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**Abstract** ee e e ea , aea e e a aa e ee  
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1. Introduction

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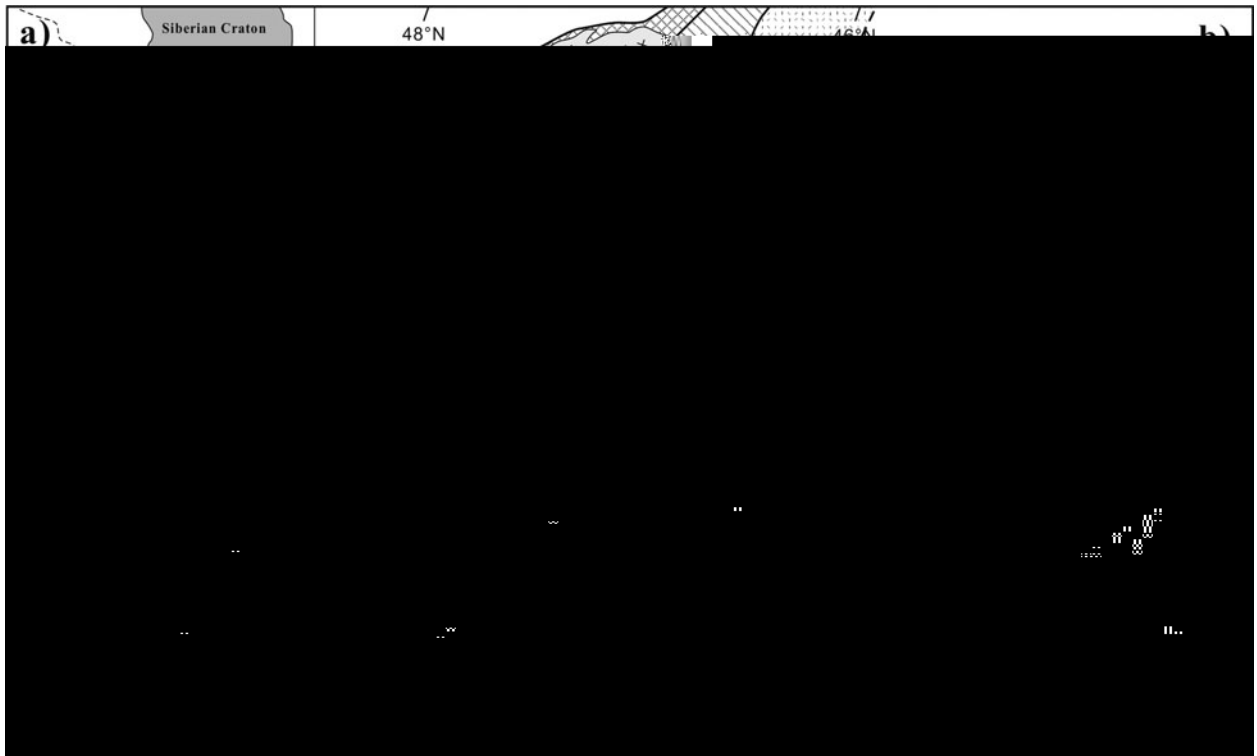


Fig. 1. (a) Geological map of the Siberian Craton showing a cross-section with coordinates 48°N and 169°E. The map displays various geological units with different patterns and colors. (b) A detailed view of a specific geological feature, possibly a fault or boundary, showing complex structural relationships between different rock units.

The study area is located in the Siberian Craton, which is a large tectonic plate. The geological structure is characterized by a complex arrangement of faults and folds. The main features include a series of parallel faults trending north-south, and a large-scale fold belt. The rocks are primarily igneous and metamorphic, with ages ranging from the Paleoproterozoic to the Mesoproterozoic. The tectonic evolution of the craton is still a subject of ongoing research.

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**2. Regional geology, field observations and petrography**

The regional geology is characterized by a complex arrangement of faults and folds. The main features include a series of parallel faults trending north-south, and a large-scale fold belt. The rocks are primarily igneous and metamorphic, with ages ranging from the Paleoproterozoic to the Mesoproterozoic. The tectonic evolution of the craton is still a subject of ongoing research.

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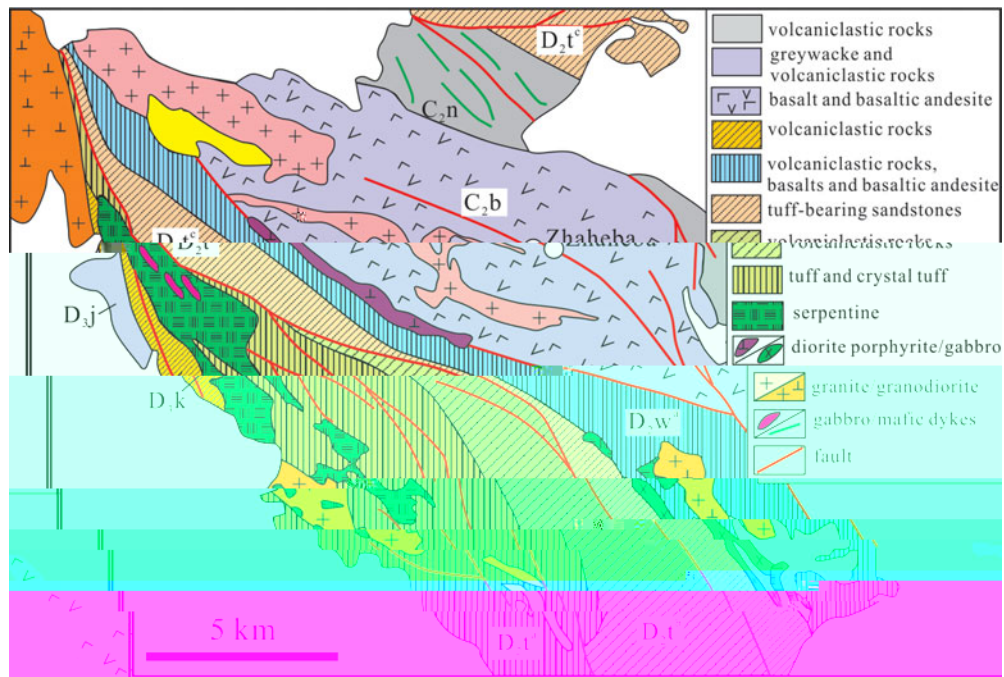


Figure 2. Geological map of the Zhaheba ophiolite (after Wang et al., 2000, 2001, 2003).

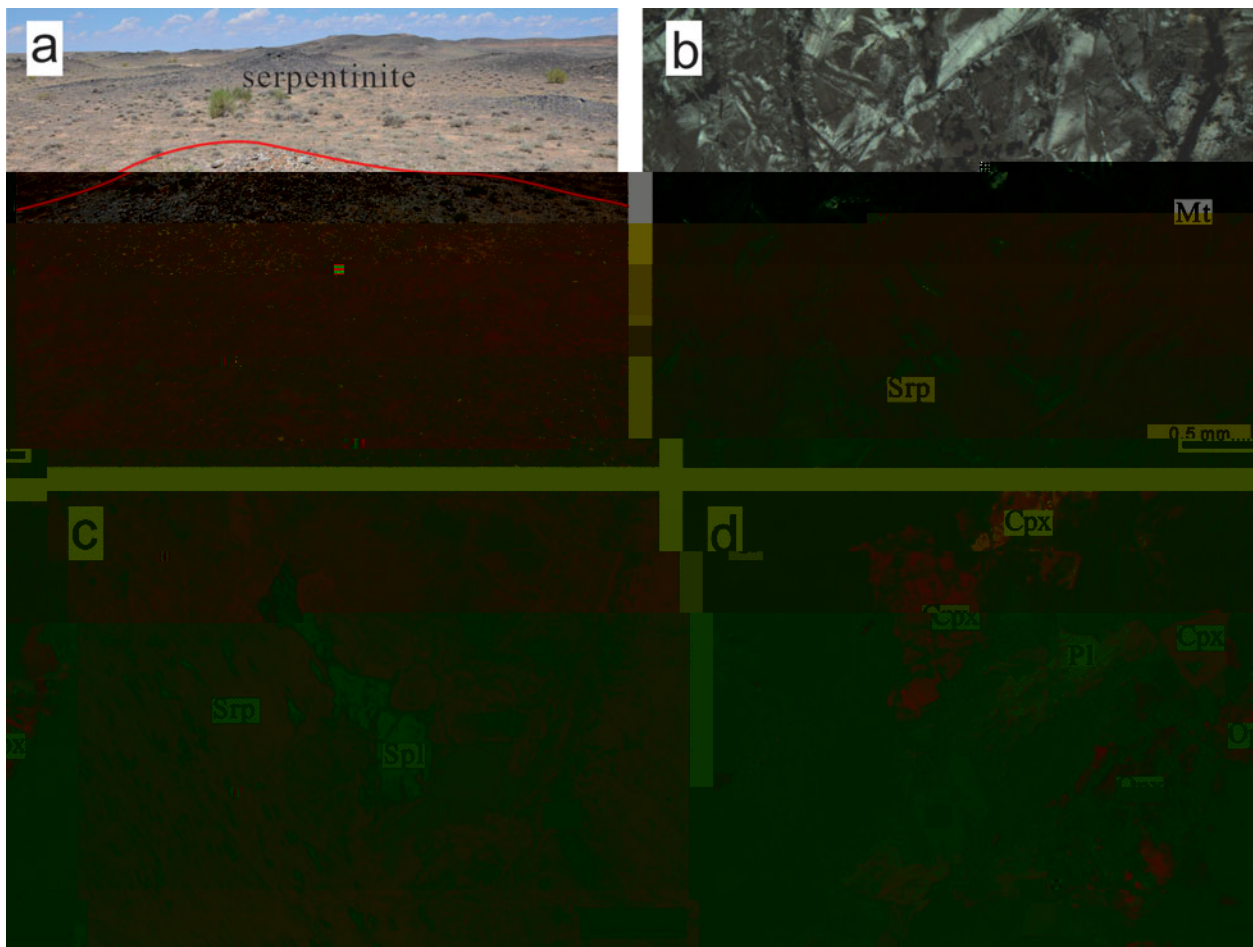


Figure 3. (a) Field photograph of serpentinite. (b) Backscattered electron (BSE) image of a mineral grain with labels Mt and Srp. (c) BSE image of a mineral grain with labels Srp and Spl. (d) BSE image of a mineral grain with labels Cpx, Pl, and Srp. Scale bar = 0.5 μm.

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3. Analytical procedures

3.a. Zircon U-Pb dating and Hf-O isotope analysis

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3.b. Mineral analysis

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3.c. Whole-rock analysis

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4. Analytical results

4.a. Zircon U-Pb ages

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<i>Major elements (%)</i>																				
2	3 . 0		4 .20		3 .41		3 .62		3 .22		3 . 2		3 .05		4 .22		46.4		51.2	
2	0.05		0.20		0.05		0.05		0.04		0.05		0.04		0.14		0.12		0.2	
2 3	0.61		1 . 6		1.04		0.6		0 . 0		0 . 4		0 . 0		1 . 2		1 .64		1 .33	
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.	3 .21		24.5		3 . 2		3 .		3 .0		3 .31		3 .44		10.04		.03		5.	
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	0.021		0.34		0.044		0.042		0.0 2		0.031		0.033		0.310		0.25		1.450	
	0.004		0.04		0.00		0.00		0.011		0.005		0.005		0.04		0.043		0.21	
	0.011		0.232		0.036		0.044		0.012		0.034		0.00		0.123		0.0 0		0. 3	
a	0.0 0		0.036		0.03		0.03		0.06		0.026		0.025		0.046		0.031		0.06	
	0.26		1. 10		6.600		1. 0		0. 3		0.233		1.150		1.5 0		0.516		0.1 5	
	0.406		0.0 2		0.12		0.112		0.0		0.1		0.054		0.16		0.1 1		0.6 5	
	0.046		0.034		0.014		0.02		0.050		0.030		0.010		0.050		0.02		0.130	
	0.1 1		0.144		0.203		0.364		0.042		0.0 4		0.0		0.066		0.042		0.0 3	
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2	4 .1		45.		4 .		53.1		51. 1		50.40		50.54		50.52		51.22		52.3	
2	0.34		0.15		1.40		1.24		1.31		1. 0		1.63		1.31		1.1		0.33	
2 3	1 .		1 .5		16.5		16.1		15. 3		15.		16. 6		15.55		15.4		1 .61	
e 2 3	4.52		3.34		.		.11		.43		.0		.50		.42		. 2		3.44	
	0.0		0.0		0.11		0.10		0.11		0.13		0.11		0.14		0.12		0.0	
	6.		.42		4. 0		4.2		4.41		5.		3.2		6.06		.14		4.	
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2	0.13		0.11		0.3		0.31		0.42		2.04		0.33		1.2		2.03		0.1	
2 5	0.04		0.02		0.62		0.62		0.65		0. 4		0.6		0.4		0.44		0.04	
	3. 2		3.26		4.24		2.54		2. 3		2.2		5.14		2.65		1. 3		2.	
	. 5		. 2		. 6		. 0		.4		.40		. 1		.6		.6		. 1	
	4.		.4		.11		. 0		.42		6.56		.64		6.0		6.11		.2	
#	5		1		55		54		54		56		41		56		64		4	
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	0.22		0.135		1.2 4		1.6 3		1.316		1. 53		1.034		1.100		0.5 5		0.62	
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		32.5		33.2		34.5		25.1		26.3		32.1		13.4		20.5	1 .	20.3
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		66.4		4.6		6.4		25.4		2 .1		66.6		.1		114	5.5	.02
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		1.2		0. 4		0. 55		11.315		11. 5		1.25		20.2		12.	21.	12.2
		0.025		0.030		0.02		0.051		0.052		0.02		/		/	/	/
		0.3 1		0.2 6		0.32		1.560		1.450		0.360		/		/	/	/
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		23.00		1 . 0		1 .40		51.50		54. 0		22.30		5 .		62.	2.3	52.5
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		2.540		2. 00		2.6 0		4.4 0		4. 00		2.3 0		4.5		5.2	6.	4. 5
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		2.1 0		2.150		2.220		3.420		3.6 0		2.130		2.5		2.	3.24	3. 5
e		0.46		0.446		0.444		0. 2		0. 5		0.46		0.4		0.52	0.5	0.
		1.350		1.230		1.240		2.120		2.2 0		1.310		1.32		1.3	1.45	2.25
		0.1 0		0.16		0.1 5		0.304		0.32		0.1 4		0.1		0.2	0.2	0.34
		1.210		1.050		1.120		1. 60		2.110		1.210		1.25		1.23	1.24	2.13
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		1.3 0		0. 41		1.040		3.2 0		3.510		1.460		5.3		3.2	4.16	3. 2
		0.0 4		0.062		0.051		0.5		0.644		0.0		1.35		0.6	1.16	0.6
		0.151		2.0		1.50		2. 5		1.		0.33		/		/	/	/
		0.3 4		0.206		0.200		45.20		35.10		0.41		.13		.0	4.1	21.06
		1. 0		0. 61		0. 1		. 60		.2 0		1. 0		4.50		2.63	3.20	.41
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2013	01	3	aa	( 2)	0.36	3 2	0.002	0.04030(2)	0.04015	2.4	10.	0.13 4	0.512 3 (40)	0.5124 4	6.
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2013	03	1	aa	( 1)	3.13	2 0	0.0335	0.06324(20)	0.06133	4.4	22.3	0.121	0.512533(4 )	0.512214	1.
2013	03	2	aa	( 1)	2.	1320	0.0063	0.042 (20)	0.04255	4. 5	2. 6	0.1046	0.512 1 (51)	0.512445	6.3
2013	03	3	aa	( 1)	.06	516	0.0452	0.0536 (43)	0.05111	5.	36.	0.0	0.512 0 (30)	0.512450	6.4
2013	03	4	aa	( 1)	.65	14 0	0.01	0.0422 (51)	0.04120	4.55	24.5	0.1123	0.512 03(53)	0.51250	.5

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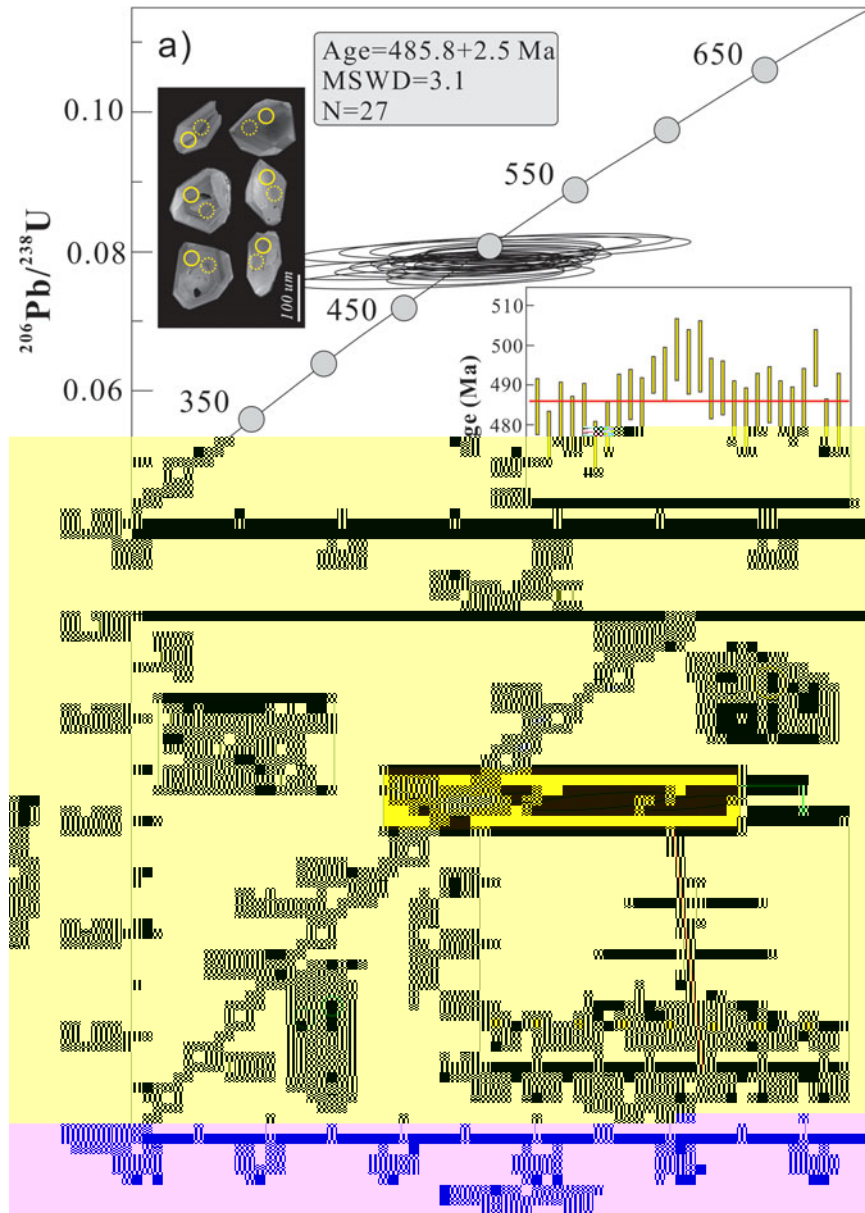


Fig. 4. (a) Concordia diagram showing the 206Pb/238U vs. 207Pb/235U relationship for zircon grains from the Zhaheba ophiolite. The age spectrum (b) shows a plateau at 485.8 ± 2.5 Ma. The detailed age spectrum (c) shows the distribution of ages for individual zircon grains. The age spectrum (b) is based on 27 grains with MSWD = 3.1. The age spectrum (c) is based on 100 grains with ages ranging from 100 to 200 Ma. The age spectrum (c) shows a plateau at 485 Ma, which is consistent with the concordia age (a). The age spectrum (c) also shows a significant spread in ages, which is likely due to the presence of inherited zircon grains. The age spectrum (c) is based on 100 grains with ages ranging from 100 to 200 Ma. The age spectrum (c) shows a plateau at 485 Ma, which is consistent with the concordia age (a). The age spectrum (c) also shows a significant spread in ages, which is likely due to the presence of inherited zircon grains.

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4.b. Mineral compositions

4.b.1. Spinel composition

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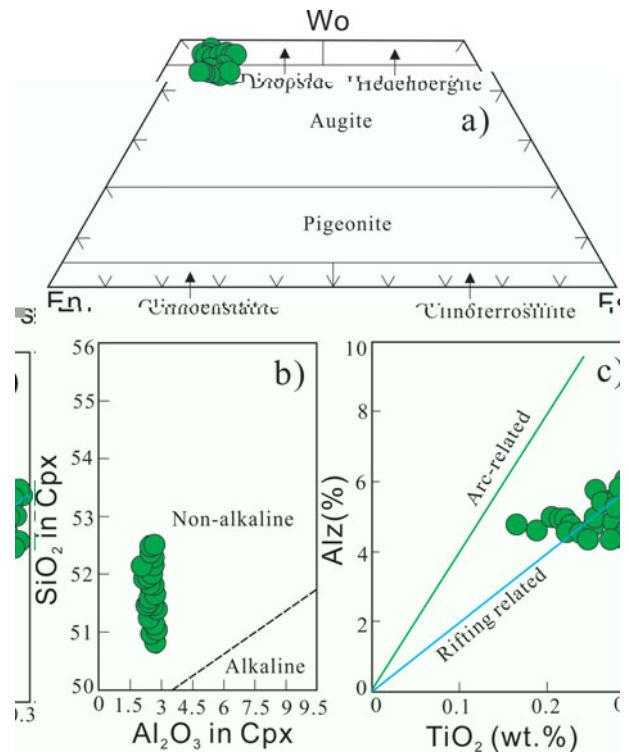
4.b.2. Pyroxene compositions

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4.c. Whole-rock elemental geochemistry

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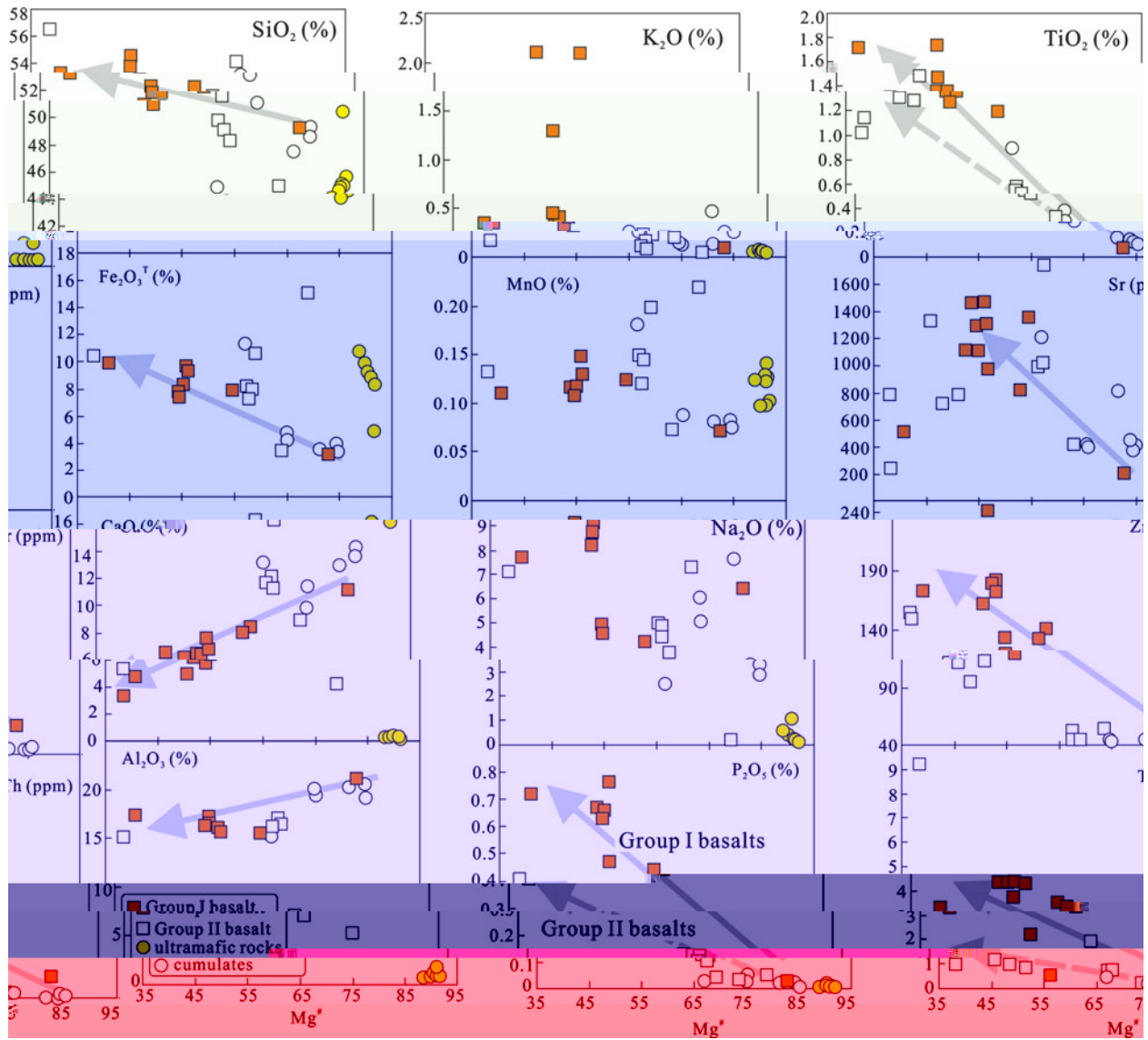


Figure 6. 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4.c.2. Basalts

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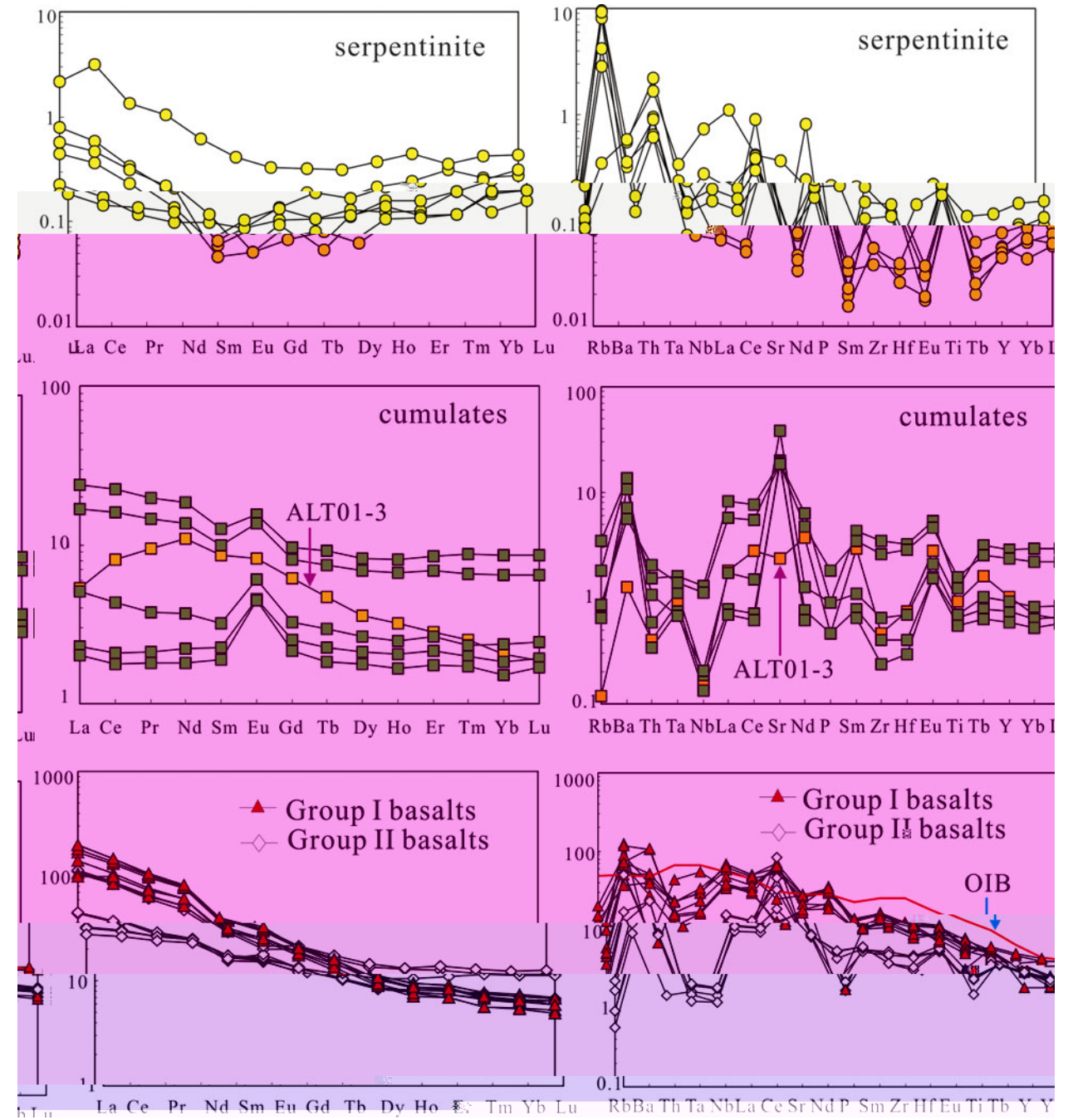


Figure 4.3. REE and trace element patterns for serpentinite and cumulates. The top row shows REE patterns for serpentinite (left) and trace element patterns (right). The middle row shows REE patterns for cumulates (left) and trace element patterns (right). The bottom row shows REE patterns (left) and trace element patterns (right) for Group I basalts (red triangles) and Group II basalts (black diamonds). The OIB line represents the Ocean Island Basalt pattern.

$\epsilon_{\text{Nd}}(t) = 0.0 \pm 0.14$   
 $\epsilon_{\text{Nd}}(t) = 2.2 \pm 0.4$   
 $\epsilon_{\text{Nd}}(t) = 1.02 \pm 0.21$   
 $\epsilon_{\text{Nd}}(t) = 0.44$   
 $\epsilon_{\text{Nd}}(t) = 0.2 \pm 0.1$   
 $\epsilon_{\text{Nd}}(t) = 1.1 \pm 0.1$   
 $\epsilon_{\text{Nd}}(t) = 0.11$

**4.d. Whole-rock Sr-Nd and zircon Hf-O isotopes**  
 $\epsilon_{\text{Nd}}(t) = 2.1 \pm 0.1$   
 $\epsilon_{\text{Nd}}(t) = 0.04030$   
 $\epsilon_{\text{Nd}}(t) = 0.04015 - 0.05111$   
 $\epsilon_{\text{Nd}}(t) = 0.0134$   
 $\epsilon_{\text{Nd}}(t) = 0.5123$   
 $\epsilon_{\text{Nd}}(t) = +6.3$   
 $\epsilon_{\text{Nd}}(t) = +0.5$

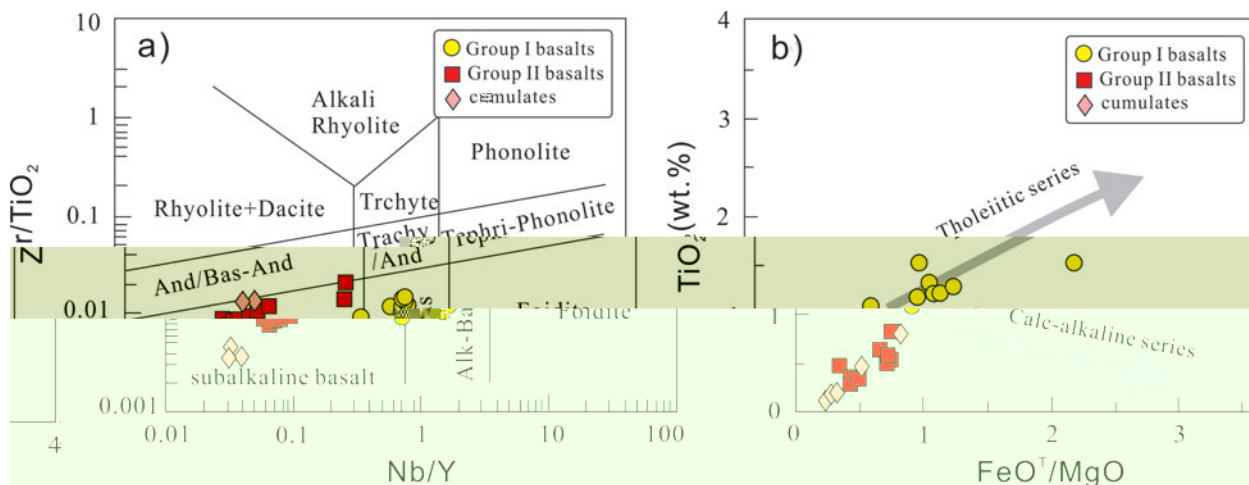


Figure 1. (a) Zr/TiO<sub>2</sub> vs Nb/Y and (b) TiO<sub>2</sub> (wt.%) vs FeO<sup>T</sup>/MgO diagrams for the Zhaheba ophiolite. The symbols represent Group I basalts (yellow circles), Group II basalts (red squares), and cumulates (red diamonds). The shaded areas indicate the fields for Tholeiitic series and Calc-alkaline series. The legend in both diagrams identifies the symbols used.

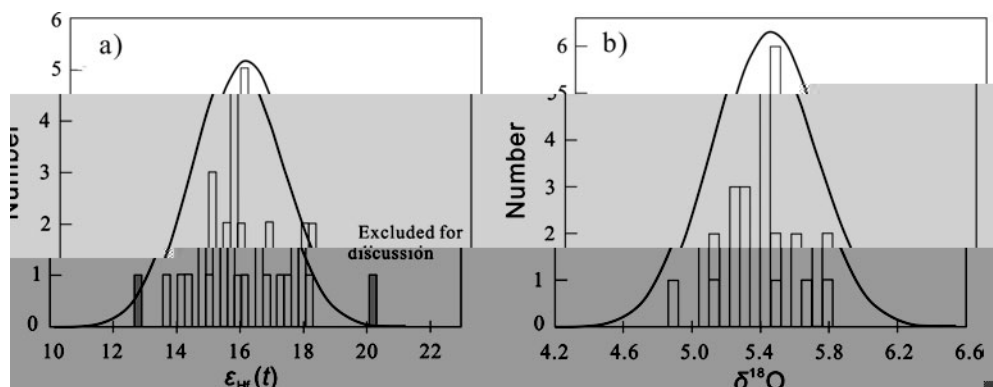


Figure 2. (a) Histogram of ε<sub>Hf</sub>(t) and (b) histogram of δ<sup>18</sup>O. The shaded areas represent the distribution of the data, and the curves represent normal distribution fits.

The ε<sub>Hf</sub>(t) values of the Zhaheba ophiolite basalts range from 4.5 to 20.0‰, with a mean of 15.3‰ (n = 45). The δ<sup>18</sup>O values range from 4.1‰ to 6.6‰, with a mean of 5.3 ± 0.23‰ (n = 400). The ε<sub>Hf</sub>(t) values are significantly higher than those of the surrounding rocks, indicating a high degree of mantle depletion in light REE. The δ<sup>18</sup>O values are also higher than those of the surrounding rocks, indicating a high degree of mantle enrichment in heavy oxygen isotopes. The ε<sub>Hf</sub>(t) values of the Zhaheba ophiolite basalts are similar to those of the Zhaheba ophiolite basalts reported by [Zhang et al. \(2013\)](#) and [Zhang et al. \(2014\)](#). The δ<sup>18</sup>O values of the Zhaheba ophiolite basalts are similar to those of the Zhaheba ophiolite basalts reported by [Zhang et al. \(2013\)](#) and [Zhang et al. \(2014\)](#).

## 5. Discussion

### 5.a. The individual members of the Zhaheba ophiolite

The Zhaheba ophiolite consists of several members, including the Group I basalts, Group II basalts, and cumulates. The Group I basalts are characterized by high ε<sub>Hf</sub>(t) values and high δ<sup>18</sup>O values. The Group II basalts are characterized by lower ε<sub>Hf</sub>(t) values and lower δ<sup>18</sup>O values. The cumulates are characterized by intermediate ε<sub>Hf</sub>(t) values and intermediate δ<sup>18</sup>O values. The Zhaheba ophiolite basalts are similar to those of the Zhaheba ophiolite basalts reported by [Zhang et al. \(2013\)](#) and [Zhang et al. \(2014\)](#). The Zhaheba ophiolite basalts are similar to those of the Zhaheba ophiolite basalts reported by [Zhang et al. \(2013\)](#) and [Zhang et al. \(2014\)](#).

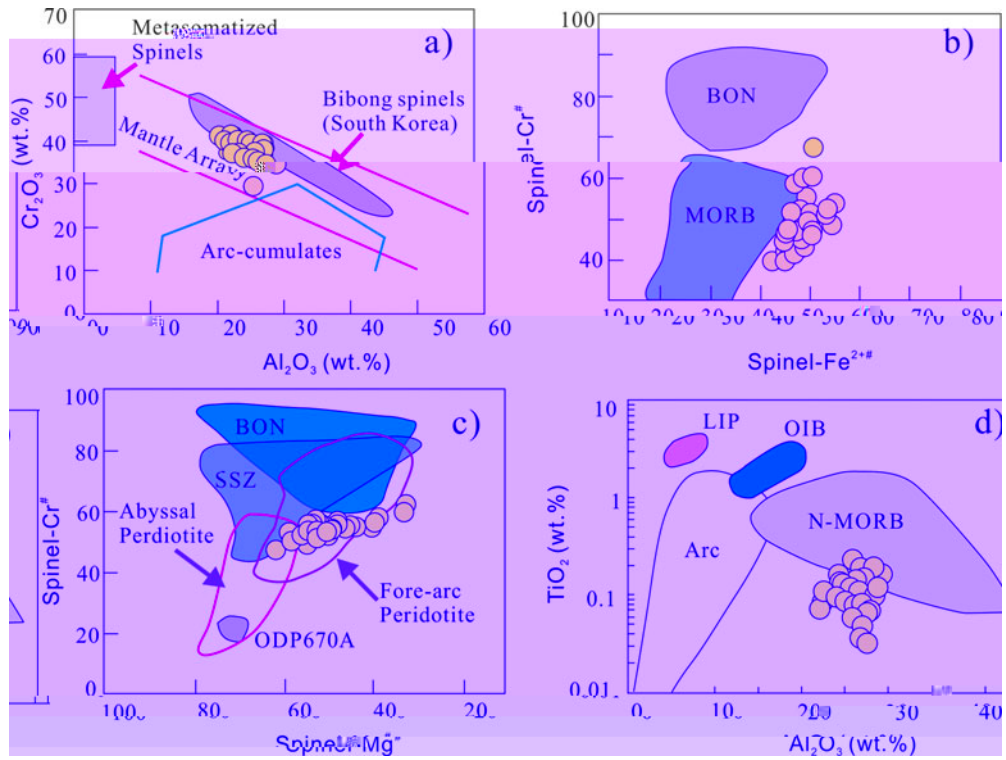


Fig. 10. (a) Cr<sub>2</sub>O<sub>3</sub> vs Al<sub>2</sub>O<sub>3</sub> (wt.%) diagram showing the Mantle Array (dotted line), Arc-cumulates (solid line), and Bibong spinels (South Korea) (orange circles). (b) Spinel-Al-Cr vs Spinel-Fe<sup>2+</sup> diagram showing the BON (Basaltic Ocean Nodule) and MORB (Mid-Ocean Ridge Basalt) fields. (c) Spinel-Cr vs Spinel-Mg diagram showing the BON, SSZ (Spreading System Zone), Abyssal Peridotite, and Fore-arc Peridotite fields, with ODP670A (orange circles) plotted. (d) TiO<sub>2</sub> vs Al<sub>2</sub>O<sub>3</sub> (wt.%) diagram showing the LIP (Large Igneous Province), OIB (Ocean Island Basalt), Arc, and N-MORB (Normal Mid-Ocean Ridge Basalt) fields.

... (500-400 a) (a et al. 2003 et al. 2015), ... (430-400 a) (a et al. 200 b, 2014 a et al. 2015), ... (300-350 a) (a et al. 2003 et al. 2006).

5.b. Origin of the serpentinite and cumulates

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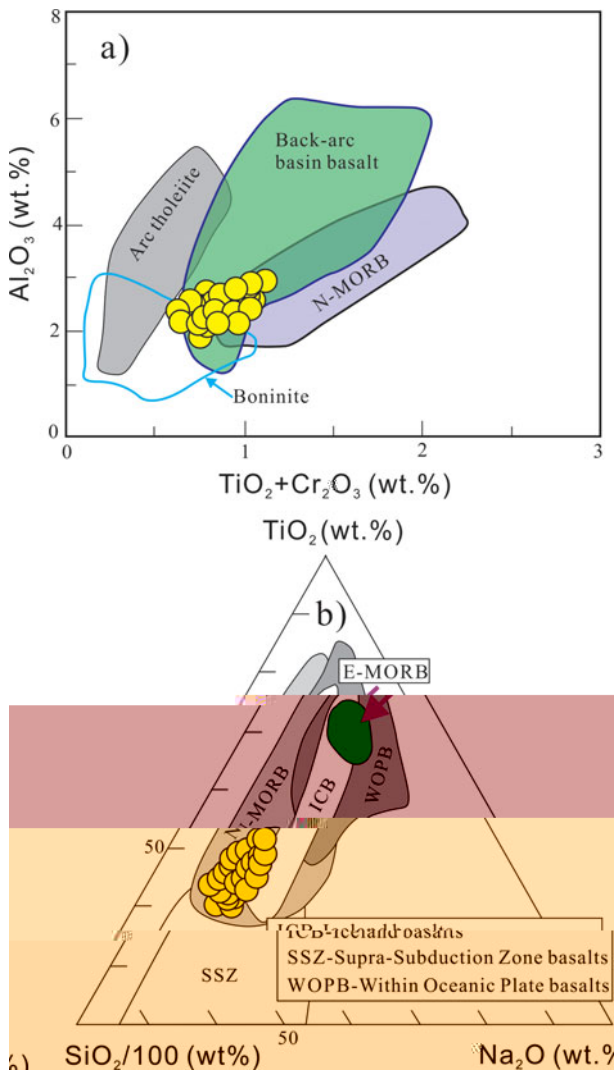


Fig. 11. (a)  $Al_2O_3$  vs  $TiO_2 + Cr_2O_3$  and  $TiO_2$  scatter plot. (b) TAS diagram. Fields are defined after [11]. The Zhaheba ophiolite samples are plotted as yellow circles. The fields are defined after [11]. The Zhaheba ophiolite samples are plotted as yellow circles.

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5.c. Petrogenesis of the Devonian basalts

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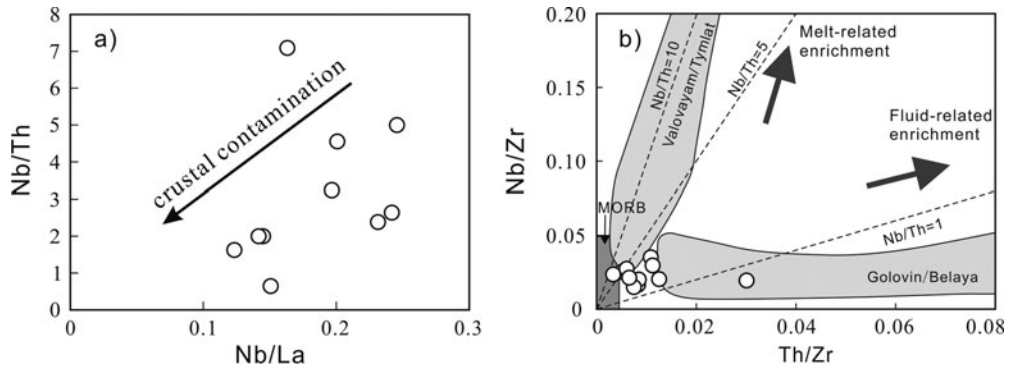


Figure 12. (a) Nb/Th vs Nb/La scatter plot showing crustal contamination. (b) Nb/Zr vs Th/Zr scatter plot with MORB, Valovayami/Tymial, Golovin/Belaya, and enrichment trends.

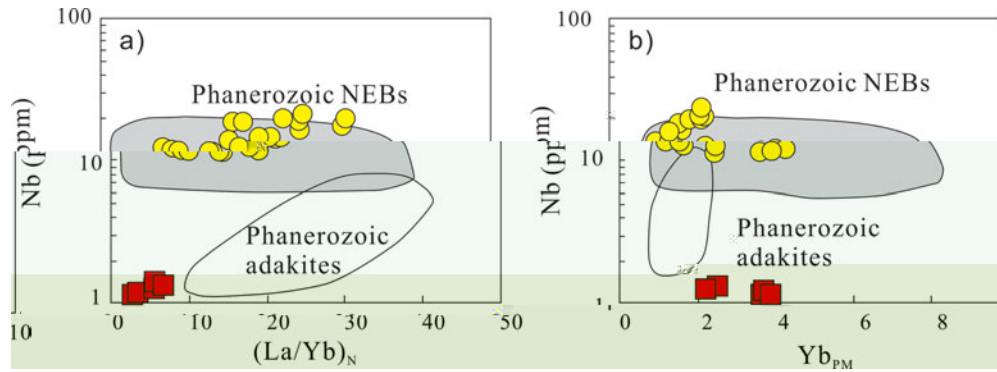


Figure 13. (a) Nb (ppm) vs (La/Yb)<sub>N</sub> scatter plot. (b) Nb (ppm) vs Yb<sub>PM</sub> scatter plot. Both plots show fields for Phanerozoic NEBs and adakites.

Figure 13. (a) Nb (ppm) vs (La/Yb)<sub>N</sub> scatter plot. (b) Nb (ppm) vs Yb<sub>PM</sub> scatter plot. Both plots show fields for Phanerozoic NEBs and adakites.

(Figure 14). Figure 14 shows two scatter plots. Plot (a) shows Nb/Th vs Nb/La and plot (b) shows Nb/Zr vs Th/Zr. Both plots show data points and fields for MORB, Valovayami/Tymial, and Golovin/Belaya, along with enrichment trends.

5.d. Implications for the Palaeozoic accretion process in eastern Junggar

Figure 14. (a) Nb/Th vs Nb/La scatter plot. (b) Nb/Zr vs Th/Zr scatter plot. Both plots show data points and fields for MORB, Valovayami/Tymial, and Golovin/Belaya, along with enrichment trends.



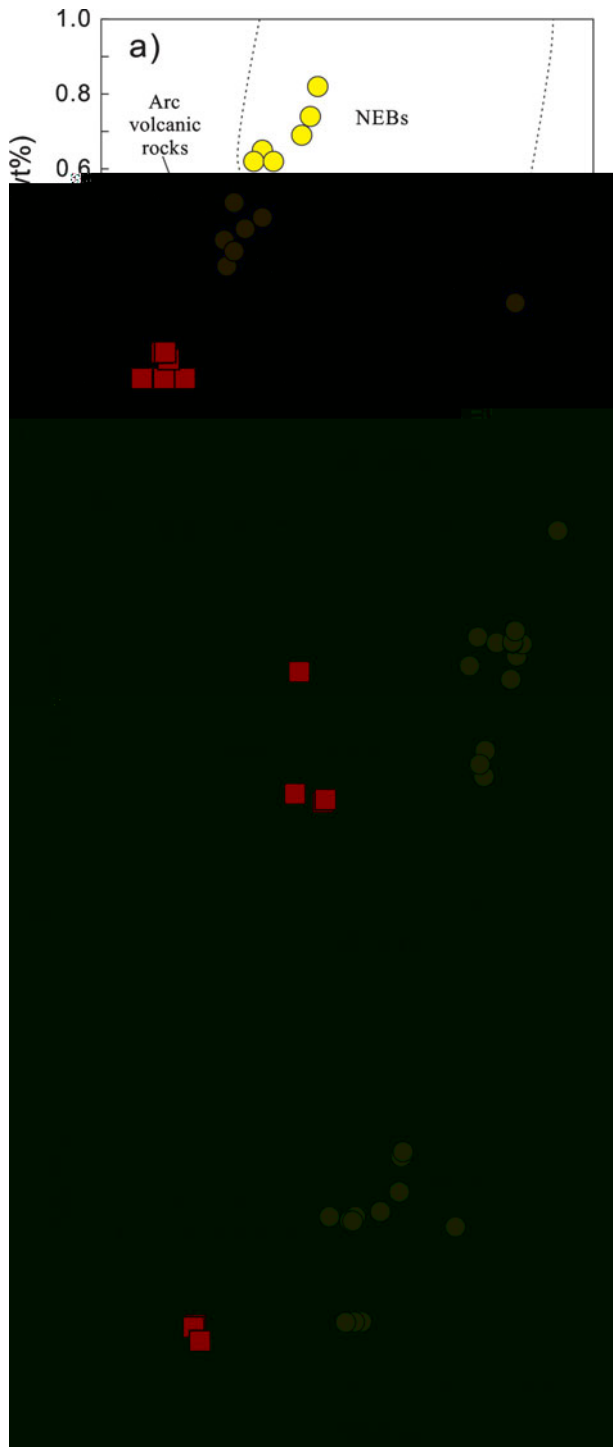


Fig. 14. (a)  $^{143}\text{Nd}/^{144}\text{Nd}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  diagram for the Zhaheba ophiolite. The data points are plotted against the theoretical values for arc volcanic rocks and NEBs. The red squares represent the data from this study, and the yellow circles represent data from other studies (e.g., *et al.* (1995), *et al.* (2005)).

The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of the arc volcanic rocks range from 0.512 to 0.514, and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios range from 0.705 to 0.715. The data points for the arc volcanic rocks are clustered in the lower left corner of the diagram. The NEBs show a wider range of  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, from 0.515 to 0.525, and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from 0.715 to 0.735. The data points for the NEBs are clustered in the upper right corner of the diagram.

The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of the arc volcanic rocks are significantly lower than those of the NEBs, indicating a different source or a different time of formation. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the arc volcanic rocks are also lower than those of the NEBs, suggesting a younger age for the arc volcanic rocks. The data points for the arc volcanic rocks are clustered in the lower left corner of the diagram, while the data points for the NEBs are clustered in the upper right corner of the diagram.

(1) The arc volcanic rocks have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.512 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.705. The NEBs have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.525 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.735.

(2) The arc volcanic rocks have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.513 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.710. The NEBs have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.520 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.725.

(3) The arc volcanic rocks have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.514 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.715. The NEBs have a  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of approximately 0.525 and a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of approximately 0.735.

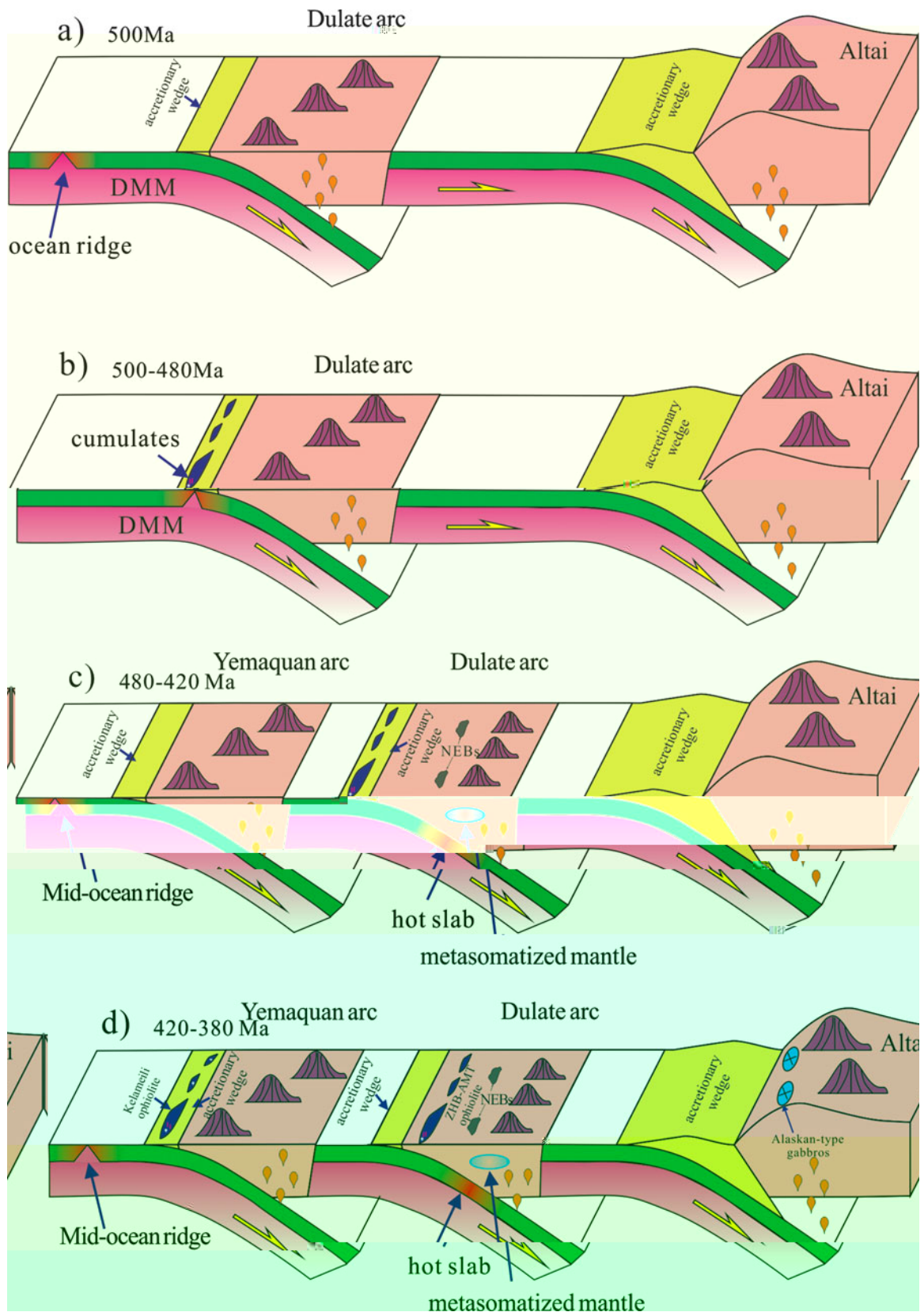


Figure 15. (a) 500 Ma Dulate arc; (b) 500-480 Ma Dulate arc; (c) 480-420 Ma Yemaquan arc and Dulate arc; (d) 420-380 Ma Yemaquan arc and Dulate arc.

(4)  $^{87}\text{Sr}/^{86}\text{Sr}$  (420 3 0 a) (Li et al. 2014; Li et al. 2015). The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the sample range from 0.706 to 0.708, which is similar to the values of the sample (0.706–0.708) (Li et al. 2015). The  $^{87}\text{Sr}/^{86}\text{Sr}$  values of the sample are similar to the values of the sample (0.706–0.708) (Li et al. 2015).

6. Conclusions

- (1) The Zhaheba ophiolite is a typical island arc ophiolite with a thickness of ~4–5 km, and is composed of a sequence of mafic rocks, including gabbro, diorite, and basalt, which are intruded by a diorite dike. The ophiolite is associated with a sequence of sedimentary rocks, including sandstone, shale, and limestone, which are deposited in a forearc basin.
- (2) The Zhaheba ophiolite is a typical island arc ophiolite with a thickness of ~4–5 km, and is composed of a sequence of mafic rocks, including gabbro, diorite, and basalt, which are intruded by a diorite dike. The ophiolite is associated with a sequence of sedimentary rocks, including sandstone, shale, and limestone, which are deposited in a forearc basin.
- (3) The Zhaheba ophiolite is a typical island arc ophiolite with a thickness of ~4–5 km, and is composed of a sequence of mafic rocks, including gabbro, diorite, and basalt, which are intruded by a diorite dike. The ophiolite is associated with a sequence of sedimentary rocks, including sandstone, shale, and limestone, which are deposited in a forearc basin.

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Supplementary material

Supplementary material is available for this article. For further information on this material please go to the journal web site at <http://www.nature.com/nature/journals/001656166000042>.

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