Multi-mechanism Orogenic Model of the Su-Jiao Orogenic Belt

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Abstract The Su-Jiao orogenic belt is the eastern part of the Central Mountain System of China. Recent studies on its orogenic system indicate that the Su-Jiao orogenic belt is a complex orogenic belt which suffered at least 3 orogenies of different mechanisms in the Mesoproterozoic, Neoproterozoic and Triassic respectively. The Meso-Neoproterozoic orogenies belong to the Wilson cycle on the plate margins. The belt is a part of the Late Mesoproterozoic supercontinent Rodinia. The Triassic orogeny belongs to the re-orogeny of the non-Wilson cycle. Delamination of mountain roots occurred after both the Wilson and non-Wilson cycles in the Su-Jiao orogenic belt. The large-amplitude isostatic uplift of mountains, magmatic activities and basin-forming and mountain-making in the upper crust, all indicate the general significance of delamination in the development of orogenic belts.

Key words: orogenic system, multi-mechanism, re-orogeny, Su-Jiao orogenic belt

The study of orogenic belts should not be limited to analysis of tectonism. It should be based on a synthetic analysis of orogenic systems. The orogenic system is the sum of geological bodies, geological phenomena and geological processes that create an orogenic belt. The Su-Jiao orogenic belt is the eastern part of the Central Mountains of China (Fig. 1). In this paper an attempt is made to construct the model of formation and evolution of the Su-Jiao orogenic belt on the basis of recent studies of fundamental geology and geophysical field analysis of the Jiangsu area of the Su-Jiao belt.

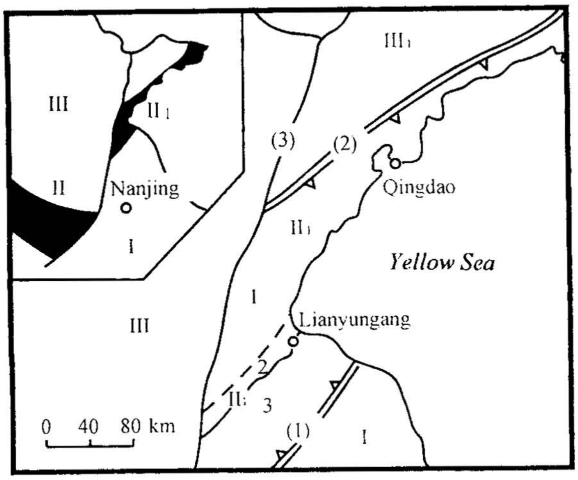

Fig. 1. Tectonic sketch map of the Su-Jiao orogenic belt.
I. Yangtze plate; II. Central Mountains; II_1. Su-Jiao orogenic belt: 1. tectonic mélange belt; 2. remnant arc belt; 3. rear arc oceanic basin belt. III. North China plate; III_1. Jiaobei terrane. (1) Xiangshui-Huaiyin junction belt; (2) Wulian-Mishan junction belt; (3) Tanlu fault belt.

1 Sequences of Metamorphic Rocks (Table 1)

(1) The amphibolite of the Haohu Formation, which is called the Dashangou Formation in Shandong province, has a zircon U-Pb evaporation age of 2618.8 Ma.

(2) The protoliths of the Donghai and Ganyu Group-complexes are generally marked by terriginous clastic rock-carbonate rock flyschoid formations with bimodal volcanic rocks, formed in the cratonic aulacogen sedimentary environment. The two complexes are products of synchronous metamorphism of different facies, with zircon U-Pb ages of 1921 and 2233 Ma respectively (Fan and Chen, 1999).

(3) The protolith of the lower part of the Haizhou Group-complex is an apatite rock-carbonate rock-clastic rock formation with alkaline basalt, belonging to aulacogen sediments, with apatite U-Pb ages of 1701 and 1735 Ma. The protolith of the upper part of the complex is a bimodal spilite-quartz keratophyre formation, belonging to rear-arc basin volcanic de-

Table 1 Sequences of metamorphic rocks in the Su-Jiao area

Neoproterozoic	Sinian	Shiqiao Group-complex
	Qingbaikouan Period	—Fault or disconformity over Neoproterozoic granite—
Mesoproterozoic	Jixian Period	Haizhou Group-complex: Yuntai Formation-complex
	Changcheng Period	Haizhou Group-complex: Jinping Formation-complex
		—Fault or disconformity over Neoproterozoic granite—
Palaeoproterozoic		Donghai Group-complex / Ganyu Group-complex
		Fault
Neoarchaeozoic		Haohu Formation-complex

posits, with whole-rock Rb-Rb ages of 929.6 and 860 Ma.

(4) The protolith of the lower part of the Shiqiao Group-complex is a coarse clastic flysch formation, belonging to estuarine-neritic deposits. The protolith of the upper part of the Shiqiao Group-complex is a fine-clastic flyschoid formation, belonging to neritic deposits, with a whole-rock isochron age of 620±22 Ma.

2 Genetic Types of Granitoids

There are 3 phases of granitoid: Palaeoproterozoic, Neoproterozoic and Mesozoic. The Neoproterozoic granitoids have four genetic types. The first is I-(Cordilleran) type granitoids formed in continental-margin arcs and include the Yushan and Liuding gneissic tonalites and granites. The second is S-type granitoids formed in the continental collision environment and includes the Kangrishan and Daixiang gneissic muscovite (biotite) granites. The third is I-(Caledonian) type granitoids formed in post-collisional orogeny uplifted areas and includes the Chengtou and Xishigou gneissic monzogranites and K-feldspar granites, with whole-rock Rb-Sr isochron of 783–850 Ma. The fourth is gneissic alkali granites formed in the post-orogenic extensional environment and include the Niushan gneissic alkali granite (Fan et al., 1990), which has whole-rock Rb-Sr ages of 646–798 Ma. Moreover, oceanic plagiogranite is found in the Jiaonan area, with a zircon U-Pb age of 1370.6±14.3 Ma (Song et al., 1999).

Mesozoic granitoids have three genetic types. The first is I-(Cordillera) type granitoids of continental margins and include quartz monzonite and quartz diorite of the Zhucang super-unit, with a zircon U-Pb age of 200 Ma. The second is I-(Caledonian) type granitoids formed in post-orogenic uplift areas and includes monzogranite and granodiorite of the Beigou and Jiashan super-units, with whole-rock K-Ar ages of 108–129 Ma. The third is A-type granites formed in the postorogenic extensional environment and includes the Tiqiushan alkali granite, with a whole-rock K-Ar age of 96 Ma.

3 Eclogite and Meta-ultramafite Rocks

Eclogite has three genetic types (Liu et al., 1994; Wang et al., 1995; Zhang Zeming et al., 1995; Zhang Changhou et al., 1998; Zhang Zeming et al., 1999; Li et al., 1999). The first is the high-pressure (HP) crust-derived type (H-type) and its protoliths are oceanic crustal tholeiite, gabbro, plagioclasite, spilite, etc. This type mainly formed in the lower crust under the Mesoproterozoic low-temperature (*T*) and high-pressure (*P*) metamorphic conditions (Fan and Cheng, 1998) and has a whole-rock Sm-Nd age of 1108 Ma and a whole-rock+mineral Sm-Nd age of 1584 Ma. It occurs as inclusions in gneiss granite or is in tectonic contact with the latter. The rocks were thrust or carried by magmas from the lower crust upwards and uplifted and exhumed to the ground surface. The second is the ultra-high pressure (UHP) crust-derived type (U-type) and its protoliths are basalt and gabbro of continental crust and oceanic crust. It mainly formed in the upper mantle in the Mesozoic under the high temperature-UHP metamorphic environment (Fan and Cheng, 1998) and has a whole-rock + mineral Sm-Nd age of 226 Ma and a whole-rock+phengite Rb-Sr age of 220 Ma. The rocks occur in association with UHP metamorphic supracrustal rocks and gneissic granite. They underwent rebound, thrusting, isostatic uplift and rapid exhumation from the upper mantle to the ground surface (Fan and Cheng, 1999). The third is the mantle-derived type (M-type). It is pyrolite formed in the Mesoproterozoic (or earlier) under high-*T*-UHP metamorphic conditions (Fan and Cheng, 1998).

Metamorphic ultramafic rocks occur with eclogite. They have three types: metaperidotite, cumulate ultramafite and primary pyrolite, and are represented dominantly by oceanic pyrolite and subordinately by continental pyrolite, with a mineral Sm-Nd age of 925±53 Ma. Some of ultramafic rocks suffered UHP metamorphism.

4 Regional Metamorphism

Regional metamorphism occurred in five phases. The first took place in the latest Archaean. The Haohu Formation-complex etc. suffered low amphibolite facies metamorphism. The second occurred in the latest Palaeoproterozoic. The Donghai and Ganyu Group-complexes underwent low amphibolite facies and high greenschist facies metamorphism. The metamorphism of the two phases belongs to basement dynamothermal regional metamorphism. The third phase mainly happened in the Meso-Neoproterozoic. The Meso-Neoproterozoic plutonic rocks and Haizhou and Shiqiao Group-complexes commonly suffered low amphibolite facies and sub-greenschist facies metamorphism, which belongs to basement dynamothermal regional metamorphism. The oceanic crust was subjected to HP amphibolite facies-HP eclogite facies-LP (low-pressure) low greenschist facies prograde and retrograde metamorphism. The metamorphism has a clockwise *PTt* path and belongs to low-medium-*T* dynamic-regional metamorphism of orogenic type. The fourth phase mainly took place in the Triassic. On the northern side of the Su-Jiao orogenic belt, plutonic rocks and supracrustal rocks underwent HP amphibolite facies-UHP eclogite facies-HP amphibolite facies prograde-retrograde metamorphism, which has a clockwise *PTt* path and belongs to medium-high-*T* dynamical regional metamorphism of orogenic type. The Yuntai Formation-complex on the southern side of the Su-Jiao orogenic belt suffered LP low greenschist facies-HP glaucophane greenschist facies metamorphism or LP low greenschist facies-kyanite high greenschist facies metamorphism, which belongs to low-medium-*T* dynamical regional metamorphism. The fifth phase occurred in the Jurassic-Cretaceous. The orogenic belt was uplifted extensively and commonly underwent LP low greenschist facies metamorphism. The third and fourth stages of HP-UHP metamorphism was accompanied by significant mineralization, giving rise to a HP and UHP metamorphosed or mantle-derived minerogenetic series of rutile, kyanite, abrasive garnet, garnet ruby, diamond, red corundum and quartz crystal (Fan et al., 1998).

5 Tectonic Units and Tectonism

5.1 Division of tectonic units

The study area (Fig. 1) may be divided into the North China plate, Su-Jiao orogenic belt and Yangtze plate by the Tanlu fault, Wulian-Mishan fault and Xiangshui-Huaiyin fault. Of them the Su-Jiao orogenic belt may be further divided into three tectonic belts. The first belt is the Donghai-Ganyu tectonic mélange belt, which includes the north zone and south zone. The former consists of eclogite and metaultramafite and mainly suffered HP metamorphism; the latter mainly underwent polyphase HP-UHP metamorphism. Its protoliths are mostly dismembered Mesoproterozoic ophiolites (Fan, 1998), therefore it is also an ophiolitic mélange zone. The second belt is the Lianyungang-Muyang remnant arc belt. It is composed of the Ganyu Group-complex, Jinping Formation-complex, Jushan gneiss and subducted granite. The third belt is the Guanyun-Siyang rear arc basin zone. It is composed of bimodal volcanic rocks and clastic rocks of the Yuntai Formation-complex. South of the Xiangshui-Huaiyin fault lies the Dongtai-Lianshui tectonic belt of the Yangtze plate, which is a foreland basin formed on the sediments of the Sinian-Permian extensional basin, on which were deposited the Cretaceous Pukou

Formation and the Pliocene.

5.2 Shear zone

There are two types of shear zone. The first is thrust-type ductile shear zones. In the Donghai-Ganyu tectonic belt are developed a NE-trending eclogite facies ductile shear zone and E-W-, NE- and NNE-trending, amphibolite or greenschist facies, polyphase ductile shear zones. They formed in the intermediate and deep tectonic levels and are characterized by low angles and high-grade metamorphism. The second type is extensive ductile-brittle shear zones mainly of NE and NNE trends, which occur in the intermediate and shallow tectonic levels of the orogenic belt. They are characterised by high angles, low-grade metamorphism and development of associated basin-and-range tectonics.

5.3 Fold structure

There are five generations of folds. The first is marked by structural foliation and tight recumbent folds. The second is tight isoclinal chevron folds in one level and discontinuous hooked bodies of minerals such as quartz. The third is outcrop-type overturned fold or reclined folds, which are superimposed on the first- and second-generation folds. The fourth is inclined folds of certain scale. The fifth is gently undulating folds. Folds of different generations are overlapped and combined in different orogenic belts, areas and geologic bodies.

6 Formation and Evolution of the Su-Jiao Orogenic Belt

According to the above study of fundamental geology and analysis of the geophysical field, the formation and evolution of the Su-Jiao orogenic belt may be divided into six stages.

(1) Stage of pre-orogenic breakup and formation of an ocean

The Donghai Group-complex in Subei (northern Jiangsu) can be correlated with the Jinshan Group in southern Jiaobei and the Ganyu Group-complex can be correlated with the Fenzishan Group in northern Jiaobei (Fan and Chen, 1999), and their volcanic rocks and clastic rocks show the features of bimodal association, suggesting that they were deposited in the same rift basin and revealing that the Subei-Jiaonan terrane was a part of the North China palaeoplate in the Palaeoproterozoic and still earlier. The discovery of Mesoproterozoic ophiolites and oceanic plagiogranites indicates that the Subei-Jiaonan terrane was separated from the North China palaeoplate and Jiaobei terrane to form an ocean— the Sujiao Ocean— in the Mesoproterozoic and became a part of the northern margin of the Yangtze palaeoplate. It belongs to the stage of breakup and ocean formation of the Wilson cycle.

(2) Mechanism of the Mesoproterozoic oceanic crust subductional orogeny

The Mesoproterozoic oceanic crust subduction and orogeny belong to the subduction stage of the Wilson cycle. While the Su-Jiao Ocean was extending continuously, the oceanic crust was subducted southwards along the Wulian-Mishan fault on the northern side of the Subei-Jiaonan terrane and formed Mesoproterozoic HP metamorphic eclogite (H-type) in the deep level of the crust. On the one hand, the interaction between the thrusting continental crust and the subducting oceanic crust let to the formation of an accretionary wedge on the margin of the terrane. On the other hand the interaction among the crust, subducting oceanic crust and upper mantle led to eruption of island-arc calc-alkali volcanic rocks and intrusion of I-(Cordilleran) type granite in Liuding, Niuxiang etc., which led to the formation of an island arc chain in Jushan etc. Furthermore, on the southern margin of the Su-Jiao Ocean, bimodal volcanic rocks of the Yuntai Formation-complex were formed in the rear arc basin on the basis of the Haizhou aulacogen. Its characteristics are the same as those of the circum-Pacific orogenic belt; the orogeny is classic plate subductional orogeny.

(3) Qingbaikouan collisional orogeny

The Qingbaikouan collisional orogeny belongs to the last stage of the Wilson cycle—the stage of collisional orogeny. Along with the continued subduction of the Su-Jiao oceanic crust, the oceanic basin was reduced progressively. And in the Qingbaikouan Period, the Jiaobei terrane collided with the Subei-Jiaonan terrane. Owing to the interaction between the subducting continental crust and the thrusting continental crust, multi-level detachment took place in the crust, thus inducing strong folding of the surface of the sediments on the margins of the blocks and producing thrust faults and nappe structure. Then anatexis of the crust and emplacement of S-type granites in Kangrishan, Daixiang etc. occurred. The characteristics of this kind of orogeny are the same as those of the Tethys orogenic belts and it belongs to the classic plate collisional orogeny.

(4) Mechanism of Sinian post-orogenic isostatic uplift

It belongs to the basin-forming and mountain-making processes after the Wilson cycle. The delamination of the high-density mountain root of eclogite under gravity resulted in large-amplitude isostatic uplift mountains, thinning of the lithosphere, upwelling of mantle flux and anatexis of the lower crust, as well as emplacement of I-(Caledonian) type granites in Chengtou and Xishigou and post-orogenic A-type granites in Niushan (enclosing eclogite-facies metamorphic bodies) to the middle crust. On the other hand, the mountian root delamination, mantle uplift and upper crust extension formed Sinian extensional sedimentary basins in Shiqiao, Penglai etc. and Sinian-Permian sedimentary basins in Dongtai etc. as well as coupling mountains.

(5) Mechanism Triassic-early Jurassic intracontinental ramp orogeny

It belongs to the re-orogenic process of the non-Wilson cycle. The intrusion of the Niushan A-type granite indicates that the Neoproterozoic orogeny in the Su-Jiao orogenic belt had already finished. In the Triassic, pushed by the North China plate, the Jiaobei terrane was again subducted under the Subei-Jiaonan terrane. The leading edge of the subducting continental crust and oceanic crust were underthrust deep into the upper mantle, forming HP-UHP eclogite. According to the geophysical field analysis and the involvement of the Sinian-Permian in the folds and deposition of the Cretaceous Pukou Formation and Pliocene in foreland basins, the Yangtze plate on the southern side of the orogenic belt also began to be subducted northwards in the Triassic along the Xiangshui-Huaiyin fault on the southern margin of the Subei-Jiaonan terrane and HP glaucophane greenschist facies metamorphism.

(6) Mechanism of Middle Jurassic-Middle Cretaceous post-orogenic isostatic uplift

It belongs to the basin-forming and mountain-making process after the non-Wilson cycle. The delamination of the high-density mountain root of eclogite under gravity brought about large-amplitude isostatic uplift of mountains, thinning of the lithosphere, upwelling of the mantle flux analexis of the lower crust, emplacement of I-(Caledonian) type granites in Taolin and Dawushan and post-orogenic A-type granites in Tiqiusan etc. and strong continental volcanism of the Qingshan Group etc. On the other hand, the mountian root delamination, mantle uplift and development of a series of extensional shear belts in Haizhou-Siyang, Shaodian-Sanxu, Xiangshui-Jiashan etc. resulted in the formation of Sinian extensional rift basins in Longju, Shuyang, Lianshui etc. and block mountians in Yushan, Yuntaishan, Dayishan etc. (Fan et al., 1999).

7 Conclusions

(1) The Su-Jiao orogenic belt is a complex orogenic belt that suffered more than three orogenies of different mechanisms in the Mesoproterozoic, Neoproterozoic and Triassic. The Meso-Neoproterozoic orogenies belong to the Wilson cycle on the plate margins and can be correlated with the northern Qiling orogenic belt. It is typified by subduction of oceanic crust, development of arcs-rear arc basins and collision of microcontinental blocks or terranes. It mainly developed during 1.0–0.9 Ga, which can be correlated with the ages of the Greenville orogenic belts in North America and Europe. It is a component part of the terminal Mesoproterozoic supercontinent–Rodinia. The Triassic orogeny belongs to the re-orogeny of the non-Wilson cycle. It can be correlated with the Mesozoic intracontinental orogenies in the Qinling and Dabie mountains, which demonstates the general significance of re-orogeny in the development of the Central Mountains of China.

(2) The mountain root delamination, large-scale isostatic uplift of mountain, magmatism and basin-forming and mountain-making in the upper crust beneath the Su-Jiao orogenic belt after both the Wilson and non-Wilson cycles, all indicate the general sig-

nificance of delamination in the development of orogenic belts.

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