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REPLY

Is there the Paleoproterozoic komatiite related to mantle plume in the Jifeng area, Northern Great Xing'an Range, NE China?

Reply to the comments on: "Timing and nature of the Xinlin–Xiguitu Ocean: constraints from ophiolitic gabbros in the northern Great Xing'an Range, eastern Central Asian Orogenic Belt" by Ni

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Introduction

It is our great pleasure to have received comments from Ni (2016) on our published paper entitled "Timing and nature of the Xinlin–Xiguitu Ocean: constraints from ophiolitic gabbros in the northern Great Xing'an Range, eastern Central Asian Orogenic Belt," in which we stated that more work will be needed to verify the existence of the Jifeng komatiite and the tectonic environment of Jifeng ophiolite according to integrated study of geochemical, zircon U–Pb ages and Lu–Hf isotopic analyses. However, Ni (2016) insists that the Paleoproterozoic komatiites definitely exists in the Jifeng area, as suggested by the previous studies more than twenty years ago (Zhao et al. 1996; Hu et al. 2001, 2003). In addition, Ni (2016) further insists that the Jifeng ophiolite should have produced in an oceanic plateau rather than in a transitional supra-subduction zone environment based on the presence of the komatiites. It is important to know whether the Jifeng komatiite do exist there, and if they do, it is also important to understand the relationship among the komatiites, gabbros, diabases and basalts exposed in the Jifeng area. Therefore, the comments give us a great opportunity to further clarify our interpretation.

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Initiation

In the early 1970s, it was claimed that there exist the ultramafic–mafic rocks in the Jifeng area, including lherzolites, harzburgites, dunites, gabbros, basalts and diabases, which were interpreted as the ophiolite complex (Hu et al. 1995). Slightly later, Zhao et al. (1996) firstly reported that there was a micro-spinifex texture in the ultramafic rocks from the Jifeng ophiolite and the rocks were lithologically determined as the Jifeng komatiite. In the latter studies, geochronology and geochemistry had been carried out on the so-called Jifeng komatiite, it claimed that the Jifeng komatiite formed in the Mesoproterozoic with the age (~1727 ± 74.7 Ma of Sm–Nd isotopic age), which was related to the notable crustal growth in the period of Mesoproterozoic (Hu et al. 2001, 2003; Li et al. 2002).

During the year of 2013 to 2015, we made a detail study for the rock association of the Jifeng ophiolite and attempt to reveal the tectonic evolution of the Xinlin–Xiguitu paleo-ocean basin between the Erguna and Xing'an blocks. We sampled the so-called Jifeng komatiite in 2013, but it did not show typical spinifex texture and obviously different from the other komatiites in the world (50°24′06.3″N; 123°10′22.4″E; Fig. 1a–e; Nicholas 2008), but it is lithologically serpentinites, which should represent a part of the Jifeng ophiolite.

According to the new data, we claimed that the Proterozoic ophiolite in the Jifeng area was, in fact, formed at ~650 Ma by the ages of Jifeng gabbros, which is probably related to transitional SSZ-type ophiolite and developed in an intra-oceanic subduction (Feng et al. 2016).

However, the main criticism from the comments was: "Jifeng ultramafic rock was the typical komatiite with high-MgO content related to mantle plume." Therefore, to check if there exist real komatiite and the tectonic setting

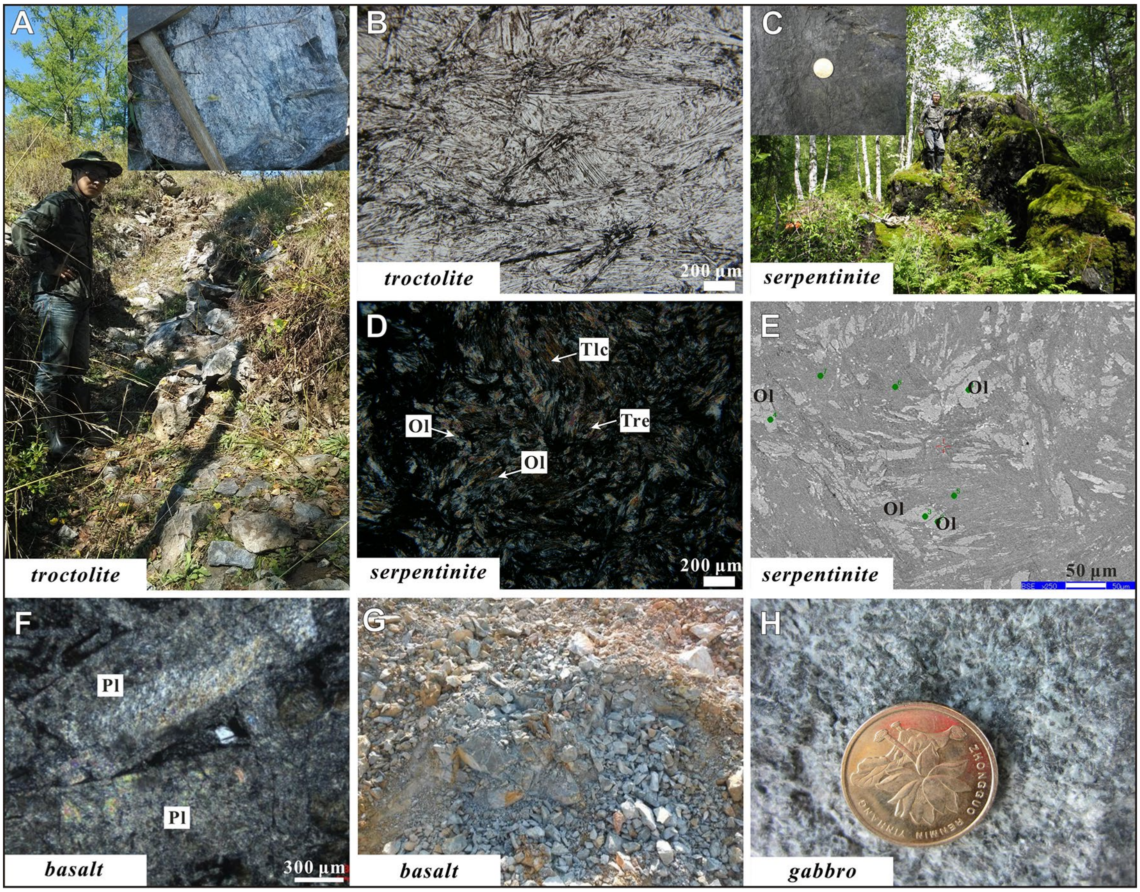

Fig. 1 Field occurrences and photomicrographs of Jifeng ophiolite. **a**, **c**, **g**, **h** Field outcrop of the troctolite, serpentinite, basalt and gabbro, respectively; **b**, **d**, **f** troctolite (JF15), serpentinite (JF13) and basalt (JF16), respectively (cross-polarized light); **e** *back*-scattered images of **d**

of the ophiolite in Jifeng area, we re-sampled the site again (Fig. 1; Table 1).

Are there the real Paleoproterozoic komatiites in the Jifeng area?

Ni (2016) claims that "there was the characteristic spinifex texture defined by extremely acicular olivine phenocryst," reported by the previous researchers. The typical spinifex texture is formed by skeletal, platy, or acicular crystals of olivine, orthopyroxene, or clinopyroxene, or their pseudomorphs in ultramafic and mafic lavas or silicate-rich furnace slag (Nicholas 2008). But, we have not found spinifex texture in Jifeng ultramafic rocks in macro scale (Fig. 1a–e) by detail field works. Meta-ultramafic rocks in Jifeng area, gray-colored in weathered surface but dark-green-colored inside, have a porphyroblastic texture and display strong deformation. The porphyroblasts are forsterite (~60% modal) and minor clinopyroxene, which was completely altered to be chlorite + talc + tremolite + serpentine, but still keeps the pseudomorph. The groundmass is dominated by serpentine + talc (~40% modal), with minor amounts of chromite and magnetite (≤5% modal). The serpentines were likely resulted from alteration of olivine, as indicated by the net-shape texture, although no fresh olivine was observed (Fig. 1a–e). These features suggest that the protolith of the meta-ultramafic rocks is dunites and lherzolites, representing relics of the paleo-oceanic lithospheric mantle rocks. More importantly, the structure and texture of the so-called komatiite also exist in the ultramafic–mafic rocks from ophiolites with SSZ type (Wang et al. 2013; Song et al. 2015).

In the view of geochemical study, owing to the high LOIs (6.22–11.09), the oxides concentrations of the samples were all recalculated on a hydrous-free basis excluding the LOIs using the method of weighted means (Wang et al. 2013). The discussions of oxide analyses below are all based on the recalculated data. The analytical results show that the so-called Jifeng komatiite have relatively low contents in SiO_2 (42.92–51.70 wt%) and high MgO (29.89–41.14 wt%), but its relative low CaO/Al_2O_3 ratio (0.14–0.72) is obviously different from the typical komatiite (CaO/Al_2O_3>1; Nicholas 2008). On the other hand, the Jifeng so-called komatiite possesses relatively flat chondrite-normalized REE patterns

Table 1 Analytical data of major elements (wt%) and trace elements (ppm) from the Jifeng ophiolite

Samples	JF13-A	JF13-B	JF13-C	JF13-D	JF13-E	JF15-A	JF15-B	JF15-C	JF16-A	JF16-B	JF16-C	JF16(D)	JF14(A)	JF14(B)	JF14(C)	JF14(D)	JF14(E)
	Serpentinite					*Troctolite*			*Basalt*				*Gabbro*				
SiO_2	42.42	41.21	45.96	42.11	41.45	38.54	38.52	38.48	51.56	46.45	51.56	54.29	44.51	46.71	46.55	46.43	46.05
TiO_2	0.08	0.04	0.20	0.05	0.04	0.26	0.25	0.25	0.65	1.56	0.65	1.64	0.34	0.35	0.46	0.49	0.41
Al_2O_3	2.36	5.20	5.43	1.92	1.48	3.07	3.06	3.09	15.69	15.56	15.69	16.54	12.59	13.12	16.21	15.96	14.47
TFe_2O_3	7.25	11.28	7.23	7.39	7.25	10.40	10.34	10.44	5.57	8.06	7.19	8.46	7.05	6.15	5.68	6.75	6.41
MnO	0.10	0.15	0.11	0.10	0.10	0.13	0.13	0.13	0.17	0.10	0.17	0.14	0.13	0.11	0.11	0.12	0.12
MgO	35.04	35.05	26.57	35.38	36.00	31.65	31.75	31.63	7.57	5.48	7.57	4.29	18.13	15.28	9.78	9.93	13.28
CaO	0.78	0.73	2.01	1.00	1.07	3.93	3.92	3.91	10.07	7.96	10.70	4.81	8.16	10.24	13.20	12.86	11.12
Na_2O	0.19	0.01	0.64	0.11	0.04	<0.01	<0.01	<0.01	4.75	2.73	4.75	3.92	2.10	1.96	2.45	2.55	2.27
K_2O	0.08	0.06	0.66	0.08	0.06	<0.01	<0.01	<0.01	0.35	1.89	0.35	1.34	0.60	0.76	0.81	0.78	0.74
P_2O_5	0.03	0.09	0.09	0.04	0.02	0.03	0.02	0.03	0.15	0.31	0.15	0.61	0.05	0.02	0.05	0.04	0.04
LOI	10.83	6.22	9.61	10.99	11.09	9.71	9.69	9.74	2.32	9.45	2.32	3.80	4.64	4.38	2.58	2.58	3.55
Total	99.16	100.04	98.51	99.17	98.60	99.39	99.34	99.39	100.47	99.55	101.10	99.83	98.30	99.08	97.88	98.49	98.44
Mg#	90.54	86.02	87.92	90.46	90.77	85.77	85.88	85.72	72.92	57.39	67.59	50.11	83.59	83.11	77.33	74.45	80.41
Li	19.69	16.07	21.66	19.87	11.92	–	–	–	–	–	–	–	43.55	42.44	50.03	62.76	49.70
Sc	8.08	7.84	9.00	7.47	6.10	–	–	–	–	26.87	43.30	17.10	35.39	38.67	48.27	48.64	42.74
V	39.05	33.72	59.95	41.63	27.42	66.00	64.00	60.00	–	196.13	390.00	131.00	141.69	159.21	192.77	209.25	175.73
Cr	2001.10	1798.99	2008.71	3036.62	1668.66	2038.95	2052.63	2038.95	–	142.16	191.00	80.20	1070.31	720.92	398.73	380.57	642.63
Co	93.68	90.78	64.60	74.93	85.94	116.00	113.10	114.70	–	32.08	66.80	28.70	50.88	49.24	36.11	40.94	44.29
Ni	2126.08	2019.96	1386.64	1755.86	1936.25	1930.00	1980.00	2052.00	–	70.44	400.00	71.10	667.33	672.96	209.22	217.85	441.84
Cu	6.69	12.73	19.59	6.27	4.95	13.85	15.16	13.79	–	–	–	–	70.73	12.55	16.19	20.67	30.04
Zn	54.53	46.01	110.23	47.86	46.75	80.64	50.71	52.10	–	–	–	–	21.79	24.51	21.59	18.38	21.57
Ga	2.87	2.46	6.59	3.34	1.80	3.00	3.00	2.90	–	19.01	31.40	21.70	8.88	9.62	11.14	11.52	10.29
Rb	3.59	3.24	22.57	2.13	2.64	0.10	0.10	0.10	–	73.02	146.00	51.10	36.31	33.70	36.80	38.45	36.32
Sr	57.64	49.82	110.75	34.22	28.69	6.20	6.30	6.90	–	379.40	80.10	695.00	416.89	397.37	487.92	537.97	460.04
Y	1.55	1.47	6.31	1.68	0.84	4.00	4.00	4.00	18.90	22.92	31.20	34.20	7.04	8.56	9.71	9.25	8.64
Zr	9.47	7.49	37.24	3.60	4.45	17.70	16.60	17.00	–	177.87	156.00	251.00	16.85	28.43	25.90	21.95	23.28
Nb	0.61	0.59	2.51	0.26	0.54	3.80	3.70	3.80	–	5.99	7.92	24.20	0.88	1.25	1.07	0.80	1.00
Cs	2.57	2.42	2.24	1.47	1.94	0.10	0.10	0.20	–	23.50	26.50	4.42	5.99	5.00	4.33	3.95	4.82
Ba	30.89	38.99	162.81	18.06	17.54	29.00	29.00	30.00	–	1206.00	116.00	484.00	107.44	141.83	176.48	142.85	142.15
La	1.40	1.18	9.10	0.82	0.70	3.50	3.30	3.60	15.30	25.98	31.20	37.90	1.81	3.53	3.11	2.66	2.78
Ce	3.12	2.69	19.15	2.01	1.65	5.20	5.60	5.40	27.20	57.46	62.90	74.20	4.44	8.66	7.55	6.42	6.77
Pr	0.39	0.32	2.25	0.30	0.19	0.59	0.61	0.58	5.22	7.54	8.61	9.58	0.68	1.13	1.12	0.98	0.98
Nd	1.57	1.31	8.55	1.31	0.76	2.80	2.90	2.80	15.00	30.73	33.60	36.60	3.40	4.99	5.49	4.84	4.68
Sm	0.33	0.27	1.61	0.32	0.17	0.71	0.57	0.73	4.39	5.99	6.19	7.65	1.09	1.41	1.61	1.48	1.40
Eu	0.11	0.08	0.41	0.15	0.04	0.16	0.16	0.15	1.02	1.96	1.26	2.04	0.47	0.51	0.71	0.63	0.58

Table 1 continued

Samples	JF13-A	JF13-B	JF13-C	JF13-D	JF13-E	JF15-A	JF15-B	JF15-C	JF16-A	JF16-B	JF16-C	JF16(D)	JF14(A)	JF14(B)	JF14(C)	JF14(D)	JF14(E)
Gd	0.32	0.25	1.44	0.35	0.15	0.86	0.80	0.82	3.04	5.00	4.66	6.54	1.24	1.56	1.82	1.71	1.58
Tb	0.05	0.04	0.21	0.06	0.02	0.13	0.13	0.13	0.55	0.81	0.78	1.18	0.21	0.27	0.32	0.29	0.27
Dy	0.28	0.24	1.15	0.32	0.16	0.78	0.78	0.84	3.72	4.86	4.49	6.58	1.33	1.60	1.90	1.78	1.65
Ho	0.06	0.06	0.25	0.08	0.03	0.15	0.18	0.15	0.71	0.93	0.89	1.26	0.28	0.35	0.40	0.38	0.35
Er	0.14	0.15	0.66	0.18	0.10	0.49	0.37	0.47	1.70	2.38	2.39	3.30	0.75	0.92	1.03	0.96	0.92
Tm	0.02	0.02	0.10	0.02	0.02	0.06	0.07	0.07	0.24	0.38	0.41	0.56	0.10	0.13	0.15	0.13	0.13
Yb	0.16	0.15	0.63	0.13	0.10	0.41	0.36	0.40	1.36	2.36	2.53	3.39	0.62	0.82	0.93	0.81	0.80
Lu	0.02	0.03	0.10	0.02	0.02	0.06	0.06	0.06	0.21	0.35	0.48	0.58	0.10	0.13	0.14	0.12	0.12
Hf	0.26	0.21	1.04	0.11	0.13	0.50	0.40	0.40	–	3.68	3.08	6.39	0.59	0.98	0.92	0.79	0.82
Ta	0.05	0.06	0.19	0.04	0.06	0.06	0.07	0.09	–	0.45	0.69	1.70	0.08	0.17	0.13	0.08	0.12
Pb	2.70	1.10	110.09	2.11	1.32	–	–	–	–	–	–	–	5.06	13.95	11.36	6.73	9.28
Th	0.27	0.23	2.37	0.12	0.20	0.30	0.20	0.40	–	2.67	2.56	6.88	0.21	0.95	0.41	0.42	0.50
U	0.08	0.08	1.17	0.05	0.07	0.08	0.08	0.09	–	0.67	6.48	2.19	0.08	0.27	0.13	0.16	0.16
ΣREE	7.97	6.79	45.61	6.07	4.11	15.90	15.89	16.20	79.66	146.73	160.39	191.36	16.52	26.01	26.28	23.19	23.01
$(La/Yb)_N$	5.90	5.30	9.74	4.25	4.72	5.76	6.18	6.07	7.58	7.42	8.31	7.54	1.97	2.90	2.25	2.21	2.34
$(La/Sm)_N$	2.67	2.75	3.56	1.61	2.59	3.10	3.64	3.10	2.19	2.73	3.17	3.12	1.04	1.57	1.22	1.13	1.25
$(Gd/Yb)_N$	1.61	1.34	1.84	2.17	1.21	1.69	1.79	1.65	1.80	1.71	1.49	1.56	1.61	1.54	1.58	1.70	1.59
$(Ce/Yb)_N$	5.04	4.64	7.86	4.00	4.27	3.28	4.02	3.49	5.17	6.30	6.43	5.66	1.85	2.73	2.10	2.05	2.19
δEu	1.02	0.93	0.81	1.36	0.75	0.63	0.72	0.59	0.81	1.07	0.69	0.86	1.23	1.05	1.26	1.21	1.19

Mg# = $Mg^{2+}/(Mg^{2+} + TFe^{2+})$; LREE = La + Ce + Pr + Nd + Sm + Eu; HREE = Gd + Tb + Dy + Ho + Er + Tm + Yb + Lu; ΣREE = LREE + HREE; $(La/Yb)_N$ = (La/0.687)/(Yb/0.493); $(La/Sm)_N$ = (La/0.310)/(Sm/0.195); $(Gd/Yb)_N$ = (Gd/0.259)/(Yb/0.493); $(Ce/Yb)_N$ = (Ce/0.808)/(Yb/0.493); δEu = (Eu)cn/[(Gd)cn + (Sm)cn]/2

LOI loss on ignition

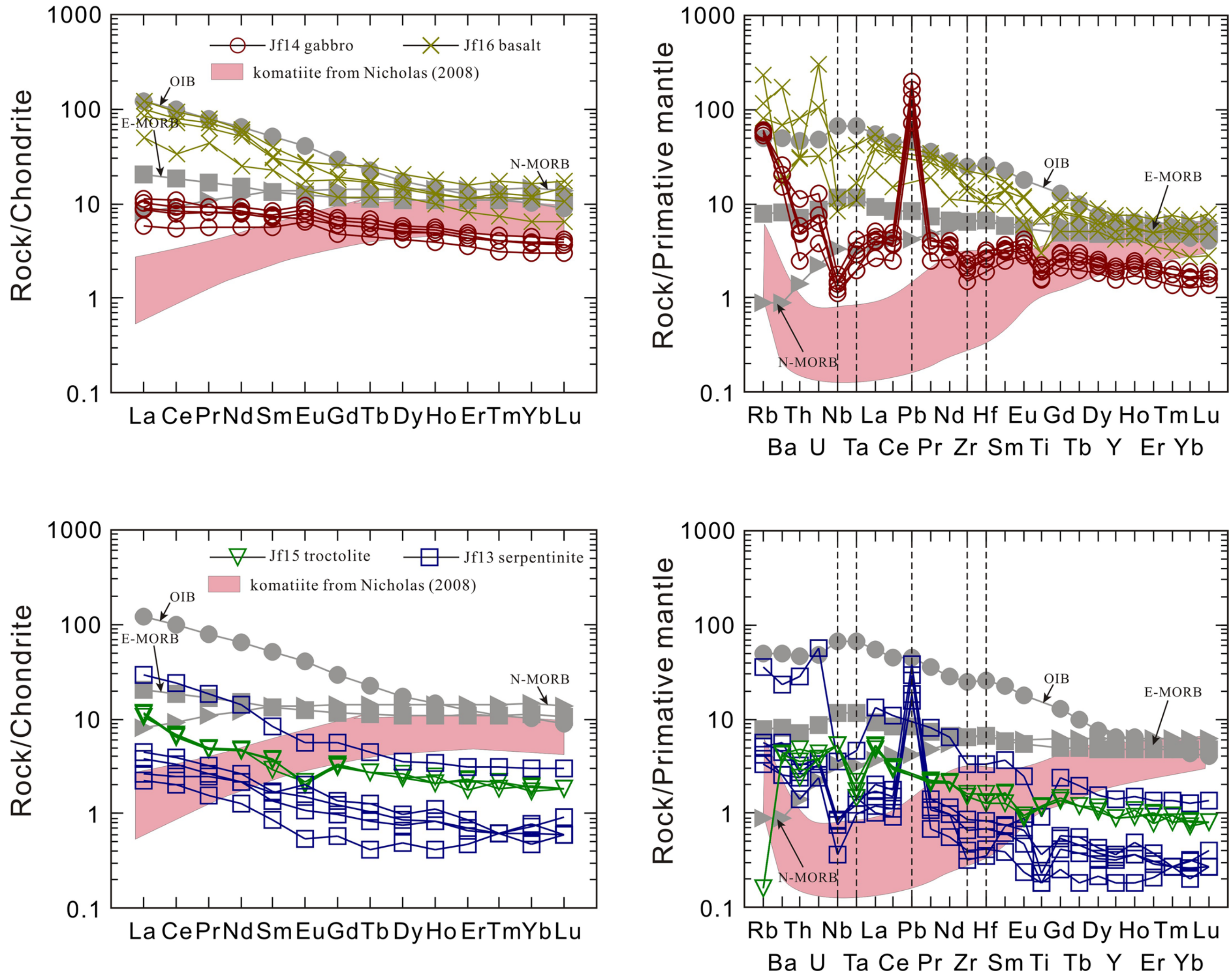

Fig. 2 Chondrite-normalized REE patterns and primitive mantle-normalized trace spider diagrams for rocks from the Jifeng ophiolite

(Fig. 2) and obviously distinguishes from some typical komatiites of the Barberton, Abitibi, Norseman-Wiluna, Belingwe, Gilmour and Gorgona (Nicholas 2008).

In summary, the detailed field investigation and geochemical studies indicated that the Jifeng ultramafic rocks are not the real/typical komatiites, but should present a part of the ophiolites derived from the oceanic crust between the Erguna and Xing'an blocks.

Genetic environment of the Jifeng ophiolite: transitional supra-subduction zone or Oceanic plateau?

It is worthy of note that the ultramafic rocks with high MgO exist in many ophiolites related to subduction (Dilek and Furnes (2011)). However, Ni (2016) argued that the Jifeng ophiolite marks an oceanic plateau environment related to mantle plume. Regarding to the typical oceanic plateau, Kerr et al. (2000) suggested that the typical features of oceanic plateau are as follows: the occurrence of high-MgO lavas, chemically homogeneous basalts with relatively flat chondrite-normalized REE patterns and low La/Nb ratio (≤1.1); pillowed lavas; low abundance of volcaniclastic deposits; and lack of sheeted dyke complex. Although the Jifeng ophiolite has high-MgO lavas or chemically homogeneous basalts with relatively flat chondrite-normalized REE patterns, it has high La/Nb ratio (1.97–2.98) and possesses some diabase dyke located in the northern Jifeng area (Hu et al. 1995; She et al. 2012). More importantly, up to now, there have been no reports of the pillowed lavas cropped out in the Jifeng area.

In some respects, Ocean Island are the small-scale equivalents of the oceanic plateau. The distinction features between oceanic plateau and Ocean Island are as follows: (1) Many oceanic islands exhibit considerable magmatic

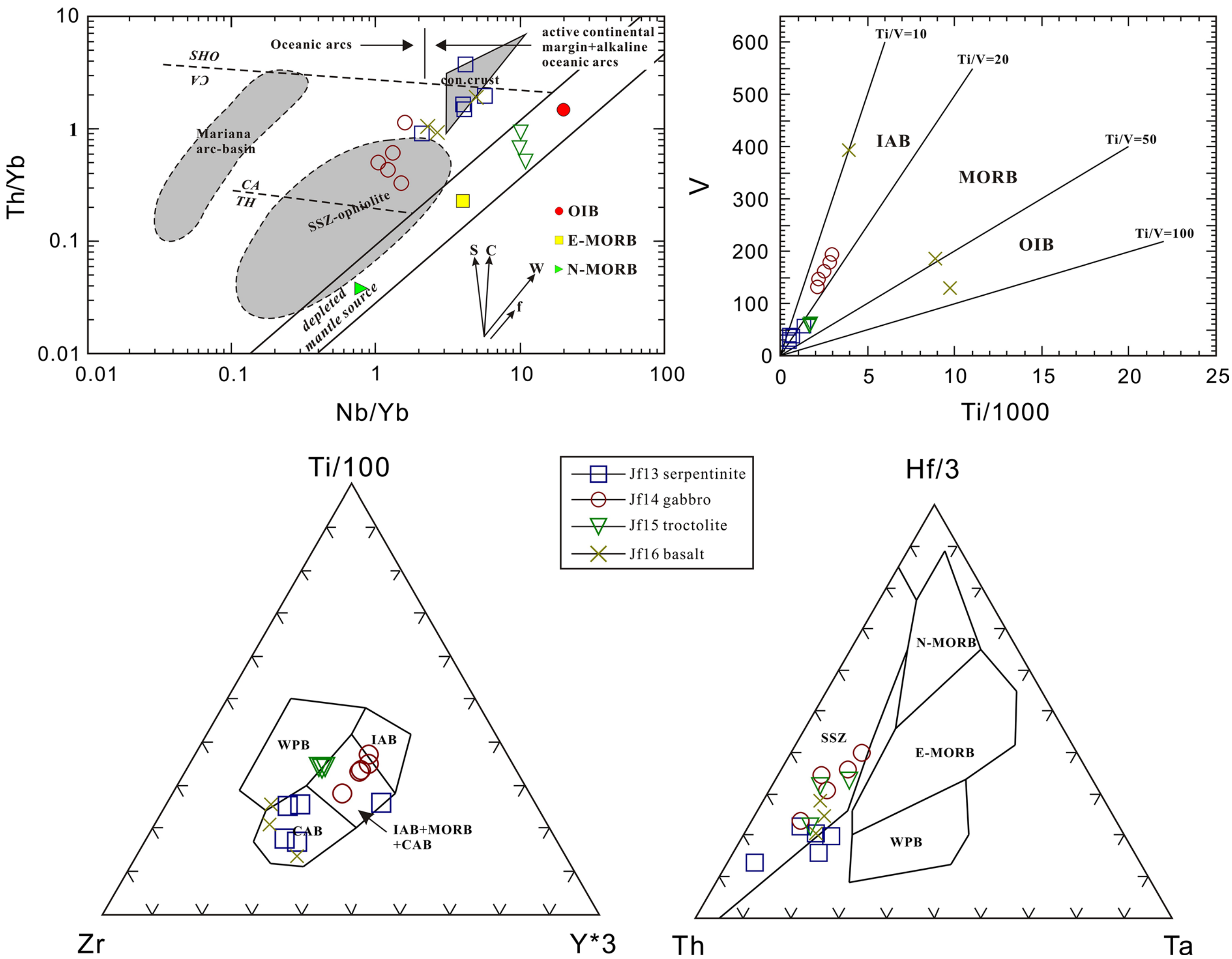

Fig. 3 Tectono-magmatic discrimination diagrams for mafic–ultramafic rocks of Jifeng ophiolite

differentiation, resulting in formation of rhyolite or phonolitic sequence and their pyroclastic equivalents. (2) A predominance of lavas, with an enriched trace element signature (high values of Sm_n/Yb_n, Nb/Zr and La/Y), would suggest that the sequence is part of an oceanic island rather than a plateau (Kerr et al. 1998, 2000; Kerr 2014). The Jifeng ophiolite is not only possess the pyroclastic from the Daminshan Formation (HBGMR 1993), but also has relative high values of Sm_n/Yb_n (>4), Nb/Zr (0.06–0.22) and La/Y (0.4–1.4) on geochemistry. In addition, the Jifeng ophiolite (including the diabases, gabbros, basalts and meta-ultramafic rocks) is derived from mantle contaminated by earth crust with depletion in high field strength element (Fig. 2). Those features of the Jifeng ophiolite further indicated that it was not driven from the oceanic plateau, but was likely the ocean island with SSZ type. (1) The Jifeng basalts and gabbros from Jifeng ophiolite display a slight enrichment of LREE in chondrite-normalized REE diagrams, which are similar to that of a typical E-MORB or OIB (Fig. 2). However, compared with E-MORB or OIB in the primitive mantle (PM)-normalized spider diagram, all samples are depleted in Nb, Ta and Ti (Fig. 2). (2) The transitional signature between MORB and OIB hints that the ophiolite formed in a supra-subduction zone (SSZ) environment (Dilek and Furnes 2011). (3) As shown in Fig. 3, the magmatic rocks of the Jifeng ophiolite are similar to those of the arc volcanic rocks in terms of their geochemical signature, suggesting that the ophiolite is of SSZ type developed in transitional supra-subduction zone.

As mentioned above, we agree that the Jifeng ophiolite is consistent with the transitional SSZ-type ophiolite. More importantly, the Jifeng ophiolite marks an intra-oceanic subduction environment within the so-called late Precambrian Xinlin–Xiguitu Ocean (Feng et al. 2016).

Conclusion

Up to now, seventeen samples from the Jifeng ophiolite have been analyzed petrologically and dated by zircon U–Pb method, including serpentinites, troctolites, basalts and gabbros. However, none of these ultramafic rocks contain typical spinifex texture. The geochemical features with enrichment in light REE indicate that the Jifeng meta-ultramafic rock is not real komatiite. Instead, the Jifeng ophiolite suite and its geochemical features suggest that it is SSZ-type ophiolite developed in transitional supra-subduction zone.

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