Geol. Mag. **154** (3), 2017, pp. 419–440. © Cambridge University Press 2016
10.101 / 0016 56 16000042

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, , 10003 ,
‡ , 210016,
, , , 36 4 -5305,

(*Received* 1 2015; *accepted* 2016; *first published online* 1 2016)

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ε (*t*) (13 20) δ1 (+5.3 ‰) .
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1. I c

(. . *et al.* 200 , & , 200 , - *et al.* 2012; *et al.* 2012, 2013; *et al.* 2013), -
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(, 1 , *et al.* 200 , *et al.* 200 a).
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(, 1 , -
& , 1 , , 1 3; *et al.* 2000;
& , 2003; *et al.* 200 , , 2014).
, & (2011) -
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( ), . -
, (2014) -

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(ö , & , 1 3; ,
& , 2000; *et al.* 2002; *et al.* 2004,
200 a) (. 1).
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(*et al.* 200 a,b; ,
& , 2012). ,
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(, 1 3; *et al.* 2003; *et al.* 2003; *et al.* 200 a) (. 1). -
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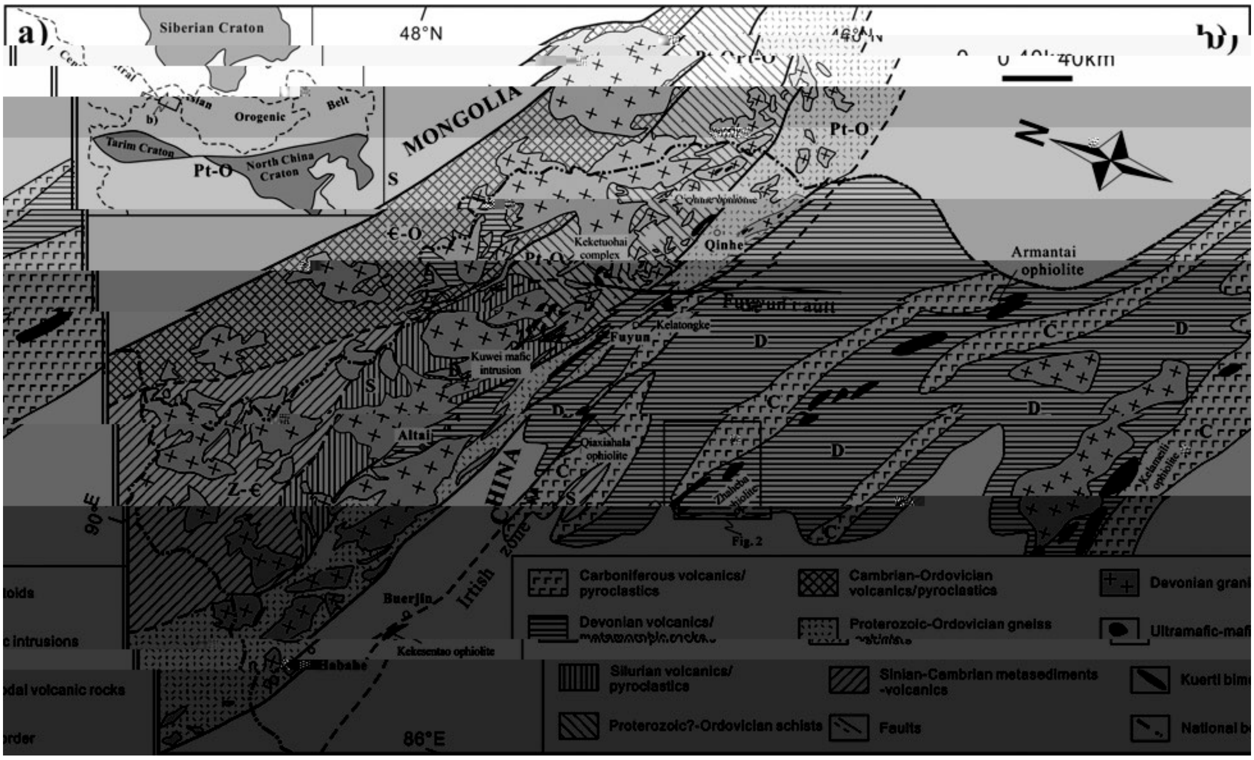
† 1 6 .



1. ( ) ( ). ( ) (
et al. 200).

> 0 % ,
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(1) *et al.* 2013). -
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(2) (40 0 %) (30 50 %)
- . (5 10 %)
(. 3).
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2. R a , b a a
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2). , , ( )
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( ) (*et al.* 2006).
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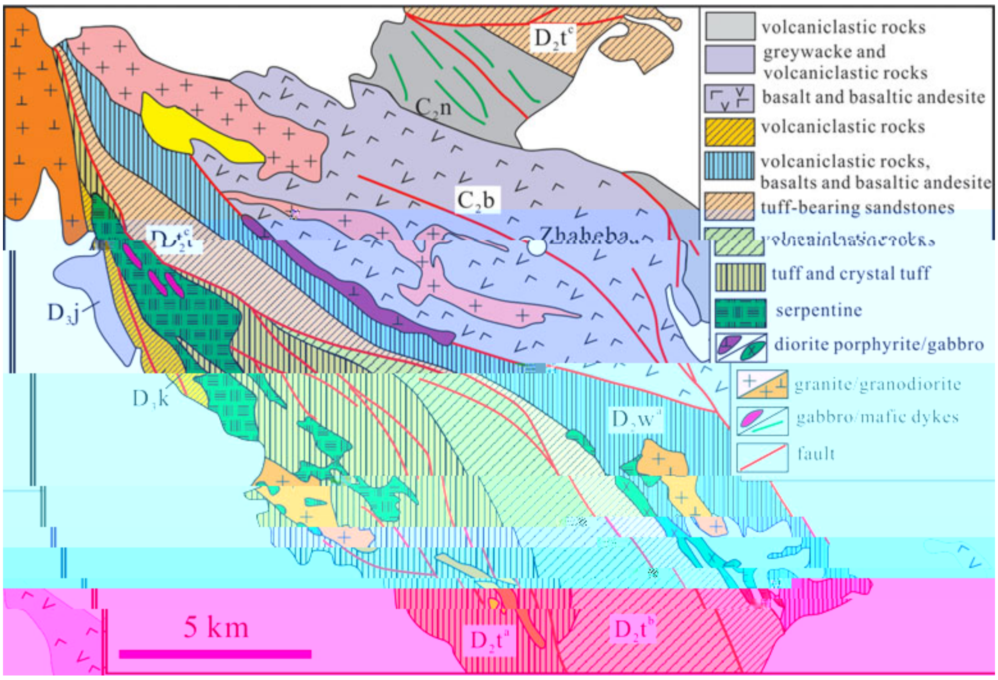
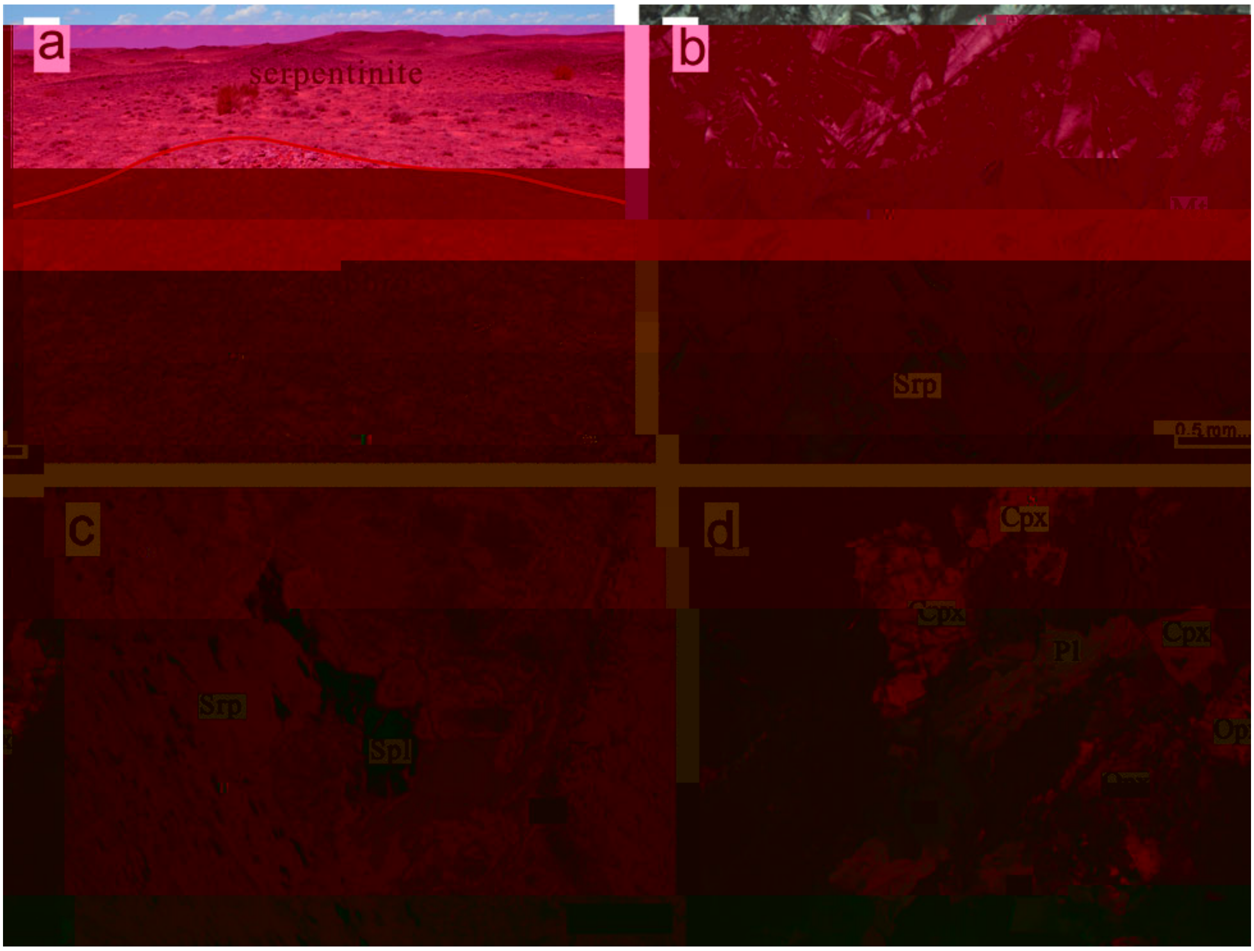


2. ( ) (*et al.* 200 , 200 *a* , 1 3).



3. ( ) . ( ) . (,) > 0% . ( ) , . , , , , , .

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3. A a ca , c

3.a. Z c U Pb a a H O a a

(2013 01, 46° 32′ 51 , ° 2′ 4)
(2013 02, 46° 33′ 2 , ° 2′ 36) -
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et al. (2011).

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- - (*et al.* 2010) (, 2003).
5 % .

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12 0
, ,
et al. (2010*a*). 1 /16

(, 1 /16 = 0.0020052),
-
( ) -
δ1 5.31 ‰ (*et al.* 2010*b*).
-
δ1 5.44 ± 0.21 ‰ (2), -
5.4 ± 0.2 ‰
(*et al.* 2013).
3
// . . / .

3.b. M a a a

- 00 -

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, . -
15 15

20 . -
-
4 5
// . . / .

3.c. W - c a a

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100 -
et al. (2004).
2 %. -
6000 - -
et al. (2004). 50

- + 3 -
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-1 -
3,
. -
3 5 %.
1.

+ 3
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et al. (2004). / 6
143 /144 6 / =
0.11 4 146 /144 = 0. 21 , .
/ 6 0. 102
0. 0506 -1,
143 /144 0.512104 -
1 0.5126 1 -1.
2.

4. A a ca

4.a. Z c U Pb a

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100 150 μ
1 1 2 1. ,
, -
(. 4).
,
(22 123) (
5) / 0.4
0. . - 30
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4 5. ± 2.5

1. ,

	2013 01-1	2013 01-3	20132 01-4	2013 01-5	2013 01-6	2013 01-	2013 01-	2013 01 1	2013 01 2	2013 01 4
					Major elements (%)					
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
2 3	.44	4.6	.	.36	.5	.16	. 4	3.6	3.24	3.
	0.0	0.10	0.11	0.11	0.11	0.0	0.11	0.0	0.0	0.0
	3 .21	24.5	3 . 2	3 .	3 .0	3 .31	3 .44	10.04	.03	5.

1 4210.0

1.

	2013 01-1	2013 01-3	20132 01-4	2013 01-5	2013 01-6	2013 01-	2013 01-	2013 01 1	2013 01 2	2013 01 4
	0.005	0.064	0.00	0.005	0.00	0.003	0.003	0.051	0.044	0.222
	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
	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
	2013 01 5	2013 01 6	2013 01 (1)	2013 01 (1)	2013 01 (1)	2013 03 2 (1)	2013 03 3 (1)	2013 03 4 (1)	2013 03 5 (1)	2013 01 3 (2)
					Major elements (%)					
$_2$	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
$_{2\ 3}$	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.
	11.03	12.61	6.22	5. 5	6.3	6. 5	4.52	.4	.26	. 0
$_2$	4. 6	.3	. 2	.3	.00	4.52	.31	4. 0	4.0	.11
$_2$	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
					Trace elements (ppm)					
	.0	4. 5	1.16	1.12	1.4	.0	40.4	5.2	6. 2	5. 1
	0.22	0.135	1.2 4	1.6 3	1.316	1. 53	1.034	1.100	0.5 5	0.62
	25.0	23.	1 .6	1 .5	1 .5	.5	1 .2	25.2	1 .	1 .0
	11	3.	1 6	166	1 2	22	22	254	1	5.
	34.	163	60.5	62.6	64.1	116	1 .	0.	203	23.
	24.2	21.6	26.	23.6	24.6	2 .	2 .5	2 .0	2 .0	16.4
	4.	1 5	63.6	50.	51.4	6.	2 .	5 .3	132	1.1

1.

	2013 01 5	2013 01 6	2013 01 (1)	2013 01 (1)	2013 01 (1)	2013 03 2 (1)	2013 03 3 (1)	2013 03 4 (1)	2013 03 5 (1)	2013 01 3 (2)
	3.	1.20	3 .60	46. 0	4 .30	23.40	43.00	25.20	32. 0	6.56

23.40 .1 .1 23.40 6.540 .1 25.20 .1 605 5 ( )-250

1.

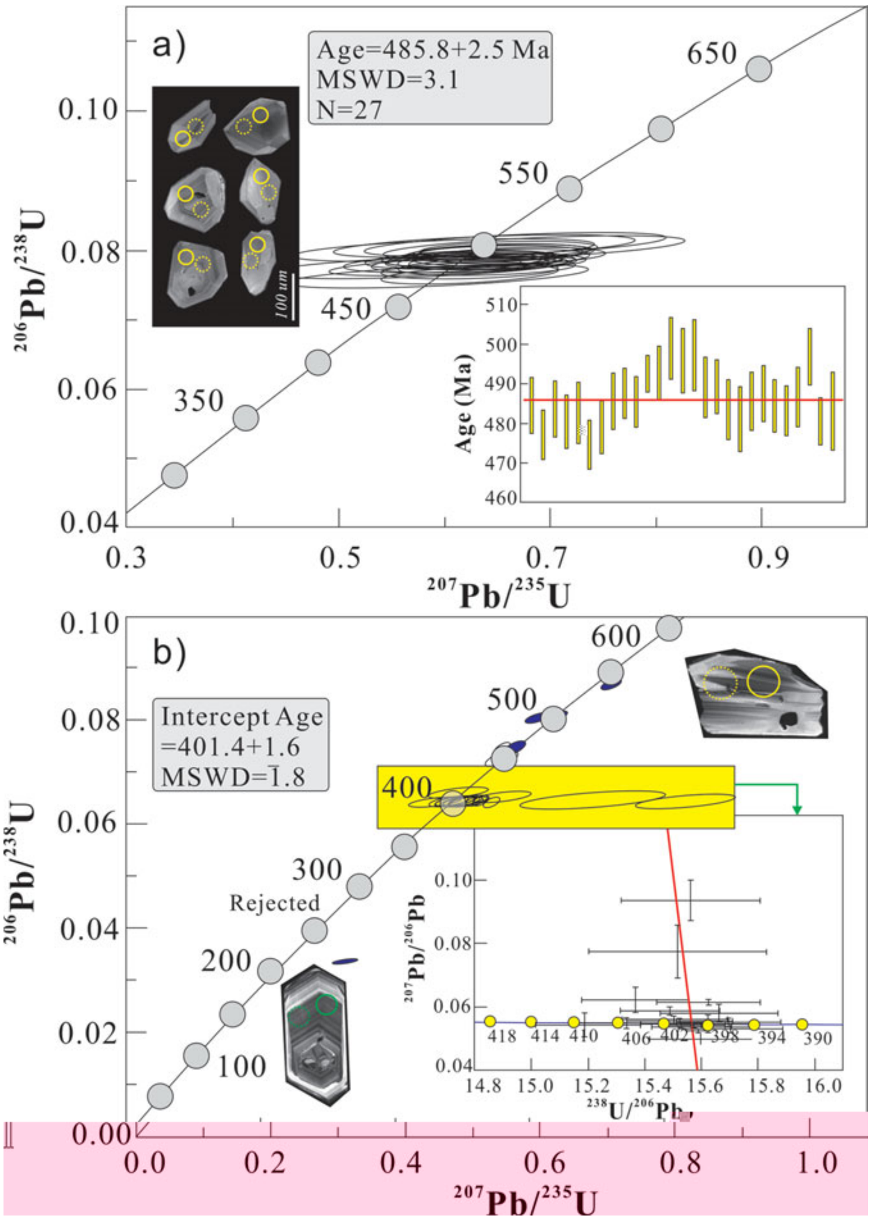
	2013 01 11 (2)	2013 02 1 (2)	2013 02 2 (2)	2013 03 1 (1)	2013 03 6 (1)	2013 01 10 (2)	04 06 (1)	04 24 (1)	04 2 (1)	03 1 (1)
					Trace elements (ppm)					
	1 .4	36.	42.4	26.0	32.4	1 .	/	/	/	/
	0.3 5	0.153	0.35	1.1	0. 4	0.46	/	/	/	/
	32.5	33.2	34.5	25.1	26.3	32.1	13.4	20.5	1 .	20.3
	1 4	203	21	33	341	1 5	144	1 4	214	265
	56.5	44.2	4 .	1 .	22.2	53.	15	162	214	265
	34.	3 .5	3 .3	23.1	24.	33.	20.6	30.	2 .	20.2
	66.4	4.6	6.4	25.4	2 .1	66.6	.1	114	5.5	.02
	6.4	236.4	256.	205.4	20 .	114.20	/	/	/	/
	4 .0	44.1	4 .0	4.	103	44.1	/	/	/	/
	12.0	11.1	11.2	14.	13.6	12.0	/	/	/	/
	0.5	1.420	1.0 0	3.130	3.2 0	0.5 3	4.	1 .1	22.0	1 .2
	1	1 50	5	2 0	24	6 6	1	31	111	6
	13.0	13.0	13.2	21.1	22.	12.5	13.2	13.2	14.	20.1
	54.	42.3	41.5	144	154	52.	243	133	164	151
	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	/	/	/	/
	0.2	1. 20	1.030	0.365	0.406	0.336	/	/	/	/
	11	3 2	346	25	50	4.3	/	/	/	/
	10. 0	. 40	.610	26.40	26. 0	10.50	30.6	32.2	40.1	26.4
	23.00	1 . 0	1 .40	51.50	54. 0	22.30	5 .	62.	2.3	52.5
	2. 0	2.520	2.510	5. 50	6.1 0	2.6 0	6.	. 4	10.5	6.4
	11. 0	11. 0	11.60	22.30	24.30	11.60	2 .5	31.2	43.1	24.4
	2.540	2. 00	2.6 0	4.4 0	4. 00	2.3 0	4.5	5.2	6.	4. 5
	0. 6	0. 1	0. 0	1.163	1.25	0. 3	1.45	1.5	2.0	1.03
	2.4 0	2. 13	2. 54	4.14	4.46	2.522	3.56	4.01	5.35	4.23
	0.3 6	0.3	0.3	0.612	0.660	0.3 4	0.4	0.54	0.64	0.63
	2.1 0	2.150	2.220	3.420	3.6 0	2.130	2.5	2.	3.24	3. 5
	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
	0.1 4	0.164	0.165	0.2 1	0.323	0.1 3	0.20	0.1	0.1	0.34
	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
	0.500	0.304	0.302	2. 30	3.4 0	0.501	1.	0.6	1.46	2.5

, , , , / .
04 06, 04 26, 04 2 04 1 *et al*. (200 *a*).

2.

		( )	( )	^{6} /	^{6} / (1σ)	(^{6} /)	( )	( )	^{14} / ^{144}	^{143} / ^{144} (1σ)	(^{143} / ^{144})	ε (*t*)
2013 01 3	(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.
2013 01 10	(2)	0.5	6 6	0.0024	0. 04 5 (23)	0. 04 45	2.3	11.6	0.1235	0.512 0 (43)	0.5124 6	.1
2013 03 1	(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	(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	(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	(1)	.65	14 0	0.01	0. 0422 (51)	0. 04120	4.55	24.5	0.1123	0.512 03(53)	0.51250	.5

ε (*t*) = 10 000((^{143} /^{144}) (*t*)/(^{143} /^{144}) (*t*)−1). ε (*t*) (/ ^{6})
401 .



4. ( ) .
1σ 2σ ( ) .

(. 4 , = 2 , = 3.1). - / 1 3. -
4 ± 4 , .
1 (1) , 0 %
(*et al.* 2003). , ,
-
, 100 200 μ . (2)

, -
(2, . 4).
-
. , 2
450
500 .
21 1 -
206 23
401 ± 2 (= 3.3).
206 23 20 235 , -
401.4 ± 1.6 (= 1.) (
206
. 4),
23
.
(, 1 3).

4.b. M a c

4.b.1. Spinel composition

(. 3). 100 300 μ .
(
4 // . . /)
2 3, 2 3 -
, , 2 .
. (100 /(+))
44 60 . (100 /(+))
25 61.
/ /
- (*et al.* 2010).
-
( )
(*et al.* 2013).

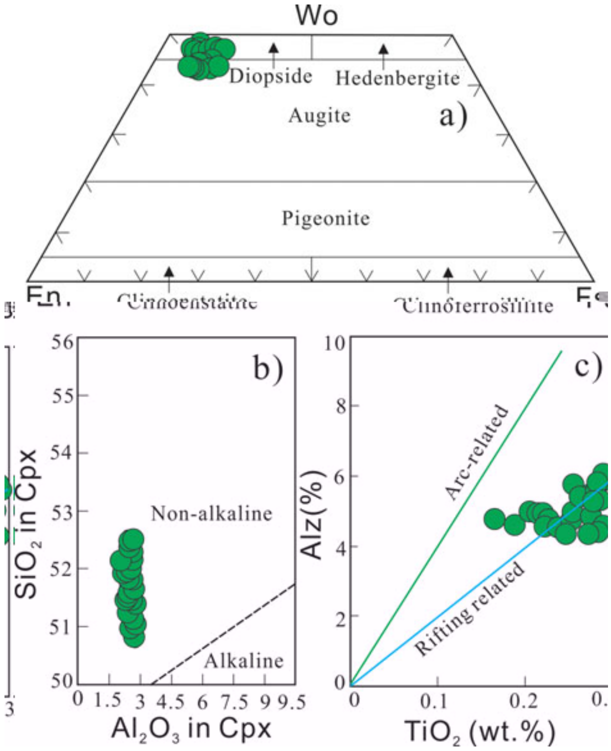
4.b.2. Pyroxene compositions

(= 4 6).
2 -
(0.5 %) -
(-
5 // .
. /). -
41 4 . , 46 55 . 1 .
(. 5). - -
2 3, 2 2
(. 5 ,).

4.c. W - c a c

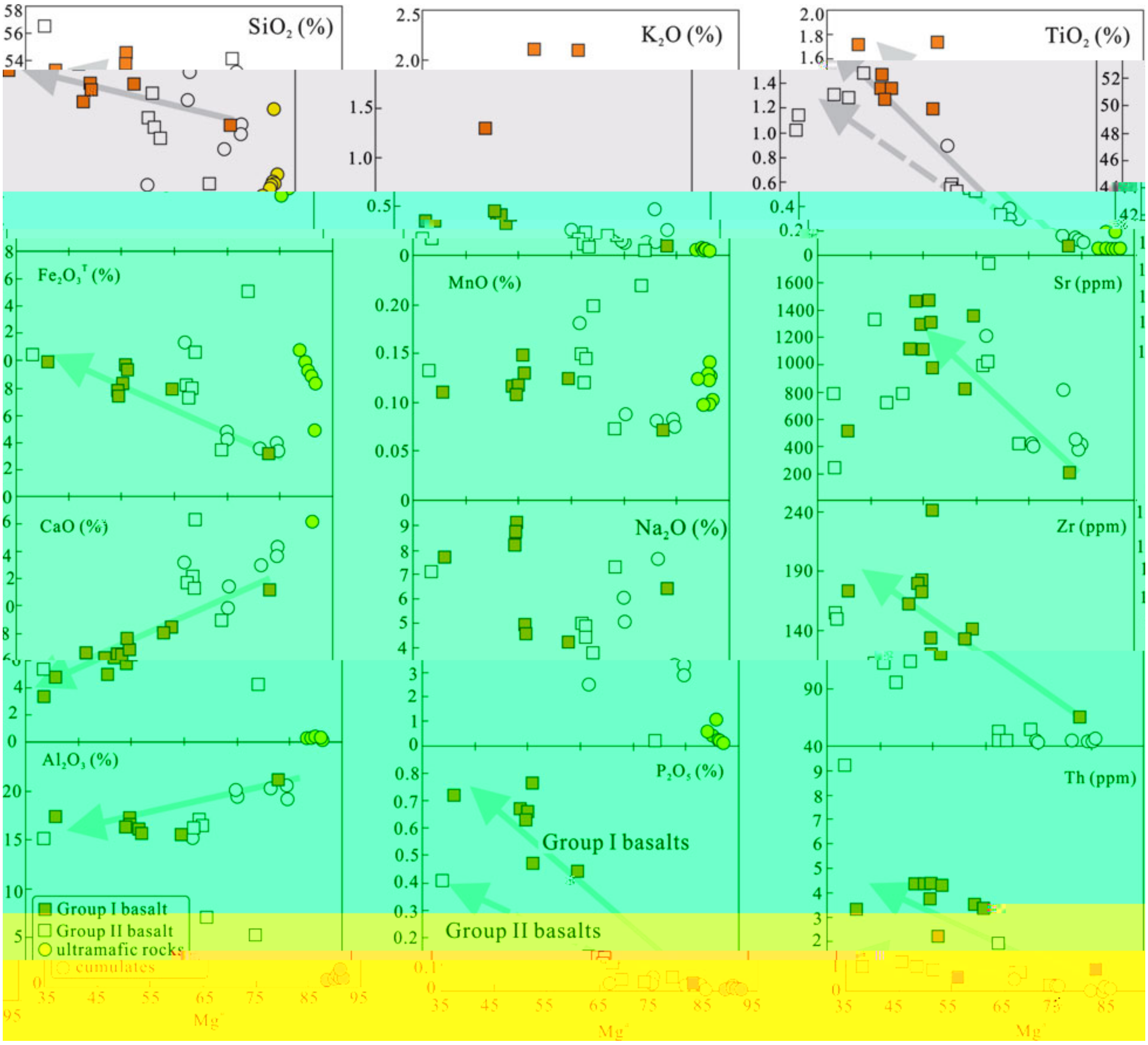
4.c.1. Serpentinites and cumulates

( )
(> 12 %, -
) 2 (40 %), 2 3 (
1.0 %), 2 (0.03 0.06 %), 2 (0.04
0. 2 %) 2 (0.04 0.05 %). 2 3 -



5. ( ) ( )
. ( ) 2 (%) . 2 3 (%) ( )
( ) . 2 (%)
.

1 (1).
,
. (. 6).
(3 103)
(5) (1). (> 12 %)
2 , 2 -
(,)
( ) (. . ,
). , -
, 2 3, 2 3 2,
-
. ,
-
.
( ) - -
( ) (1). , -
- -
(.),
(, 2014
& -
, 1).
2
45. % 51.2 %,
2 3 (3.24 4.6 %), 2 3 (1 .3 1 .6 %,
2013 01-3), (.54 15.42 %), 2
(0.12 0.34 %), 2 (2. 1 .3 %,
2013 01-3) 2 (0.11 0.46 %) -
/ (1).



6. ( ) (. . 2, 2 , 2 , 2, 2 3 , 2 3, , ,) (*et al.* 200 *a*).

. - 1). ,

(. 6). . / . / 2 ,

5 41 , - , . . -

- 1 (1) 2 (2).

( ) ((/) = 1.3 2.) 2 ,

(/ = 1.1 2.2). -

2013 01-3 , (.). 1 2

. / . 2 (.).

- . - , 2, 2 3 , 2 5, 2, ,

( ) - 2 3

(.), . 1 . 2

(/ = 0.2 0.4) , 2 5, 2,

, . . (. 6).

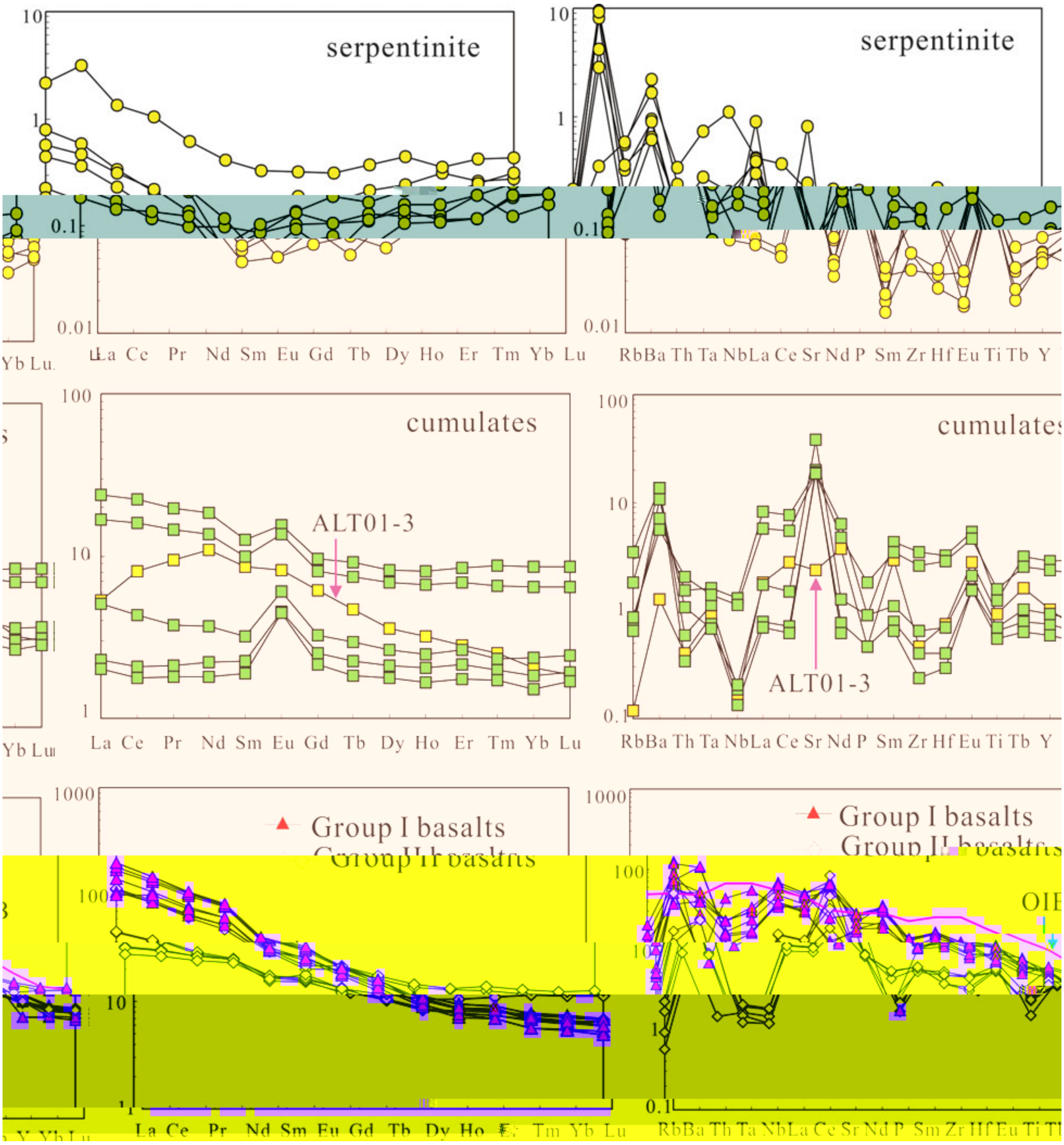
1 -

4.c.2. Basalts 124 205 2

50 60 . 1

2 (/) 10

43.15 % 5 .65 % (52 %, 30 (20)



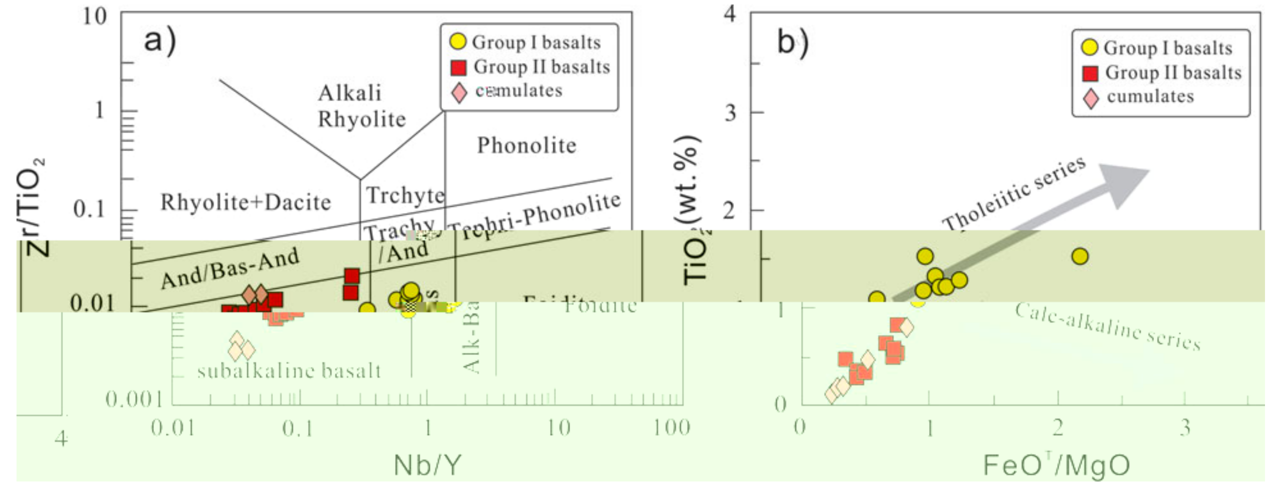
. ( ) - - - - .

& (1).

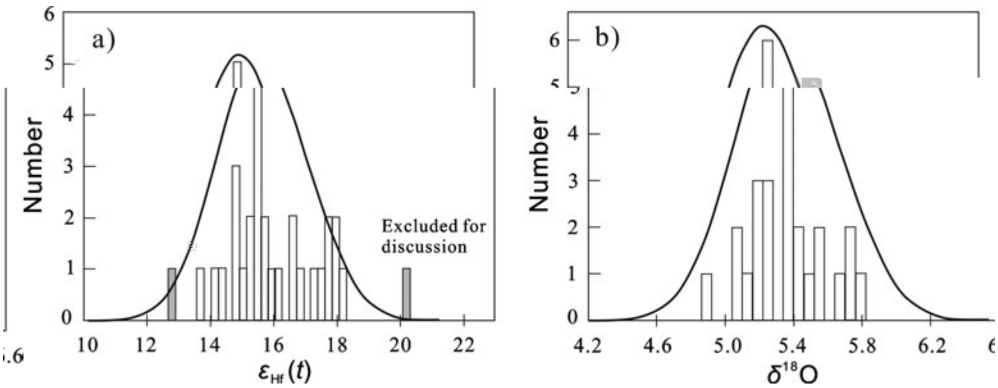
(/ = 0. 0 1.14) (.). 2 - (/) 4 6 (/ = 1.02 1.21) (.). - - , 1 - / 0.44 0. , - . 2 1 - / (~0.11). (.).

4. . W - c S N a c H

2. 1 2 - . / 6 - (0.0024 0.0452) / 6 (0. 04030 0. 0536), / 6 (0. 04015 0. 05111, 2013 03 1). 14 /144 0.0 0.13 4 143 /144 0.512 0 0.512 3 ε (*t*) - +6.3 + .5 (2013 03 1 +1.).



. ( ) ( ) (/ $_2$. /)
(& , 1). ( ) - $_2$. /
- . (1 4).



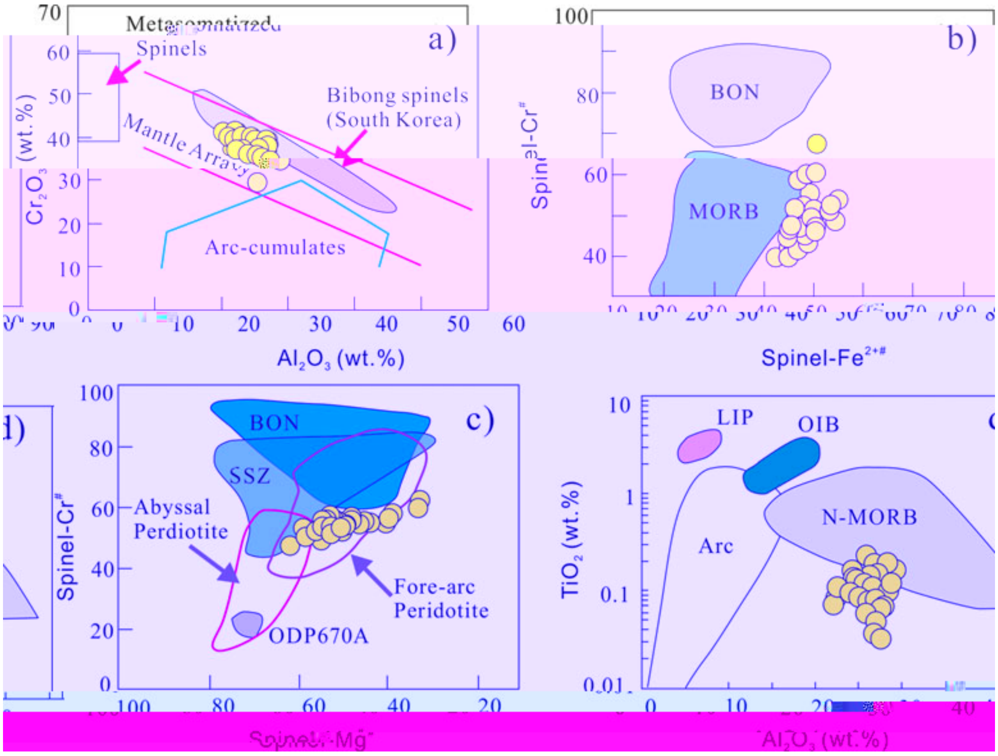
. ( ) ε (*t*) ( ) .

(2013 01) (- 2 // . . / , .), ε (= 4 5) 13 20. 2 5 5 . ε (*t*) (> 16) , . ε (*t*), 15. . - δ1 4. 1 ‰ 5. 3 ‰, (.). , - δ1 5.3 ± 0.23 ‰ (.). ~400 ε (*t*) 1.4 .2 - 6 0 20 . - (*et al.* 200).

5. D c

5.a. T a b Z a ba

, - *c.* 4 6 401 , . (503 ±) - (416 ± 3) (*et al.* 2012, *et al.* 200 *b*, . 1). - (401) (4 6) (-) . , - . (, 1 3). (. 1), , . .



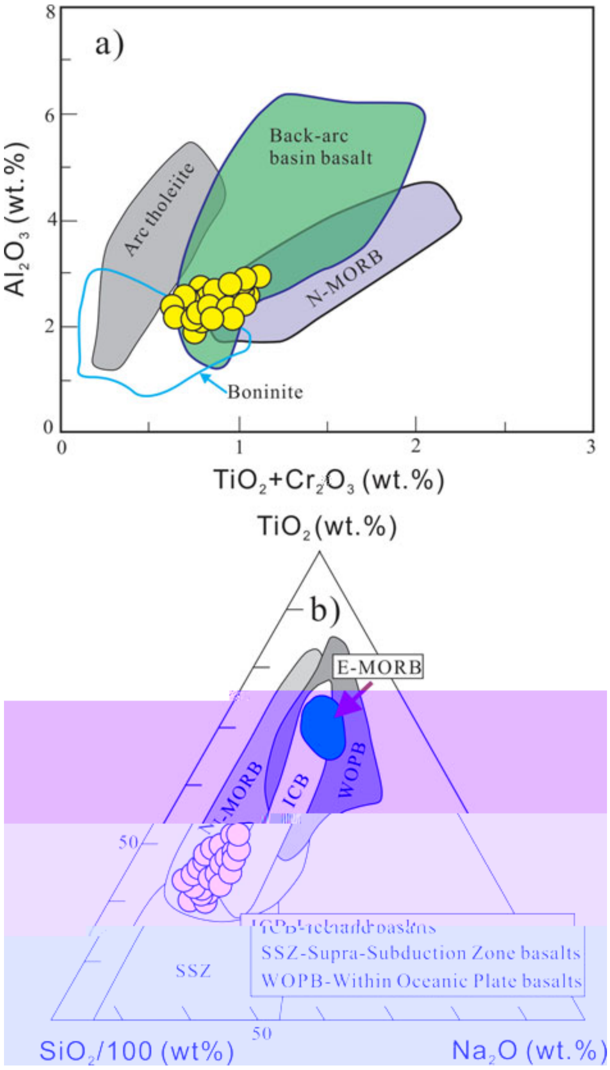
10. ( ) . ( ) 2 3 2 3 (%) (& , 2000). ( ) . (100 /(+)) 2+ . (100 2+/(2+ +)) (, 1 4, & , 2001). ( ) . (100 /(+)) . (100 /(+)) (*et al.* 1 5). ( ) 2 2 3 (, & , 2001). , - , - .

(500 4 0) (*et al.* 2003, *et al.* 2015,), (430 400) (*et al.* 200 b, 2014) - (3 0 350) (*et al.* 2003, *et al.* 2006).

5.b. O a c a

-

(, & , 2002, *et al.* 2010



11. ( ) ( ) $_2$ $_3$. $_2$ + $_2$ $_3$
( ) $_2$ $_2$/100 $_2$

(-).

5 ,

. $_2$ $_3$. $_2$ + $_2$ $_3$

(. 11). $_2$/100 $_2$ $_2$

(. 11).

(.).

/ / (. 12),

(. 12).

. *et al.* (2002)

( ).

5.c. P D a ba a

2. 1 (11 24 , 15), $_2$ $_5$ (0.4 0.6 %) / (11 15, 60) (/)

( ) (, & , 1 2, & , 2001) (. 13).

(1)

(. . , & , 2002) (2) (, & , 1 2, & , 1 3, *et al.* 1 6).

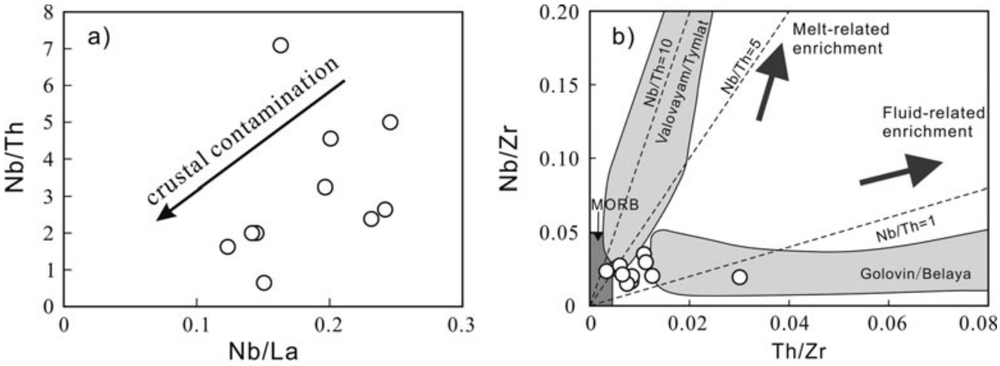
1 .

(, & , 200 , *et al.* 2011). , 1 / ^{6} (0. 04120 0. 06133) ε (*t*) (+1. + .5). / (3.44 20.4) , / (1.51 2.54) (. . & , 1 6). 1

(*et al.* 1 6, , 1 6).

(& , 2000).

(, & , 1 2, *et al.* 1 6). *et al.* (200)



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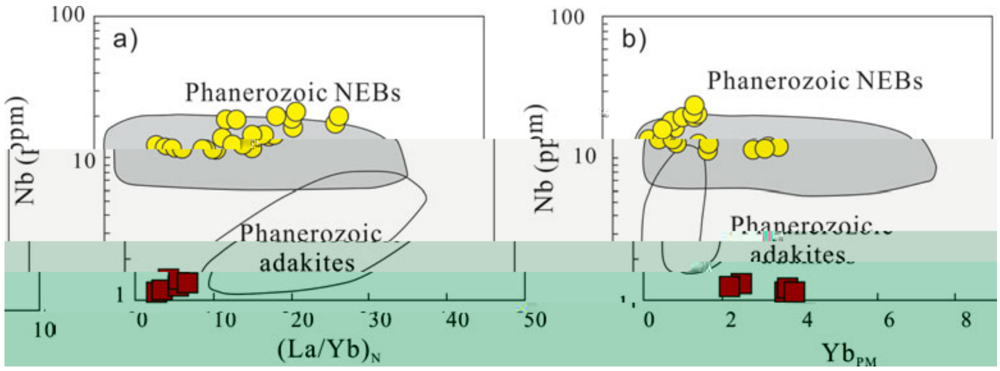

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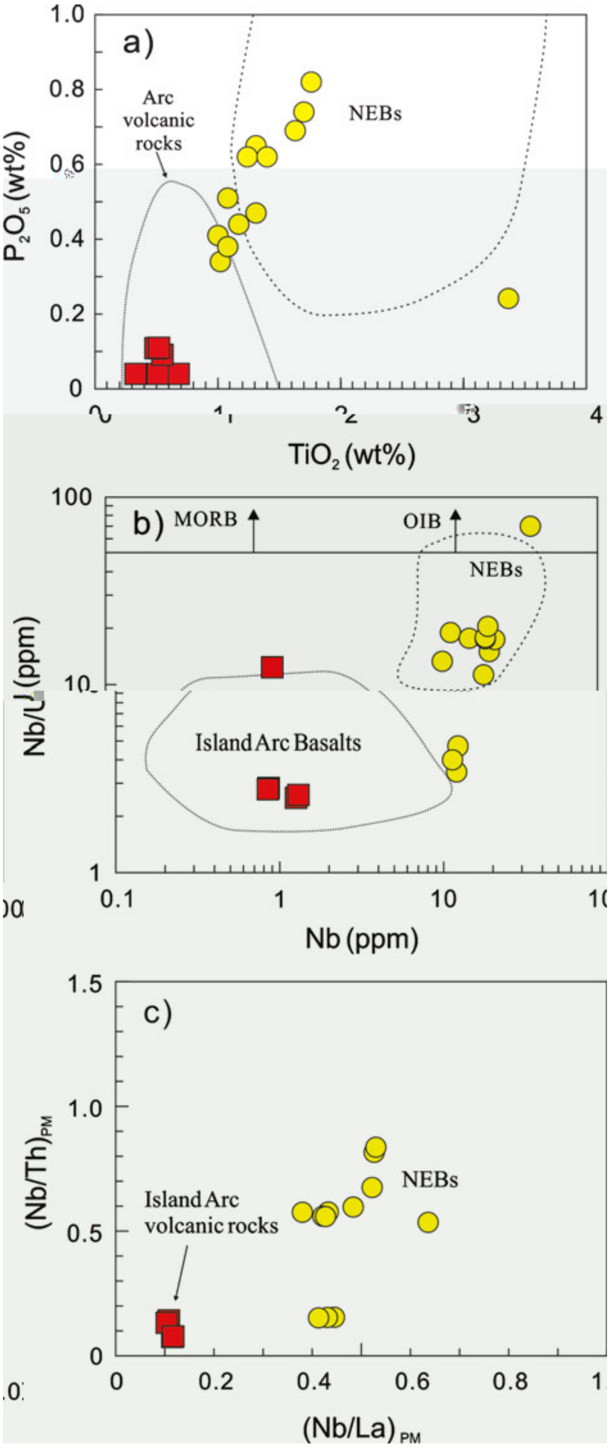

14. ( ) ( ) 2 5 2 . ( ) / . ( ) (/) (/) - . - ( ) , & (1 2) et al. (1 5), .

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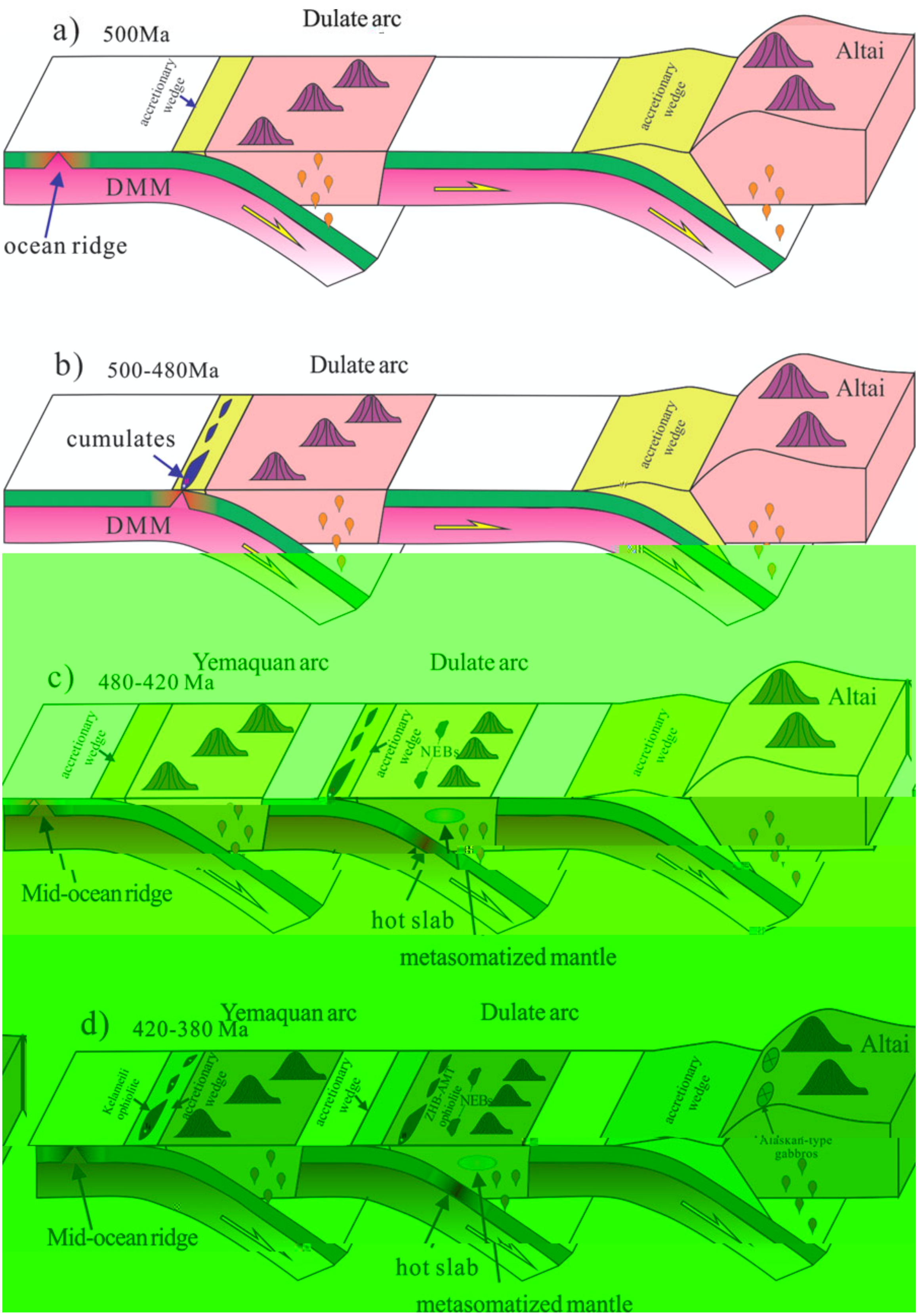
a) 500Ma
Dulate arc
accretionary wedge
accretionary wedge
Altai
DMM
ocean ridge
b) 500-480Ma
Dulate arc
cumulates
accretionary wedge
Altai
DMM
c) 480-420 Ma
Yemaquan arc
Dulate arc
accretionary wedge
accretionary wedge
NEBs
accretionary wedge
Altai
Mid-ocean ridge
hot slab
metasomatized mantle
d) 420-380 Ma
Yemaquan arc
Dulate arc
Kelameili ophiolite
accretionary wedge
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