Profile of Jinhua-Quzhou (Jinqu) tectonic basin, Zhejiang province [64] (K-Ar ages from [65]).

study of zircon Hf-O isotopes and trace elements. Therefore, fluids released from subduction slabs were commonly invoked to explain the elevation of oxidation state of the arc lavas. Thus, we concluded that high oxygen fugacity can indicate that magmas formed in a subduction-related setting to a certain extent.

6. Dynamic Mechanism of Tectonic Evolution

The tectonic evolution of Southeast China during the Late Mesozoic period has always been a topic of debates [77]-[83]. The following are the mainstream theories regarding this issue: the flat-slab subduction model presented by Li and Li [1]; the slab dip angle of Paleo-Pacific plate subduction underneath Southeast China increased

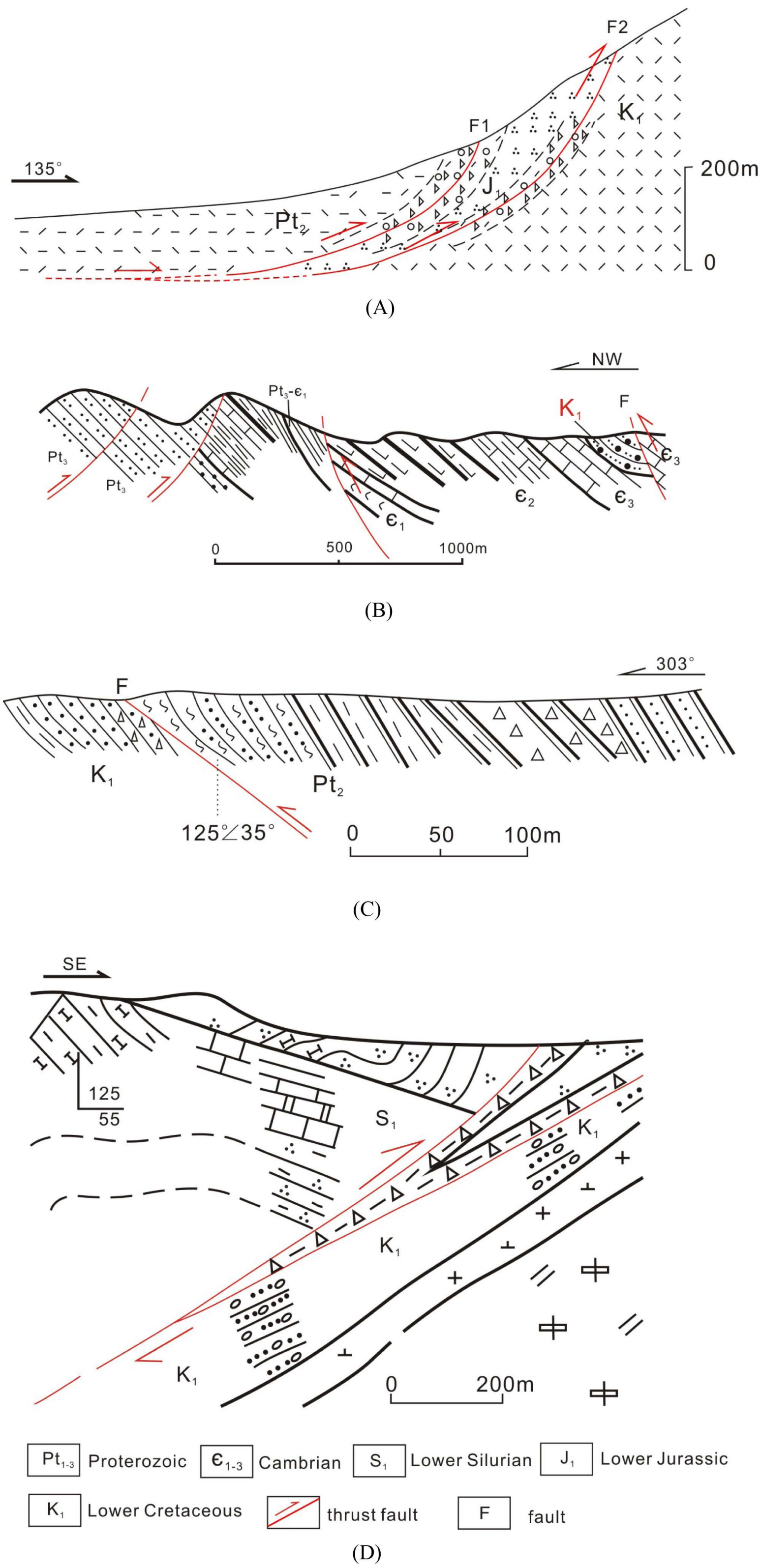


Figure 7. (A) Thrust structure in the Huangbi deposit, Jiangxi province [72]; (B) Section of the Ningguo-Jixi fault zone, Anhui province [63]; (C) Thrust structure in the Ningguo-Jixi fault zone, Anhui province [63]; (D) Thrust structure in Junying-Hongling tectonic zone, Hainan province [73].

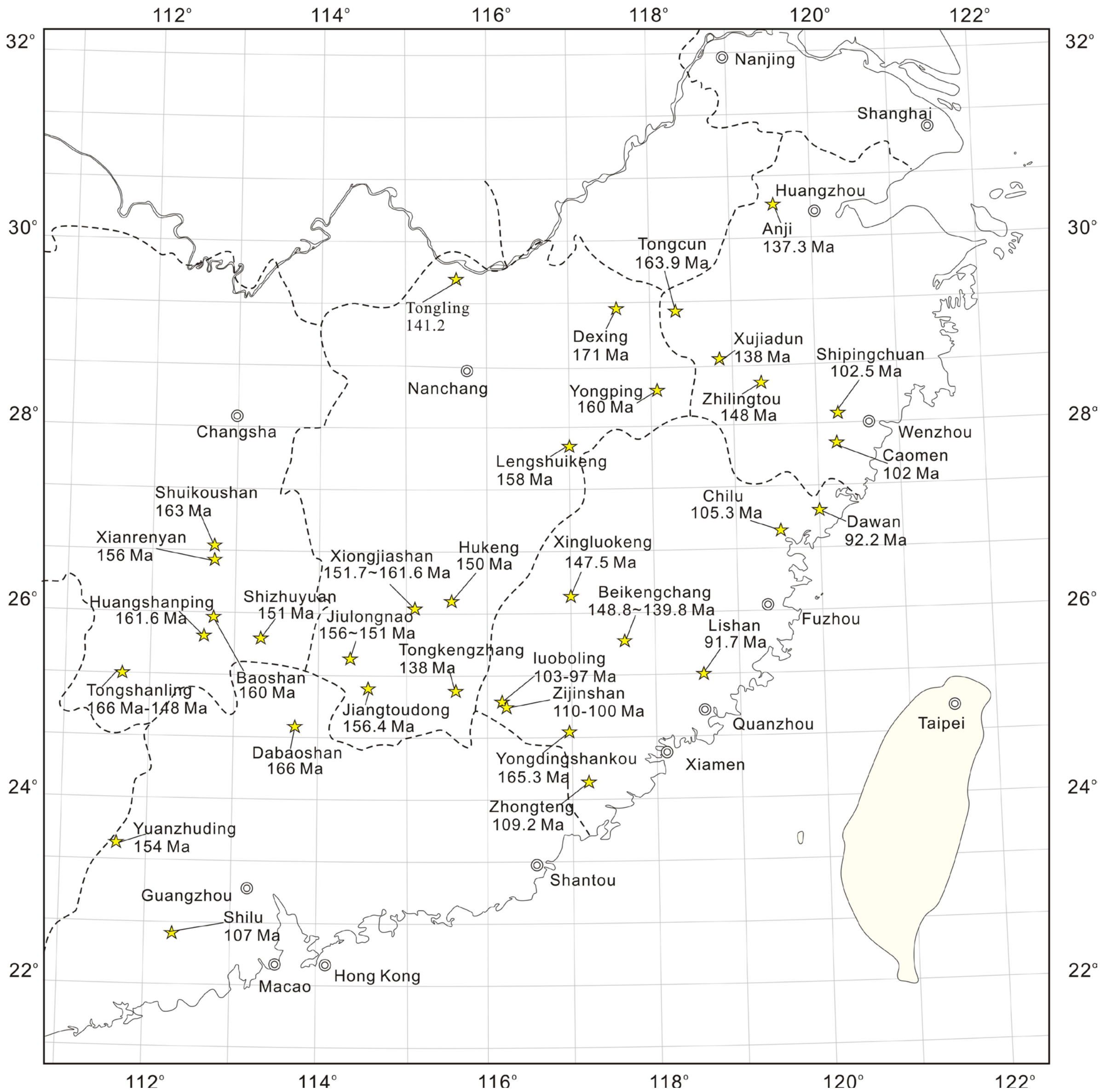


Figure 8. Distribution of Cu, Mo, and Au deposits in southeast China.

from a very low angle to a median angle [2]. An important geological event in the flat-slab subduction model shows that the age of synorogenic magmatism represents a trend of younging toward the cratonic interior. However, this event is not evident in South China in Mesozoic magmatism. The increasing slab dip angle model demonstrates a gradual change process. However, the geologic phenomenon is not evident in this gradual change process, which reflects two tectonic events instead. The first event occurred in Late Jurassic and was largescale, thereby leading to the formation of nappe structures, magmatic rocks, and hiatus from coastal to inland areas; the second event occurred in Early Cretaceous and was smaller than the first event. Therefore, the geologic phenomenon in the second event can be seen along the coastal areas. Some small-scaled nappe structures, brief hiatus, and magmatic rocks formed during the second geological event.

The change in the drifting direction of the Paleo-Pacific plate can explain the above geological events (**Figure 9**). Under the drastic NW-SE compression during Late Jurassic, NE trending nappe structures thrust from SE to NW in Southeast China. The compressional stress came from the southeast of Eastern China. However, no continent is located to the southeast of Eastern China [6]. Consequently, the NW-striking subduction of the Paleo-Pacific plate is the origin of compressional stress. Thus, a series of compressional phenomena formed during

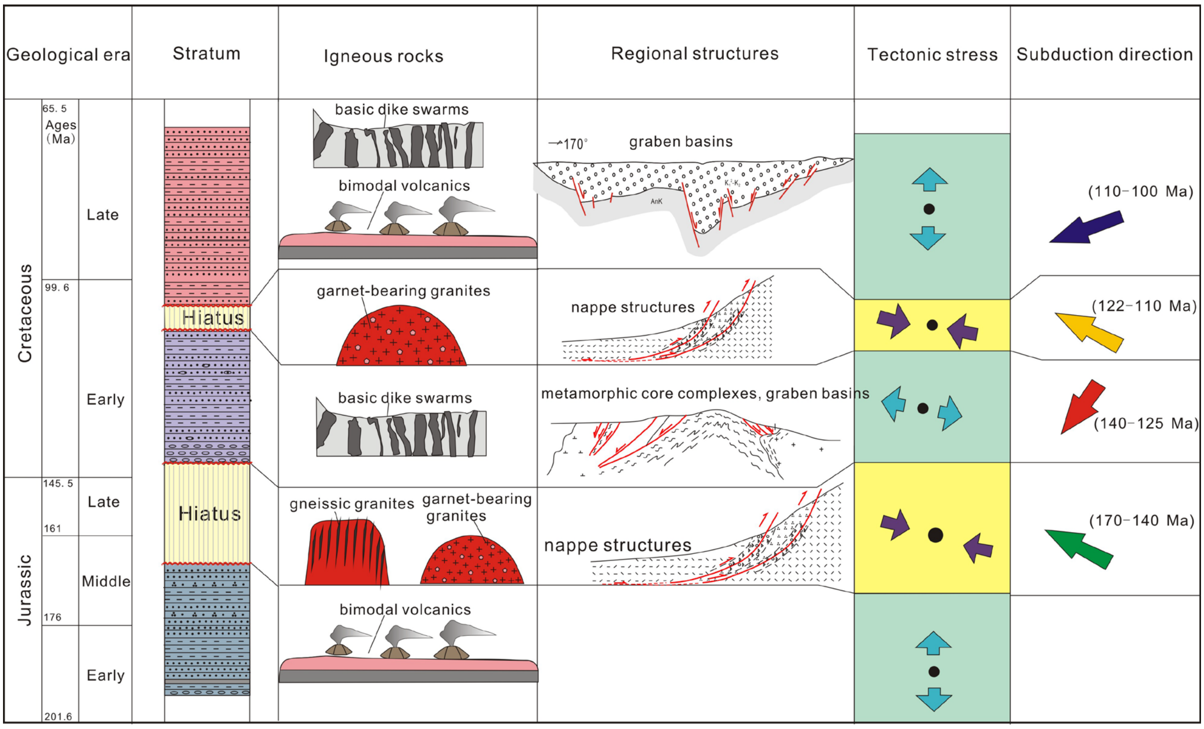


Figure 9. Tectonic evolution diagram of southeast China during Late Mesozoic. (Tectonic stress from [51]; Subduction direction from [84]-[86]).

Middle-Late Jurassic (170 Ma to 145 Ma). The drifting direction of the Paleo-Pacific plate has changed several times since 140 Ma [84]-[86]. First, the Paleo-Pacific plate moved roughly southward during 140 Ma to 120 Ma, with the drifting direction nearly parallel to the east boundary of the Eurasian continent. Therefore, many undeformed granites, alkali granites, metamorphic core complexes, graben basin, and some basic dike swarms formed under the extensional background in Southeast China during Early Cretaceous. Meanwhile, the synchronous widespread volcanic series formed.

The subduction direction changed by ~80˚ at ~125 - 122 Ma and persisted until ~110 Ma [86]. Correspondingly, the subduction of the Paleo-Pacific plate turned out to be NW-striking. The second compressional event occurred at ~125 Ma to 110 Ma, when some nappe structures and a brief hiatus formed.

From ~110 Ma to ~100 Ma, the subduction direction changed by ~30˚ and changed again by ~75˚ at ~100 Ma. When the extensional event occurred again in South China during 110 Ma to 80 Ma, largescale bimodal volcanics, basic dike swarms, and alkali granites formed.

The subduction direction of the plate varied with time. The Jurassic-Cretaceous tectonic evolution of Southeast China is coupled with the subduction of the Paleo-Pacific plate. With the changes in the subduction direction of the Paleo-Pacific plate, the tectonic evolution demonstrated an alternation between compression and extension, which generated numerous geological events (**Figure 9**).

7. Conclusions

A multistage tectonic evolution history during Late Mesozoic was established, which included the following stages: 1) Early-Middle Jurassic (196 - 175 Ma) extension, represented by bimodal volcanics; 2) Middle-Late Jurassic (165 - 140 Ma) compression, evidenced by largescale nappe structures; 3) Early Cretaceous (140 ± 5 - 120 Ma) extension, represented by metamorphic core complexes, graben basins, and some basic dike swarms; 4) Early Cretaceous (120 - 110 Ma) compression, featured by nappe structures; and 5) Early-Late Cretaceous (110 - 80 Ma) extension, evidenced by largescale bimodal volcanics, basic dike swarms, and graben basins.

The Late Mesozoic tectonic evolution of Southeast China may be attributed to the drifting history of the Paleo-Pacific plate. The drifting direction of the Paleo-Pacific plate has changed several times since 140 Ma, and this may lead to prominently different tectonic phenomena between Jurassic and Cretaceous.

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