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RESEARCH ARTICLE

Comparison of element abundance between the exposed crust of the continent of China and the global averaged upper continental crust: Constraints on crustal evolution and some speculations

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Abstract Based on the results of a study of regional element abundance in eastern China and the 1:200 000 geochemical surveys in northern Xinjiang, the element geochemical characteristics of the exposed crust in 23 tectonic units of the continent of China are summarized. Compared with the global average abundance of the upper continental crust, the exposed crust of the continent of China is compositionally more evolved than the upper crust of the island arc, but less evolved than the mature Precambrian Canadian shield. The exposed crust of the North China and Yangtze platforms has a lower SiO_2 content, but markedly higher CaO and MgO contents due to the presence of widespread carbonate strata, which suggests that we should not neglect the contribution of carbonate rocks in the study of the exposed crust and the element abundance of the upper crust. In comparison with two recently published average compositional models of the global upper continental crust, the exposed crust of the continent of China is depleted in Au, Hg, Mo, Sn, and W, which suggests that their abundance in the present global models is overestimated. The exposed crust of the North China platform and the Qinling–Dabieshan fold belt to its south has lower $\mu(^{238}U/^{204}Pb)$ values (<8), but other regions of the continent of China exhibit much higher μ values, which implies that the low μ feature of the North China platform and its adjacent regions does not have global significance. Considering the apparent lateral variation in composition of the exposed crust for the tectonic units of the continent of China, there is no adequate reason to take the average upper crust compositional model of the North China platform and its adjacent regions as a reliable composition representative for Chinese and global upper continental crust composition.

Keywords geochemistry, element abundance, exposed crust, continent of China

After the initial efforts by Clark and Washington, as well as by Goldschmidt, crustal composition has become an important aspect of modern geochemistry. In the middle to late 1990s, several models of crustal composition based on modern analysis techniques were published (Rudnick and Fountain, 1995; Taylor and McLennan, 1995; Wedepohl, 1995), and Chinese earth scientists also provided contributions to this topic (Yan and Chi, 1997; Gao et al., 1998, 1999). Of these models, the composition of exposed crust taken from the systematic sampling and analysis of exposed crust rocks, as well as the composition of upper crust that is directly derived from that of exposed crust, is more accurate and reliable than those of other crustal layers. As such, it is easier for the compositions of the exposed or upper crust to provide lateral correlation among different tectonic units or domains.

Research into crustal composition is gaining more significance in modern society, which faces increasingly severe environment and resource problems due to the fact that in the foreseeable future, human activity will remain limited to the subariel surface, and the minerals maintaining modern industry are still mainly taken from ore deposits in the uppermost 1–2 km layer of the continental crust. Therefore, the composition model of the exposed crust can be taken as the background reference for environment and resource evaluation research, such as the element pollution of land, and the relation between trace element abundance in soil and

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local disease, as well as potential evaluation of mineral resources.

In this article, the chemical compositions of 23 tectonic units of eastern and northwestern China, which are derived from research into regional element abundance of the upper crust of eastern China (Yan and Chi, 1997), and a geochemical survey of northern Xinjiang in the scale 1:200 000 (Du, 1997), are compared with composition models of the upper crust published after 2001. The aim is to reveal the lateral heterogeneity of chemical composition in the exposed crust of the China continent, and discuss its implication for crustal evolution.

1 Area coverage, data source, and correlation standard

In this study, data are compiled from 23 tectonic units of five major geotectonic units of the China continent. The regions are: (1) Tianshan orogenic belt (TS), Altay orogenic belt (ALT), West Junggar (WJU), and East Junggar (EJU) in northern Xinjiang (Du, 1997), Inner Mongolia–Xing'an orogenic belt (MX), and Jilin–Heilongjiang orogenic belt (JH) in northeastern China, all of which belong to the paleo-Asian fold system (Central Asia fold system); (2) Inner Mongolia geanticline (MG), Yanshan orogenic belt (YAN), East Liaoning anticlise (ELN), Shanxi anticlise (SHX), West Shandong anticlise (WSD), East Shandong anticlise (ESD), and West Henan anticlise (WHN) in the North China platform; (3) Qinling–Dabieshan orogenic belt including North Qinling (NQL), South Qinling (SQL), West Qinling (WQL), and Dabieshan (DB); (4) Lower Yangtze massif (LYZ), Jiangnan massif (JN), Yichang–Shennongjia platformal fold belt (YCS), and Longmen–Daba platformal fold belt (LMD) in the Yangtze platform; (5) southeast coast volcanic belt (SECV), and West Fujian–South Jiangxi fold belt (WFJ) in the South China fold system (Yan and Chi, 1997).

The abundance of 39 elements is presented to demonstrate the chemical composition of the exposed crust, listed in Table 1. Of these, 10 major elements are listed in oxides (SiO_2, TiO_2, Al_2O_3, TFe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5) with weight percent unit; and other 26 trace elements (As, B, Ba, Be, Bi, Cd, Co, Cr, Cu, F, La, Li, Mo, Nb, Ni, Pb, Sb, Sn, Sr, Th, U, V, W, Y, Zn, and Zr) are listed in 10^{-6}; while the abundances of three elements (Ag, Au, and Hg) are given in 10^{-9}. The original data of northern Xinjiang are from Du (1997), and the data of eastern China are from Yan and Chi's (1997) values of the carbonate strata bearing exposed crust. It should be noted that the contents of the 10 oxides are normalized to volatile-free value.

The element abundance of the crust is the weighted average of the contents of different lithological units or rock types, and it does not mean the element abundance of a specified rock type. In northern Xinjiang, the samples of each tectonic unit were collected area-equally (Du, 1997). The composite samples of each tectonic unit of eastern China were obtained by weighted sampling from strata, magmatic rocks, and crystalline basement (Yan and Chi, 1997). Therefore, the contents listed in Table 1 reveal the bulk composition heterogeneity of exposed crust among different tectonic units, not the lateral composition variations of specified lithologies. We do not calculate the average abundance for each geotectonic unit, such as North China platform, paleo-Asian fold system, etc., because our purpose is to show composition heterogeneity.

To directly illustrate the enrichment or depletion of element abundance, the element contents of 23 tectonic units of the China continent are normalized by the upper crustal model of McLennan (2001) and of Rudnick and Gao (2004), and the results are illustrated in Figs. 1 and 2, respectively.

The reasons for using the upper crust composition model for normalization and correlation are as follows. First, the upper crust composition models are mainly based on the systematic sampling of exposed rocks in the continent (Shaw et al., 1986; Rudnick and Fountain, 1995; Wedepohl, 1995; Yan and Chi, 1997; Gao et al., 1998; Togashi et al., 2000; Rudnick and Gao, 2004). A very significant correlation exists between the upper and exposed crustal composition models, while some researchers directly use the average element abundance of exposed crust as those of the upper crust (e.g., Togashi et al., 2000). Second, the composition of the lower portion of the continental crust is significantly different from that of the exposed crust. Therefore, the composition of the bulk crust is a less suitable reference than the upper crust model for normalization or correlation standard. Third, the chemical composition models for the lower crust are more subjective than those of the upper crust, because various methods were used by different researchers to construct the lower crust lithologies. This difference is amplified by the scarcity and inhomogeneous distribution of xenoliths or cross-sections that can represent the lower portion of the crust. For example, the estimations from Wedepohl (1995) and from Yan and Chi (1997) are very close for the element that abundance is greater than 1×10^{-6} in bulk crust; but there is noteworthy difference between the estimations by Wedepohl (1995), and Taylor and McLennan (1995). Apparently, it could be concluded that Wedepohl's (1995) data are more reliable, because it is closer to the estimation of Yan and Chi (1997), in which they used a more accurate technique in element analysis. Whereas the composition model of the bulk crust by Wedepohl (1995) uses an intermediate lower crust, the Taylor and McLennan's (1995) model uses a mafic lower crust. This is why some significant differences exist for the element abundance of the bulk crust between the two models. In fact, the composition models of the upper crust by Wedepohl (1995) and by Taylor and McLennan (1995) are very close.

The reasons for adopting the upper crust models of McLennan (2001) and of Rudnick and Gao (2004) are based on the following considerations. McLennan's (2001) model is a recent modification of the model of Taylor and McLennan (1995), which used fine-grained sedimentary rocks as a natural sample representing the average composition of the continental upper crust, especially for REEs (Rare Earth Elements) and some trace insoluble elements, though the major element contents of this model are directly taken from those of the Canadian shield. The model by Rudnick and Gao (2004) adopted a recently published dataset on the composition of the upper crust (or exposed crust) from central eastern China by Gao et al. (1998) and from the Japan arc by Togashi et al. (2000). Therefore, Rudnick and Gao's (2004) model contains more information about the composition of Phanerozoic orogenic belts than that of McLennan (2001). The upper crust compositions of the Canadian shield by Shaw et al. (1986) and of the Japan arc by Togashi et al. (2000) are also listed in Table 1 for comparison. Accordingly, the datasets of Togashi et al. (2000), Rudnick and Gao (2004), McLennan (2001), and Shaw et al. (1986) represent roughly an evolution sequence of the upper crust composition from active island arc to stable Precambrian craton.

2 Geochemical characteristics of the exposed crust

2.1 Element abundance

Compared with the upper crust composition model of McLennan (2001), the exposed crusts in the paleo-Asian orogenic belt (northern Xinjiang, Inner Mongolia–Xing'an, and Jilin–Heilongjiang fold belt) exhibit an obvious depletion of Au, Co, Cr, Mo, Ni, Sn, and W, a slight depletion of Be, Sr, V, and obvious enrichment of As, as well as slight enrichment of Sb. But the differences in other element abundance

Table 1 Composition estimates of the exposed crust for different tectonic units in the continent of China

	ALT	WJU	EJU	TS	MX	JH	MG	YAN	ELN	SHX	WSD	ESD	WHN	DB
SN	1 114	786	939	966	178	134	237	218	227	267	111	83	64	30
SiO_2	69.84	66.57	68.76	70.50	68.77	68.69	64.49	61.47	66.37	57.50	51.21	68.92	60.42	63.90
TiO_2	0.57	0.69	0.72	0.54	0.46	0.39	0.72	0.54	0.55	0.50	0.45	0.38	0.64	0.64
Al_2O_3	15.21	14.99	13.87	15.13	14.32	15.05	14.05	12.92	13.81	12.44	11.77	13.97	12.25	14.24
Fe_2O_3	5.01	6.21	5.32	4.28	4.33	3.58	5.38	4.71	4.57	4.41	4.35	3.46	6.06	5.53
MnO	0.09	0.10	0.11	0.10	0.07	0.06	0.10	0.09	0.07	0.08	0.10	0.06	0.10	0.09
MgO	1.89	2.06	1.54	1.75	1.83	1.34	2.46	4.82	2.45	3.92	4.22	2.10	4.44	3.06
CaO	1.45	3.16	2.75	1.69	3.39	3.61	6.16	9.48	5.57	16.54	22.68	4.27	10.64	5.56
Na_2O	3.02	3.96	4.38	3.50	3.16	3.81	3.17	2.74	3.12	2.01	2.58	3.42	2.36	3.81
K_2O	2.69	2.08	2.38	2.39	3.55	3.35	3.26	3.06	3.35	2.48	2.51	3.31	2.95	2.98
P_2O_5	0.23	0.16	0.17	0.13	0.11	0.11	0.20	0.17	0.14	0.12	0.13	0.09	0.16	0.18
Ag	51	63	63	60	67	58	56	64	47	47	53	67	47	45
As	2.2	6.1	4.8	3.3	6.2	3.4	2.2	3.0	1.9	2.2	2.7	1.8	2.0	0.65
Au	0.49	0.62	0.54	0.50	0.60	0.81	0.71	0.68	0.54	0.73	0.63	0.75	0.54	0.62
B	12.6	19.6	13.0	10.7	15	8.5	11	22	24	30	29	12	28	3.7
Ba	367	440	442	412	520	530	700	670	610	490	500	1010	860	946
Be	1.8	1.2	1.7	1.4	2.5	2.6	1.8	1.5	2.0	1.2	1.1	1.6	1.4	1.1
Bi	0.13	0.09	0.11	0.15	0.16	0.14	0.091	0.13	0.13	0.13	0.14	0.11	0.11	0.067
Cd	0.07	0.08	0.09	0.08	0.083	0.065	0.088	0.067	0.07	0.076	0.081	0.083	0.074	0.073
Co	10.4	11.8	8.3	7.7	7.3	7.4	15	12	11	9.7	10	9	15	14
Cr	52	26	26	14	43	21	51	47	49	40	49	51	55	32
Cu	15.3	32.4	22.5	23.5	14	8	20	18	16	14	19	15	19	25
F	542	381	344	437	420	350	525	510	470	500	420	440	570	515
Hg	7.9	9.3	14.3	11.9	14	5.8	8.9	9.9	9.4	11	9.1	10	11	6.5
La	28.7	19.4	23.8	21.4	36	29	40	32	41	31.5	21	32	37	50
Li	25	16	18	17	18	21	15	23	15	20	13	14	15	11
Mo	0.49	0.44	0.70	0.34	0.69	0.49	0.74	0.55	0.56	0.38	0.53	0.39	0.68	0.55
Nb	11.3	7.1	8.3	8.3	14	11	16	12	19	10	7.9	9.8	13	13
Ni	27	14	10	12	25	14	31	22	25	19	22	23	23	16
Pb	11.9	11.2	10.3	13.7	18.0	17.0	17.0	14.4	17.2	14.4	14.0	18.6	26.4	20.0
Sb	0.21	0.41	0.31	0.25	0.38	0.26	0.20	0.18	0.20	0.26	0.19	0.13	0.21	0.064
Sn	2.5	1.4	1.8	1.6	2.1	1.6	1.3	1.3	1.9	1.1	1.2	1.2	1.3	1.2
Sr	149	288	274	215	210	280	330	320	300	215	300	340	250	368
Th	10.6	6.4	6.1	7.8	9.6	11	8.7	6.1	11.1	8.0	5.9	7.3	7.7	9.6
U	1.78	1.56	1.58	2.15	2.2	2.3	1.7	1.2	2.0	1.5	1.2	1.3	1.4	1.5
V	72	96	97	59	62	45	73	63	56	57	55	53	57	87
W	1.21	0.58	0.76	0.70	0.83	0.51	0.53	0.61	0.80	0.74	0.48	0.52	3.00	0.34
Y	22	21	23	17	20	17.5	18	16	19	14	13	15	17	18
Zn	65	70	63	62	69	54	69	58	63	47	47	49	67	67
Zr	154	128	156	130	200	160	183	160	203	155	102	135	186	194

(*Continued*)

	NQL	SQL	WQL	LYZ	JN	YCS	LMD	SECV	WFJ	McLennan (2001)	Rudnick and Gao (2004)	Togashi et al. (2000)	Shaw et al. (1986)
SN	89	114	61	314	109	61	39	158	212	—	—	—	—
SiO_2	64.18	60.70	53.96	66.81	70.36	50.98	52.65	72.89	71.55	66.00	66.60	67.52	64.93
TiO_2	0.58	0.70	0.62	0.57	0.62	0.50	0.52	0.37	0.54	0.68	0.64	0.62	0.52
Al_2O_3	14.12	13.63	10.48	12.8	13.59	9.92	11.32	14.19	13.84	15.19	15.40	14.67	14.63
Fe_2O_3	5.18	5.41	4.26	4.4	4.53	3.54	4.13	2.73	4.33	5.62	5.60	5.39	4.42
MnO	0.08	0.08	0.09	0.07	0.06	0.08	0.07	0.07	0.07	0.08	0.10	0.11	0.07
MgO	3.49	4.33	2.07	2.06	1.87	6.49	4.39	0.75	1.48	2.22	2.48	2.53	2.24
CaO	6.16	10.17	25.05	8.68	4.44	24.96	22.44	1.41	2.57	4.20	3.59	3.9	4.12
Na_2O	2.89	2.11	1.56	1.52	1.56	0.83	1.97	2.93	1.73	3.90	3.27	2.72	3.46
K_2O	3.18	2.72	1.80	2.98	2.87	2.62	2.40	4.58	3.79	3.37	2.80	2.42	3.10
P_2O_5	0.15	0.16	0.12	0.11	0.10	0.10	0.12	0.08	0.09	0.16	0.15	0.12	0.15
Ag	47	56	67	64	57	76	54	55	61	50	53	—	—
As	3.3	4.7	7.7	5.3	5.2	5.6	3.6	3.0	4.1	1.5	4.8	6.8	—
Au	0.91	0.94	1.70	0.93	0.97	1.03	0.87	0.61	1.14	1.8	1.5	—	1.81
B	13	39	35	37	56	39	33	6.5	24	15	17	—	9.2
Ba	828	707	322	608	439	373	509	748	581	550	628	458	1070
Be	1.7	1.9	1.4	1.8	2.1	1.5	1.3	2.2	2.8	3	2.1	—	1.3
Bi	0.18	0.18	0.19	0.21	0.34	0.19	0.14	0.17	0.33	0.127	0.16	—	0.035
Cd	0.078	0.11	0.14	0.09	0.075	0.09	0.12	0.085	0.10	0.098	0.09	—	0.075
Co	15	13	11	8.8	9.9	7.4	8.4	3.4	8.4	17	17.3	15	12
Cr	62	65	45	45	58	38	40	8	47	83	92	84	35
Cu	28	25	—	17	21	16	23	5.4	15	25	28	25	14
F	614	545	497	607	536	561	482	452	546	—	557	—	500
Hg	19	27	37	23	19	16	19	5	7.6	—	50	—	96
La	38	29	24	38	35	25	26	51	49	30	31	21.7	32.3
Li	24	27	25	25	38	23	23	20	32	20	24	—	22
Mo	0.66	0.75	0.50	0.84	0.43	0.92	0.90	1.13	0.78	1.5	1.1	—	—
Nb	14	14	10	15	13	9.3	10	18	18	12	12	9	26
Ni	33	29	20	23	23	19	22	6.7	23	44	47	38	19
Pb	32	17	15	19	18	11	21	25	27	17	17	16.9	17
Sb	0.3	0.5	—	0.58	0.53	0.43	0.30	0.33	0.36	0.2	0.4	0.61	—
Sn	1.8	1.9	1.9	2	3.1	1.6	1.4	1.8	3.2	5.5	2.1	—	—
Sr	307	207	262	167	109	333	266	165	115	350	320	225	316
Th	14	9.5	7.4	11	11	7.5	5.8	18	16	10.7	10.5	8.3	10.3
U	2.6	1.8	1.7	2.8	2.6	2.0	1.9	3.7	3.5	2.8	2.7	2.32	2.45
V	92	89	66	97	79	58	68	30	65	107	97	110	53
W	0.78	1.00	1.30	1.25	1.9	0.81	0.60	1.14	1.8	2	1.9	—	—
Y	18	18	13	22	23	13	15	27	28	22	21	26	21
Zn	66	68	54	64	71	45	51	61	69	71	67	74.1	52
Zr	162	164	128	186	190	119	121	193	196	190	193	135	237

The unit is weight % for oxide; 10^{-9} for Ag, Au, Hg; and 10^{-6} for others; SN. sample numbers, that of each tectonic unit in eastern China means the number of composite samples.

between the paleo-Asian orogenic system exposed crust and the McLennan model are within an absolute log unit of 0.20 (see Table 1 and Fig. 1).

The exposed crust of each tectonic unit in the North China platform displays an enrichment trend for As, B, and Ba, but depletion of Au, Be, Mo, Sn, and W (except WHN, which exhibits an anomaly of W), and slight depletion of Co, Cr, Ni, Ti, and U. Besides these, Ca and Mg enrichment exists in the exposed crust of YAN, SHX, WSD, and WHN.

The exposed crusts of tectonic units of the Qinling orogenic belt exhibit an enrichment of As, Sb, Ca, and Mg, but depletion of Mo, Sn, and W, and slight depletion of Au, Be, Cr, and Ni. The exposed crusts of DB have obviously depleted As, Au, B, Be, Bi, Cr, Ni, and Sb. Many tectonic units in South China, including the Yangtze platform and South China fold system, exhibit apparent enrichment of As, Sb, and B, slight enrichment of Bi and Li, but depletion of Au, Sn, and Na, and the tendency of depletion of Be, Co, Cr, Fe, Ni, Sr, and W. Besides these, there is an observable enrichment of Ca and Mg in the LYZ, YCS, and LMD, and enrichment of As and Sb, and obvious depletion of Au, B, Ca, Co, Cr, Fe, Mg, Ni, Sn, Ti, and V in the exposed crust of the SECV.

Compared with the upper crust composition model of Rudnick and Gao (2004), the exposed crusts in the paleo-Asian orogenic belt show an obvious depletion of Au, Cr, Hg, Mo, Ni, and W, and depletion tendency of Co and V, but no enrichment or even slight depletion of As and Sb. For the tectonic units in the North China platform, there is depletion of As, Au, Hg, Mo, and W (but WHN still exhibits

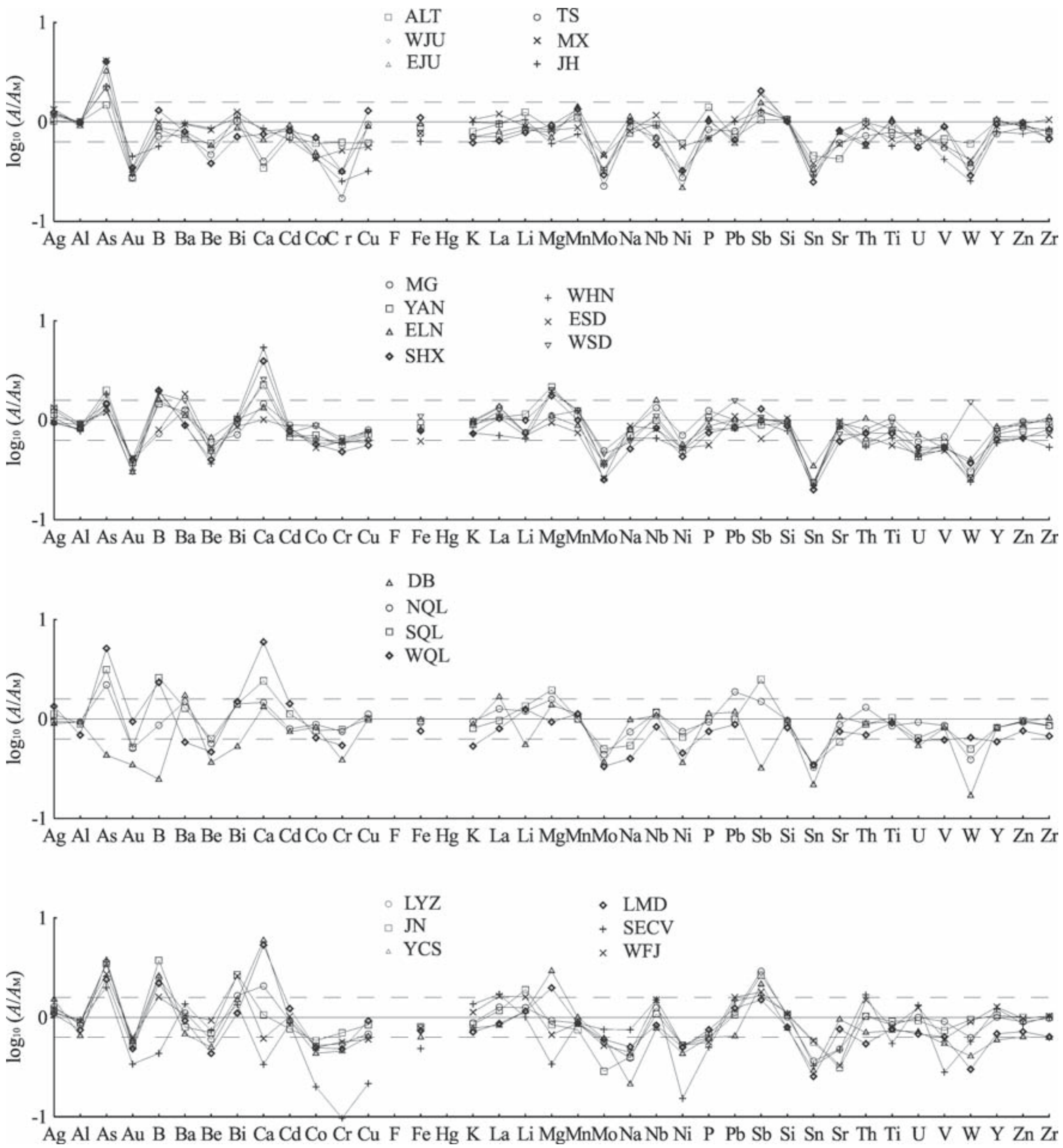

Fig. 1 Comparison of element abundances between McLennan upper crust model and the exposed crust of the eastern and northwestern parts of China

A: abundance; A_M: abundance of McLennan (2001) model for upper crust. The absolute value represented by dashed lines equals 0.20.

an anomaly of W), and slight depletion of Cr and Sb. An obvious enrichment of Ca and Mg exists, but there is depletion of U in the exposed crust of YAN, SHX, WSD, and WHN. The exposed crusts of tectonic units of Qinling orogenic belt show enrichment of Ca and Mg, but depletion of Hg, and slight depletion of Be, Co, Cr, Mo, and W. The exposed crusts of DB have obviously depleted As, Au, B, Be, Bi, Cr, Ni, Sb, and W. For tectonic units in South China, a slight enrichment of Bi, La, Li, and Pb is exhibited, but there is depletion of Hg and Ni, and slight depletion of Au, Co, Cr, Sr, and W. Besides these, there is enrichment of Ca and Mg in LYZ, YCS, and LMD, and obvious depletion of Au, B, Ca, Co, Cr, Fe, Hg, Mg, Ni, and V in the exposed crust of the SECV (see Table 1 and Fig. 2).

In summary, the exposed crusts in eastern China and northern Xinjiang exhibit the following characteristics in comparison with the average composition of global continent upper crust: (1) there is an apparent feature of systematic depletion of Au, Hg, Mo, Sn, and W; (2) the abundances of Co, Cr, Ni, and V are lower than global average in general; (3) a high enrichment of Ca and Mg exists in the tectonic units that contain a lot of carbonate strata, i.e. YAN, SHX, WSD, and WHN in the North China platform, and LYZ, YCS, and LMD in the Yangtze platform; (4) the abundances of As and Sb in the exposed crust of the China continent are limited within the values of McLennan's (2001) and of Rudnick and Gao's (2004) model; (5) the North China platform exhibits a depletion of U.

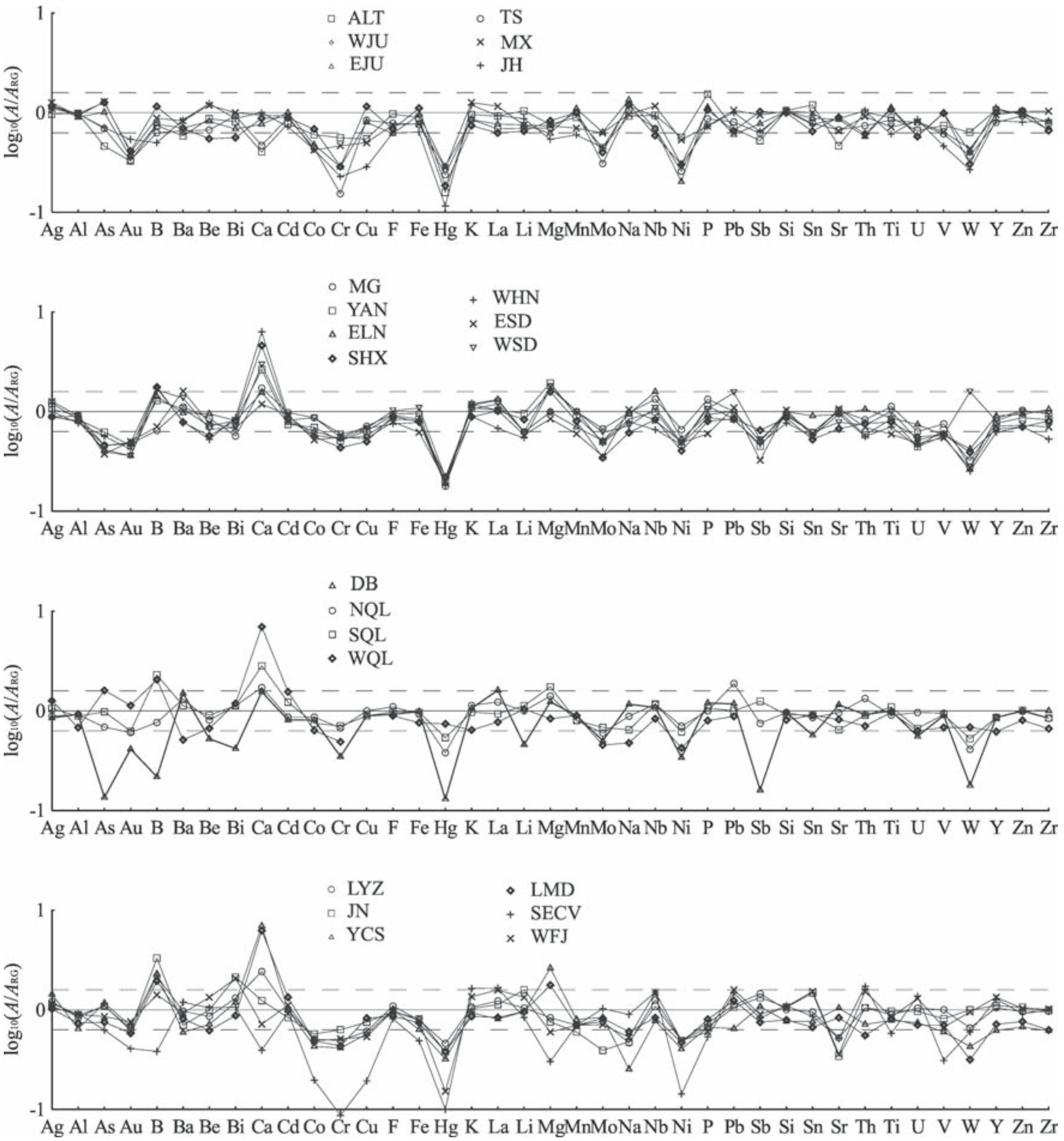

Fig. 2 Comparison of element abundance between Rudnick and Gao upper crust model and the exposed crust of eastern and northwestern parts of China

A: abundance; A_{RG}: abundance of Rudnick and Gao (2004) model for upper crust. The absolute value represented by dashed lines equals 0.20

2.2 Element ratio characteristics

For a better understanding of the geochemical characteristics of exposed crusts in eastern China and northern Xinjiang, the ratios of some element pairs are calculated. These ratios are compared with those of the Canadian shield, Japan arc, and two global models (Table 2).

2.2.1 Ratios indicating arc magmatism

For the ratios indicating arc magmatism, i.e., La/As, La/B, La/Nb, Nb/Th, Nb/U, and Ba/Th, there is significant difference between the upper crust of an island arc and of the Precambrian shield. For the island arc, the ratios of La/As, La/B, Nb/Th, Nb/U, and Ba/Th are lower than those of the Precambrian shield, but the La/Nb ratio of the island arc is higher than that of the shield. For example, the La/As ratio of the Japan arc is 3.19, and 6.46 in Rudnick and Gao's model, 20 in McLennan's model. The La/B ratio is 1.82 in Rudnick and Gao's model and 3.51 in the Canadian shield. The Nb/Th ratio is 1.08 in the Japan arc, 1.14 in Rudnick and Gao's model, 1.12 in McLennan's model, and 2.52 in the Canadian shield. The Nb/U ratio of the Japan arc is 3.9, and 10.6 for the Canadian shield. The Ba/Th ratios of the Japan arc and the Canadian shield are 55 and 104, respectively. The La/Nb ratio is 2.41 in the Japan arc, and 1.24 in the Canadian shield (Table 2).

Table 2 Selected element ratios in the exposed crust in the continent of China

	La/Nb	La/As	La/B	Ba/Th	Th/U	$(K/U)/10^4$	U/Pb	$(K/Pb)/10^4$	Nb/U	Nb/Th	$(Cu/Au)/10^4$	μ	A
ALT	2.53	12.9	2.27	34	5.98	1.25	0.15	0.22	6.4	1.06	3.12	9.7	1.45
WJU	2.75	3.19	0.99	68	4.12	1.11	0.14	0.10	4.5	1.10	5.22	9.1	1.04
EJU	2.87	4.91	1.82	73	3.84	1.25	0.15	0.18	5.2	1.37	4.17	10	1.05
TS	2.57	6.41	2.00	53	3.61	0.92	0.16	0.17	3.9	1.07	4.71	10	1.32
MX	2.57	5.81	2.40	54	4.36	1.34	0.12	0.21	6.4	1.46	2.33	8.0	1.56
JH	2.64	8.53	3.41	48	4.78	1.21	0.14	0.15	4.8	1.00	0.99	8.8	1.67
MG	2.50	18.2	3.64	80	5.12	1.59	0.10	0.13	9.4	1.84	2.82	6.5	1.34
YAN	2.67	10.7	1.45	110	5.08	2.12	0.08	0.15	10	1.96	2.65	5.4	1.00
ELN	2.16	21.6	1.71	55	5.55	1.39	0.12	0.19	9.5	1.71	2.96	7.6	1.60
SHX	3.15	14.3	1.05	61	5.33	1.37	0.10	0.12	6.7	1.25	1.92	6.8	1.17
WSD	2.26	7.78	0.72	85	4.92	1.74	0.09	0.14	6.6	1.34	3.02	5.6	0.94
ESD	3.27	17.8	2.67	138	5.62	2.11	0.07	0.20	7.5	1.34	2.00	4.6	1.14
WHN	2.85	18.5	1.32	112	5.50	1.75	0.05	0.13	9.3	1.69	3.52	3.5	1.16
DB	3.85	76.9	13.5	98	6.40	1.65	0.07	0.15	8.7	1.35	4.03	4.9	1.33
NQL	2.71	11.5	2.92	59	5.38	1.01	0.08	0.10	5.4	1.00	3.08	5.3	1.95
SQL	2.07	6.17	0.74	74	5.28	1.25	0.11	0.07	7.8	1.47	2.66	6.9	1.38
WQL	2.40	3.12	0.69	44	4.35	0.88	0.11	0.07	5.9	1.35	—	7.4	1.13
LYZ	2.53	7.17	1.03	55	3.93	0.88	0.15	0.16	5.4	1.36	1.83	9.6	1.78
JN	2.69	6.73	0.63	40	4.23	0.92	0.14	0.13	5.0	1.18	2.16	9.4	1.71
YCS	2.69	4.46	0.64	50	3.75	1.09	0.18	0.12	4.6	1.24	1.55	12	1.28
LMD	2.60	7.22	0.79	88	3.05	1.05	0.09	0.18	5.3	1.72	2.64	5.9	1.12
SECV	2.83	17.0	7.85	42	4.86	1.03	0.15	0.22	4.9	1.00	0.89	9.6	2.65
WFJ	2.72	12.0	2.04	36	4.57	0.90	0.13	0.13	5.1	1.12	1.32	8.4	2.39
McLennan (2001)	2.50	20.0	2.00	51	3.82	1.00	0.16	0.16	4.3	1.12	1.39	10.7	1.78
Rudnick and Gao (2004)	2.58	6.46	1.82	60	3.89	0.86	0.16	0.14	4.4	1.14	1.87	10.4	1.70
Togashi et al. (2000)	2.41	3.19	—	55	3.58	0.87	0.14	0.12	3.9	1.08	—	8.9	1.41
Shaw et al. (1986)	1.24	—	3.51	104	4.20	1.05	0.14	0.15	10.6	2.52	0.77	9.4	1.64

μ value ($^{238}U/^{204}Pb$): the $^{206}Pb/^{204}Pb = 19.3$, $^{207}Pb/^{204}Pb = 15.8$, $^{208}Pb/^{204}Pb = 39.3$ of upper crust are used in calculation (Asmerom and Jacobsen, 1993). A. heat-production rate ($\mu W/m^{-3}$), the density is taken as 2.8×10^3 kg/m^3 in calculation.

For the tectonic units of the paleo-Asian fold system exposed in the China continent, the La/As ratios of exposed crusts range from 3.19 to 12.9, and are less than 9 for many units. The La/B ratios range from 0.99 to 3.41, and are less than 2.4 for many units. The Nb/Th ratios vary from 1.00 to 1.46, and are less than 1.10 for many units. The ratios of Nb/U, Ba/Th, and La/Nb are 3.9 to 6.4, 34 to 73, and 2.53 to 2.87, respectively. Therefore, the exposed crust of the paleo-Asian fold system is similar to the island arc upper crust in terms of the ratios of La/As, La/B, La/Nb, Nb/Th, Nb/U, and Ba/Th.

For the tectonic units of the North China platform, the La/As ratios of exposed crusts range from 7.78 to 21.6, and are greater than 10 for most units. The La/B ratios range from 0.72 to 3.64, and are less than 3 for most units. The Nb/Th ratio varies from 1.25 to 1.96. The ratios of Nb/U and La/Nb are 6.6 to 10, and 2.16 to 3.27, respectively. The Ba/Th ratio ranges from 55 to 138, and is greater than 80 for many units. Accordingly, the exposed crust of the North China platform is close to the upper crust of the Precambrian shield in terms of the ratios of La/As, Nb/Th, Nb/U, and Ba/Th, but the ratios of La/B and La/Nb in the North China platform are more similar to those of an island arc.

The La/As ratios of the exposed crusts in Qinling vary from 3.12 to 11.5, and the Nb/Th ratios range from 1.00 to 1.47. The ratios of Nb/U, Ba/Th, and La/Th vary from 5.4 to 7.8, 44 to 74, and 2.07 to 2.71, respectively. Therefore, the exposed crusts of Qinling present similar characteristics to that of an island arc in terms of the ratios of La/Nb, La/As, Nb/Th, Nb/U, and Ba/Th.

The exposed crust of Dabieshan (DB) has a La/As ratio of 76.9, a Nb/U ratio of 8.7, a Nb/Th ratio of 1.35, and a Ba/Th ratio of 98, but a La/Nb ratio of 3.85. Except the La/Nb ratio, the exposed crust of Dabieshan exhibits element ratio characteristics close to that of the Precambrian shield.

The exposed crusts of the tectonic units in the Yangtze platform have La/As ratios of 4.46 to 7.22, Nb/Th ratios of 1.18 to 1.36, Nb/U ratios of 4.6 to 5.4, Ba/Th ratios of 40 to 55, and La/Nb ratios of 2.53 to 2.69. However, Longmen–Daba (LMD) has exceptionally high ratios of Nb/Th and Ba/Th, of 1.72 and 88, respectively. Accordingly, the ratios of La/As, Nb/Th, Nb/U, and Ba/Th in the exposed crusts of the Yangtze platform are closer to those of the upper crust of an island arc, and exhibit an obvious difference from those values of the exposed crusts in the North China platform.

For tectonic units of the South China fold system, the ratios of La/Nb (2.72–2.83), Nb/Th (1.00–1.12), Nb/U (4.9–5.1), and Ba/Th (36–42) are similar to those of the upper crust of an island arc; whereas the ratios of La/As (12–17) and La/B (2.04–7.85) are closer to those of the upper crust of the Precambrian shield.

In general, the exposed crusts of the North China platform and Dabieshan present similar characteristics to those of the upper crust of the Precambrian shield in the ratios of La/As, La/B, La/Nb, Nb/Th, Nb/U, and Ba/Th, but the exposed crusts of the paleo-Asian fold system, Qinling orogenic belt, South China fold system, and Yangtze platform show features closer to island arc.

2.2.2 Ratios related to radioactive heat-production elements

For radioactive heat-production elements such as U, Th, and K, the upper crust of an island arc has Th/U and K/U ratios of 3.58 and 0.86, respectively, and these values are apparently lower than those of the Precambrian shield (4.20 and 1.05). However, the U/Pb ratios of both geotectonic domains are greater than 0.13 and μ-values ($^{238}U/^{204}Pb$ ratio) are greater than 8 (Table 2).

The Th/U ratios of the exposed crusts of the paleo-Asian fold system tectonic units vary from 3.61 to 5.98, with the majority greater than 4. K/U ratios range from 0.92 to 1.34, and many values are greater than 1.1. The U/Pb ratio and μ-value are greater than 0.12 and 8, respectively. A positive tendency exists between the Th/U ratio and heat-production rate (A), but the heat-production rates of the exposed crusts in the paleo-Asian fold system are lower than those of the upper crusts of island arc, Precambrian shield, or global averages (Table 2).

For exposed crusts in the North China platform, Th/U ratios range from 4.92 to 5.62 and K/U ratios from 1.37 to 2.12 with a majority greater than 1.5. U/Pb ratios of the North China platform are lower than 0.13, and μ-values are less than 8. A positive tendency exists between the Th/U ratio and heat-production rate (A), but the heat-production rates of the exposed crusts in the North China platform are much lower than those of the upper crusts of island arc, Precambrian shield, or global averages (Table 2).

Th/U and K/U ratios of the exposed crusts of Qinling vary from 4.35 to 5.38, and 0.88 to 1.01, respectively; while the U/Pb ratios are less than 0.12 and the μ-values are less than 8. The Th/U ratio is positively correlated to the heat-production rate. Higher ratios of Th/U and K/U are observed in the exposed crust of Dabieshan (DB), with values of 6.40 and 1.65, respectively; however, the U/Pb ratio and μ-value of Dabieshan are only 0.07 and 4.9, respectively.

The exposed crusts of the tectonic units in the Yangtze platform have Th/U ratios of 3.05 to 4.23, with a majority less than 4. The K/U ratios range from 0.88 to 1.09, and the U/Pb ratios and the μ-values are greater than 0.14 and 8, respectively, except for the Longmen–Daba belt (LMD), where values are only 0.09 and 5.9, respectively.

Th/U and K/U ratios of the exposed crusts of the South China fold system are 4.57 to 4.86, and 0.90 to 1.13, respectively. U/Pb ratios and μ-values are greater than 0.13 and 8, respectively. Considering the Yangtze platform and South China fold system as a whole, a positive correlation exists between the Th/U ratio and heat-production rate among tectonic units.

In general, a southward decreasing tendency is exhibited for the K/U ratio in the exposed crusts of the China continent, and the boundary between lower and higher values is approximately along the boundary of the North China platform and Qinling fold belt. Accordingly, the heat-production rates of the exposed crusts of the China continent present a stepwise increasing trend from north to south. The exposed crusts of the North China platform and Qinling–Dabieshan fold belt have unique characteristics of low U/Pb ratios and μ-values, compared with the upper crusts of an island arc, the Precambrian shield, and global averages. The exposed crusts of the Yangtze platform have lower Th/U ratios in comparison with other tectonic domains of the China continent.

3 Discussion

3.1 Crustal evolution of China continent

Magmatism is the main factor determining the composition and evolution of crust, and under a plate tectonic regime, the growth of continental crust is achieved by arc magmatism (Rudnick, 1995; Taylor and McLennan, 1995). The main geochemical features of arc magmatic rock include significant depletion of Nb and Ta in comparison with Th, U, and La, etc., and the noteworthy enrichment of As, B, and Sb (Rudnick, 1995; Togashi et al., 2000). Accordingly, the ratios of Nb/Th, Nb/U, and La/As in arc magmatic rocks are low, whereas the La/Nb ratio is high. The ratios of Nb/Th, Nb/U, La/As, and La/Nb of the exposed crusts of the China continent sit in intermediate positions between the upper crust values of the Japan arc and Canadian shield.

The abundances of Co, Cr, Ni, and V in the exposed crusts of the China continent are slightly lower than the global averages of upper continental crust, but higher than the values of the Canadian shield (Table 1, Figs. 1 and 2). Therefore, it can be argued that the composition maturity of the exposed crusts of the China continent is situated between the mature Precambrian shield and the immature island arc. As a whole, the composition of exposed crusts of the China continent is close to the global average composition of upper continental crust by Rudnick and Gao (2004).

The composition of the exposed crusts of eastern China and northern Xinjiang present a significant spatial heterogeneity. The ratios of Nb/Th, Nb/U, and La/As of the North China platform and Dabieshan exhibit noteworthy differences from those of other geotectonic domains. The North China platform and Qinling–Dabieshan have unique features of low U/Pb ratio and low μ-value in comparison with other domains. The ratios of Nb/Th, Nb/U, La/As, and La/Nb of the exposed crusts of the Yangtze platform are closer to the values of the upper crust of an island arc in comparison with others; while the Th/U ratios of the Yangtze platform are the lowest among the tectonic units of the China continent. For most fold belts (orogenic belts), they exhibit a similarity in the values of Nb/Th, Nb/U, La/Nb, and Th/U ratios, as well as μ-values; the main discrepancy among them is the K/U ratio.

For a continent like China, which has experienced multiple tectonothermal events since its formation, the lower portion of its crust might be completely reformed by magmatic underplating and delamination of the lower crust. However, the exposed crust may contain information about composition evolution. The general composition similarity of the exposed crusts among the fold belts (orogenic belts) of eastern China and northern Xinjiang indicate that their geochemical features were inherited from arc magmatism. This means that arc magmatism related to the plate tectonics regime is the main mechanism of continental crust formation and growth for these fold belts. The geochemical imprints of arc magmatism in these belts are not erased by later tectonic activities. In contrast, the higher Nb/Th and Nb/U ratios in the exposed crusts of the North China platform suggest some influence from intraplate magmatism to their geochemical features (Rudnick, 1995).

Following the above we argue that: (1) if the North China platform and Yangtze platform are the historical analogues of a continental submarine plateau, as suggested by Ren et al. (1999), the North China platform might be an oceanic plateau related to a mantle plume, because its exposed crusts still contain some geochemical imprints of intraplate magmatism; whereas the Yangtze platform might be a portion of the active margin of a supercontinent. During the break-off of the supercontinent, it separated to form a continental submarine plateau. Accordingly, the geochemical characteristics of the Yangtze platform are significantly different from those of the North China platform; (2) the arc magmatism under a plate tectonics regime is the main mechanism for the growth of the continental crust in eastern China and northern Xinjiang, e.g., the paleo-Asian fold system to the north of the North China platform, and the South China fold system to the east of the Yangtze platform. The low U/Pb ratio and μ-value of the Qinling–Dabieshan fold belt are due to the involvement of the southern margin of the North China platform during the Triassic collision; (3) the composition of the exposed crusts of the North China platform and Qinling–Dabieshan cannot be taken as a reliable representative of the composition of exposed crust of China continent, because their low U/Pb ratio and μ-value are unique even in eastern China. Accordingly, the upper crust composition model of central eastern China is mainly based on sampling in the North China platform and its adjacent areas (Gao et al., 1998, 1999), and may not reliably represent the average composition of the upper crust of China and the global continent.

3.2 Speculations on the estimation of continental crust composition

It is noteworthy that the abundances of Au, Hg, Mo, Sn, and W in the exposed crusts of eastern China and northern Xinjiang are much lower than the values of the upper continental crusts of recent global average models. Because the analyzed data of the China continent are based on reliable analysis techniques and passed strict quality controls (Du, 1997; Yan and Chi, 1997; Xie, 2004), it is reasonable to believe that the upper or bulk continental crust abundances from the published global models for the less than 1 ppm content "difficult" elements, such as Au, Hg, Mo, Sn, and W, are inaccurate. It should be noted that there are abundant large Sn and W deposits in the southeastern part of the China continent (Liu, 2002; Xie and Liu, 2002; Liu and Xie, 2005), and Mo is one of the preponderant mineral resources of China. Therefore, the global average abundances of Mo, Sn, and W of the exposed or upper continental crust should be lower than those of the China continent. An accurate estimation of the abundance of these "difficult" elements has very important significance for mineral resource evaluation, because the resource researchers are apt to establish a direct connection between the reserves of mineral resources in the land and the element abundance of the surficial layer of the land (from surface to 1 000 m depth) (Erikson, 1973; Liu and Xie, 2005).

The carbonate strata are usually not included in the most current models for upper crust chemical composition (Taylor and McLennan, 1995; Wedepohl, 1995; Gao et al., 1998, 1999; McLennan, 2001; Rudnick and Gao, 2004). However, this treatment could underestimate significantly the abundance of Ca and Mg in the exposed crust, especially for regions that contain a lot of carbonate strata, e.g., North China and Yangtze platforms (cf. Figs. 1 and 2), and overestimate the abundance of other major elements, such as Si, Al, and Fe (cf. the Table 2 of Gao et al., 1998).

Furthermore, neglecting carbonate strata in a composition model could affect estimations of the abundance of CO_2 stored in the crust by carbonate, thus affecting the reliable evaluation of carbon cycling and equilibrium in the earth system. A lot of carbonate strata in the Yanshan belt and North China platform were involved in Mesozoic thrust systems by tectonic stacking, and had been buried in the lower portion of the upper or middle crust or both (Davis et al., 1996). Carbonate exposed in the Dabieshan belt, accompanied by other supracrust lithologies, experienced ultrahigh pressure metamorphism at depth during the Triassic continental subduction (Wang and Rumble, 1999). Therefore, carbonate occupies a significant portion in the lithologies of the upper crust, especially for the carbonate-strata abundant regions. There are many large continental submarine plateaux in the ocean, and some of them have been covered by carbonate sediments, such as the Falkland plateau and Seychelles plateau (He and Ren, 1994), and the North China and Yangtze platforms are regarded as historical continental submarine plateaux by Ren et al. (1999). During the subduction of the oceanic plate, the continental submarine plateaux would accrete to the continent and become a portion of the continent (Ren et al., 1999). Considering these facts, it can be argued that current global composition models of the upper continental crust overestimate the abundance of SiO_2 and underestimate the contents of CaO and MgO.

Based on research into the crustal composition of the North China platform and Qinling fold belt, Gao et al. (1998, 1999) argued that the average μ-value of the upper continental crust should be about 5, lower than the value of ~7 obtained from the upper crust of the Precambrian shield (i.e. Canadian shield). However, the μ-values of the lower continental crust in different regions, including eastern China, range from 2.9 to 4.5 (Rudnick and Fountain, 1995; Taylor and McLennan, 1995; Wedepohl, 1995; Gao et al., 1998, 1999). If the μ-value of the bulk continental crust is about 7 (Rudnick and Fountain, 1995; Taylor and McLennan, 1995; Wedepohl, 1995), the μ-value of the upper crust must be greater than 7. In fact, the μ-value of the bulk crust ranges from 8.7 to 9.5, according to previous studies (Rudnick and Fountain, 1995; Taylor and McLennan, 1995; Wedepohl, 1995). However, the μ-value of the upper crust of the North China platform and Qinling belt is only 5.7 (Gao et al., 1998, 1999).

Gao et al. (1998, 1999) provided circumstantial evidence to support their argument. That is, the μ-value of the bulk crust estimated by Zindler and Hart (1986) from their chemical geodynamics model is low to 5.7; meanwhile, the μ-value of bulk crust in an arc region is low, according to the lead isotope study on the river water suspended loads of a young island arc (Asmerom and Jacobsen, 1993). For the latter point, Asmerom and Jacobsen (1993) argued that the U loss during weathering is a cause of low μ-values. However, there is evidence to argue that the low μ-value in the North China platform and Qinling belt originated from lithologies rather than the weathering process (Zhang et al., 1997; Gao et al., 1998, 1999). Accordingly, the question becomes: Is the μ-value of upper continental crust as high as 7 or as low as 5.7?

The μ-values of the exposed crusts of eastern China and northern Xinjiang estimated by this study reveal that the low μ-value is a unique feature of the North China platform and Qinling–Dabieshan fold belt, and μ-values are as high as 8 or more for other tectonic domains, such as the paleo-Asian fold system, South China fold system, and the main portion of the Yangtze platform. Based on this, we infer that: (1) the crusts of eastern China and northern Xinjiang cannot represent the global average upper crust, so the possibility still exists for a low μ-value of global upper/bulk crust that is less than most estimates (e.g. Rudnick and Fountain, 1995; Taylor and McLennan, 1995; Wedepohl, 1995); (2) the global average μ-value of bulk crust is high, such that the chemical geodynamics model of lead isotope by Zindler and Hart (1986) has some errors; (3) if Zindler and Hart's (1986) chemical geodynamics model is right, the low μ-value of bulk crust and high μ-value of upper crust require a lower μ-value for lower continental crust, which is much less than the current estimates. This implies that the abundance of U in the lower continental crust should be much less than the current estimates, if the current estimates of the Pb content of the lower crust are accurate. Of course, all these problems need further study.

The spatial inhomogeneous composition of the exposed crusts in eastern China and northern Xinjiang as revealed here suggest that the regional heterogeneity of composition needs more emphasis in the study of the chemical composition of continental crust. However, research in the twentieth century focuses on the Precambrian crystalline basement of Europe and North America, especially on the Canadian shield. Although the work of Gao et al. (1998) provides an invaluable dataset of crustal composition of central eastern China for the international geochemistry circle, the unique geochemical characteristics of the North China platform and Qinling belt, in comparison with other tectonic domains of the China continent as presented here, indicate that the crust composition model of central eastern China by Gao et al. (1998, 1999), which is mainly based on sampling in the North China platform and Qinling belt, cannot be regarded as a suitable representative of the global average composition of the continental crust. The newest model by Rudnick and Gao (2004) considered composition datasets of the orogenic belts of Qinling and the Japan arc, besides that of craton and platform; but both Qinling and Japan orogenic belts do not have enough volumetric representatives for global Phanerozoic orogenic belts. Furthermore, the composition heterogeneity among the global orogenic belts might be obvious, such as the differences among the fold belts in the China continent and Japan arc as revealed in this study. Accordingly, the crustal composition model of Rudnick and Gao (2004) may need revision.

It should be emphasized that the regions that have been systematically sampled and analyzed for upper crust composition have been situated in northern hemisphere until the present day. Therefore, even if a more complete coverage of sampling areas in the China continent were achieved for the construction of a composition model of the upper continental crust, the model itself might be only representative of the northern continents (north of Tethyan domain) at best. There are some clues to show that southern continents (i.e. Gondwanaland south of the Tethyan domain) contain more radioactive heat-production elements in their crust. For example, the upper crust of some Proterozoic exposed regions in Australia has a heat-production rate of 3–6 $\mu W/m^3$ (Neumann et al., 2000), and the upper crust of northern India also has a high heat-production rate (1.5– > 6 $\mu W/m^3$) (Cuney et al., 1984). The China continent, Yangtze platform, and South China fold system, which have more affiliation to Gondwanaland, also exhibit higher heat-production rates of exposed crust than those of northern regions (Table 2). Accordingly, it is reasonable to infer that the upper crust of Gondwanaland is more abundant in radioactive heat-production elements than upper crusts of northern continents.

This might represent the hemisphere heterogeneity of chemical composition in the upper continental crust. Therefore, we suggested that systematic sampling in southern continents should be emphasized in crustal composition study. Nevertheless, the systematic sampling of exposed crust is costly and time-consuming, especially for underdeveloped regions such as Africa, India, and South America. It could be very useful to obtain a rough average estimate of the southern continent using ultralow density geochemical sampling methods, as suggested by applied geochemists Wang (2001) and Xie (2003). This achievement might be an important contribution of applied geochemistry to theoretical geochemistry.

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