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Tectonic setting of the low-grade metamorphic rocks of the Dabie Orogen, central eastern China

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ABSTRACT

The tectonic setting on both the northern and southern sides of the Dabie Mountains reveals that low-grade metamorphic rocks are important constituents produced by the subduction of the oceanic crust prior to collision between the Sino-Korean and Yangtze cratons. The Zhangbaling Group/Mulanshan schist is a pre-Ordovician oceanic crust. The Sujiahe and Xinyang/Foziling Groups are trench sediments of the Ordovician-Devonian age, and constitute an accretionary prism associated with subduction. The Yangshan coal measures/Meishan Group was a forearc basin sediment of Carboniferous age, and was overthrust by the accretionary prism during collision. The Susong Group is composed of passive continental margin sediments of the Yangtze craton. Backarc basin sediments are postulated to be concealed by Mesozoic–Cenozoic sediments to the north of the Dabie Mountains. High-ultrahigh pressure terrains are exotic tectonic slices exhumed from depths, located between low-grade metamorphic rocks, and disturb the integrity of the earlier subduction orogen. Subduction occurred during the Ordovician to Devonian periods, and collision initiated at the beginning of the Permian.

1. Introduction

The Dabie Mountains are one of the best known ultrahigh pressure (UHP) metamorphic terrains of China, and even in the world (Carswell and Compagnoni, 2003). The region has been the subject of considerable international research that has lead to advances in aspects of metamorphism, geochronology, geochemistry, and in particular the discovery of the UHP signature. The most important UHP metamorphic signatures have been found, including coesite at many localities (Xu, 1987; Okay et al., 1989; Wang and Liou, 1991; Wang et al., 1989, 1993; Zhang et al., 1993), microdiamonds at some localities (Xu et al., 1992, 2003, 2005a; Liu et al., 2006), magnetite lamellae in olivine (Zhang et al., 1999), and rod-like apatite, rutile and clino-pyroxene exsolutions in garnet (Xu et al., 2005a). From this evidence, two UHP belts having continental affinity (TG and ECL_2 in Fig. 1) and a high pressure (HP) metamorphic belt of oceanic affinity (ECL_1 in Fig. 1) were identified. However, ECL_1 was once defined as a "Cold eclogite" belt because there were no UHP signatures until the discovery of quartz pseudomorphs after coesite (Li et al., 2004) and clino-zoisite pseudomorphs after lawsonite (Castelli et al., 1998) indicating an oceanic affinity. As yet, no UHP signatures have been found in the western equivalent of the ECL_1. The northernmost UHP belt, TG, has been recognized as having affinity with the lower continental crust of the Yangtze craton (Ma et al., 2000; Zhang et al., 2002).

Extensive isotopic dating of eclogite, mainly Sm–Nd and U–Pb (Li et al., 1996, 1998, 2000; Chavagnac and Jahn, 1996; Chen et al., 2004; Hacker et al., 1998; Liu et al., 2007; Jian et al., 2000) shows positive values of $\varepsilon_{Nd}(t)$ in ECL_1, but negative in ECL_2 and TG, units, and demonstrates that the three HP–UHP metamorphic belts were subducted and exhumed separately at different times. Isotopic ages of the protoliths of most of the blocks and matrix gneisses fall within the range 750–800 Ma (Hacker et al., 1998; Xie et al., 2004). Although great achievements have been made in the Dabie Mountains' research in the last 20 years, there are still some important problems remaining to be solved. These include questions such as where is the remnant of the subducted oceanic crust that exist prior to the collision between the Sino-Korean and Yangtze cratons, what are the tectonic settings of the low-grade metamorphic rocks on both sides of the Dabie Mountains, and where is the suture between the Sino-Korean and Yangtze cratons. These problems are closely related to each other, and the tectonic setting of low-grade metamorphic rocks is crucial. Gao and Liu (1988), Liu et al. (1993, 1995, 1996), Jin et al. (1994) and Ma et al. (1997) successively discovered Paleozoic fossils in some low-grade metamorphic rocks, which together with papers on UHP minerals, geochemistry and geochronology of UHP rocks, laid the ground-work for analyzing the tectonic settings of low-grade

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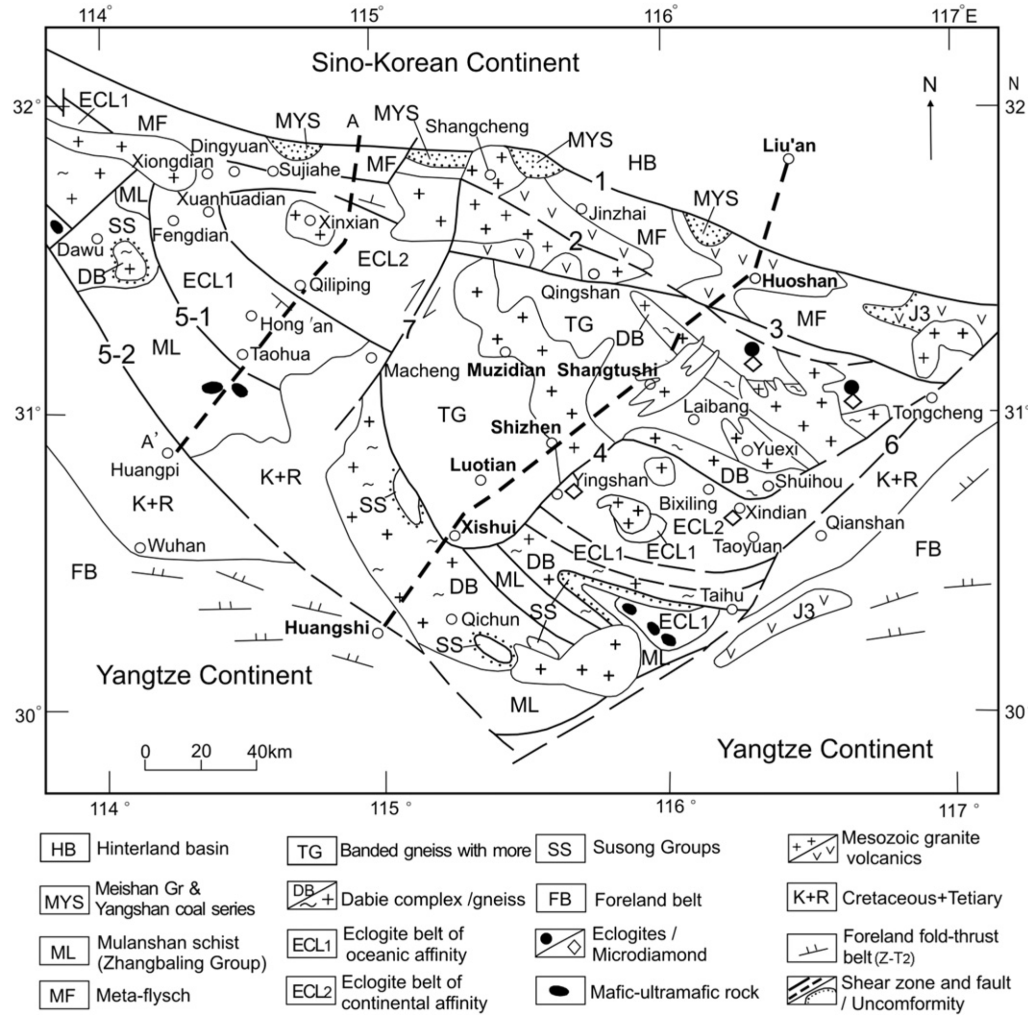

Fig. 1. Geological sketch of the Dabie Mountains (modified after Xu et al., 2005b). A–A′ denotes the line of the geological profile (see Fig. 8). Huangshi–Liu'an denotes the route of the reflection seismic profile (Xu et al., 2008a). All the Mesozoic granitoid is younger than <159 Ma and is in intrusive contact with their country rocks. All the petro-tectonic units are in fault contact with each other, except for the unconformity between SS/DB, and Mesozoic volcanics/MF.

metamorphic rock, which have been poorly understood to date. There are no papers concerning about the tectonic setting of the low-grade metamorphic rocks of the Dabie Mountains, except for some older literatures we cited from the past 20 years. Therefore most geologists are still unclear as to what units are related to subduction, what units were affected by collision event, and how the subduction was transformed to collision. All these questions will prevent one from understanding the location of suture and tectonic evolution of the Dabie Mountains. Some authors discussed the structural elements of the Tongbo orogen to the immediate west of the Dabie orogen recently. Although there is some similarity between the tectonic setting of these elements of the Dabie and Tongbo orogens, they did not focus on the tectonic setting of these structural elements, especially the low-grade metamorphic rocks (Li et al., 2009; Liu et al., 2011). Therefore this discussion of the tectonic setting of low-grade metamorphic rocks in the Dabie Mountains is new research.

2. Geological outline of the Dabie Mountains and neighboring areas

It is known that the Dabie Mountains are a collision orogen between the Sino-Korean and Yangtze cratons. Geological contrast between the two cratons (Table 1) suggests that there should have been an oceanic plate between them during the pre-Ordovician to Carboniferous periods (Table 1), which we term the "Dabie oceanic plate".

Table 1 is generalized from the Bureau of Geology and Mineral Resources of Anhui Province (1987), Bureau of Geology and Mineral Resources of Henan Province (1989), Department of Geology and Mineral Resources of Henan Province (1997), and the Bureau of Geology and Mineral Resources of Hubei Province (1990).

It shows that the middle Ordovician to early Carboniferous strata in the Sino-Korean craton are absent, whereas all of them are present in the Yangtze craton. Absence of the Middle Ordovician to early Carboniferous strata in the Sino-Korean craton implies that the Sino-Korean craton was uplifted due to subduction of the oceanic crust of the suggested "Dabie oceanic plate" under the Sino-Korean continental plate. Since the Permian (295 Ma), the sediments in the Sino-Korean craton were converted to terrestrial facies in some intercontinental basins, with plenty of plant remnants, such as *Emplectopteridium alatum* (Bureau of Geology and Mineral Resources of Anhui Province, 1997), dating lower (295 Ma) to upper (250 Ma) Permian; it is seemingly caused by further rising of the Sino-Korean continental plate. This means that

Table 1

Correlation of petrotectonic units and strata of the Dabie Mountains and neighboring regions

Epoch	Stratum (petro-tectonic unit)		Sino-Korean craton	Dabie Mountains orogen: North, Henen Prov		Dabie Mountains orogen: North, Anhui Prov		Dabie Mountains orogen: South, Hubei Prov	Yangtze craton, Anhui Prov
250 ～ 295	Permian	Upper	Shiqianfeng Fr Upper-Shihezi Fr	—		—		?	Longtan Fr
		Lower	lower Shihezi Fr Shanxi Fr					?	Gufeng Fr Qixia Fr
295 ～ 354	Carboniferous	Upper	Taiyuan Fr Benxi Fr	Yangshan Coal Series	Huangshitou Fr Yangxiaozhuang Fr Huyoufang Fr	Meishan Group		?	Chuanshan Fr Huanglong Fr
		Lower	absent		Daorenchong Fr Yangshan Fr Huayuanqiang Fr			?	Hezhou Fr Gaolishan Fr Jinling Fr
354 ～ 410	Devonian		absent	Xinyang Group	Nanwan Fr Guishan Fr.?	Foziling Group	Zhufo an Fr Panjialing Fr	?	Wutong Fr
410 ～ 443	Silurian	Upper	absent	Sujiahe Group	Dingyuan Fr ?		Xangyunzhai Fr	?	Maoshan Fr
		Middle	absent		Huwan Formation		Xianrenchong Formation	?	Fentou Fr
		Lower	absent					?	Gaojiabian Fr
443 ～ 490	Ordovician	Upper	absent					?	Wufeng Fr Tangtou Fr
		Middle	absent Laohushan Fr					?	Sanyuanzhi Fr
		Lower	Majiagou Fr Xiaoxian Fr Jiawang Fr					?	Guniutan Fr Dawan Fr Honghuayuan Fr Longpan Fr

(continued on next page)

Table 1 (*continued*)

<table>
<tr><td rowspan="3">490 ~ 543</td><td colspan="2" rowspan="3">Cambrian</td><td>Upper</td><td colspan="2">Fengshan Fr
Changshan Fr
Gushan Fr</td><td rowspan="4">?</td><td rowspan="5">Foziling Group</td><td rowspan="5">? Xiaoxihe Formation [627-721Ma(Zr: U-Th-Pb)]</td><td colspan="4">?</td><td colspan="3">Cheshuitong Fr
Langyashan Fr
Longpan Fr</td></tr>
<tr><td>Middle</td><td colspan="2">Zhangxia Fr
Xuzhuang Fr
Maozhuang Fr</td><td colspan="4">?</td><td colspan="3">Yangliugang Fr</td></tr>
<tr><td>Lower</td><td colspan="2">Mantou Fr
Houjiashan Fr</td><td colspan="4">?</td><td colspan="3">Huanglishu Fr</td></tr>
<tr><td rowspan="3">543 ~ 1000</td><td rowspan="3">Neopfoterozoic</td><td rowspan="2">Sinian</td><td>Upper</td><td colspan="2">Langan Gr
Suxian Gr</td><td rowspan="2">Hong’an Group(Mulanshan schist)</td><td>Ta’ergang Formation</td><td rowspan="2">Zhangbaling Group</td><td>Beijiangiun Fr</td><td colspan="2">Sujiawan Fr
Zhougang Fr</td><td>Dengying Fr
Doushantuo Fr</td></tr>
<tr><td>Lower</td><td colspan="2">Xuhuai Gr</td><td>Yaolinghe Gr
?</td><td>Mopanzhai Formation</td><td>Xileng Formation</td><td>Susong Group</td><td>Qijiaoshan Formation</td><td>Nanni Fr
Datangpo Fr
Gucheng Fr
Liantuo Fr</td></tr>
<tr><td colspan="2">Qingbaikou System</td><td colspan="2">Bagongshan Gr</td><td colspan="9" rowspan="5">Dabie Complex
(750-800Ma)
?</td><td rowspan="5">Feidong Group
?</td></tr>
<tr><td rowspan="2">1000 ~ 1800</td><td rowspan="2">Meso-Proterozoic</td><td colspan="2">Jixian System</td><td colspan="2">—</td></tr>
<tr><td colspan="2">Chang-Cheng System</td><td colspan="2">—</td></tr>
<tr><td>1800 ~ 2500</td><td>Paleo-Proterozoic</td><td colspan="2">Hutuo System</td><td colspan="2">Fengyang Gr</td></tr>
<tr><td>2500</td><td colspan="3"></td><td>Wuhe</td><td>Huooiu</td></tr>
</table>

Symbols for zoolite and plant remnants or micro-fossils

the two continents had started to collide at 295 Ma, earlier than previous estimates that have placed this collision no earlier than 270 Ma (Chen et al., 2009). If there was an ancient oceanic plate prior to the collision (Condie, 1989) in the Dabie Orogen as we suggested, the convergent margin between the “Dabie oceanic plate” and Sino-Korean continental plate should contain some important sedimentary basins (Fig. 2).

In Fig. 2, the dark portion is oceanic crust, and a zone of underplating is always composed of intensively deformed sequences such as the mylonite belt (detachment), duplex folds, and tectonic or flow mélange. All of these comprise the boundary between the oceanic and continental plates. In this model, at least three major sedimentary units can be recognized in the Dabie Mountains (see below).

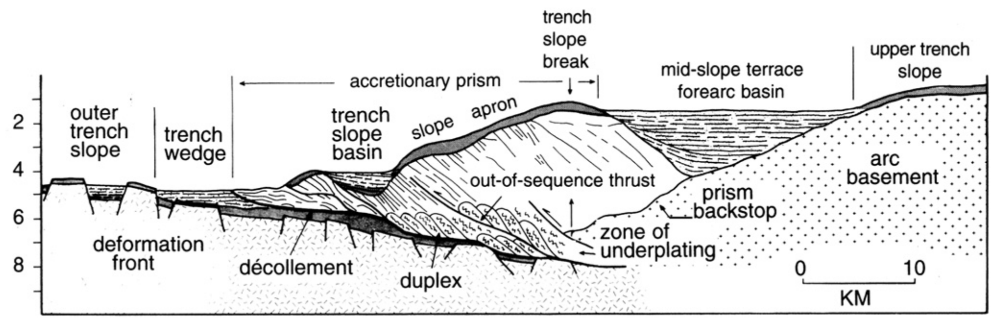

Fig. 2. A schematic illustration showing major bathymetric domains, regional-scale structural features and sites of deposition within subduction zones (after Underwood and Moore, 1995).

In most the earlier studies, petro-tectonic units of the Dabie Mountains were treated as sedimentary strata and termed as a "Formation" or "Group" (Bureau of Geology and Mineral Resources of Anhui Province, 1987, 1997; Bureau of Geology and Mineral Resources of Henan Province, 1989, 1990; All China Stratigraphic Commission of Stratigraphy, 2005). These petro-tectonic units were ascribed to either the Sino-Korean or the Yangtze cratons, with only a few exceptions (Bureau of Geology and Mineral Resources of Hubei Province, 1990; Bureau of Geology and Mineral Resources of Anhui Province, 1997). Subsequent confusion of incorrect isotopic dating further obscured the actual orogen features of the Dabie Mountains. In view of such mistakes, the present authors ascribe the petro-tectonic units in the Dabie Mountains to a special "stratum region", isolated from Yangtze and Sino-Korean cratons (Table 1). Fossils found in, and discussion on, low-grade metamorphic rocks on northern side of the Dabie Mountains (Gao and Liu, 1988; Ye et al., 1991; Liu et al., 1993, 1995, 1996; Jin et al., 1994; Ma et al., 1997), are helpful to recognize tectonic settings of these low-grade metamorphic rocks.

Although there are still some different opinions (Suo and Zhong, 1998; Hacker et al., 2000; Ma et al., 2000; Tang et al., 2003), the seven petro-tectonic units (Xu et al., 2002, 2005b) approximately represent the geology of the Dabie Mountains (Fig. 1). From north to south, these units are as follows. (1) *Meta-flysch,* (MF in Fig. 1) composed of the upper rhythmically layered metasediments, and the lower Xiaoxihe gneiss of greenschist–lower amphibolite metamorphic facies. The upper part was shown to be Ordovician to Devonian by its fossil record (see later). Some isolated, very low-grade or nonmetamorphic Carboniferous sediments (MYS in Fig. 1) are located in the northernmost part of the MF. (2) A *banded gneiss* (TG in Fig. 1) with more ultramafic blocks and eclogite in the north. It was confirmed to be UHP terrain by the presence of micro-diamonds in eclogite and gneiss, and the rod-like exsolution of apatite, rutile and clino-pyroxene in garnet (Xu et al., 2003, 2005a; Liu et al., 2006). This unit has been recognized to have an affinity with the lower crust of the Yangtze craton (Ma et al., 2000; Zhang et al., 2002). (3) An *eclogite-tonalite gneiss* (ECL_2 in Fig. 1) that has been shown to be UHP terrain by the occurrence of coesite, microdiamond in garnet, and magnetite lamenae in olivine (Okay et al., 1989; Wang et al., 1989; Xu et al., 1992; Zhang et al., 1999); the eclogites were recognized to have continental affinity with their negative $\varepsilon_{Nd}(t)$ values (Cong et al., 1996; Li et al., 2000). (4) An *eclogite and mica-plagiogneiss assemblage* (ECL_1 in Fig. 1) that was originally regarded as a "cold eclogite belt" because no UHP signatures have been reported. Eclogites have an oceanic affinity provided by the positive value of $\varepsilon_{Nd}(t)$, and pseudomorph after lawsonite (Jahn et al., 1999, 2005; Sun et al., 2002; Castelli et al., 1998). (5) A blue-schist and quartz-sericite schist assemblage (Mulanshan schist/Zhangbaling Group) of transitional greenschist-blue-schist facies metamorphism (ML in Fig. 1). Its protolith is the spilite and quartz-keratophyre association. (6) *The Dabie Complex* (DB in Fig. 1) composed mainly of monzonitic granite gneiss of amphibolite and greenschist metamorphic facies, corresponding to the upper part of the crystalline basement of the Yangtze craton. (7) *The Susong Group* (SS in Fig. 1) is a metamorphic phosphorous series of epidote-amphibolite metamorphic facies. According to the geological section measured across the western Dabie Mountains (A–A′ in Fig. 1, cf. Fig. 8), ECL_2 tectonically underlies ECL_1 (Liu et al., 2002, 2004). Isotopic ages of the protoliths of most of the seven petro-tectonic units fall within the range 750–800 Ma (Hacker et al., 1998; Xie et al., 2004). Assemblages (2)–(4) are considered to be tectonic collision mélanges of HP–UHP metamorphism (Xu et al., 2005c, 2008a). Assemblages (1), (5) and (7) are low-grade metamorphic rocks, tectonic setting of which and unit (6) will be discussed in the present paper. Units (1)–(6) in the Dabie orogen roughly correspond to units (4)–(9) in the Tongbo orogen (Liu et al., 2011).

3. Low-grade metamorphic rock units of the Dabie Mountains

3.1. Low-grade metamorphic rocks in the northern Dabie Mountains

The low-grade metamorphic rocks in the northern Dabie Mountains include two parts: intermittently distributed non-metamorphic and very low-grade metamorphic rock suites in the northernmost Dabie Mountains (MYS in Fig. 1), and the meta-flysch (MF in Fig. 1) of greenschist metamorphic facies.

3.1.1. Yangshan coal measures and Meishan Group

Both rock suites unconformably rest above, and are immediately located in the north of the meta-flysch (MF, in Fig. 1), but underthrust southward beneath the MF during subsequent deformation (Bureau of Geology of Anhui Province, 1974; Jin, 1989; Jin et al., 1994) at some places. Possible arc rocks are buried in the locality to the north of the coal measures (Fig. 3). Upon this, the Yangshan coal measures and Meishan Group are the forearc sediments, and are dated as being from the Carboniferous period according to their fossil record (Table 1). The Yangshan coal measures occur in the western and the Meishan Group in the east of the Dabie Mountains (Fig. 1). These Carboniferous sediments differ from those in the Sino-Korea and Yangtze cratons in terms of their petrology, succession, sedimentary facies, deformation, metamorphism (Ma, 1991) and tectonic settings.

3.1.1.1. Yangshan coal measures. The Yangshan coal measures include the Huayuanqiang Formation, which was mistaken for the

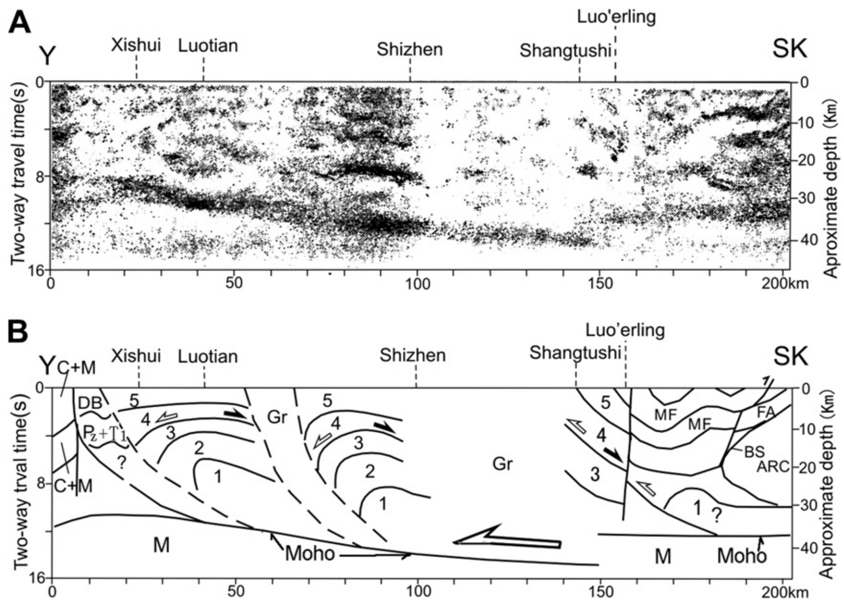

Fig. 3. Reflection seismic profile and geological interpretation of the eastern Dabie Mountains (revised from Xu et al., 2008a). (A) Migrated seismic reflection profile from Huangshi to Liu'An (Fig. 1) on a true scale (no vertical exaggeration; after Xu et al., 2008a). (B) Geological interpretation of the section in part (A). 1–3 are the lower, middle and upper crusts of the Yangtze craton; Sk is the Sino-Korean craton; MF is the meta-flysch (accretionary prism); 5 is the overthrust sheet of the lower crust of the Yangtze craton (TG). FA is the forearc basin sediments; BS is a back slope; ARC is the arc produced by subduction of the oceanic crust; C + M denotes the Cenozoic + Mesozoic sediment groups; T denotes the Triassic strata; Pz denotes the Paleozoic strata; Gr is Mesozoic granite [Tiantangzhai granite is the larger feature, a granite sheet in the south is postulated to be a branch of the larger one, which was generated by remelting of the lower crust of the Yangtze craton during Mesozoic (Zhang et al., 2002)]. M is mantle. The small open arrow shows the shear sense in the early events during metamorphism of granulite and eclogite facies; the solid arrow represents the direction of movement in the extension stage and the large open arrow indicates the direction of movement in the last event, as proven by the overlapped Moho. Other symbols are the same as in Fig. 1.

Devonian originally (Jin et al., 1994). Fossils of Carboniferous and plant remnants and zooliths have been found latterly. They contain conglomerates (marking unconformity), sandstone, coal seams, silt, shale, dolomitic carbonate, and the Huayuanqiang Formation was finally proved to be lower Carboniferous (Table 2). The Yangshan Coal measures were subdivided into six formations. Table 2 summarizes the formation, lithology, and some fossils of the Yangshan coal measures.

The sediments of the Yangshan coal measures show a transition from fluvio-deltatic to basin plain sedimentary facies, indicating progressive subsidence of the basin (Table 2). The high frequency of arkose in the section (Table 2; Department of Geology and Mineral Resources of Henan Province, 1997) suggests proximity to a volcanic arc. The basement of the coal measures is mainly the accretionary prism (see Section 2.1.2). Moreover, there are no common features of backarc basin sediments (produced by extension), such as ophiolite (or ophiolite mélange) and oceanic crust in this sequence. The coal measures are also different from the backarc basin sediments in the immediate west, the Erlangping group of the Tongbo orogen (Department of Geology and Mineral Resources of Henan Province, 1996), implying that the Yangshan coal measures and Meishan Group are not backarc basin sediments.

Table 2
Lithology and fossils of the Yangshan coal measure (after Department of Geology and Mineral Resources of Henan Province, 1997).

Era (Carboniferous)	Stratum	Major lithology	Thickness (m)	Fossil	Sedimentary facies
LATE	Shuangshitou Fr.	Pebble-bearing sericite quartzite with interlayers of thin-bedded coal seam, quartz schist	310		Basin plain
	Yangxiaozhuang Fr.	Carbonaceous silt, silty claystone, lenticular coal seam, brecciated silty claystone	1539	*Neuropteris* sp.	Basin plain
MIDDLE	Huyoufabf Fr	Upper: Dark colored mica-sandstone, inter-bedded with thin-bedded limestone, Lower: Mottled sandstone, gray-colored slate intercalated with arkose and polygenetic	425	*Mesocalamites* sp.	Turbidite fan
	Daorenchong Fr.	Upper: Polygenetic conglomerate intercalated with fine grained Ferruginous silic-arenite, claystone, dolomitic limestone and quartzo conglomerate.		Drachiopoda Bivalves Gastropoda	Slope
		Lower: Ferruginous-quartz silt, claystone with thin-bedded conglomeratic sandstone, quartz sandstone	1160	Crinoidea	
EARLY	Yangshan Fr.	Upper: Ferruginous-quartz sandstone, silty claystone Intercalated with quartz conglomerate and coal seam.	1177	*Rhodea hsiganhsingan* *Bothradendron* sp.	Shelf
		Middle: Gray-colored quartz conglomerate, sandstone, sandy claystone, and coal seam. Lower: Thick-bedded quartz conglomerate		*Lepidostrobophullum* cf. *Lanceolatatum* *Sublepidodendrum mirabil*	Delta
	Huayuanqiang Fr.	Upper: Fine grained silic-arenite, intercalated with quartz conglomerate. Lower: Calcic fine grained feldsparthic quartz silt.	560	*Adiantites* sp. *Cadiopteridum* sp.	Delta

A semi-circular reflector (convex to the south) in the reflection seismic profile, beneath the MF and forearc sediments (Fig. 3) is thought to be the arc, and therefore the Yangshan and Meishan units should be the forearc sediments. In Fig. 3, we show only a possible concealed arc (ARC), and will not discuss the others.

3.1.1.2. Meishan Group. The Meishan Group is the eastern equivalent of the Yangshan coal measures described above. The group comprises lower greenschist facies rocks with penetrative mylonite bands that suggest formation by dynamic metamorphism. Fossils, such as *Calamites* sp., *Neuropteris* sp. (in carbonaceous shale at the lower part), *Brachiopoda* and *Crinoidea* (in crystalline limestone in the middle part) show the group to be Carboniferous age (Bureau of Geology of Anhui Province, 1974).

From field measurements at Sanxianshan of Jinzhai county, the lithologic section of the Meishan Group in a upwards direction is: (1) yellowish, thick-bedded quartz arenite with interbeds of thin-bedded silicic slate; (2) dark gray, medium-thick-bedded, carbonic-sericite quartz schist; (3) light gray, thick-bedded quartzite, meta- and fine-silicic-arenite and (4) gray phyllite alternated with thick-bedded quartzite. The total exposed thickness is 758 m. A borehole drilled at Shishuyuan, close to Jinzhai, has revealed dolomitic marble 400 m thick and four layers of graphitized hard-coal. Protoliths of these rocks are mainly shale, silt, conglomerate, dolomite and coal seam. A few hornblende and chlorite schists may be derived from pyroclastic rocks. Although the Meishan Group can not be precisely correlated with the Yangshan coal measures due to the different degrees of investigation, the lithology, sedimentary facies, epoch, basement, and distribution are identical (Bureau of Geology of Anhui Province, 1974; Department of Geology and Mineral Resources of Henan Province, 1997; Jin, 1989).

Both the Yangshan coal measures and the Meishan Group are paralic coal measures, with an accretionary prism (Sujiahe, Xinyang/Foziling Groups) basement, which overthrusts the Yangshan and Meishan units by subsequent deformation. As the Yangshan coal measures and Meishan Group are Carboniferous, the underlying Foziling Group (MF) should be early Paleozoic at the latest (Fig. 3, Table 1). Liu et al. (1996) and Ma et al. (1997) also recognized that the Meishan Group is the equivalent of the Yangshan coal measures.

3.1.2. Foziling/Sujiahe and Xinyang Groups (MF in Fig. 1)

The Foziling Group is the domainal term of the unit MF in Anhui Province and the Sujiahe and Xinyang Groups are the domainal terms of the unit MF in the Henan Province (Fig. 1, Table 1). The Foziling Group has been found to be composed of meta-flysch in the eastern segment of the Dabie Mountains (Xu, et al., 1994, 2002). The Foziling, Sujiahe and Xinyang Groups are rich in Paleozoic fossils. These groups constitute the accretionary prism generated by subduction of the oceanic crust and act as the basement of the forearc basin sediments (the Yangshan coal measures and Meishan Group).

The Foziling Group in the eastern Dabie Mountains is divided into five formations, which, in an upwards direction, are: (1) Xiaoxihe Formation, (2) Xianrenchong Formation, (3) Xiangyunzhai Formation, (4) Panjialing Formation, and (5) Zhufo'an Formation. The Foziling Group was originally ascribed to the Sinian System (Neoproterozoic) (Bureau of Geology of Anhui Province, 1974; Bureau of Geology and Mineral Resources of Anhui Province, 1997), and subsequently the pre-Sinian System (Bureau of Geology and Mineral Resources of Anhui Province, 1987, 1997). In view of fossil records and correlation to the western counterpart, the Sujiahe Group, we ascribe the Foziling Group to Sinian-Devonian (Table 1). Some authors defined the Luzhenguan Group (the lowest portion of the Foziling Group including the Xiaoxihe and Xianrenchong Formations) as a separate group beneath the Foziling Group (Xu et al., 1994; Faure et al., 1999; Hacker et al., 2000), but their description is practically and mainly the Xiaoxihe Formation in lithology. Therefore, we follow the original usage, keeping the Xiaoxihe Formation as the lowest unit of the Foziling Group in the present paper (Table 1), and the term "Luzhenguan Group" is excluded.

(1) *Xiaoxihe Formation.* The lithology of the Xiaoxihe formation is predominantly (from bottom to top): K-feldspathic gneiss intercalated with albite-amphibolite, amphibolite schist, plagio-amphibolite and minor mica-quartz schist. Plagio-amphibolite alternates with monzonite gneiss (Bureau of Geology of Anhui Province, 1974). Migmatization mentioned in some studies is mainly the product of Mesozoic processes (Liu et al., 2007) and the "augen migmatite" is practically mylonite converted from sub-volcanics. The total thickness of the Xiaoxihe Formation exceeds 2600 m (Bureau of Geology of Anhui Province, 1974). The plagio-amphibolites in the lower part can be compared with metamorphic volcanics or sub-volcanics. As measured in the section from Xiaoxihe to Sigushan villages in Huoshan County, there are six plagio-amphibolite horizons with individual layer thicknesses of 50–230 m and a total thickness of 802 m (including intercalations) (Regional Geological Survey of Anhui Bureau of Geology and Mineral Resources, 1987). The chemical composition of these horizons (Table 3) is similar to the alkaline basalt of oceanic islands (Turner and Verhoogen, 1960; Carmichael, et al., 1974). Recent chemical analysis of these rocks exhibits that their precursors were similar to sub-alkaline basalt ~ basaltic andesite. They are also characterized by concentration of HREE. Three samples of plagio-amphibolite

Table 3
Representative analysis of amphibolites of the Xiaoxihe Formation (Bureau of Geology and Mineral Resources of Anhui Province, 1987).

Sample	Major elemental compositions (%)												
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	LOI	Total
1	46.52	2.05	13.85	7.40	7.59	0.21	5.55	10.17	2.99	1.44	0.90	0.76	1.14	99.81
2	43.81	2.50	16.27	5.79	5.79	0.16	5.10	8.81	3.57	1.40	1.49	2.55	4.06	98.75
3	45.19	1.64	18.04	3.64	6.48	0.19	7.25	10.60	2.71	0.98	0.67	1.22	1.72	99.11
4	47.04	1.35	16.60	3.63	6.32	0.17	7.15	9.03	3.48	1.08	0.50	1.68	2.96	99.31
5	48.66	1.05	16.67	5.88	4.18	0.19	6.75	9.11	3.71	1.30	0.28	1.11		98.89
6	53.67	1.90	16.40	0.71	9.58	0.15	4.23	6.94	3.48	0.83	0.24	1.46		99.59
7	45.15	0.65	15.14	2.56	6.87	0.14	13.44	8.56	1.29	1.50	0.30	2.53	2.42	98.02
8	44.74	0.12	11.04	2.75	7.28	0.15	15.62	9.29	1.53	1.70	0.28	2.46	4.51	99.01
9	48.17	1.35	15.96	6.15	3.39	0.20	6.72	9.11	3.29	1.70	0.53	1.89		98.46
10	46.10	2.38	14.24	3.95	7.90	0.15	9.25	10.45	3.10	0.63	0.53	1.12	0.10	99.90

Samples 1–9 are from the Xiaoxihe Formation. Sample 10 is Olivin basalt (after Carmichael et al., 1974, Table 8-II).

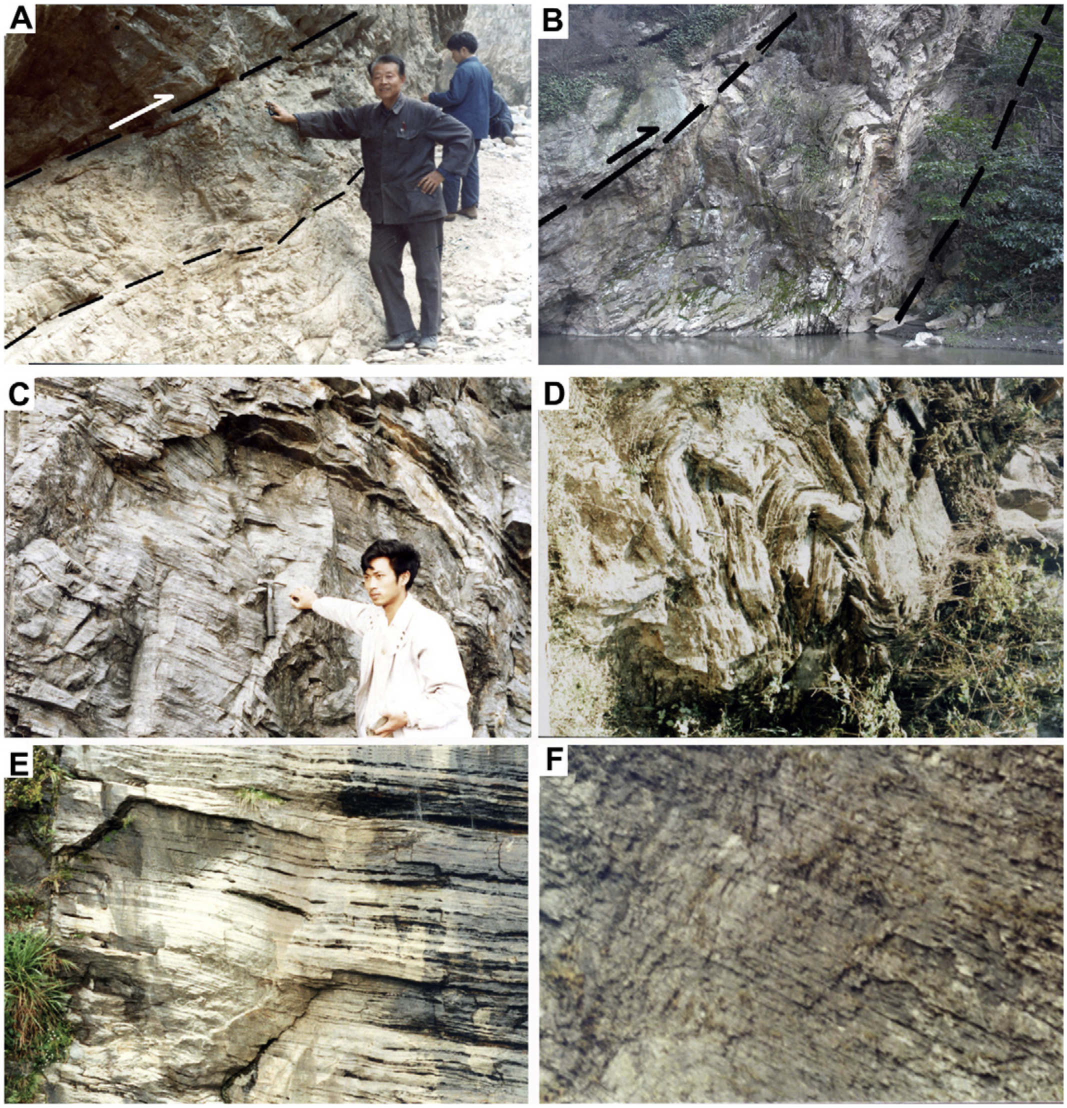

Fig. 4. Field photographs of meta-flysch in the Dabie Mountains. (A) and (B) show the thrust fault zone occurred in the Xiangyunzhai Formation in close contact with the fault 2 in Fig. 1. The heavy dashed line is the major fault plane and the finer line denotes the next fault plane. (C) Outcrop of meta-flysch in Panjialing Formation at Luo'erling close to the Foziling power station. (D) Outcrop of deformed meta-flysch close to Zhufo'an town. (E) Outcrop of Guishan Formation, to the west of Jinzhai. (F) Outcrop of Cretaceous to Tertiary flysch at Sorenburg in Switzerland.

exhibit the chemical composition of $SiO_2 = 44.09–57.35\%$, $K_2O + Na_2O = 4.81–6.16\%$, $K_2O = 1.38–2.17\%$, and the chondrite-normalized REE patterns slightly inclined to right (close to horizontal), and low Nb, Cr content in the normalized spider diagram of trace elements (Liu Y., private communication), showing tectonic setting similar to that of island arc or active continental margin (Jahn et al., 1999).

These horizons are presumably produced by underplating, and are located at the base of the accretionary prism (Underwood and Moore, 1995; Dickinson, 1995). The Xiaoxihe formation was originally ascribed to Sinian because of microfossils of Devonian (see later) in the upper part of Foziling Formation, (Bureau of Geology of Anhui Province, 1974), and zircon U–Th–Pb age of 627–761 Ma (Bureau of Geology and Mineral Resources of Anhui Province, 1987). After that, it was put into middle- to lower-Proterozoic without any reliable evidence (Bureau of Geology and Mineral Resources of Anhui Province, 1997). It is unclear whether there are any older age records (older than Ordovician) in the lowermost part of the Xiaoxihe Formation (Table 1). In addition, Sinian to Devonian is a long time for formation of an accretionary prism during a single ocean stage. Therefore it can not be excluded that the Xiaoxihe Formation is of Cambrian, if there would be more precise dating obtained in the feature. In this regard, the oceanic subduction might be of Caledonides. However, based on the present data, we prefer to put the Foziling Formation to Sinian to Devonian temporarily (Table 1).

(2) *Xianrenchong Formation.* The lithology of the Xianrenchong formation is mainly marble and mica- (partially graphite-) quartz schist. The formation exceeds 606 m thickness and looks like a carbonate turbidite. At Xianrenchong village, marble is intermediate to thick-bedded with a lamellar texture, and is intensively deformed.

(3) *Xiangyunzhai Formation.* This formation is composed of thin- to thick-bedded quartzite with a laminated texture and a few intercalations of mica-quartz schist. The quartzite is composed of 92–97% SiO_2 (Xu et al., 1994). The exposed thickness is 477 m

(Regional Geological Survey of the Anhui Bureau of Geology and Mineral Resources, 1985). The Xiangyunzhai quartzite is well exposed at the southern margin of the MF (Fig. 1), where folds and thrusting structures of outcrop-scale are of different generations (Xu and Wu, 1984) (Fig. 4A and B). By the laminated texture, pure composition, and rhythmic texture of the formations above and beneath it, this quartzite is postulated to be converted (recrystallized) from siliceous beds (Xu et al., 2002), and the early ductile deformation should respond to subduction of the "Dabie oceanic plate".

(4) *Panjialing Formation.* The Panjialing Formation is composed of light yellow to green colored, thin- to thick-bedded metasandstone and mica-quartzite. There are distinct rhythmic light and dark colored sandy and muddy bands (Fig. 4C and D), comprising rhythmic layers with total thickness >3623 m. The graded bedding is usually composed of quartz and a few feldspar grains. Most layers of the Panjialing Formation have been mylonitized and folded by dynamic deformation (Fig. 4B); it looks very like the appearance of nonmetamorphic flysch of the Cretaceous to Tertiary in Switzerland (Fig. 4F) in aspects of having apparent graded bedding and an incomplete Bouma Sequence. Some arkose interlayers with more epidote, hornblende, and carbonate debris are visible (thin sections 881051, 881952). In the mylonite bands, the ribbon quartz is typically $5\ mm \times 0.2\ mm$. Quartz grains in the upper part of the rhythmic layers are as fine as <0.2 mm. Rounded zircon grains ($0.6\ mm \times 0.5\ mm$) are still preserved. Microfossils *Laminarites antiguissimus* Eichw and *Stenomarginata pusilla* Naum are present and indicative of shallow marine sedimentary facies.

(5) *Zhufo'an Formation.* The Zhufo'an Formation mainly comprises mica-quartz schist, lenticular limestone and slaty biotite-quartz-schist, with a brecciated layer of 80–100 m thickness formed by intensive shearing. Microfossils (*Protosphaeridium* sp, *Poliporata obsolata* Sin et Liu) were found in the upper part, and thus the Foziling Group was ascribed to Sinian to Devonian (Bureau of Geology of Anhui Province, 1974). The maturity of this formation is lower than that of the Panjialing formation.

Generally, the Foziling Group is actually the meta-flysch (MF in Fig. 1) as was recognized many years ago (Xu et al., 1994, 2002), and the Xiaoxihe formation represents the initial deposits in the trench with the exception of some orthogneiss. Based on the presence of more mica and K-feldspar grains, the provenance of most paragneiss is postulated from terrestrial debris derived from the Sino-Korean continent (Regional Geological Survey of the Anhui Bureau of Geology and Mineral Resources, 1985), and the plagio-amphibolite is probably derived from the "oceanic crust" by associated underplating (Condie, 1989; Underwood and Moore, 1995; Moores and Twiss, 1995). The Xiangyunzhai and Xianrenchong Formations are the sediments deposited in deep and relatively still water. The Xiangyunzhai quartzite is likely to be converted from siliceous beds by recrystallization during metamorphism. The Xianrenchong formation appears to be like a carbonate turbidite. The lower maturity of pyroclasts in the Panjialing and Zhufo'an Formations indicates that the volcanic arc had acted as the provenance of these two formations. The five formations mentioned above comprise a synclinorium in the northern Dabie Mountains (Bureau of Geology of Anhui Province, 1974).

Along the southern margin of the Foziling Group, the intensive deformation belt is common at the base of an accretionary prism (Underwood and Moore, 1995). The deformation exhibits mesoscopic folds and thrusts (Fig. 4A, B and D), in which three generations of fault rocks have been recognized, the first generation fault rock is mylonite, the second is cataclasite, and last is brecciated mylonite. The asymmetric folds in mylonite indicate upside to south movement. The greenschist facies siliceous mylonite bands are possibly simultaneous with subduction, and the last southward thrusting is indicated by a series of imbricate thrusts of brittle deformation in the neighboring section (Figs. 3–6 in Xu et al., 1994). Moreover, there are also extensional and strike-slip movement records after Jurassic in the same fault zone as revealed by the texture of a crack-seal in Jurassic sandstone in the fault zone 3 in Fig. 1 (Xu and Wu, 1984). The last generation of thrusting is revealed by the overlapped Moho (Fig. 3). By the balance rate, the date of the overlapped Moho is postulated to be formed at ca 30 Ma or younger.

The Foziling Group should pre-date the Meishan Group, which lies unconformably above the Foziling Group. With reference to the geological differences between the Sino-Korean and Yangtze cratons (Table 1), and data from the western Dabie (see later), the epoch of the Foziling Group should be Sinian or even Cambrian, Ordovician to Devonian. Based on the 400 Ma Rb–Sr isochrone of orthogneiss of Xiaoxihe Formation of the orthogneiss (Liu Y., private communication), the country rock of the orthogneiss could be of Cambrian to Sinian. If this is true, the Dabie Oceanic plate will span the Sinian-lower Paleozoic. This is consistent with the microfossils records mentioned above.

3.1.2.1. Sujiahe Group. The Sujiahe Group is divided into two Formations. The lower part is the Huwan Formation composed mainly of marble, quartz schist, quartzite, gneiss, meta-sandstone, and sometimes eclogite of oceanic affinity (Jahn et al., 2005; Liu et al., 2004). Eclogites and marble occur as lenses of various sizes. According to their "block in matrix texture", and different ages of the

Table 4
Chemical composition of the Dingyuan Formation (Li et al., 2001).

Sample	95HN-S-1	95HN-S-2	95HN-S-3	95HN-S-4	95 HN-S-5	95HN-S-6	A	B
SiO_2	55.01	75.75	51.86	75.15	48.25	50.41	49.90	48.56
TiO_2	0.99	0.25	1.23	0.28	1.45	3.71	1.08	0.24
Al_2O_3	16.60	12.82	16.05	13.37	17.08	12.25	17.30	18.69
Fe_2O_3	3.90	0.87	3.69	1.12	0.38	7.22	7.06	2.27
FeO	3.40	0.32	5.52	0.30	10.36	8.34		4.03
MnO	0.107	0.011	0.133	0.007	0.153	0.155		0.11
MgO	3.96	0.45	6.30	0.58	5.59	4.56	7.08	9.26
CaO	7.82	0.90	6.03	0.70	8.95	6.84	12.78	12.67
Na_2O	4.00	5.84	2.87	5.07	1.60	1.06	2.45	1.88
K_2O	0.99	1.13	1.83	1.90	1.14	0.42	0.18	0.07
H_2O^+	2.74	0.70	3.72	1.29	4.26	4.35	0.80	1.89
CO_2	0.06	0.64	0.72	0.01	0.29	0.08		
P_2O_3	0.023	0.016	0.088	0.019	0.018	0.033		0.02
Total	99.60	99.70	100.04	99.80	99.52	99.43	99.17	99.96

A, Gordo rise; B, Romanche trench gabbro (Carmichael et al., 1974).

protoliths of eclogites, this formation was recognized as tectonic mélange (Ye et al., 1993; Xu et al., 2002; Li et al., 2001). Based on the fossils *Articuiata*, *Crinozoa*, and *Foraminifera* found in marble, it is inferred to be sediments from the early Ordovician to early Devonian periods (Ye et al., 1991), and correlated its protolith to the Xianrenchong Formation in the eastern Dabie Mountains (Table 1). The upper is the Dingyuan Formation, which is composed of greenschist, and is postulated to be from arc volcanics (Li et al., 2001; Bureau of Geology and Mineral Resources of Henan Province, 1989; Bureau of Geology of Henan Province, 1980). The chemical composition, however, also shows some properties of the oceanic crust. Most the samples are rich in Na_2O (Table 4), with two of the six samples showing Na_2O/K_2O ratios as high as 4.0 and 5.16, and only the sample 95HN-s-6 is rich in Fe, which is the diagnostic feature of island volcanics. In addition, the predominant trace elemental characteristics of both meta-basalt (spilite) and acid rocks in the Dingyuan Formation are high Ba, Pb and Sr but low Nb, Ti and P contents. They display positive Ba, Pb and Sr anomalies and negative Nd, Ti and P anomalies in the primitive-mantle normalization diagram. These are the typical features of subduction zone related magmas (Li et al., 2001). Therefore, an alternative explanation is that the Dingyuan formation is a tectonic slice of the Mulanshan schist, the oceanic crust (Fig. 2 and later). A more detailed provenance for the Dingyuan formation needs further investigation.

3.1.2.2. Xinyang Group. This group comprises two formations: the Guishan Formation (lower), and the Nanwan Formation (upper). The Xinyang Group is also a meta-flysch with obvious rhythmic layering (Fig. 4E) similar to that of the Panjialing Formation (Fig. 4C) in the west of the Dabie Mountains. Both their lithologies are mica-quartz schist (metamorphic sediments), granofel, epidote- and plagio-amphibolite (metamorphic volcanics). Lenticular marble in the Guishan formation contains fossils of crinoidea, brachiopoda and sponge spicule, as well as many Devonian microfossils, suggesting a formation age of middle-upper Devonian (Shang et al., 1992; Gao and Liu, 1988).

In the present paper, we correlate the Huwan Formation to Xianrenchong, and Xinyang Group with the Panjialing and Zhufo'an Formations in the east of the Dabie Mountains (Table 1). To sweepingly correlate the Foziling Group with the Xinyang Group is incorrect (Xu et al., 1994, 2002). Some differences between the western and eastern counterparts can be interpreted as the different provenances and different deformation conditions. For instance, eclogite will be present if the mafic rocks involved in deep subduction, otherwise it will be absent. A stable metamorphic spilite and quartz-keratophyre association found in the Guishan Formation (Liu et al., 1993) of the Xinyang group is possibly also a tectonic slice (similar to the Dingyuan Formation mentioned above) of a remnant oceanic slice from the "slope apron" on the accretionary prism (Fig. 2).

Overall, the Sujiahe and Xinyang Formations in the west and their eastern equivalent (the Foziling Group) are the accretionary prism. The Yangshan coal measures and their eastern counterpart (the Meishan Group) are the forearc basin sediments, which rest unconformably on the accretionary prism.

As the accretionary prism is dated to be Sinian, or Cambrian, Ordovician to Devonian, there must be a corresponding oceanic plate dating coeval with, or prior to the formation of the accretionary prism. "Where was the oceanic plate prior to the collision between the Yangtze and Sino-Korean cratons in the Dabie Mountains?" has been a perplexing question for geologists working in the area during the past 20 years. We suggest that the Mulanshan schist/Zhangbaling Group, which comprises a metamorphic spilite and quartz-keratophyre association, and related pelagic sediments in the southern Dabie, is an oceanic crust (see next section), subduction of which impelled the formation of the accretionary prism (the MF in Fig. 1). This tectonic setting of the Mulanshan

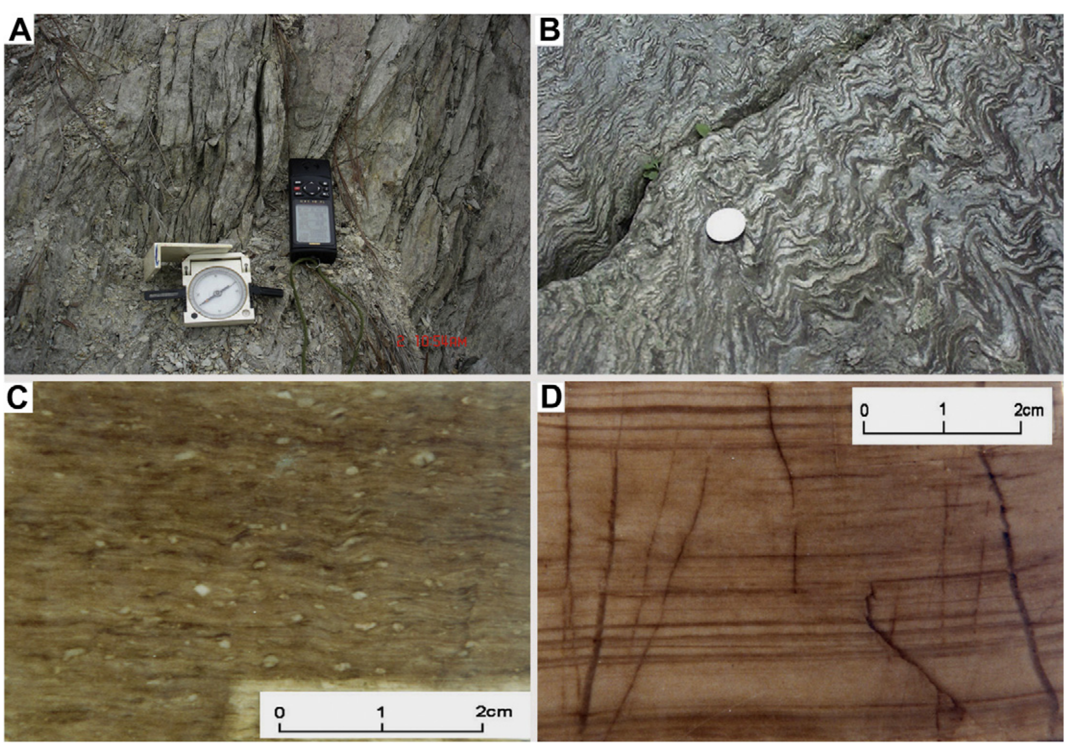

Fig. 5. Photographs of the Mulanshan schist. (A) and (B) so-called blue-schist cropped at Mulanshan Lake in western Dabie Mountains (provided by Prof. L. Sang, China University of Geosciences, Hubei). Intensive crenulations are evident in (B). (A) and (B) are metamorphic spilite. (C) and (D) are polished specimen of felsic schist composed of albite, quartz and sericite, converted from quartz-keratophyre collected from the Zhangbaling area (eastern Dabie Mountains). The white colored grains in (C) are mainly albite. (D) shows tuffaceous beds intercalated with red colored mudstone.

schist/Zhangbaling Group has been misunderstood *for at least* 20 years (see next section).

3.2. Low-grade metamorphic rocks in southern Dabie Mountains

The low-grade metamorphic rocks in southern Dabie Mountains include the Hong'an Group including the Mopanzhai and Ta'ergang Formations (Mulanshan schist) in the west and, their equivalent, the Zhangbaling Group in the east (Table 1). Each of these formations represents the metamorphic ocean crust converted from a spilite and quartz-keratophyre association. The Qijiaoshan Formation which was originally placed at the lower part of the Hong'an Formation in the old literature is ascribed to the western counterpart of the Susong Group in the present paper. The protolith of the Susong Group/Qijiaoshan Formation is the sediments of a passive continental margin (see later), and thus it is excluded from the Mulanshan schist (Table 1).

3.2.1. Mulanshan schist/Zhangbaling Group or the Hong'an Group

Mulanshan schist is characterized by its special color and fine lamination on outcrop (Fig. 5). This metamorphic volcanic rock suite is best exposed in the Mulanshan area in the western Dabie Mountains, thus it is commonly termed the Mulanshan schist (Bureau of Geology and Mineral Resources of Hubei Province, 1990; You et al., 1996) (Table 1). According to their mineral (see later) and chemical compositions (Table 5), tectonic setting (oceanic crust) (Fig. 6), intermittent distribution, and especially similar Rb–Sr age 744 Ma and two zircon ages 612 and 872 Ma from the western part (Sang et al., 1987; Zhang et al., 1989), and Rb–Sr age 800 Ma in the eastern part (Bureau of Geology and Mineral Resources of Anhui Province, 1997), we correlate the Mopanzhai and Ta'ergang Formations in the western Dabie Mountains to the Zhangbaling Group in the eastern Dabie Mountains (Table 1).

The Mopanzhai Formation is the lower part of the Mulanshan schist. Its mineral composition comprises albite, epidote, and actinolite. Lithologically, the Mopanzhai Formation is expressed as actinolite schist, riebeckite and crosstie schist (Fig. 5A and B), the total thickness of the Mopanzhai Formation is 2000–4000 m.

Their chemical compositions of the Mulanshan/Zhangbaling Group are similar to that of spilite and quartz-keratophyre (Table 5). This is in agreement with the early statement by Sang (1991) who correlated the metabasite (Mulanshan schist) in western Dabie Mountains through the meta-basites (Xileng Formation) in eastern Dabie to that to the further east in Su-Lu region. The meta-basites are distributed from west to east intermittently with similar chemical composition (Table 5) and the trace and REE elements showing features of oceanic crust (Fig. 6). However, we have different opinions with Sang (1991) about the era of these meta-basites (Table 1). Apart from the chemical (Table 5) and mineral compositions, slightly deformed pillow structures of spilite are found at Yuji (Shang L.K., 2009, private communication), further indicating its oceanic crust origin (Hydman, 1972; Carmichael et al., 1974).

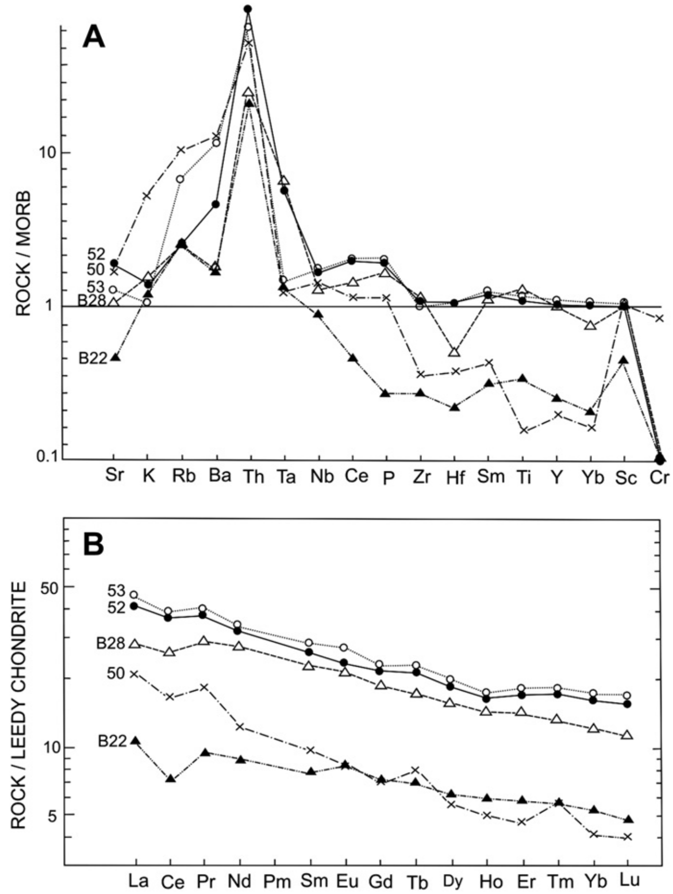

Fig. 6. Geochemical patterns for the Mulanshan schist (samples 50, 52 and 53) in the west, and samples B22 and B28 are meta-volcanics from Xileng Formation in the east. (A) Primitive-mantle-normalized spider diagrams and (B) Chrondrite-normalized REE patterns (after Sang, 1991).

The Ta'ergang Formation is mainly composed of sericite-albite-quartzite schist, leuco-granofel, and is mainly converted from quartz-keratophyre with a total thickness of ca 1500 m. Common minerals are quartz, albite, chlorite, epidote, piedmontite, phengite, riebeckite and crosstie. No glaucophene has been found in both the Mopanzhai and Ta'ergang Frs, indicating that the Mulanshan schist has never been subducted to HP depth (You et al., 1996; Eide and Liou, 2000).

The Zhangbaling Group is the eastern equivalent of the Mulanshan schist. It includes the Xileng Formation, composed of spilite and quartz-keratophyre association (Fig. 5C and D) with thickness >1500 m, The lower Zhangbaling Group includes phyllite >800 m thick, with interlayer of graphite and manganese, and lenticular fine grained marble or limestone. In some areas, lamellar limestone (or fine grained marble) exceeds 600 m thickness, with

Table 5
Chemical compositions of the Mulanshan schist (Mopanzhai + Ta'ergang) and Xileng Formation (lower part of the Zhangbaling Group) (Bureau of Geology of Anhui Province, 1974).

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	Total
Metamorphic spilite														
Xileng	49.07	1.08	16.55	10.19	2.49	0.22	5.86	4.17	5.10	0.57	0.23	4.21		99.74
Mulanshan	48.14	1.97	14.62	4.82	8.05	0.21	6.44	9.42	2.87	0.51	0.35	2.37	1.22	99.77
Hydman (1972)	48.8	1.3	15.7	3.8	6.6	0.15	6.1	7.1	4.4	1.0	0.34			
Metamorphic quartz-keratophyre														
Xileng	76.67	0.29	12.33	1.67	0.37	0.04	0.31	0.68	4.78	1.90	0.04	0.97		99.87
Mulanshan	72.87	0.32	13.78	1.83	0.85	0.06	0.60	0.98	4.78	2.39	0.05	1.00		99.51
[a]	77.08	0.15	11.98	1.26	0.63	0.05	0.63	0.77	5.42	1.15	0.10	0.73	0.12	100.27

[a] Quartz-keratophyre after Turner and Verhoogen (1960).

intercalations of thin-bedded phyllite (or meta-sandstone) in the upper part. Very thin lamellae of siliceous beds in both the limestone and phyllite are common. This phyllite and limestone sequence was termed the Beijiangjun Formation (Table 1) and ascribed originally to the lower part of the Zhangbaling Group (Bureau of Geology and Mineral Resources of Anhui Province, 1987, 1997). In contrast, the same sequence was ascribed to the upper part of the Mulanshan schist in the west Dabie Mountains (Bureau of Geology and Mineral Resources of Hubei Province, 1990). The phyllite, siliceous beds, and lamellar limestone series with graphite seams are pelagic sediments converted from carbonate ooze and detritus, siliceous ooze and detritus, and abyssal clay, in which microfossils *Trachysphaeridium* sp., *Leiominuscula* sp, *Gloeocapsarmorphora* sp., *Polyedrosphaeridum* sp., etc. in meta-sedimentary interlayers were reported (Bureau of Geology and Mineral Resources of Anhui Province, 1997).

Since the metamorphic spilite and quartz-keratophyre association (Zhou et al., 1993) is the initiation of oceanic crust, it should underlie the pelagic sediments – the Beijiangjun Formation. The overturned sequence in the east is probably due to intensive deformation (large scale recumbent fold and overthrust) in the Zhangbaling area (Xu et al., 1994, 2002). Therefore, we ascribe the Beijiangjun and Xileng Formations as the upper and lower parts of the Zhangbaling Group respectively; this is in agreement with the sequence of Mulanshan schist in western Dabie (Table 1).

This meta-volcanic suite was suggested to be related to the subduction of an ocean crust (Eide and Liou, 2000; Zhou et al., 1993), while Nakajima et al. (1990) recognized the existence of a plate tectonic regime of the late Proterozoic. The HP eclogite (ECL_1 in Fig. 1) with eclogite of oceanic affinity, closely associated with the Mulanshan schist (Hacker et al., 2000), which is possibly a deeply subducted and intensively deformed part of the same oceanic crust (Chen et al., 2010) associated with some continental materials. This is the case why Mulanshan schist shows negative ε_{Nd} value, although it is definitely an oceanic crust (Jahn et al., 2005).

Both the Mulanshan schist and the Qijiaoshan Formations were ascribed to the Paleoproterozoic era (Bureau of Geology and Mineral Resources of Hubei Province, 1990), whereas the corresponding Zhangbaling Group was ascribed to the Mesoproterozoic era in another literature (Bureau of Geology and Mineral Resources of Anhui Province, 1987, 1997). This is obviously in contradiction to each other. Upon these reasons mentioned at the beginning of this section, both the Mulanshan schist/Zhangbaling Group and the Susong Group/Qijiaoshan Formation are therefore taken to be Neoproterozoic (All China Stratigraphic Commission of Stratigraphy, 2005), but are of different tectonic settings (Table 1). However, more epochal evidences are needed in future investigations.

3.2.2. Susong Group

The Susong Group is the domainal term for a phosphoric sequence in the eastern Dabie Mountains, and the Qijiaoshan Formation is the domainal term for its equivalent in the western Dabie Mountains (Table 1). The Susong Group is divided into two formations (Bureau of Geology and Mineral Resources of Anhui Province, 1997); they are (from bottom to top).

3.2.2.1. Daxinwu Formation. The Daxinwu Formation unconformably contacts the underlying Dabie Complex (DB in Fig. 1). Evidence for the unconformity is basal conglomerate at several places, and manganiferous and vermiculite horizons (Bureau of Geology and Mineral Resources of Anhui Province, 1987, 1997). The basal conglomerates are cross-cut by fracture cleavage parallel to the unconformity (Fig. 7A) due to basal sliding, and most gravels are rounded (Fig. 7B), especially on the weathered surface (Fig. 7C and D). The maximum thickness of the Daxinwu Formation is 599 m.

Foliation of the Dabie Complex below the unconformity differs from that in the Susong Group above the unconformity (Fig. 7E and F). The Susong Group was considered to be of Paleoproterozoic age based on the isotopic age of 1900 Ma of the Susong Group and the isotopic age of ca 2424 Ma from the underlying Dabie Complex (Bureau of Geology and Mineral Resources of Anhui Province, 1987). However, the isotopic dating technique 20 years ago was relatively new, and most of the rocks ascribed to the Dabie Complex (or Dabieshan Group) in older studies have now been identified as components of UHP terrains, dated recently to 750–800 Ma (Hacker et al., 1998, 2000). Thus, the Paleoproterozoic age is less likely. An isotopic age of 787 Ma (Hacker et al., 2000) for protoliths of the Dabie complex just below the unconformity was recently obtained close to Dawu town in the western Dabie Mountains, and a similar isotopic age of 806 Ma (Xu et al., 2002) was obtained from the Dabie complex between TG and ECL_2 units in the eastern Dabie Mountains (Fig. 1). Both ages place the top of the Dabie Complex in the Neoproterozoic era (Table 1). If the 787–806 Ma age of the Dabie Complex is reliable, the age of protolith of the Susong Group above the unconformity should be less than 787 Ma. In addition, microfossils such as *Trachyspaeridium levies*, *Trimatosphaeridium sp*, *Asperatopsophosphaera* sp., *Laminarites antiguissimus*, and *Prototracheites* cf. *porus* found in the Susong Group (Bureau of Geology and Mineral Resources of Anhui Province, 1997) are consistent with the isotopic dating. However more evidences for the date of both the Dabie Complex and the Susong Group are needed in further investigations.

3.2.2.2. Liuping Group. The Liuping Group is mainly a phosphoric series of the Susong Group. Lithologically it is composed of mica-quartzite schist and dolomitic marble with interlayers of manganiferous, gypsum-bearing, and phosphorite horizons. Maximum thickness is ca 1287 m.

In addition to the confusion epoch of the Susong Group and Mulanshan schist mentioned above, the tectonic setting of them is still uncertain. Although the different tectonic setting was recognized in the literature (Bureau of Geology and Mineral Resources of Anhui Province, 1997), the realistic tectonic setting has never been discussed in the plate tectonic framework to date. The tectonic setting of the Susong Group (including Qijiaoshan Formation) is characterized by (1) unconformably rest above the crystalline basement (the Dabie Complex) (Table 1; Fig. 7); (2) the stable neritic facies sediments, such as dolomitic marble with interlayers of manganiferous, gypsum beam, and phosphorite horizons; (3) there are some plagio-amphibolite (meta-basaltic rocks) at the lower part of the Susong Group (Regional Geological Survey of the Anhui Bureau of Geology and Mineral Resources, 1985). These are the diagnostic features of passive continental margin sediments (Moores and Twiss, 1995). It means that the protolith of the Susong Group was passive continental margin sediments, which differ from the oceanic crust association, the Mulanshan schist, mentioned above.

The data described above indicate that: (1) the protolith of the Susong Group should be younger than 787–806 Ma; (2) upper part of the protolith of the Dabie complex (a part of the Dabieshan group or Dabieshan complex in older literatures) is Neoproterozoic (All China Stratigraphic Commission of Stratigraphy, 2005) and is the crystalline basement of the Yangtze continent; (3) the tectonic setting of the Susong Group differs from that of the Mulanshan schist: the former is the sediments of a passive continental margin, and the latter is an oceanic crust; and (4) the metamorphic facies of both Dabie Complex and Susong Group show that they have never been subducted to HP–UHP depth, and they are the mobilized (crystalline) basement and cover of the Yangtze continents respectively.

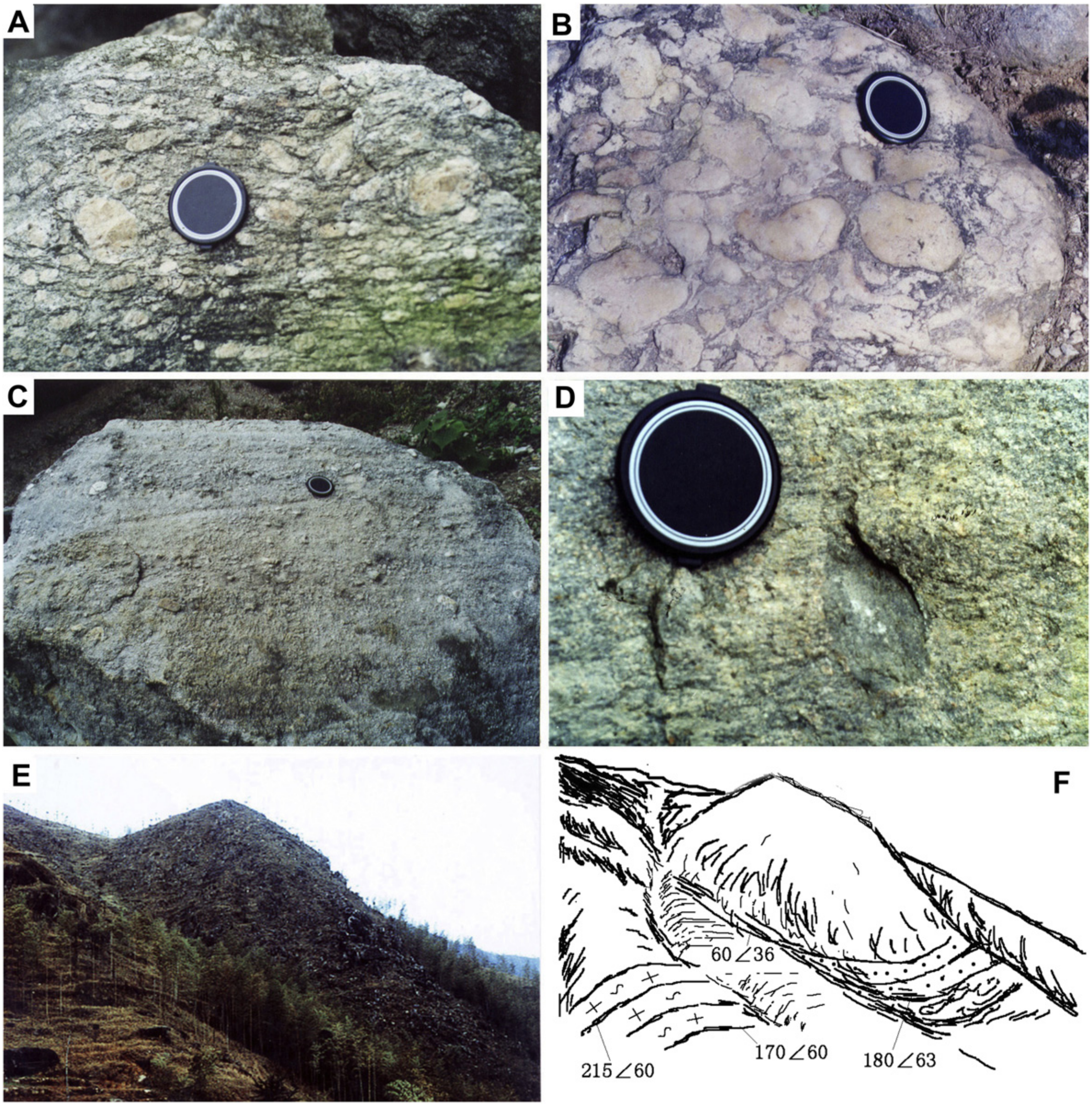

Fig. 7. Basal conglomerate of the Susong group at different locations. (A–D) Pebbles in the conglomerate; (E) Overview of the unconformity; (F) A sketch of E. See the text for an explanation.

4. Relationship between the low-grade metamorphic rocks in the northern and southern Dabie Mountains

According to plate tectonics, in a convergent margin, the accretionary prism, volcanic arc, forearc basin and backarc basin are produced by subduction of an oceanic crust. We have discussed the forearc basin, the accretionary prism in the Dabie Mountains, and also the oceanic crust in foregoing sections. Although they are the major units produced by subduction of oceanic crust in the Dabie Mountains, they are now separated and disturbed by HP–UHP units, which were exhumed from great depth (Xu et al., 1992, 2002; Wang et al., 2008). In order to recognize the relationships between low-grade rocks on both northern and southern sides, some important geological features should be noted: There is an intensive

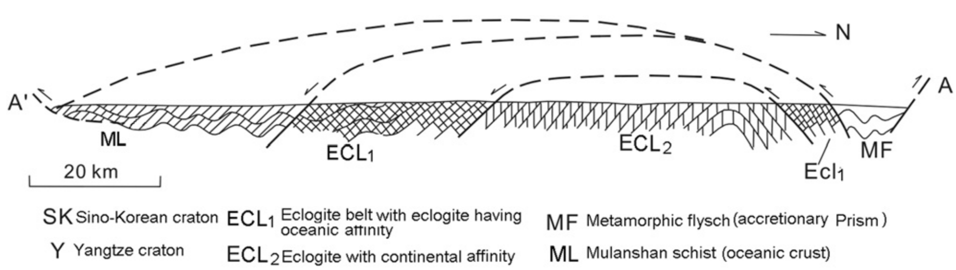

Fig. 8. A measured cross profile of the western Dabie Mountains (simplified after Liu et al., 2002). The profile line shown in Fig. 1.

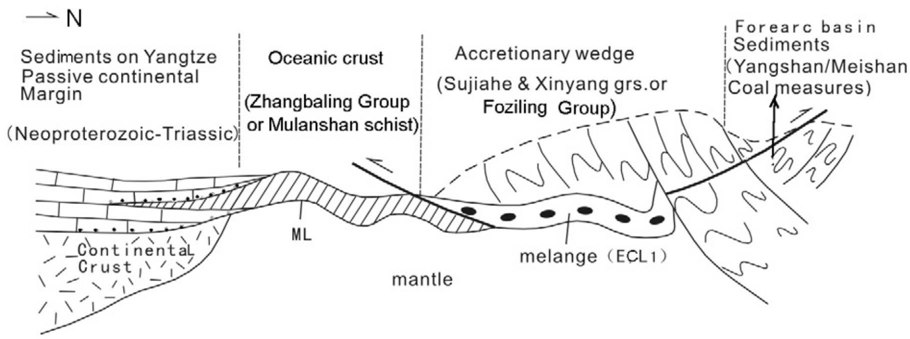

Fig. 9. Sketched model for the Dabie orogen during oceanic subduction since the Sinian. ML refers to Mulanshan schist and also the Zhangbaling Group (no scale).

deformation belt (Fig. 6A and B) at the base of the accretionary prism close to the suture (shear zone 2 and fault zone 3 in Fig. 1). The units ECL_2 and TG (Fig. 1) have been documented to be collision mélange (Xu et al., 2008b). These structures are always associated with and occurred at the boundary between oceanic and continental plates, constituting the tectonic boundary between two plates (Underwood and Moore, 1995). Based on these structures, the boundary between the Yangtze and Sino-Korean continents, and also the boundary between the Sino-Korean continental and "Dabie oceanic" plates are recognized (Fig. 2). It means that the rock units (TG, RCL_2 and ECL_1 in Fig. 1) to the south of the MF are the composite boundary of oceanic crust subduction and continental collision between "Dabie oceanic" and Sino-Korean continental plates, and also the boundary between the Sino-Korean and Yangtze cratons.

As mentioned above, the forearc sediments of Upper Carboniferous (Yangshan coal measures and Meishan Group, MYS in Fig. 1) rest on the accretionary prism (Foziling Group/Sujiahe and Xinyang Groups, MF in Fig. 1) of Ordovician-Devonian age, but the Xiaoxihe Formation should be of late Proterozoic to Cambrian (Table 1). Based on the age of the accretionary prism, there must be an oceanic crust in the south of the Dabie Mountains that pre-dates the Ordovician or Cambrian. However, the Cambrian strata above the Mulanshan schist/Zhangbaling Group (the oceanic crust) have not yet been identified.

Field observations show that the ECL_1 has thrust southward over the ECL_2 unit (Fig. 8), while the accretionary prism (Foziling Group/ Sujiahe and Xinyang Formations) always thrusts northward over the forearc sediments (Yangshan coal measures/Meishan Group), probably due to progressive deformation or collision during and after subduction of the oceanic crust (Fig. 9).

Fig. 8 shows the present position of the oceanic crust (ML). As the HP–UHP rocks were exhumed from separate depths (Liu and Li, 2008), the HP–UHP terrains, especially those having continental affinity (TG and ECL_2 in Fig. 1) were exotic tectonic slices. If the UHP continental crust unit (ECL_2) is removed from Fig. 8, and the strata of the Yangtze continental craton and accretionary prism are taken into account, the relationship between the remnant units are easily understood to match well with the regime of a subduction orogen (early Paleozoic) before collision (Fig. 9, cf. Fig. 2). Further reliable epochal evidence (including metamorphic age), especially for the oceanic crust (Zhangbaling Group/Mulanshan schist), is needed to support this model.

5. Discussion and conclusion

5.1. Discussion

5.1.1. The main part of the Puhe formation

The Puhe Formation is a part of the Susong Group in the older literature (Bureau of Geology and Mineral Resources of Anhui Province, 1987; Li, 1988), but some lenticular peridotite and marble enclaves were documented to be UHP rocks with a lot of UHP mineral moisanite, and its country rock is similar to those of ECL_1 (Xu et al., 2008c). Moreover, the similar lithologic association was reported from the Mulanshan schist (Liu et al., 2002), and thus it is ascribed to ECL_1 and ML units respectively; so there is no Ganghe Formation in the present Susong Group (Table 1). In addition, this unit has been also identified as a UHP unit by the occurrence of lazulite (Jin et al., 1995; Liu and Hu, 1999).

5.1.2. Why there are no Sinian (or Paleozoic) strata of marine sediments above the suggested oceanic crust

A tectonic slice of lower greenschist facies enveloped in the UHP belt at a site close to Changpug (near the Bixiling in Fig. 1) is termed the Ganghe Formation which is composed of pyroclasts, and was found to be of Sinian age based on its microfossil content and isotopic (U–Pb) dating (760–820 Ma) (Tang et al., 1995). In addition, there is another rock slice of UHP metamorphism with microfossils: *Lanmina rites* sp., *Leosphaeridia* sp and *Baltisphaeridium* sp (Bureau of Geology of Anhui Province, 1996) of Sinian to lower Cambrian age found in fine crystallized and mylonitized marble at Taoyuan village (Fig. 1). Moreover, it is known that the sediments overlying the ocean crust are commonly sparse or even absent (Table 1) because of under-current erosion and subduction. These low-grade and UHP supracrustal rock slices are probably the remnant sediments of the marine sediments of Sinian to Paleozoic, most of which may be involved in the tectonic mélange by underplating during subduction. Of course, more evidences remain for further investigation.

5.1.3. Where is the suture between Sino-Korean and Yangtze cratons

Some authors insist that the suture includes all the units of TG, ECL_1 and ECL_2, and suggested that the ECL_1 and ECL_2 are the thin-skinned components (Hsü, 1981; Seeber, 1983), and the TG is the root belt of the suture (Xu et al., 2008a); others recognize only the Balifan-Mozitan-Xiaotain fault zone (consistent with 2 + 3 faults in Fig. 1) as the suture (Suo et al., 1999; Faure et al., 1999; Wang et al., 2008), but they didn't give any explanation for the tectonic setting of the meta-flysch (MF in Fig. 1), which is always occur at the hanging wall of the major subduction zone (Condie, 1989) as is showing in Figs. 2, 4A and B, and 9. However, Balifan-Mozitan-Xiaotain fault zone is a new one which cuts all the rock units as shown in Fig. 3. If there is any suture to the north of MF unit of the Dabie Mountains found in the future, it would be the suture between a backarc basin and a arc, like that in the Erlangping Group of the Tongbo orogen (Bureau of Geology and Mineral Resources of Henan Province, 1989; Department of Geology and Mineral Resources of Henan Province, 1997; Liu et al, 2011). As for the composite suture between Sino-Korean and Yangtze cratons will be discussed in a separate paper.

6. Conclusion

1. The low-grade metamorphic rocks in the northern and southern Dabie Mountains are members of the (oceanic crust) subduction orogen prior to collision between the Sino-Korean and Yangtze cratons, but the Susong Group is composed of the sediments of a passive continental margin of the Yangtze craton. The Mulanshan schist/Zhangbaling Group is an oceanic crust, and the Sujiahe and Xinyang/Foziling Group is the accretionary prism associated with subduction of the oceanic crust. The Yangshan coal measures and Meishan Group are forearc basin sediments.
2. If there are any sediments of a backarc basin generated by oceanic subduction, it should be buried by the Cenozoic–Mesozoic sediments to the north of the Dabie Mountains.
3. HP–UHP belts (between low-grade metamorphic rocks) are exotic terrains exhumed from depths of more than 100 km, which disturbed the integrity of the orogen of oceanic subduction prior to collision between the Yangtze and Sino-Korean cratons.
4. More data are needed to support the model we suggested.

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