Available online at www.sciencedirect.com
ScienceDirect
Journal of Asian Earth Sciences 32 (2008) 336–347
Journal of Asian Earth Sciences
www.elsevier.com/locate/jaes

Geochemistry of the Mian-Lue ophiolites in the Qinling Mountains, central China: Constraints on the evolution of the Qinling orogenic belt and collision of the North and South China Cratons

Ji-feng Xu [a,*], Ben-ren Zhang [b], Yin-wen Han [b]

[a] Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, China Academy of Sciences, P.O. Box 1131, Guangzhou 510640, PR China
[b] Geochemical Institute, China University of Geosciences (Wuhan), Wuhan 430074, PR China

Abstract

The Anzishan ophiolite, a typical ophiolitic block of early Carboniferous age in the Mian-Lue suture zone of the Qinling Mountains, central China, consists of amphibolites/metabasalts, gabbros and gabbroic cumulates. All of these rocks, as well as those in the Hunshuiguan-Zhuangke (HZ) block, have compositions similar to normal MORB and back-arc basin basalts (BABB) with high $\varepsilon_{Nd(t)}$ values, indicating that they were derived from a depleted mantle source. The Mian-Lue suture zone also contains blocks of other lithologies, e.g., rift volcanic rocks in the Heigouxia block and arc volcanic rocks in the Sanchazi block. Although they are in fault contact with each other, the presence of these different blocks in the Mian-Lue suture zone may represent a complete Wilson cycle, from initial rifting to open ocean basin to final subduction and continent-continent collision, during the late Paleozoic-early Triassic. In this region, the North and South China Cratons were separated by Paleo-Tethys at least until the early Carboniferous, and final amalgamation of both cratons along the Qinling orogenic belt took place in the Triassic.

Keywords: Geochemistry; Mian-Lue suture; Ophiolite; Qinling orogenic belt; Central China

1. Introduction

Ophiolites contain valuable information on the genesis and evolution of oceanic lithosphere and provide clues to the tectonic history of orogenic belts. Ophiolites were previously believed to represent fragments of oceanic crust produced by spreading at mid-oceanic ridges (e.g., Coleman, 1977), but by the early 1980s, it was recognized that they can also form in supra-subduction zones (SSZ) (Pearce et al., 1984). It is now generally accepted that ophiolites can be produced in a variety of tectonic settings, but that most have a suprasubduction zone signature (Bloomer et al., 1995; Dilek et al., 2000; Dilek and Robinson, 2003).

However, identification of the precise paleotectonic environments of ophiolites is difficult. For example, MORB produced by extension at a mid-ocean ridge may be very similar to lavas formed in a mature back-arc basin (Wallin and Metcalfe, 1998; Nicholson et al., 2000). Thus, constraining the geochemistry of the ophiolites and determining their geological relationships with adjacent lithotectonic elements are critical to identifying specific tectonic settings.

The Qinling orogenic belt separates the North and South China Cratons in north-central China (Fig. 1). Previous studies suggested that these two cratons were joined along the Shangdan suture zone (Fig. 1) (Zhang, 1988; Xu et al., 1988, 1996), but there was little agreement on the timing of collision. Contrasting models proposed collision ages ranging from middle Paleozoic to Triassic (e.g., Xue et al., 1996; Gao et al., 1995; Li et al., 1993; Enkin et al., 1992). More recently, a second

* Corresponding author. Tel.: +86 20 85290282; fax: +86 20 85290130.
E-mail address: jifengxu@gig.ac.cn (J.-f. Xu).

1367-9120/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jseaes.2007.11.004

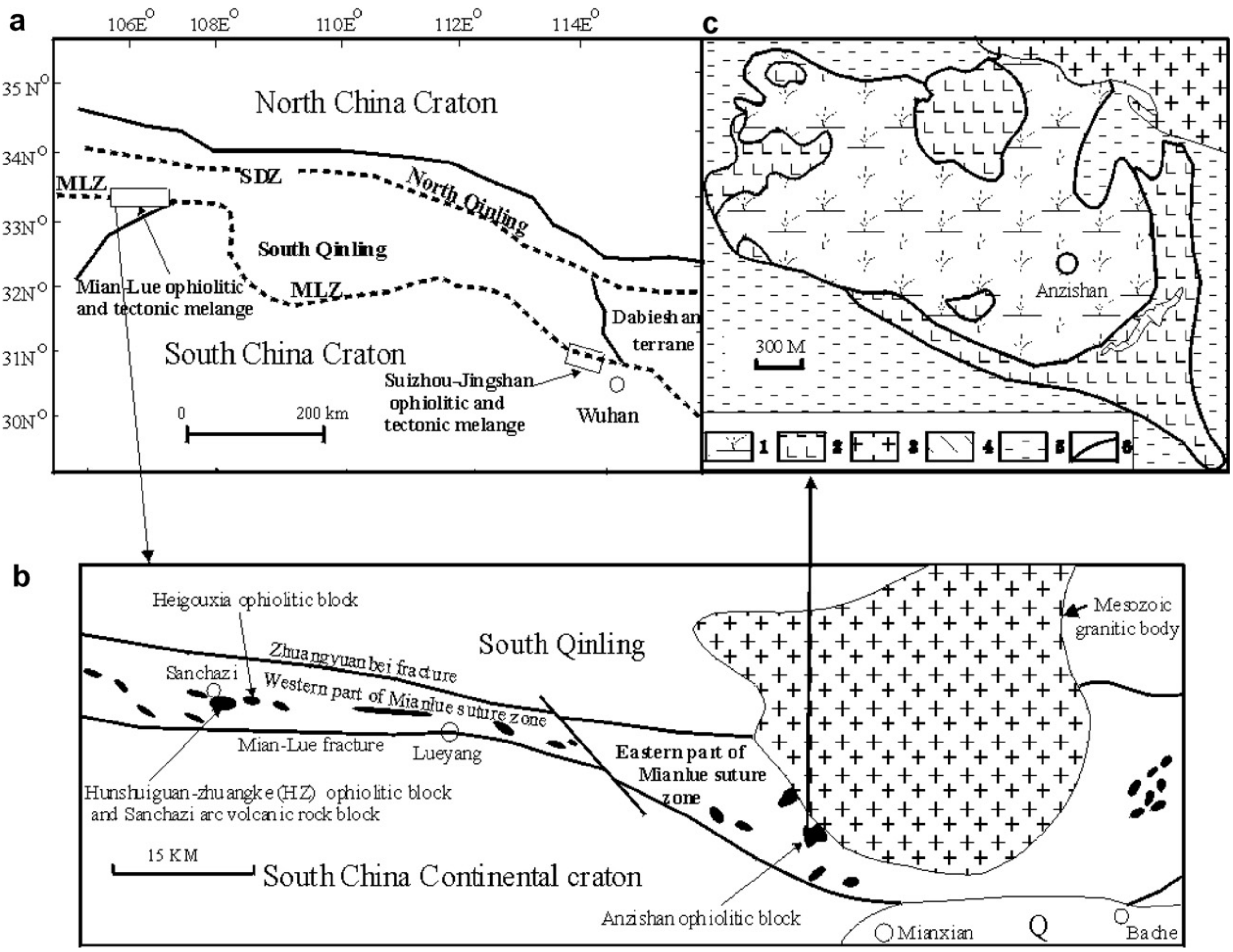

Fig. 1. Geological map of the Mian-Lue suture zone. (a) The location of the Mian-Lue suture zone. MLZ, Mian-Lue suture zone; SDZ, Shangdan suture zone. The location of the Suizhou-Jingshan ophiolite is also shown in the map (after Dong et al., 1999). (b) Distribution of ophiolitic blocks within the Mian-Lue zone. The area between the Mian-Lue and Zhuangyuanbei fractures is the Mian-Lue suture zone. Dark areas are ophiolitic blocks with mafic and ultramafic rocks. (c) Geological map of the Anzishan ophiolite. 1. serpentinized peridotite, 2. meta mafic rocks, 3. Mesozoic granite, 4. plagioclase granite dyke, 5. meta sedimentary rocks, 6. fault.

suture zone, marked by a discontinuous belt of ophiolites (the Mian-Lue ophiolites or MLO), was recognized in the southern Qinling Mountains (Xu et al., 1994; Zhang and Lai, 1995; Zhang et al., 1996). The presence of this suture zone and the MLO indicate that the Qinling orogenic belt underwent a more complex tectonic evolution than previously suspected. Previous workers suggested that the Mian-Lue suture zone marks the site of Paleo-Tethys (e.g., Zhang and Lai, 1995; Xu et al., 1998, 2000a, 2002; Xu and Han, 1996; Li et al., 1996; Meng and Zhang, 1999), but the evidence for this interpretation was inconclusive and the tectonic environment in which the MLO formed was still unresolved. Thus, we have undertaken a detailed investigation of the ophiolites in order to understand their origin and their role in the evolution of the suture zone. In this paper, we present new geochemical data on the MLO, which provide insights into their origin and emplacement. Combined with previous studies, this work places additional constraints on the tectonic development of the Qinling orogenic belt.

2. Geologic setting

The Mian-Lue suture zone (Xu et al., 1994; Zhang and Lai, 1995) extends for about 160 km from east to west through the southern Qinling Mountains (Fig. 1). A recent study by Dong et al. (1999) suggests that the suture zone extends eastward to the Suizhou-Jingshan area (Fig. 1) on the southern side of the Dabie orogenic belt where a contemporaneous ophiolitic belt is present.

The suture zone, which varies in width from 1 to 5 km in the Mian-Lue area (Fig. 1), contains a mélange composed of numerous tectonic slices or blocks of variable size. Most of the blocks or slices are strongly sheared and contain numerous lithologies, including ophiolitic material, arc volcanic rocks, Devonian-Carboniferous and Sinian-Cambrian sedimentary rocks and Precambrian metamorphic rocks. Radiolarian cherts and limestones are locally associated with the ophiolitic blocks. Nearly all of the rocks in the suture zone have been metamorphosed with the metamorphic grade generally increasing from lower greenschist facies in the west to upper greenschist or amphibolite facies in the east.

Of the many ophiolitic blocks within the suture zone, the Anzishan and Hunshuiguan-Zhuangke (HZ) blocks (Fig. 1) are the best developed and most complete. The HZ block, located in the western part of the zone, is well preserved and has been described in detail by** Xu et al. (1998, 2000b, 2002). In contrast, the original structures and lithology of the Anzishan block, located in the eastern part of the suture zone, have been obscured by metamorphism and deformation. Within the Anzishan block, serpentinized harzburgite with minor dunite and listwanite forms an ultramafic core surrounded by amphibolites whose protoliths were mafic volcanic and intrusive rocks. Although highly metamorphosed, the amphibolites still preserve some of their original igneous structures and compositional characteristics, and are distinct from the layered metasedimentary rocks surrounding the ophiolitic block. Locally, a clear depositional contact between the ophiolitic blocks and surrounding sedimentary rocks can be observed, e.g., the amphibolites (meta-basalts and gabbros) underlie layered marbles and schists on the southeast side of the Anzishan block (Fig. 1c).

Previous studies have revealed a number of blocks in the suture zone with a variety of igneous rocks. Based on a bimodal igneous association (meta-tholeiites and dacite–rhyolite), Li et al. (1996) concluded that the meta-volcanic rocks in the Heigouxia block were probably generated in a continental margin rift basin. Xu et al. (1998) reported the presence of highly depleted, N-MORB-type rocks in the HZ block and concluded that they formed by seafloor spreading in an oceanic or back-arc basin setting. Some arc volcanic rocks of the same age as the ophiolites are also preserved within the suture zone (Xu et al., 1998, 2000b; Lai et al., 1998), e.g., in the Sanchazi and Qiaozigou blocks where the volcanic rocks show geochemical features characteristic of Andean-type volcanism (Xu et al., 2000b). The ophiolitic and arc volcanic blocks are now mixed with blocks of Devonian-Carboniferous sedimentary rocks to form the Mianlue tectonic mélange.

The ages of the meta-volcanic rocks are still poorly constrained. Meta-volcanic rocks in the Heigouxia block have a metamorphic age of 242 Ma (Li et al., 1996). On the other hand, radiolarians in the siliceous sedimentary rocks, associated with the HZ and Sanchazi blocks, indicate an early Carboniferous age (Feng et al., 1996), suggesting that the ophiolite was formed earlier. Based largely on the radiolarian ages, Zhang and Lai (1995), Zhang et al. (1996), Xu et al. (1998) and Lai et al. (1998) suggested that the Mian-Lue ocean-arc system was part of the late Paleozoic Paleo-Tethys system. The oceanic basin was probably contiguous with the coeval Kunlun branch of the Tethyan Ocean to the west (Yang et al., 1996; Chen et al., 2001) and the Suizhou-Jingshan branch on the southern side of the Dabie orogenic belt to the east (Dong et al., 1999).

3. Sample descriptions and analytical methods

The present study focuses mainly on the Anzishan block in the eastern part of the Mian-Lue suture zone. The analyzed samples were collected in the central, southeastern and western parts of the block (Fig. 1) and include serpentinized peridotites and amphibolites. All of the original igneous minerals in the amphibolites are replaced by metamorphic assemblages of amphibole, plagioclase, biotite, chlorite and epidote.

The samples were grouped into different rock types based on their petrography and the least altered samples were selected for analysis. The samples were split into small chips, soaked in 5% hydrochloric acid (HCl) for 2 h to leach out any secondary carbonate, then dried and powdered. The major element compositions were measured by wet chemical techniques and Atomic Absorption Spectrometry (AAS), following the procedures described by Gao et al. (1995). Trace elements, including the rare earth elements (REE), were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, using the analytical procedures of Li (1997). Instrumental drift was monitored using the standard sample W-2. Analytical uncertainties are generally better than 5% for most elements but 10% for Cr, Ni and Co. Nd and Pb isotopic ratios of the rocks were analyzed on a VG 354 thermal ionization mass spectrometer (TIMS) also at the Guangzhou Institute of Geochemistry, using the procedures described by Li and McCulloch (1998) and Xu et al. (2002). Nd isotopic ratios were measured in metal form, corrected for fractionation to $^{146}Nd/^{144}Nd = 0.7219$ and are reported relative to $^{143}Nd/^{144}Nd = 0.511860$ for the La Jolla Standard. Analytical uncertainty for the $^{143}Nd/^{144}Nd$ measurements is ±0.00002. Pb isotopic ratios were corrected for fractionation using replicate analyses of the standard NBS981 and normalized to the values of Todt et al. (1984); analytical uncertainties are better than 0.10/00per amu.

4. Effects of alteration and metamorphism

It is generally believed that medium- to high-grade regional metamorphism is isochemical (Winkler, 1976; Mason, 1978). On the other hand, studies have shown that seawater alteration of ocean floor rocks may modify their mobile elements such as Sr, K, Rb, Ba, and U, but that it generally does not affect high field strength elements (HFSE) and REE (e.g., Ludden and Thompson, 1978; Bienvenu et al., 1990; Verma, 1992). The mafic rocks from the MLO underwent variable degrees of metamorphism and alteration as mentioned above. Their mobile elements show a variable range of concentrations, suggesting that the original contents of these elements have been modified, but the REE and HFSE display coherent and subparallel trace element patterns (Figs. 2 and 3), indicating little mobility. Thus, the mobile elements are not used in the following geochemical discussions.

$^{143}Nd/^{144}Nd$ ratios of rocks are little affected by alteration because seawater is exceedingly low in Nd (4×10^{-6} ppm; Mahoney et al., 1998) thus, the high

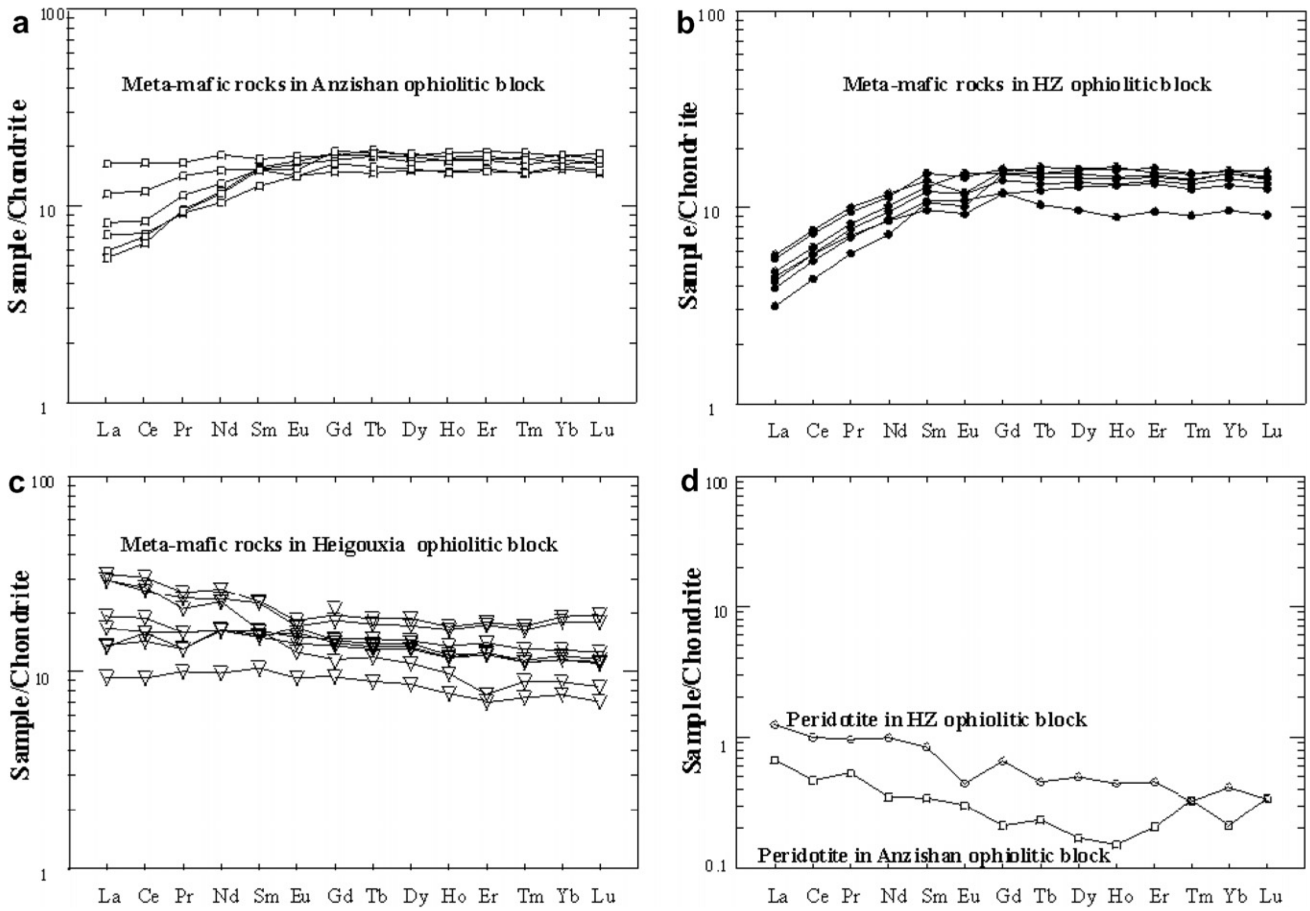

Fig. 2. Chondrite-normalized REE patterns of several Mian-Lue ophiolites (MLO). (a) Meta-mafic rocks (amphibolites) in the Anzishan ophiolitic block, (b) Meta-basalts and gabbros in the HZ ophiolitic block (Xu et al., 1998, 2002), (c) REE patterns of the meta-basalts in the Heigouxia block (data after Li et al., 1996) are shown for comparison. (d) Ultramafic rocks (harzburgites) from the Anzishan and HZ ophiolitic blocks (Xu et al., 1998). The chondrite normalizing values are after Sun and McDonough (1989).

$^{143}Nd/^{144}Nd$ ratios of the MLO samples cannot be attributed to alteration because alteration decreases, rather than increases, $^{143}Nd/^{144}Nd$ ratios (e.g., Cheng et al., 1987; McCulloch et al., 1981). On the other hand, with absence of Pb concentration data, the measured Pb isotopic ratios listed in Table 2, cannot be assumed to be original. Thus, we do not use Pb isotopic compositions in the discussions below.

5. Analytical results

Major and trace element compositions of the analyzed samples are listed in Table 1. The samples are divided into ultramafic and mafic based on their SiO_2 contents. Ultramafic samples are serpentinized harzburgites with major element compositions very similar to peridotites in other ophiolites such as Semail and Troodos (Coleman, 1977; Batanova and Sobolev, 2000; Girardeau et al., 2004). Mafic rocks (meta-basalts, meta-gabbros, and amphibolites) from the MLO are subalkaline basalts based on the Nb/Y vs. Zr/TiO_2 classification scheme (Fig. 4). Based on their TiO_2, MgO, SiO_2, and CaO contents, these rocks are tholeiitic in composition, very similar to normal MORB. No intermediate and silicic rocks have been observed in the Anzishan and HZ ophiolitic blocks, unlike the Heigouxia (Li et al., 1996) and Sanchazi blocks (Xu et al., 2000b; Lai et al., 1998).

Serpentinized harzburgites in the Anzishan and HZ ophiolites have flat to U-shaped, chondrite-normalized REE patterns (Fig. 2d) similar to those of typical ophiolite peridotites (Henderson, 1984). On the other hand, the Anzishan mafic rocks have variable REE patterns ranging from flat to light rare earth (LREE) depleted, with La/$Yb_{(N)}$ values ranging from 0.32 to 1.11. Rocks from the HZ ophiolite show the strongest LREE depletion, followed by those from Anzishan, which vary from LREE depleted to undepleted. Those from the Heigouxia block have chondrite-normalized patterns ranging from flat to weakly LREE enriched (Li et al., 1996).

The Anzishan mafic rocks are relatively depleted in highly incompatible trace elements in a primitive mantle-normalized diagram (Fig. 3), similar to those from the HZ ophiolite. Their incompatible trace element patterns are similar to those of N-MORB (Fig. 3), except for some mobile elements (e.g., Rb, Ba, Sr, and U), the concentrations of which are easily influenced by seawater alteration.

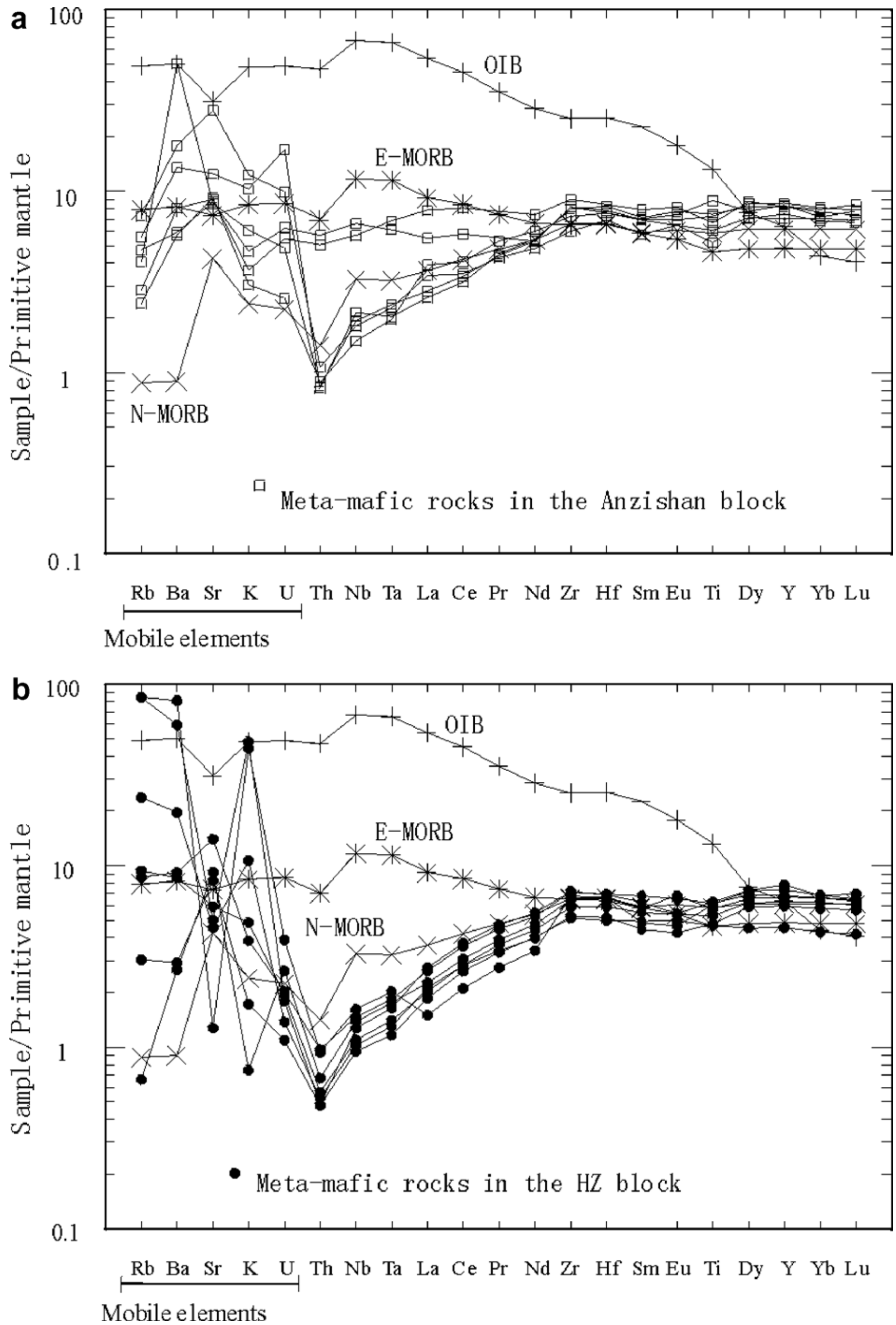

Fig. 3. Primitive mantle-normalized trace element patterns of mafic rocks in the MLO. a) Anzishan ophiolitic block. b) HZ ophiolitic block shown for comparison with data from Xu et al. (1998, 2002). Mafic rocks in both blocks show a clear depletion of incompatible elements relative to primitive mantle values, except for several mobile elements. Most of the mafic rocks are even more depleted than N-MORB. Data for the primitive mantle, N-MORB, E-MORB and OIB are from Sun and McDonough (1989).

These samples do not exhibit negative Nb and Ta anomalies (Fig. 3), which are characteristic of arc volcanic rocks (e.g., Wood et al., 1979). The trace element compositions of the mafic rocks also differ from those of the Heigouxia block, which show flat incompatible element spider diagrams (Li et al., 1996). In summary, the mafic rocks of the Anzishan ophiolitic block are characteristically depleted in incompatible trace elements. They are closer in composition to N-MORB than to any other modern rock type, although some are more depleted than N-MORB (Fig. 3a and b).

The Anzishan mafic rocks have high Nd isotopic ratios ($^{143}Nd/^{144}Nd$ up to 0.51336), and the εNd($t = 350$ Ma) ranges from +6.0 to +12.8. These values confirm that all the rocks were derived from a depleted mantle source similar to that of N-MORB. The Anzishan mafic rocks have a

Table 1
Major and trace element compositions of rocks from the Anzishan ophiolite

Sample	97050	97051	95007	95008	10052	10053	93176
Rock	Am	Am	Am	Am	Am	Am	Hz
SiO_2	53.53	47.10	50.08	47.74	51.40	52.19	38.64
TiO_2	1.44	1.91	1.10	1.57	1.54	1.29	0.01
Al_2O_3	14.99	15.00	13.94	13.46	13.04	12.75	0.88
Fe_2O_3	12.35	15.70	5.43	4.19	4.05	3.32	6.35
FeO	0.00	0.00	6.94	9.58	8.94	9.07	2.04
MnO	0.17	0.20	0.21	0.23	0.20	0.27	0.08
MgO	5.51	8.04	6.28	8.18	6.66	7.73	37.16
CaO	7.84	7.91	12.35	9.16	9.63	9.57	0.73
Na_2O	3.42	3.28	0.80	2.62	1.95	1.60	0.04
K_2O	0.14	0.11	0.36	0.30	0.18	0.09	0.02
P_2O_5	0.12	0.11	0.05	0.08	0.12	0.10	<0.01
H_2O	n.d.	n.d.	1.42	2.25	1.97	1.88	11.89
CO_2	n.d.	n.d.	0.82	0.43	0.00	0.00	1.35
LOI	0.46	0.63	n.d.	n.d.	n.d.	n.d.	n.d.
SUM	99.97	99.99	99.78	99.79	99.68	99.86	99.19
Cr	22	191	161	145	81	161	3220
Ni	24	87	61	81	49	89	1850
Co	24	46	45	63	50	54	107
Sc	43	53	45	58	54	58	7.5
V	430	441	402	497	492	462	
Zn	98	104	114	152	147	116	54
Rb	3	2	5	3	3	2	<2
Ba	41	56	121	92	344	39	17.2
Sr	183	189	575	255	176	190	15.1
Ta	0.28	0.24	0.09	0.08	0.09	0.08	<0.10
Nb	4.0	4.7	1.3	1.5	1.3	1.0	<1
Hf	2.32	2.25	2.09	2.47	2.36	2.29	0.34
Zr	100	91	66	87	89	80	19.3
Y	37	38	33	36	38	31	0.3
Th	0.52	0.48	0.09	0.07	0.07	0.07	3.9
U	0.14	0.12	0.20	0.34	0.10	0.05	0.4
La	5.37	3.76	2.29	1.73	1.89	2.64	0.19
Ce	14.21	10.20	6.07	5.44	5.90	7.09	0.35
Pr	2.14	1.83	1.16	1.21	1.19	1.44	0.06
Nd	11.34	9.45	6.37	7.18	7.05	7.97	0.19
Sm	3.48	3.09	2.49	3.07	3.02	3.01	0.06
Eu	1.36	1.24	1.06	1.26	1.14	1.06	0.02
Gd	4.92	4.67	4.00	4.87	5.08	4.42	0.05
Tb	0.95	0.88	0.71	0.87	0.90	0.77	0.01
Dy	6.10	5.67	5.06	5.91	6.13	5.16	0.05
Ho	1.42	1.31	1.12	1.26	1.32	1.11	0.01
Er	4.20	3.81	3.36	3.70	3.90	3.29	0.04
Tm	0.65	0.61	0.50	0.55	0.58	0.50	0.01
Yb	3.88	3.53	3.30	3.66	3.90	3.42	0.04
Lu	0.62	0.57	0.48	0.53	0.57	0.50	0.01
La/Yb*	0.92	0.71	0.46	0.32	0.32	0.52	3.18

* Am, amphibolites (meta-mafic rocks), Hz, serpentinized harzburgite. La/Yb, $(La)_N/(Yb)$. n.d, not determined.

wider range of Nd isotopic values than those from the HZ and Heigouxia blocks (Table 2). Measured Pb isotopic ratios ($^{206}Pb/^{204}Pb$) of the Anzishan meta-mafic rocks vary from 17.044 to 18.101. Four mafic rocks from the south-eastern part of the Anzishan block show an unradiogenic Pb isotopic composition ($^{206}Pb/^{204}Pb < 17.474$), similar to the MORB-type rocks in the HZ block, but the two samples collected in the western part of this block have relatively high $^{206}Pb/^{204}Pb$ ratios ($\sim$18.000), which are similar to those of arc volcanic rocks in the Sanchazi block (Xu et al., 2000b). It is uncertain if the relatively high $^{206}Pb/^{204}Pb$ ratios are due to addition of a subducted component.

6. Discussion

6.1. Tectonic environment of the MLO and evolution of the Mian-Lue ocean basin

One major objective of this study is to constrain the tectonic evolution of the Qinling orogenic belt in which the ophiolites occur. For this purpose, we must first determine the tectonic environment(s) in which the ophiolites formed. Previous investigations suggested that the MLO were formed in a variety of different tectonic environments. The Anzishan and HZ mafic rocks have high $\varepsilon_{Nd(t)}$, and low $(La/Yb)_N$ values with no Nb and Ta anomalies, generally comparable to N-MORB. This assignment is confirmed by primitive mantle-normalized trace element diagrams (Fig. 3), in which the mafic rocks have patterns similar to N-MORB, but with even greater depletion in most incompatible elements. Moreover, all of the Anzishan and HZ mafic samples plot in the N-MORB field on Th–Hf–Ta (Fig. 5a) and Th/Yb vs. Ta/Yb diagrams (Fig. 5b), except for two samples from the western part of the Anzishan block that plot in the arc tholeiite field. Except for these two samples, all of the Anzishan and HZ mafic rocks are typical of modern N-MORB (e.g., Castillo et al., 1994), but as observed above, such rocks may also occur in mature back-arc basin lavas, e.g., the Mariana backarc basin (Gribble et al., 1996, 1998) and the Zambales BABB-ophiolite (Evans et al., 1991; Encarnacion et al., 1999). Thus, we are unable to determine unequivocally the environment of formation of the Anzishan and HZ mafic rocks. However, based on their geochemistry and general tectonic position, we suggest that these rocks were probably generated from depleted asthenosphere in a mature back-arc basin.

The Sanchazi arc volcanic block is located near the HZ block. Previous studies revealed that the volcanic rocks within the Sanchazi block are mainly meta-andesites that show arc volcanic geochemical signatures, thus they were interpreted as the product of suprasubduction zone magmatism in an active continental margin (Xu et al., 1998, 2000b; Lai et al., 1998). Such close spatial association of ophiolitic and arc blocks suggests a possible tectonic link between them. If the HZ ophiolite was formed in a backarc basin, the Sanchazi volcanic rocks most likely formed in the nearby arc, which was probably an Andean-type magmatic arc (Xu et al., 2000b).

Unlike the Sanchazi block with its arc volcanic rocks, the Heigouxia block contains a bimodal volcanic suite composed of meta-basalts and dacites-rhyolites; no andesites have been found within the block. In addition, the meta-volcanic rocks in the Heigouxia block are associated with meta-sedimentary marbles and phyllites. Geochemically, the Heigouxia meta-basalts have higher La/Yb ratios

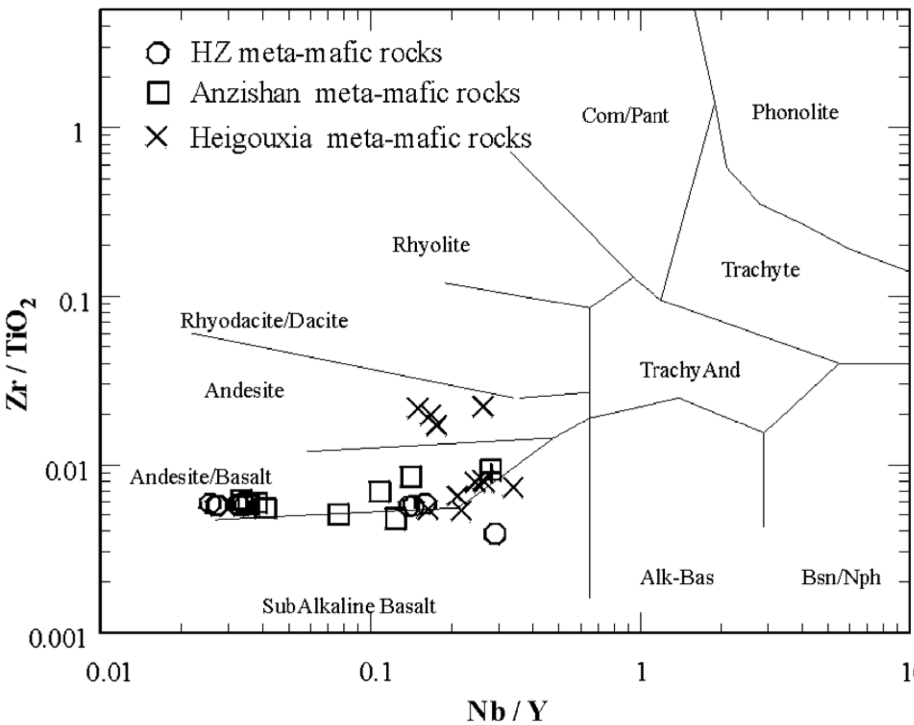

Fig. 4. Classification of mafic rocks in the MLO using the Nb/Y- Zr/TiO_2 diagram (Winchester and Floyd, 1976). The data for rocks in the Heigouxia and HZ blocks are after Li et al. (1996) and Xu et al. (1998, 2002), respectively. The Anzishan and HZ ophiolitic blocks have rock associations different from the Heigouxia block that contains intermediate-silicic rocks.

Table 2
Nd and Pb isotopic compositions of mafic rocks (amphibolites) in the Anzishan ophiolitic block

Sample #	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd(t)}$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
95007	2.49	6.37	0.2364	0.51336	12.2	17.389	15.487	36.997
95008	3.07	7.18	0.2589	0.51344	12.8	17.474	15.468	36.899
10047	5.78	17.29	0.2034	0.51296	6.0			
10052	3.02	7.05	0.2586	0.51334	10.8	17.044	15.472	36.953
10053	3.01	7.97	0.2285	0.51321	9.6	17.341	15.484	37.069
93181	2.78	10.77	0.1586	0.51297	8.2	18.101	15.542	37.753
93183	2.26	6.10	0.2244	0.51318	9.2	17.993	15.601	37.932

$\varepsilon_{Nd(t)}$ values were calculated using $t = 350$ (Ma) for the early Carboniferous age. Sm and Nd concentrations were analyzed by ICP-MS at the Isotopic Lab of Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Nd and Pb isotopic ratios were measured by TIMS at the same lab.

and lower $\varepsilon_{Nd(t)}$ values (Li et al., 1996) than the Anzishan and HZ lavas. The Heigouxia mafic samples also display flat or slightly LREE-enriched chondrite-normalized REE patterns (Li et al., 1996) (Figs. 2 and 6). Thus, the igneous association and geochemistry of the meta-basalts suggests formation in an early ocean basin developed by rifting of a continental margin (Li et al., 1996).

We conclude that the MLO and other igneous blocks in the Mian-Lue suture zone record the full evolution of the ancient Mian-Lue ocean basin. First, an initial ocean basin was created by rifting of continental basement, which produced the bimodal volcanic suite in the Heigouxia block. Continued spreading of the initial ocean (or rift) produced a mature ocean basin in which the N-MORB-type mafic rocks such as those in the HZ block were erupted. Southward subduction of the oceanic lithosphere produced the arc volcanic rocks of the Sanchazi block and created a back-arc basin in which some of the Anzishan lavas were erupted. Consumption of the oceanic lithosphere caused closure of the ocean basin and continent–continent collision along the Mian-Lue suture zone.

If this interpretation is correct, the Mian-Lue branch of Tethys in the late Paleozoic was a fully developed ocean basin with an arc-trench-ridge system. Dong et al. (1999) suggested that the basin extended eastward about 1000 km to the Suizhou-Jingshan area (Fig. 1b), where there is a contemporaneous MORB-type ophiolite. In addition, Chen et al. (2001) proposed that the Mian-Lue ophiolite belt extends westward to Dur'ngoi in West Qinling where a Carboniferous ophiolite has been recognized. The pres-

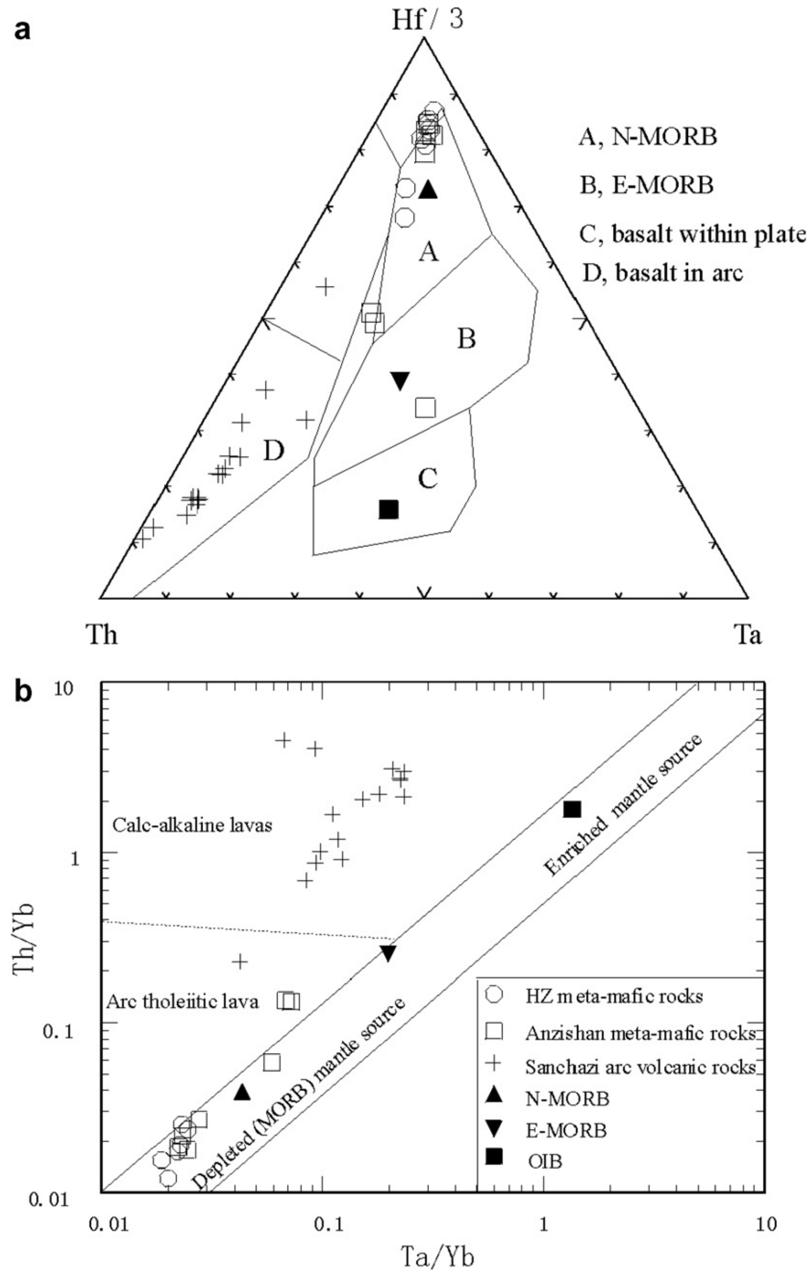

Fig. 5. Discrimination of the tectonic setting of mafic rocks in the MLO using the Th–Hf–Ta diagram (after Wood et al., 1979) and the Th/Yb–Ta/Yb diagram (after Pearce et al., 1984). Data for the Sanchazi arc volcanic rocks are after Xu et al. (2000b).

ence of such widespread MORB-type ophiolites is consistent with the interpretation that the Mian-Lue Tethys was a major ocean basin.

6.2. Implications for the tectonic evolution of the Qinling orogenic belt

Two different ages of collision between the North and South China Cratons have been proposed; middle Paleozoic and late Triassic. Evidence for a middle Paleozoic collision comes largely from geological and geochemical data. For example, Mattauer et al. (1985) argued on the basis of regional tectonic patterns that the ocean basin between the two cratons closed prior to the middle Devonian. From geochemical variations of sedimentary rocks in the Qinling region through time, Gao et al. (1995) suggested that the South China Craton was accreted to the North China Craton along the Shangdan suture zone during Silurian-Devonian time. Zhang et al. (1997) deduced that the South China crust was subducted beneath the North China Craton in the Devonian based on Pb isotopic variations of Paleozoic granitoids in the Qinling Mountains.

In contrast, paleomagnetic and geochronologic data for ultrahigh-pressure (UHP) metamorphic rocks in the Dabie terrane, which extends westward to the Qinling Mountains, do not support a middle Paleozoic collision. Paleomagnetic

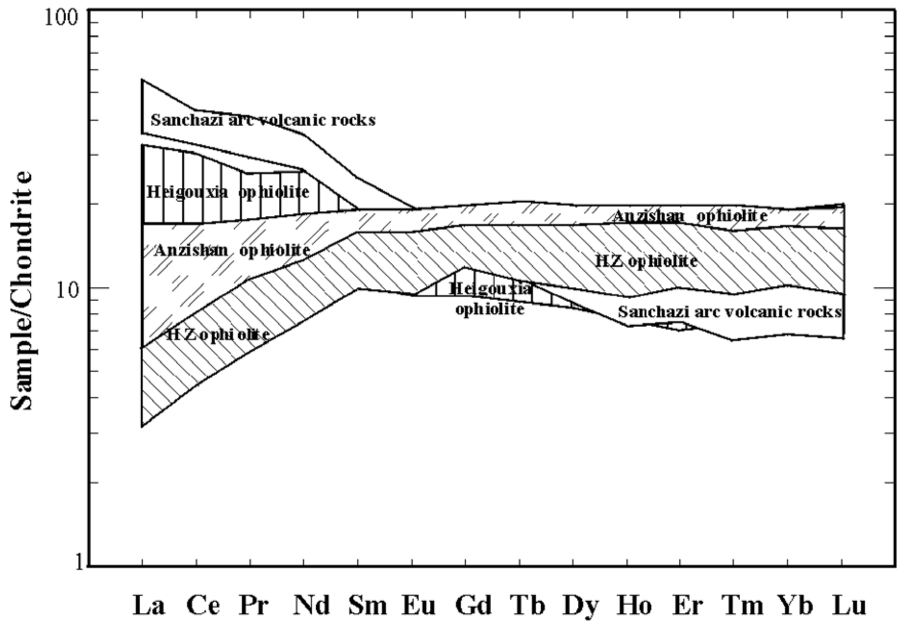

Fig. 6. Comparison of chondrite-normalized REE compositions for the different mafic rocks of the Mian-Lue suture zone. The HZ ophiolite shows the most depleted pattern (Xu et al., 2002), followed by the Anzishan ophiolite, which varies from LREE depleted to un-depleted. The Heigouxia meta-basalts have flat to weakly LREE-enriched patterns (Li et al., 1996), and the Sanchazi arc volcanic rocks have LREE-enriched patterns (Xu et al., 2000b; Lai et al., 1998).

data (Lin et al., 1985; Enkin et al., 1992; Yang et al., 1992) suggest that South China was still separated from the North China Craton in the Permian and that collision did not begin until the Triassic. The paleomagnetic interpretations are consistent with geochronological data on the Dabie UHP metamorphic rocks, which are believed to have formed by continent-continent collision between the North and South China cratons. Ages of the UHP rocks range from 209–232 Ma (Li et al., 1993; Ames et al., 1993; Okay and Sengor, 1993), suggesting that collision occurred in the late Triassic.

It should be noted that although the Dabie terrane extends westward to the East Qinling Mountain, no paleomagnetic or geochronologic data are available from the Mian-Lue area. Nevertheless, our data strongly support the presence of a fully developed oceanic basin, with an associated arc-trench system, in the Mian-Lue region in the Late Paleozoic, according to the age of siliceous sedimentary rocks within the Mian-Lue suture zone. Evidence for an intracontinental tectonic regime in the Qinling Mountains in the latest Triassic (Zhang and Lai, 1995; Meng and Zhang, 2000) places an upper limit on the time of accretion. The Mian-Lue branch of Tethys probably opened prior to the early Carboniferous (Feng et al., 1996). As mentioned above, this oceanic basin was part of a larger Tethyan Ocean that extended as far east as the Suizhou-Jingshan area in the Late Paleozoic.

On the other hand, evidence for a middle Paleozoic collision does exist in the Qinling orogenic belt, although not in the Mian-Lue suture zone. A possible interpretation is that there was an initial collision along the Shangdan suture zone (Fig. 1) between the South and North China cratons during the middle Paleozoic that did not produce a final amalgamation. In this model, the initial collision in the Devonian would have been followed by rifting along the Mian-Lue suture zone to produce the Mian-Lue branch of Tethys in the late Paleozoic (Fig. 7). Closure of this basin would have led to final amalgamation along the Mian-Lue suture zone in the late Triassic as discussed above.

7. Conclusions

The Anzishan and HZ blocks are ophiolitic bodies in the Mian-Lue suture zone. Most of the mafic rocks in these ophiolites were derived from an extremely depleted mantle source and were probably erupted in a mature backarc basin, although a mid-oceanic ridge origin can not be excluded. In addition to the Anzishan and HZ blocks, the Mian-Lue suture zone contains blocks composed of arc volcanic rocks and a bimodal mafic/dacite-rhyolite suite. These various blocks record the evolution of the Mian-Lue Tethyan Ocean in the late Paleozoic, from initial rifting to generation of a mature oceanic basin, followed by subduction and closure of the basin.

The Mian-Lue Tethyan Ocean separated the North and South China cratons during the Late Paleozoic. Amalgamation of the two cratons was initiated with closure of the Mian-Lue oceanic basin in the late Paleozoic. Final amalgamation most likely occurred in the late Triassic. However, an earlier collision between the North and South China cratons could have taken place in the middle Paleozoic along some part of the Qinling orogenic belt, such as the Shangdan suture zone.

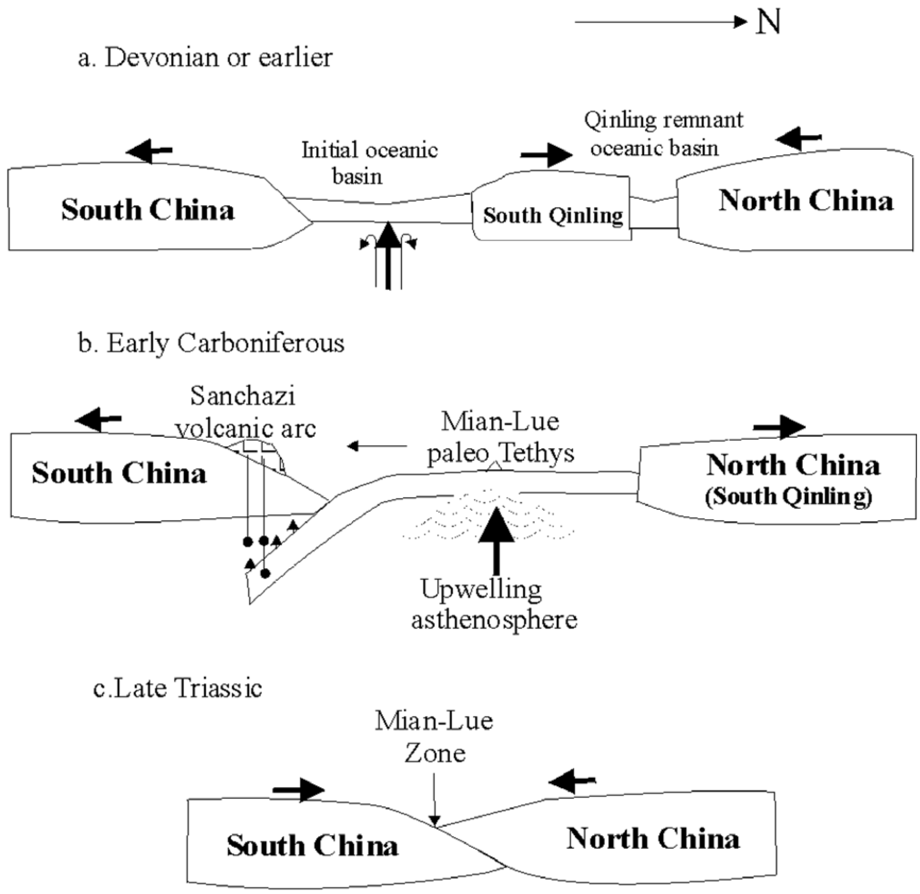

Fig. 7. Tectonic evolution model of the Mian-Lue Tethyan Ocean. (a). In the Devonian or earlier, the North China Craton started to collide with the South China Craton along the Shangdan suture zone on the northern side of the south Qinling block (Gao et al., 1995). Meanwhile, the Mian-Lue rift was initiated by extension along the Mian-Lue zone. The south Qinling block was part of the South China Craton, but was separated from the latter by spreading of the Mian-Lue initial rift. Arrows on the diagram indicate the direction of movement of the continental cratons. (b). By the Early Carboniferous, the full Mian-Lue Tethyan ocean basin had been generated by seafloor spreading, and the oceanic lithosphere was being subducted beneath the South China Craton producing the Sanchazi continental margin arc. The Mian-Lue Tethyan Ocean separated the South China Craton from the North China Craton at that time. (c). In the Triassic the South China and North China Cratons were joined to create the present continent along the Mian-Lue suture zone.

Acknowledgments

We thank Dr. P. R. Castillo for assistance with an early version of the manuscript, Dr. M.-F. Zhou for constructive comments and J. Bedard and Y. Dilek for constructive reviews. We also thank Zhang Fa-cheng for his help during fieldwork, and Liu Yin, Liu Hanchen, and Tu Xianglin for their help with the analyses. This work was supported by grants from the NSFC (project No. 40425003, 49603045).

References

Ames, L., Tilton, G.R., Zhou, G., 1993. Timing of collision of the Sino-Korean and Yangtze Cratons: U–Pb dating of coesite-bearing eclogites. Geology 21, 339–342.

Batanova, V.G., Sobolev, A.V., 2000. Compositional heterogeneity in subduction-related peridotites, Troodos massif, Cyprus. Geology 28, 55–58.

Bienvenu, P., Bougault, H., Joron, M., Dmitriev, L., 1990. MORB alteration: rare-earth element/non-rare-earth hygromagmaphile element fractionation. Chemical Geology 82, 1–14.

Bloomer, S.H., Taylor, B., MacLeod, C.J., Stern, R.J., Fryer, P., Hawkins, J.W., Johnson, L., 1995. Early arc volcanism and ophiolite problem: A perspective from drilling in the western Pacific. In: Taylor, B., Natland, J. (Eds.), Active Margins and Marginal Basins of the Western Pacific, vol. 88. American Geophysical Union Monograph, Washington D.C., pp. 1–30.

Castillo, P.R., Pringle, M.S., Carlson, R.W., 1994. East Mariana basin tholeiites: Cretaceous intraplate basalts or rift basalts related to the Ontong Java plume? Earth and Planetary Science Letters 123, 139–154.

Chen, L., Sun, Y., Pei, X.-Z., Gao, M., Feng, T., Zhang, Z.-Q., Chen, W., 2001. Northernmost paleo-tethyan oceanic basin in Tibet: Geochronological evidence from Ar-40/Ar-39 age dating of the Dur'ngoi ophiolite. Chinese Science Bulletin 46, 1203–1205.

Cheng, Q., Park, K.H., Macdougall, J.D., Zindler, A., Lugmair, G.W., Hawkins, J., Lonsdale, P., Staudigel, H., 1987. Isotopic evidence for a hotspot origin of the Louisville seamount chain. In: Keating, B., Fryer, P., Batiza, R., Boechlert, G. (Eds.), Seamounts, Islands and Atolls, vol. 43. American Geophysical Union Monograph, pp. 283–296.

Coleman, R.G., 1977. OphiolitesAncient Oceanic Lithosphere? Springers-Verlag, Berlin, pp. 5–90.

Dilek, Y., Moores, E., Elthon, D., Nicolas, A., 2000. Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program. Geological Society of America Special Paper 349, 3–34.

Dilek, Y., Robinson, P.T., 2003. Ophiolites in Earth History, vol. 218. Geological Society, London Special Publications, 717 pp.

Dong, Y.-P., Zhang, G.-W., Lai, S.-C., Zhou, D.-W., Zhu, B.-Q., 1999. An ophiolitic tectonic mélange first discovered in Huashan area, south margin of the Qinling orogenic belt, and its tectonic implications. Science in China (D) 43, 292–302.

Encarnacion, J., Mukasa, S.B., Evans, C.A., 1999. Subduction components and generation of arc-like melts in the Zambales ophiolite, Philippines: Pb, Sr and Nd isotopic constraints. Chemical Geology 156, 343–357.

Enkin, R.J., Yang, Z., Chen, Y., Courtillot, V., 1992. Paleomagnetic constraints on the geodynamic history of the major blocks of China from Permian to the present. Journal of Geophysical Research 97, 13953–13989.

Evans, C.A., Casteneda, G., Franco, H., 1991. Geochemical complexities preserved in the volcanic rocks of the Zambales ophiolite, Philippines. Journal of Geophysical Research 96, 16251–16262.

Feng, Q.-L., Du, Y.-S., Yin, H.-F., Shen, J.-H., Xu, J.-F., 1996. Carboniferous radiolarian fauna firstly discovered in Mian-Lue ophiolitic mélange belt of South Qinling Mountains. Science in China (Series D) 39 (supp.), 87–92.

Gao, S., Zhang, B.-R., Gu, X.-M., Xie, X.-L., Gao, C.-L., Guo, X-M., 1995. Silurian-Devonian provenance changes of South Qinling basin: implications for accretion of the Yangtze (South China) to the North China Craton. Tectonophysics 250, 183–197.

Girardeau, J., Monnier, C., Lemée, L., Quatrevaux, F., 2004. The Wuqbah peridotite, central Oman Ophiolite: Petrological characteristics of the mantle in a fossil overlapping ridge setting. Marine Geophysical Researches 23, 43–56.

Gribble, R.F., Stern, R.J., Bloomer, S.H., Stuben, D., O'Hearn, T., Newman, S., 1996. MORB mantle and subduction components interact to generate basalts in the southern Mariana Trough back-arc basin. Geochemica et Cosmochimica Acta 60, 2153–2166.

Gribble, R.F., Stern, R.J., Newman, S., Bloomer, S.H.D., O'Hearn, T., 1998. Chemical and isotopic composition of lavas from the Northern Mariana Trough: implications for magma genesis in back-arc-arc basins. Journal of Petrology 39, 125–154.

Henderson, P. (Ed.), 1984. Rare Earth Element Geochemistry. Elsevier, Amsterdam, p. 510 p.

Lai, S.-C., Zhang, G.-W., Yang, Y.-C., Chen, J.-Y., 1998. Geochemistry of the ophiolite and island arc volcanic rock in the Mianxian-Lueyang suture zone, Southern Qinling and their tectonic significance. Geochemica 27, 283–293 (in Chinese with English abstract).

Li, S.-G., Chen, Y., Cong, B.-L., Zhang, R., Liou, D., Hart, S.R., Ge, N., 1993. Collision of the North China and Yangtze blocks and formation of coesite-bearing eclogites: timing and processes. Chemical Geology 109, 70–89.

Li, S.-G., Sun, W.-D., Zhang, G.-W., 1996. Chronology and geochemistry of metavolcanic rocks from Higouxia valley in the Mian-Lue tectonic belt, South Qinling evidence for a Paleozoic oceanic basin and its closure time. Science of China (Series D) 39, 300–310.

Li, X.-H., 1997. Geochemistry of the Longsheng ophiolite from the southern margin of Yangtze Craton, SE China. Geochemical Journal 31, 323–337.

Li, X.-H., McCulloch, M.T., 1998. Geochemical characteristics of Cretaceous mafic dikes from Northern Guangdong, SE China: age, origin and tectonic significance. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia, vol. 27. American Geophysical Union Geodynamics Series, Washington, pp. 405–419.

Lin, J., Fuller, M., Zhang, W., 1985. Preliminary Phanerozoic polar wander paths for the North and South China blocks. Nature 313, 444–449.

Ludden, J.N., Thompson, G., 1978. Behavior of rare earth elements during submarine weathering of tholeiitic basalts. Nature 274, 147–149.

Mason, R., 1978. Petrology of the Metamorphic Rocks. George Allen & Wnwin, 256 p.

Mahoney, J.J., Frei, R., Tejada, M.L.G., Mo, X.X., Leat, P.T., Nagler, T.F., 1998. Tracing the Indian Ocean mantle domain through time: isotopic results from old west Indian, east Tethyan, and South Pacific seafloor. Journal of Petrology 39, 1285–1306.

Mattauer, M., Matte, P., Malavieille, J., Tapponnier, P., Maluski, H., Xu, Z., Lu, Y., Tang, Y., 1985. Tectonics of the Qinling belt: Build-up and evolution of eastern Asia. Nature 317, 496–500.

McCulloch, M.T., Gregory, R.T., Wasserburg, G.J., Taylor, H.T., 1981. Sm–Nd, Rb–Sr, and $^{18}O/^{16}O$ isotopic systematics in an oceanic crustal section: evidence from the Samail ophiolites. Journal of Geophysical Research 86, 2721–2735.

Meng, Q.-R., Zhang, G.-W., 1999. Timing of collision of the North and South China blocks: Controversy and reconciliation. Geology 27, 123–126.

Meng, Q.-R., Zhang, G.W., 2000. Geologic framework and tectonic evolution of the Qinling orogen, central China. Tectonophysics 323, 183–196.

Nicholson, K.N., Black, P.M., Picard, C., 2000. Geochemistry and tectonic significance of the Tangihua ophiolite complex, New Zealand. Tectonophysics 321, 1–15.

Okay, A.I., Sengor, A.M.C., 1993. Tectonics of an ultrahigh-pressure metamorphic terrane: the Dabie Shan/Tongbai Shan orogen, China. Tectonics 12, 1320–1334.

Pearce, J.A., Lippard, S.J., Roberts, S., 1984. Characteristics and tectonic significance of super-subduction zone ophiolites. In: Kokelaar, B.P., Howells, M.F. (Eds.), Marginal Basin Geology, vol. 16. Geological Society London Special Publication, pp. 77–94.

Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematic of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, J. (Eds.), Magmatism in the Ocean Basins, vol. 42. Geological. Society London, Special Publication, pp. 313–345.

Todt, W., Cliff, R.A., Hanzer, A., Hofmann, A.W., 1984. $^{202}Pb+^{205}Pb$ double spike for lead isotopic analysis. Terra Cognita 4, 209.

Verma, S.P., 1992. Seawater alteration effects on REE, K, Rb, Cs, Sr, U, Th, Pb and Sr-Nd-Pb isotope systematics of Mid-Ocean Ridge basalt. Geochemical Journal 26, 159–177.

Wallin, E.T., Metcalfe, R.V., 1998. Supra-subduction zone ophiolite formed in an extensional forearc: Trinity Terrane, Klamath Mountains, California. Journal of Geology 106, 591–608.

Winchester, J.A., Floyd, P.A., 1976. Geochmical magma type discrimination: application to altered and metamorphosed basic igneous rocks. Earth and Planetary Science Letters 28, 459–469.

Winkler, H.G.F., 1976. Petrogenesis of Metamorphic Rocks. Springer-Verlag, Berlin, 334 pp.

Wood, D.A., Joron, J.L., Treuil, M., 1979. A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings. Earth and Planetary Science Letters 45, 326–336.

Xu, J.-F., Zhang, B.-R., Han, Y.-W., 1994. Recognition of ophiolite belt and granulite in Northern Area of Mian-Lue, Southern Qinling, China and their implication. Journal of China University of Geosciences 5, 25–27.

Xu, J.-F., Han, Y.-W., 1996. High radiogenic Pb-isotope composition of ancient MORB-type rocks from Qinling area: Evidence for the presence of Tethyan-type oceanic mantle. Science in China (Series D) 39 (sul), 33–42.

Xu, J.-F., Yu, X.-Y., Li, X.-H., Han, Y.-W., Shen, J.-H., Zhang, B.-R., 1998. The discovery of the high depleted N-MORB-type volcanic rocks: new evidence for Paleo Ocean of Mian-Lue. Chinese Science Bulletin 43, 510–514.

Xu, J.-F., Yu, X.-Y., Li, X.-H., Zhang, B.-R., Han, Y.-W., 2000a. Geochemistry of the Anzishan ophiolitic complex in the Mian-Lue belt of Qinling: evidence and implications for the palaeo-ocean crust. Acta Geologica Sinica 74, 39–50 (In Chinese with English abstract).

Xu, J.-F., Wang, Q., Yu, X.-Y., 2000b. Geochemistry of high-Mg andesite and adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic mélange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Paleo-Tethyan crust and its implications. Geochemical Journal 34, 359–377.

Xu, J.-F., Castillo, P.R., Li, X.-H., Yu, X.-Y., Zhang, B.-R., Han, Y.-W., 2002. MORB-type rocks from the Paleo-Tethyan Mian-Lueyang northern ophiolite in the Qinling Mountains, central China: implications for the source of the low $^{206}Pb/^{204}Pb$ and high $^{143}Nd/^{144}Nd$ mantle component in the Indian Ocean. Earth and Planetary Science Letters 198, 323–337.

Xu, Z.-Q., Lu, Y.-L., Tang, Y.-Q., Zhang, Z.-T., 1988. Formation of composite mountain chains of the East Qinling: formation, evolution, and plate dynamics. China Environmental Science Press, Beijing, pp. 90–102. (In Chinese with English abstract).

Xue, F., Lerch, M.F., Kroner, A., Reischmarnn, T., 1996. Tectonic evolution of the East Qinling Mountains, China, in the Palaeozoic: a review and new tectonic model. Tectonophysics 253, 271–284.

Yang, J.-S., Robinson, P.-T., Jiang, C.-F., Xu, Z.-Q., 1996. Ophiolites of the Kunlun Mountains, China and their tectonic implications. Tectonophysics 258, 215–231.

Yang, Z.-Y., Ma, X.-H., Xing, L.-S., Xu, S.-J., Zhang, J.-X., 1992. Jurassic paleomagnetic constraints on the collision of the North and South China blocks. Geophysical Research Letters 19, 577–580.

Zhang, H.-F., Gao, S., Zhang, B.-R., Luo, T.-C., Lin, W.-L., 1997. Pb isotopes of granitoids suggest Devonian accretion of the Yangtze (South China) to North China Cratons. Geology 25, 1015–1018.

Zhang, G.-W. (Ed.), 1988. Formation and evolution of Qinling orogen. Northwest University Press, Xian, pp. 5–106 (In Chinese with English abstract).

Zhang, G.-W., Lai, S.-C., 1995. Tectonics and structures of Qinling orogenic belt. Science in China (Series B) 38, 1379–1394.

Zhang, G.-W., Meng, Q.-R., Yu, Z.-P., Sun, Y., Zhou, D.-W., Guo, A.-L., 1996. Orogenic processes and dynamics of the Qinling. Science in China (Series D) 39, 225–234.