Characteristics and geological significance of olivine xenocrysts in Cenozoic volcanic rocks from western Qinling*

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Abstract Cenozoic volcanic rocks from the Haoti, Dangchang County of the western Qinling Mountains, contain a few clearly-zoned olivines. These olivines are relatively big in grain sizes and usually have cracks or broken features. Their cores have similar compositions ($Mg^{\#}$=90.4—91.0) to those for the peridotitic xenoliths entrained in host volcanic rocks and their rims are close to the compositions of olivine phenocrysts ($Mg^{\#}$=85.5—81.9). The CaO contents in these zoned olivines are lower than 0.1%. These features demonstrate that the clearly-zoned olivines are xenocrysts and disaggregated from mantle peridotites. The zoned texture was the result of the interaction between the olivine and host magma. Available data show that the volcanic rocks would have been derived from the mantle source metasomatized by subducted hydrathermally-altered oceanic crust. The formation of these Cenozoic volcanic rocks was perhaps related to the rapid uplift of the Tibetan Plateau.

Keywords: **Western Qinling, Dangchang Haoti, Cenozoic volcanic rocks, olivine xenocrysts, zoned texture.**

Studies on the nature and evolution of the lithospheric mantle have been focused on the mantle peridotitic xenoliths for a long time. Recently, xenocrysts from volcanic rocks are becoming an important target to probe the nature of the lithospheric mantle, and many significant achievements have been made[1—5]. The zoned texture of olivine xenocrysts was commonly considered to be formed through rapid interaction between the olivine and host magma[4,6]. The zoned texture can also provide the degree of the reaction between the olivine and host magma and compositional change, and further define the compositional characteristics and ascending rates of magmas. The core composition of olivine xenocrysts can also be used to reflect the nature of the lithospheric mantle, especially in the volcanic regions where there is no mantle perodotitic xenolith.

Cenozoic volcanic rocks in the western Qinling Mountains are sparsely distributed in the regions of three counties (Lixian-Dangchang-Xihe counties), Gansu Province, China. Volcanic rocks contain a plenty of mantle peridotitic xenoliths and few olivine xenocrysts. Many researches have been focused on the volcanic rocks and peridotitic xenoliths[7—17], but the work on the xenocryst has never been made until now. This paper reports the mineralogical characteristics of the zoned olivines from the volcanic rocks, and their formation and geological significance.

1 Geological setting

The western Qinling Mountains are located in the western part of Qinling-Dabie Orogenic Belt, central China. It is adjacent to the North China Block in the northeast, to the Qilian Orogen in the northwest, to the Chaidamo Block in the west, and to the Tibetan Plateau and Yangtze Block in the south which is separated by the Songpan-Ganzi Orogenic Belt (Fig. 1). In other words, the western Qinling Orogen is a conjunction region of China major blocks. This tectonic framework resulted from a three-dimensional compression of these blocks, forming a key tectonic region of the SW-trending Central China Orogen, nearly NS-trending Chuandian-Helanshan Orogen and Tibetan Plateau[18—20].

Haoti volcanic rocks outcrop to the southeast of the Haoti Village, Dangchang County, Gansu Province, within the Tianshui-Lixian Cenozoic fault basin (Fig. 1). Volcanic rocks covered the Tertiary red sediments and erupted at 7.1 Ma, 7.9 Ma, 18.9 Ma and 22—23 Ma[7,10,20]. The volcanic rocks have a porphyritic texture and massive structure with well-

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developed fumarolic and amygdaloidal. The phenocrysts are mainly olivine, clinopyroxene and phlogopite, and the groundmass is aphanitic and hyaline[10]. There are many mantle peridotitic xenoliths, including spinel lherzolites, garnet lherzolites, wehrlites and dunites[9,16]. Most of these peridotitic xenoliths are small and fresh and in a range of 1—4 cm with a few up to 7—8 cm in size. The volcanic rocks also contain a few clearly-zoned minerals, mainly olivine and clinopyroxene.

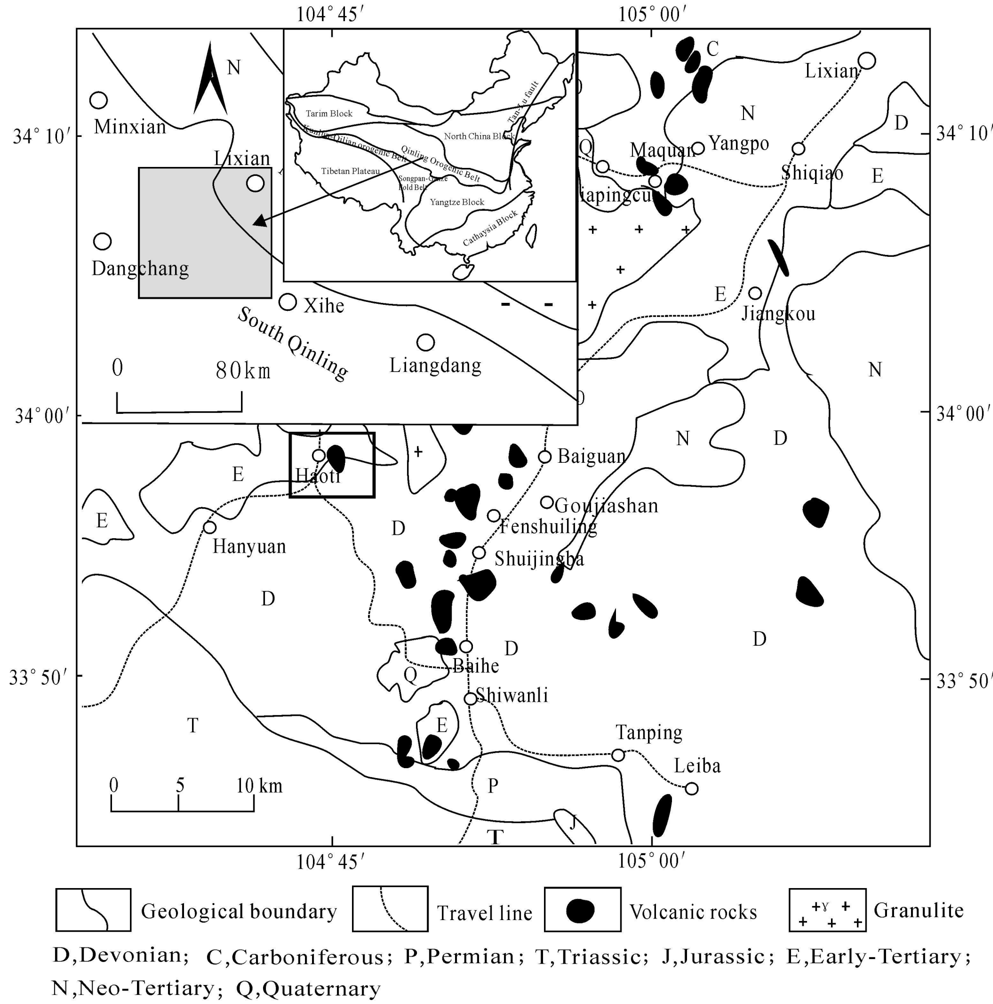

Fig. 1. Sketch map showing the distribution of volcanic rocks in the western Qinling (modified from [10, 15, 17]).

2 Olivine mineralogy

Clearly zoned olivines from the Cenozoic volcanic rocks of the western Qinling are normally in the size of 200 μm—800 μm (Fig. 2). These olivines normally have eroded embayment and well-developed cracks (Fig. 2). The zoned olivines in the backscattered electron image have a darker core (Mg-rich) and a lighter rim (Fe-rich). These characteristics demonstrate that the zoned texture was formed through the interaction between the olivine and host magma. Olivine phenocrysts are small, subhedral or euhedral and generally have not a zonation.

3 Analytical method and results

Major elemental compositions of olivines were obtained with a Cameca SX50 at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Analyses were performed with a beam of 15 keV and 20 nA. The results are given in Table 1.

Olivines have an apparently compositional zonation. The cores are rich in MgO and NiO contents and poor in FeO, CaO and MnO contents relative to the rim (Table 1 and Fig. 3). SiO_2, MgO and NiO contents decrease and FeO, CaO and MnO contents increase from the core to the rim, in which CaO content increases from 0.08 to 0.92 (Fig. 3). The cores of predominantly zoned olivines have lower CaO contents than those of the phenocrysts (> 0.20%) (Table 1). $Mg^{\#}$ values in the olivine cores (90.4—91.0) are similar to those olivines from mantle peridotitic xenoliths (90.0—92.5)[12]. Olivine phenocrysts have not an apparently compositional zoning and their $Mg^{\#}$ are in a range of 85.5—81.9 (Table 1).

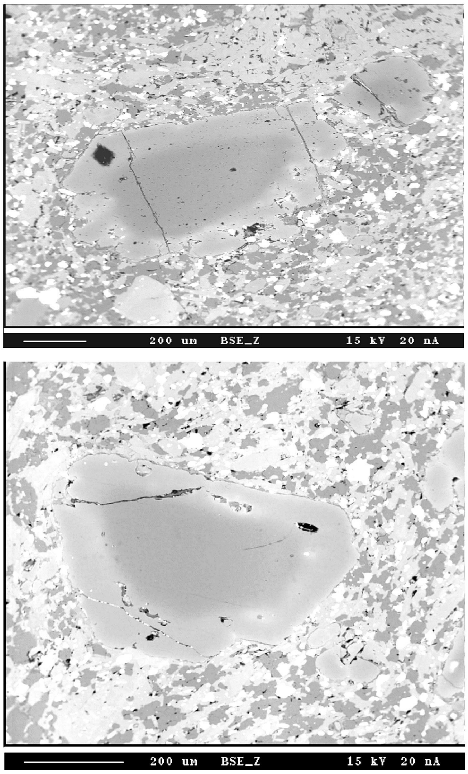

Fig. 2. Backscattered electron image of zoned olivines.

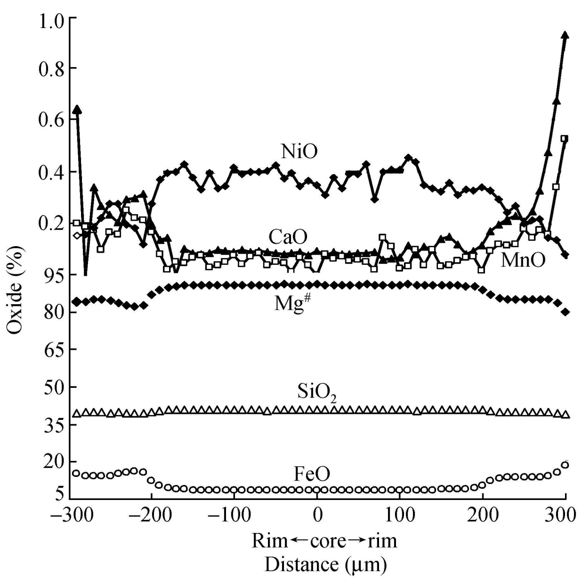

Fig. 3. Compositional traverse for a zoned olivine (HT-15grain1).

Table 1. Electron microprobe analyses of olivines from Haoti Cenozoic volcanic rocks

Olivine		SiO_2	MgO	CaO	MnO	FeO*	NiO	Total	$Mg^{\#}$
		39.46	43.23	0.64	0.20	15.22	0.15	99.07	84.1
		39.94	44.35	0.00	0.19	14.58	0.16	99.40	84.3
		40.05	44.95	0.34	0.18	14.25	0.18	100.11	85.1
		39.93	44.77	0.27	0.10	14.36	0.22	99.75	85.0
		39.74	43.92	0.23	0.16	14.57	0.27	99.13	84.4
		39.88	44.02	0.20	0.16	15.33	0.28	100.05	83.7
		39.70	43.15	0.29	0.25	15.99	0.19	99.78	82.9
		39.42	42.69	0.30	0.22	16.40	0.18	99.38	82.4
		39.60	42.99	0.31	0.21	15.99	0.12	99.26	82.9
		40.22	45.75	0.20	0.16	12.55	0.27	99.32	86.7
		40.61	46.97	0.14	0.08	10.60	0.37	98.87	88.9
		40.79	48.05	0.14	0.02	9.79	0.39	99.34	89.9
		41.10	48.45	0.00	0.05	9.27	0.40	99.32	90.3
	R	41.02	48.67	0.10	0.05	9.03	0.43	99.44	90.7
		40.95	48.58	0.08	0.07	8.94	0.38	99.19	90.7
		40.96	48.66	0.08	0.08	8.79	0.33	99.08	90.8
		40.98	49.00	0.08	0.03	8.79	0.39	99.40	90.9
		41.11	48.63	0.10	0.04	8.81	0.34	99.19	90.9
		41.10	48.73	0.09	0.05	8.88	0.35	99.35	90.8
		41.19	49.25	0.09	0.08	8.76	0.42	99.92	91.0
		40.94	48.62	0.10	0.04	8.78	0.39	99.02	90.9
	↑	40.79	49.01	0.09	0.07	8.87	0.40	99.39	90.8
		40.94	49.23	0.09	0.08	8.84	0.40	99.72	90.9
		40.75	48.95	0.09	0.04	8.93	0.40	99.30	90.8
		41.13	49.01	0.08	0.05	8.83	0.42	99.72	90.9
		41.16	49.35	0.08	0.05	8.73	0.37	99.84	91.0
		40.97	48.75	0.09	0.01	8.76	0.39	99.09	90.9
		40.98	48.69	0.09	0.07	8.84	0.34	99.18	90.8
Xenocrysts		40.99	48.96	0.07	0.04	8.75	0.37	99.32	90.9
HT-	C	41.07	48.95	0.09	0.00	8.75	0.35	99.34	91.0
15grain1		41.05	48.85	0.08	0.08	8.83	0.31	99.38	90.8
		40.83	48.70	0.09	0.06	8.77	0.38	98.93	90.9
		41.05	48.75	0.08	0.07	8.69	0.33	99.12	90.9
		40.96	48.90	0.08	0.05	8.76	0.39	99.26	90.9
		40.97	48.74	0.08	0.06	8.70	0.39	99.02	90.9
		41.12	49.01	0.09	0.05	8.68	0.43	99.57	91.0
	↓	41.04	48.63	0.09	0.02	8.74	0.29	98.95	90.9
		41.22	48.66	0.06	0.14	8.87	0.40	99.51	90.7
		41.00	48.78	0.06	0.11	8.69	0.41	99.19	90.9
		41.18	49.06	0.07	0.03	8.94	0.41	99.81	90.8
		41.11	48.97	0.11	0.03	8.71	0.46	99.60	91.0
		40.67	48.50	0.08	0.10	8.70	0.44	98.67	90.9
		40.97	48.84	0.11	0.04	8.89	0.35	99.36	90.8
		41.07	48.65	0.10	0.10	8.86	0.33	99.28	90.8
	R	41.04	48.83	0.14	0.03	9.04	0.32	99.52	90.7
		41.18	48.90	0.15	0.04	9.28	0.36	100.04	90.5
		40.90	48.88	0.12	0.05	9.21	0.31	99.64	90.5
		40.84	48.82	0.08	0.07	9.21	0.33	99.51	90.5
		40.98	48.66	0.10	0.07	9.56	0.33	99.84	90.1
		40.78	47.43	0.11	0.02	10.65	0.34	99.51	88.9
		40.46	46.01	0.17	0.09	12.62	0.33	99.86	86.8
		40.20	45.13	0.19	0.12	13.66	0.29	99.80	85.6
		39.89	44.80	0.22	0.11	14.20	0.24	99.61	85.0
		40.28	44.53	0.23	0.12	14.13	0.27	99.73	85.0
		40.28	44.82	0.21	0.18	14.06	0.20	99.92	85.1
		40.06	44.55	0.24	0.14	14.02	0.21	99.27	85.2
		40.13	44.71	0.32	0.17	14.16	0.22	99.88	85.1
		40.08	44.14	0.47	0.16	14.28	0.14	99.51	85.1
		39.76	43.17	0.67	0.34	15.79	0.13	100.06	83.4
		39.07	40.79	0.93	0.52	18.94	0.08	100.61	79.9

To be continued

Continued

Olivine		SiO_2	MgO	CaO	MnO	FeO^*	NiO	Total	$Mg^{\#}$
HT-15grain2	C	41.23	48.71	0.05	0.14	9.14	0.42	99.7	90.4
	↓	41.17	48.63	0.02	0.18	9.08	0.37	99.5	90.4
		40.81	47.92	0.02	0.19	10.00	0.38	99.4	89.4
	R	39.92	44.55	0.18	0.16	13.84	0.29	99.1	85.2
HT-20grain1	C	41.26	48.26	0.10	0.13	9.13	0.40	99.4	90.4
HT-20grain2	C	41.30	48.58	0.11	0.14	9.11	0.40	99.7	90.5
Phenocrysts	C	40.27	44.78	0.37	0.21	14.23	0.25	100.2	85.1
HT-15grain1	R	39.65	42.08	0.61	0.30	16.40	0.15	99.4	82.5
HT-15grain2	C	39.44	42.11	0.70	0.45	16.97	0.17	100.0	81.9
HT-15grain3	C	40.22	45.37	0.20	0.25	13.73	0.23	100.1	85.5

FeO^* represents total Fe; $Mg^{\#} = 100\ Mg/(Mg + Fe^{2+})$; C, Core; R, Rim.

4 Discussion

4.1 Olivine with zoned texture is xenocryst

Available data[1—6] manifest that olivine xenocrysts normally have a rounded shape, eroded embayment, and well-developed cracks. In contrast olivine phenocrysts are dominantly euhedral or subhedral without cracks. In the backscattered image, olivine xenocrysts show a clear zonation, generally the core is darker (Mg-rich) and the rim lighter (Fe-rich). In chemical composition, olivine xenocrysts approach the phenocrysts from the core to the rim. $Mg^{\#}$ value is an important indicator to distinguish the xenocryst from the phenocryst. The cores of the zoned olivines have $Mg^{\#}$ values close to those olivines from the mantle peridotitic xenoliths in these rocks, while their rims have $Mg^{\#}$ values close to those olivine phenocrysts. These features demonstrate the zoned olivines are xenocrysts. CaO content is an important parameter to distinguish the magmatic from residue origin for the olivine. CaO content in the olivines from mantle peridotites is commonly less than 0.1 %[23]. Almost all of olivine xenocrysts fall in the mantle peridotite field (Fig. 4(b)). This indicates that these xenocrysts were disaggregated from mantle peridotites. Thus, these olivine xenocrysts can provide some information about the nature and evolution of Cenozoic lithospheric mantle beneath the western Qinling region.

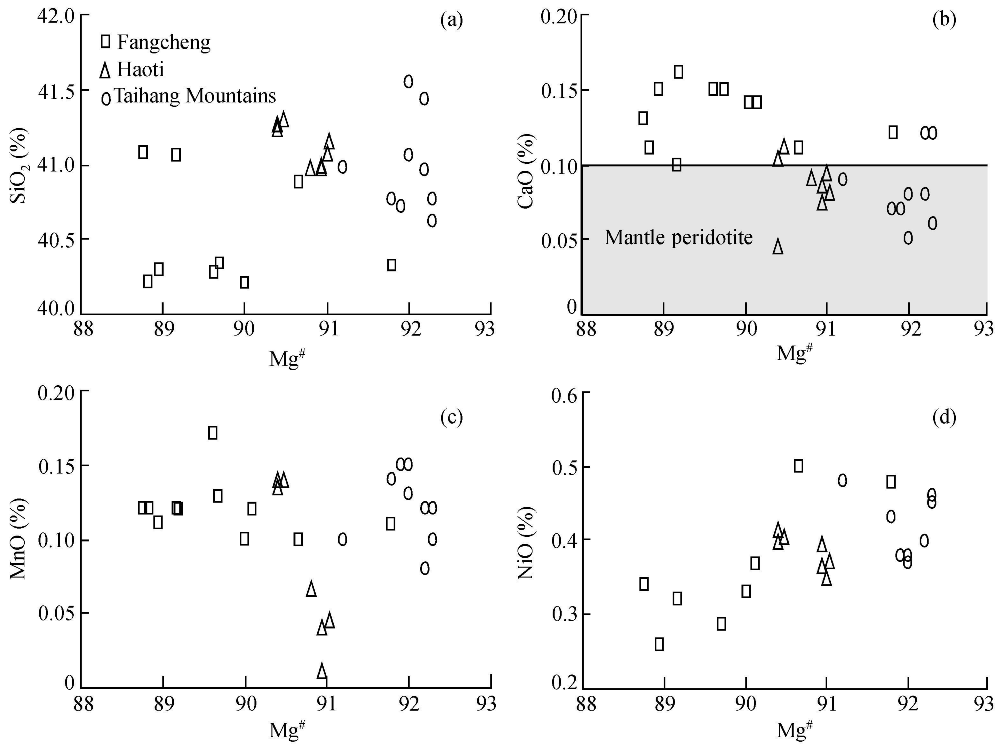

Fig. 4. $Mg^{\#}$ vs. SiO_2, CaO, MnO, NiO in the core of olivine xenocrysts from Haoti Cenozoic volcanic rocks in the western Qinling. Data of olivines from the Fangcheng Mesozoic basalts are from Refs. [1, 4] and from Taihang Mountains from [2].

4.2 Formation of zoned texture

Relative to the composition of olivine xenocrysts, Cenozoic volcanic rocks from the western Qinling are rich in CaO (11.1%—15.5%), FeO^* (11%—13%), MnO (0.16%—0.27%) and poor in MgO (8.4%—16.7%) and SiO_2 (37.7%—42.7%)[15]. When the olivine was trapped in the host magma, its erosion and reaction with the magma would happen due to the compositional disequilibria[6]. This will result in the compositional evolution towards the enrichment in Ca, Fe, Mn and the depletion in Mg in its rim, which finally approach the composition of the olivine phenocrysts or directly crystallize from the magma.

When temperature and/or pressure decreases to a certain degree, the reaction of the olivine xenocryst with the host magma will be terminated, leading to the preservation of this disequilibrated zoned texture. The rate of the reaction under such a high temperature of magma is so quick, thus preservation of such an excellent zonation requires very short reaction time. That is to say, magma erupted quickly to the surface after the entrapment. This is consistent with the Bailey's standpoint[24] that the alkali volcanic and carbonatitic magmas erupted quickly from the mantle depth to the crust. Therefore, the zoned texture of olivine xenocryst resulted from the interaction between the olivine and host magma.

4.3 Origin of host magma

Volcanic rocks in the western Qinling are rich in Cr, Ni, Co contents and have an enriched character of light rare earth elements and large ion lithophile elements[11,15]. The trace element patterns (Fig. 5) and isotopic ratios (Fig. 6) are very similar to the characteristics of the oceanic island basalt. These features demonstrate that the volcanic rocks in the western Qinling originated from a mantle source similar to that of the oceanic island basalts, i.e. asthenosphere. Some samples have Sr-Nd isotopic compositions with a trend of oceanic water alteraction (Fig. 5). These geochemical features indicate that the volcanic rocks would have been derived from the mantle source metasomatized by hydrathermally-altered oceanic crust.

Yu[10] proposed that the volcanic rocks in the western Qinling were the result of low degree partial melting in the thermal boundary layer of the lithospheric keel induced by the local uprising of the asthenosphere, i.e. a lithospheric mantle origin. However their similarities in trace element patterns (Fig. 5) and isotopic compositions (Fig. 6) to the OIB argue such an assumption. The enriched component was probably derived from the recycled crustal materials. Deng et al.[26], on the basis of the studies on the Cenozoic volcanic rocks around the Tibetan Plateau, discovered that these volcanic rocks have both the island-arc and intra-continental plate volcanic characteristics. These illustrate that the recycled crust was involved in the sources for these volcanic rocks. Hydrathermally-altered oceanic crust may be the disappeared Tethyan ocean.

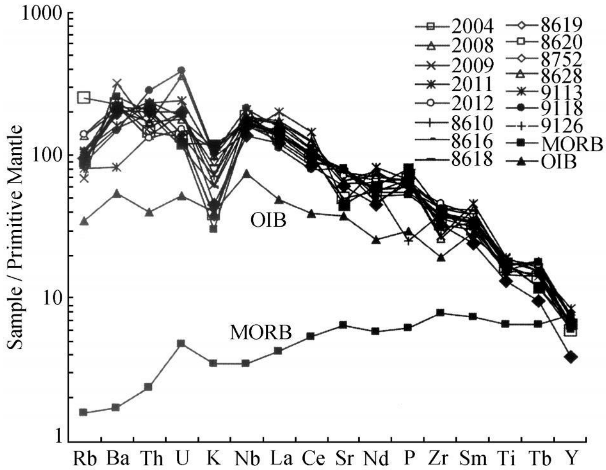

Fig. 5. Primitive mantle-normalized trace element diagrams. Data for Cenozoic volcanic rocks are from [15]. Values for MORB, OIB and Primitive mantle values are from [25].

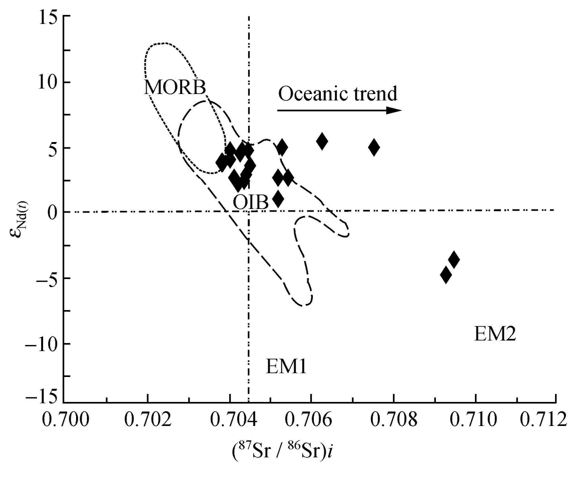

Fig. 6. $(^{87}Sr/^{86}Sr)i$ vs. $\varepsilon_{Nd(t)}$ diagram. Data of Cenozoic volcanic rocks are from [15]. The MORB, OIB field are from [25].

4.4 Comparison of olivine xenocrysts in different regions and its significance

Apparent differences exist between the olivine xenocrysts from Cenozoic volcanic rocks in the western Qinling and those from Mesozoic and Cenozoic basalts in the North China. $Mg^{\#}$ values (90—91) and SiO_2, CaO, NiO contents in the cores of olivine xenocrysts from the western Qinling are between the olivine xenocrysts from Mesozoic Fangcheng basalts and the olivine xenocrysts from Cenozoic Taihangshan basalts (Fig. 4(a), (b), (d)), and MnO content is slightly low (Fig.4(c)). This indicates the existence of compositional differences in the lithospheric mantle beneath the western Qinling and the North China. Even more clearly-zoned texture of the olivine xenocrysts from the western Qinling manifests a larger compositional difference between the xenocryst and the host magma in the western Qinling. Olivine xenocrysts of the Cenozoic volcanic rocks from the west Qinling have lower Mg# values relative to those for olivine xenocrysts of the Cenozoic basalts from the Taihang Mountains (7.8 Ma)[2] (Fig. 4). This is consistent with the evolutionary history of China's major tectonic blocks. North China Block is an old craton and its lithospheric mantle should be refractory. Thus, the cores of olivines from the lithospheric mantle should have higher Fo, such as in the case of the Taihang Mountains[2]. Relatively low Fo values in olivine xenocrysts from the Fangcheng[4] and Liaoxi[5] regions, eastern North China, were believed to be the result of the peridotite-melt interaction. The western Qinling Mountains is a young orogenic belt and its lithospheric mantle should be young as well and composed of less refractory peridotite, i.e. lower Fo value in the olivine.

The western Qinling region has undergone a complicated geological evolution. It was a part of Paleo-Tethyan Ocean in the Paleozoic, and with its spreading, subduction, collision of Paleo-Tethyan Ocean it closed in Triassic to form a western Qinling Orogen[26]. In the Cenozoic, the severe collision of the India plate with the Euroasia plate resulted in the rapid uplift of the Tibetan Plateau (8 Ma)[27—30]. This collision also resulted in intensive tectonic movements and magmatism in the region, forming fault-related basins, strike-slip faults as well as volcanic rocks. Volcanism in the western Qinling in the Cenozoic was related to the collision between the India plate and the Euroasia plate and the uplift of the Tibetan Plateau.

In the Cenozoic, due to the uneven rapid uplift of the Tibetan Plateau, the western Qinling Orogen suffered from strong squeezing and shearing[28—30]. This tectonic process perhaps affected the deep lithospheric mantle, leading to the fragmentation, deformation, and the formation of the peridotites with excellent mineral orientation. These deformed peridotites were captured by the Cenozoic volcanic rocks. Therefore, The Cenozoic magmatism and their entrained xenoliths and xenocrysts were the witness of tectonic movements in the western Qinling.

5 Conclusions

(1) The clearly zoned olivines from Cenozoic volcanic rocks in the western Qinling are xenocrysts and disaggregated from mantle peridotites. Their core compositions are similar to those olivines from mantle peridotitic xenoliths and their rims close to those phenocrysts in the volcanic rocks. The zoned texture of olivine xenocrysts was the result of the olivine-magma interaction. The host volcanic rocks would have been derived from the asthenospheric source modified by subducted hydrathermally-altered oceanic crust.

(2) During the Cenozoic, tectonic deformation induced by the rapid uplift of the Tibetan Plateau in the western Qinling might have affected to the depth of the lithospheric mantle. Thus, Cenozoic magmatism and their entrained xenoliths and xenocrysts are the witness of the tectonic movements in the western Qinling region.

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