

中国黄土的平均化学成分： 上部大陆地壳的一种典型代表

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本文通过对黄河中游地区马兰黄土的大面积野外实地考察,系统采样和室内分析测试,并采用质量加权平均的计算方法,给出了较为准确的中国黄土平均化学成分数据。中国黄土相对于下地壳和全地壳较富大离子半径的亲石元素而贫亲铁元素;与上部大陆地壳相比,中国黄土除相对较富Ca、B而贫Na、Nb外,其余绝大多数化学元素的丰度均非常接近甚至几乎相等。由此表明,中国黄土确属典型的上部大陆地壳物质,它不仅为暴露的上部大陆地壳提供了一种理想的天然平均样品,而且中国黄土的平均化学成分完全可以作为上部大陆地壳化学成分的代表而加以应用。

AVERAGE CHEMICAL COMPOSITION OF LOESS IN CHINA: AS A GOOD REPRESENTATIVE OF THE UPPER CONTINENTAL CRUST

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ABSTRACT

The average chemical composition of loess in China has been measured and calculated by the method of mass-weighted average calculation on the basis of extensive sampling and laboratory chemical analysis. Great differences are noticed in chemical composition between loess of China and the lower or the bulk crust, the former being characterized by the relative enrichment of LIL elements and the latter two by the enrichment mainly of siderophile elements. Much similarity is indicated in chemical composition between loess of China and the upper crust. In addition to the enrichment of Ca and B and the depletion of Na and Nb, the majority of the other elements in the loess of China show little or even no difference in contents from those in the upper

crust. The above characteristics indicate the loess of China typically belongs to upper crustal material. Loess of China not only provides a kind of ideal natural average samples of the exposed upper continental crust, but also can be used, if its average chemical composition is taken into consideration, to represent the chemical composition of the upper continental crust.

INTRODUCTION

No other equivalents can be found in the world that can be compared with loess of China with respect to its extensive distribution, great thickness and completely developed stratigraphy, specially the Late Pleistocene Malan loess which is most widely distributed. As the Malan loess was formed relatively late (100,000–10,000 yrs B. P. and thus is almost free from the influence of chemical weathering and epigenetic diagenesis, it has still preserved more primitive features at the time of loess accumulation. Compositional and fine-structural studies of loess (Liu Tungsheng *et al.*, 1964, 1965, 1966, 1985; Su Lianyi *et al.*, 1959; Zhu Haizhi, 1963; Zhu Haizhi *et al.*, 1964; Wen Qizhong *et al.* 1989) showed that the Malan loess is of relative homogeneity in chemical composition and possessed of a zonal distribution pattern in going from northwest to southeast. Moreover, the distribution areas of the Malan loess are closely related with deserts and gobi and there has been almost no controversy on the hypothesis that it was derived from farther source regions and was highly mixed during its wind-transportation (Wen Qizhong *et al.*, 1989; Wu Mingqing *et al.*, 1991). So the Malan loess is the typical representative of China's loess and this viewpoint has been commonly accepted by more and more geologists.

The chemical composition data so far accumulated show that either major or trace elements in the Malan loess distributed along the middle reaches of the Yellow River, like its grain size and mineral composition, have nothing to do with the local basement rocks and display no remarked regional variations (Wen Qizhong *et al.*, 1989). So the Malan loess is considered to be the product of highly homogenized mixing of weathered fragments (silts-sized rock flour) derived from various types of continental rocks on a large scale. Therefore, the Malan loess in China may be better natural samples representing the average composition of the upper continental crust. It is believed that from the average chemical composition of the Malan loess of China we can postulate the average chemical composition of the upper continental crust. It seems to be the simplest and most reasonable to the determination of the chemical composition of the upper continental crust.

SAMPLES AND METHODS

1. Distribution of samples

Extensive studies of the chemical composition and fine structure of loess in the past years showed that although it is of relative homogenization in composition, the Malan loess

is possessed of obvious zonation from northwest to southeast (Su Lianyi *et al.*, 1959; Zhu Haizhi *et al.*, 1963; 1964; Liu Tungsheng *et al.*, 1985). That is to say, the whole Malan loess can be divided into three zones; sandy loess, loess, and clayey loess. In order to make our research as systematic and representative as possible, nine investigation routes were chosen in the vast area of about 300,000km² along the middle reaches of the Yellow River where the Malan loess is widely distributed from Lanzhou in the west to Changzhi in the east and from the margin of the Maowusu desert in the north to the northern bank of the Weishui River in the south. Repeated traverses were made through the three Malan loess zones, accompanied with detailed field observations, thickness measurement and systematic sampling of sandy loess, loess and clayey loess. A total of 147 loess samples were collected and the sample localities are shown in Fig. 1. The sampling depth ranges from 2.5m to 3m from the surface and the sampling interval is about 25–30km. At the laboratory the 147 loess samples collected from the field were first organized into 100 pieces, then ground as fine as about 200 mesh by means of agate mortar and finally analyzed with various measuring and analytical approaches.

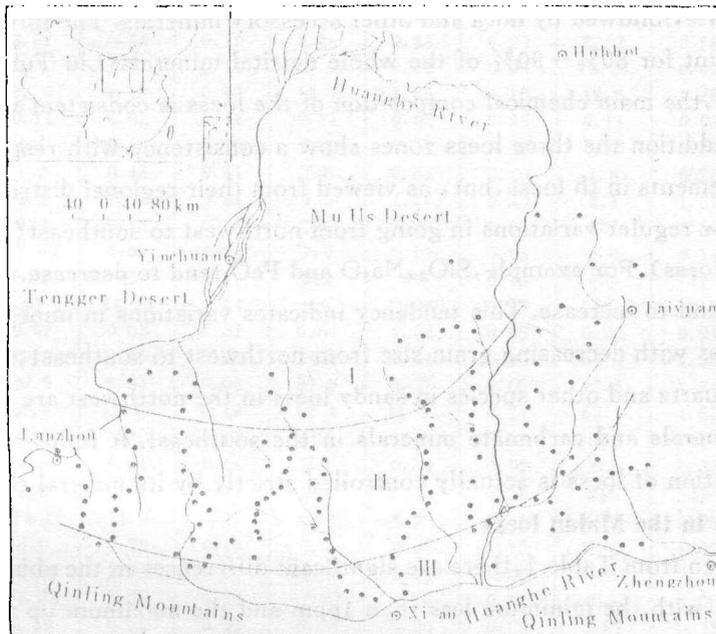


Fig. 1 Sketch map showing the sample localities of the Malan loess in China

I = sandy loess; II = loess; III = clayey loess

2. Analytical methods and uncertainties

The 100 composite samples collected from the three loess zones were analyzed for 53 chemical elements. The major elements were analyzed by classical wet chemical analysis and atomic absorption spectrometry; most of the trace elements were analyzed by atomic absorption spectrometry and ICP transmission spectrometry; F and B by ion-selective electrode techniques; Nb, Ta, Zr and Hf by paper chromatography separation-photometry; Sc by ion-exchange separation-photometry. Analytical uncertainties of major elements were

estimated to be generally less than $\pm 0.5\%$ except for that Nb, Ta, Zr, Hf, F, and B were $\pm 5\%$ — 10% and W, Sn and Mo were $\pm 10\%$ — 20% .

RESULTS AND DISCUSSION

1. The abundances and distribution characteristics of major elements in the Malan loess

The results of the analysis of 53 chemical elements in the Malan loess are listed in Table 1. The former three sets of data represent respectively the average values, standard deviations and variation coefficients of the chemical elements in loess samples from the three different loess zones, and the last set of data represents the mass-weighted average abundances of the chemical elements in the whole Malan loess. As viewed from the major element analyses, loess of China contains mainly SiO_2 (59.81% on average), Al_2O_3 (11.88% on average) and CaO (7.79% on average), and subordinately Fe_2O_3 (2.77% on average), MgO (2.35% on average), K_2O (2.25% on average), Na_2O (1.79% on average), FeO (1.26% on average), etc. It is shown that the main minerals in the loess are quartz, feldspar and calcite, followed by mica and other accessory minerals. The former three kinds of minerals account for 80%—90% of the whole detrital minerals (Liu Tungsheng *et al.*, 1985). Therefore, the main chemical composition of the loess is consistent with its mineral composition. In addition the three loess zones show a consistency with respect to the contents of major elements in the loess, but, as viewed from their regional distribution, the major elements show regular variations in going from northwest to southeast (i. e. sandy loess \rightarrow loess \rightarrow clayey loess). For example, SiO_2 , Na_2O and FeO tend to decrease whereas Al_2O_3 , CaO and Fe_2O_3 tend to increase. This tendency indicates variations in mineral composition of the Malan loess with decreasing grain size from northwest to southeast, suggesting that the contents of quartz and other species in sandy loess in the northwest are high relative to those of clay minerals and carbonate minerals in the southeast. It follows that the main chemical composition of loess is actually controlled strictly by its mineral composition.

2. Trace elements in the Malan loess

As can be seen from Table 1, there are significant differences in the abundance of trace elements in loess, with the minimum less than 1ppm and the maximum up to several hundred ppm. Such differences are closely related to the composition of detrital minerals in the loess on one hand and to the geochemical behavior of the trace elements themselves under hypergenic conditions and their average crustal abundances on the other hand. Regionally, the contents of most trace elements show regular variations from northwest to southeast (i. e. sandy loess \rightarrow loess \rightarrow clayey loess). Many trace elements, such as Zn, Cu, Co, Ni, V, Li, Rb, Cs, REE and others, tend to increase in the order of clayey loess $>$ loess $>$ sandy loess, while a few trace elements, such as Ta, Mo and Sr, show an opposite trend. Some trace elements, such as Sc, Se and Be, are of little variation in the three loess zones. The main factors leading to the zonal distribution of many trace elements in the Malan loess

Table 1 Chemical composition of the Malan loess from the middle reaches of the Huanghe River

Elements	Sandy loess (n=23)			Loess (n=97)			Clayey loess (n=27)			Chinese loess
	mean	σ	σ/x	mean	σ	σ/x	mean	σ	σ/x	
SiO ₂ (%)	62.25	1.73	0.06	58.38	0.78	0.03	57.16	0.98	0.04	59.81
TiO ₂	0.58	0.03	0.11	0.62	0.03	0.07	0.62	0.02	0.06	0.60
Al ₂ O ₃	11.62	0.27	0.04	12.07	0.23	0.04	12.13	0.22	0.03	11.88
Fe ₂ O ₃	2.52	0.42	0.24	2.95	0.09	0.05	2.93	0.08	0.04	2.77
FeO	1.30	0.16	0.15	1.26	0.12	0.12	1.17	0.13	0.14	1.26
MnO	0.05	0.01	0.12	0.06	0.01	0.07	0.08	0.01	0.09	0.06
MgO	2.29	0.31	0.22	2.40	0.20	0.14	2.32	0.18	0.13	2.35
CaO	7.00	0.92	0.13	8.24	0.62	0.11	8.77	0.92	0.15	7.79
Na ₂ O	1.94	0.20	0.14	1.68	0.09	0.07	1.58	0.13	0.11	1.78
K ₂ O	2.22	0.12	0.06	2.28	0.10	0.05	2.23	0.13	0.07	2.25
P ₂ O ₅	0.14	0.01	0.19	0.14	0.02	0.25	0.16	0.03	0.49	0.14
CO ₂	4.98	0.31	0.23	5.83	0.22	0.14	6.16	0.32	0.19	5.53
H ₂ O _±	2.31	0.25	0.18	3.84	0.21	0.15	5.26	0.31	0.21	3.96
Total	99.20			99.75			100.57			100.17
Zn (10 ⁻⁶)	58.6	8.94	0.15	69.7	6.35	0.09	69.5	8.62	0.12	65.3
Cu	18.4	3.24	0.18	23.0	2.52	0.11	24.2	2.62	0.11	21.3
Co	16.1	2.71	0.17	19.6	1.77	0.09	21.5	1.21	0.06	18.4
Ni	29.8	6.96	0.23	36.1	3.00	0.08	37.5	2.87	0.08	33.8
Pb	25.5	4.59	0.18	29.0	2.91	0.10	30.3	2.71	0.09	27.7
Nb	9.94	1.35	0.14	10.63	1.59	0.15	10.79	1.80	0.17	10.37
Ta	1.62	0.56	0.35	1.71	0.46	0.27	1.53	0.57	0.37	1.66
U	2.87	0.56	0.19	2.49	0.58	0.23	2.57	0.58	0.23	2.64
Th	11.07	1.21	0.11	11.76	0.71	0.06	12.27	0.97	0.08	11.53
Sc	12.0	1.43	0.12	12.7	1.26	0.10	12.3	1.25	0.10	12.4
Se	0.11	0.02	0.14	0.11	0.02	0.16	0.11	0.02	0.20	0.11
Mo	1.5	0.59	0.39	1.3	0.53	0.40	0.10	0.22	0.22	1.4
W	1.2	0.48	0.41	1.6	0.65	0.40	1.6	0.76	0.47	1.4
Sn	2.9	1.19	0.41	3.0	1.20	0.40	3.1	1.31	0.42	3.0
Zr	223	9.12	0.04	225	7.70	0.03	227	7.36	0.03	225
Hf	7.0	0.22	0.03	7.0	0.19	0.03	7.0	0.14	0.02	7.0
F	454	88	0.19	512	68	0.13	470	77	0.16	486
B	63	14.90	0.24	64	10.60	0.16	61	10.9	0.18	63
Ag	0.07	0.02	0.31	0.06	0.02	0.25	0.06	0.01	0.24	0.07
Li	29.0	4.13	0.14	34.5	2.24	0.06	34.2	2.34	0.07	32.3
Rb	89.9	5.64	0.06	97.8	5.12	0.05	97.5	7.74	0.08	94.7
Cr	60.6	11.47	0.19	67.4	14.20	0.21	63.2	4.67	0.07	64.3
Ba	524	68	0.13	501	64	0.13	540	65	0.12	513
Be	1.9	0.21	0.11	2.1	0.19	0.09	2.1	0.23	0.11	2.0
Sr	242	30	0.12	227	43	0.19	215	42	0.20	232
V	74.1	11.0	0.15	82.1	8.99	0.11	86.3	9.73	0.11	79.3
Cs	6.0	0.79	0.13	7.7	0.92	0.12	7.6	1.00	0.13	7.0
La	30.43	2.71	0.09	33.12	1.93	0.06	33.80	2.29	0.07	32.12
Ce	61.27	5.68	0.09	67.27	4.16	0.06	68.62	4.06	0.06	65.03
Pr	6.29	0.52	0.08	6.76	0.36	0.05	6.87	0.38	0.06	6.59
Nd	26.30	2.55	0.10	28.24	1.74	0.06	28.91	1.78	0.06	27.53
Sm	5.37	0.49	0.09	5.77	0.32	0.06	5.86	0.34	0.06	5.62
Eu	1.07	0.06	0.06	1.15	0.08	0.07	1.17	0.07	0.06	1.12
Gd	4.67	0.52	0.11	5.07	0.36	0.07	5.18	0.37	0.07	4.92
Tb	0.77	0.08	0.10	0.84	0.06	0.07	0.86	0.06	0.07	0.81
Dy	4.29	0.51	0.12	4.63	0.34	0.07	4.69	0.38	0.08	4.50
Ho	0.88	0.10	0.11	0.95	0.07	0.07	0.97	0.08	0.08	0.93
Er	2.52	0.30	0.12	2.68	0.20	0.07	2.72	0.23	0.09	2.62
Tm	0.40	0.39	0.10	0.43	0.03	0.07	0.44	0.03	0.07	0.42
Yb	2.58	0.29	0.11	2.74	0.21	0.08	2.78	0.24	0.09	2.68
Lu	0.41	0.04	0.09	0.43	0.03	0.08	0.43	0.04	0.08	0.42
Y	23.38	2.27	0.10	25.98	7.06	0.27	25.32	1.60	0.06	24.90

n=the number of samples; mean=the average concentration; σ =the standard deviation; σ/x =the variation coefficient.

with respect to their abundances may be presented as follows:

(1) The influence of grain size

The influence of grain size is reflected in the relative enrichment of Zn, Cu, Co and Ni in the finer grain-sized fractions of loess. With decreasing grain size of loess from coarse to fine, the contents of the above elements in the clay particle-sized fraction of the Malan loess show that the average contents of the above trace elements are higher than those of the whole rock, with Zn and Cu in the clay particle-sized fraction being higher than those in the whole rock by a factor of 2.5—3 (Wen Qizhong *et al.*, 1986). This implies that higher contents of the above trace elements in clayey loess are probably due to their absorption on clay minerals.

(2) The influence of mineral composition

In regard to such elements as Li, Rb, and Cs, their independent minerals have not yet been found in the loess. These elements appear to be present mainly as isomorphs or impurities in detrital heavy minerals in the loess and hence regional variations in the contents of the detrital heavy minerals would necessarily affect the distribution of these elements. For example, the content of quartz is relatively high in sandy loess, because quartz (SiO_2) may serve the function of dilute for other elements. This may explain the reason why the content of quartz tends to decrease in the order of sandy loess, loess, clayey loess, while the contents of some other detrital heavy minerals tend to increase, resulting in a progressive increase in abundance of some trace elements.

3. Comparison of the average chemical composition of loess in China with the abundance of chemical elements in the crustal materials

Comparisons of loess of China with the lower and bulk crust (Taylor and McLennan, 1985) show that there is a significant difference in average chemical from the latter. For instance, loess of China is rich in the major elements K and Si and poor in other major elements relative to the lower and bulk crust. In regard to trace elements, loess of China is relatively rich in large-ion lithophile (LIL) elements such as Li, Rb, Cs, Ba, Th, etc, while the lower and bulk crust are rich largely in Fe, Mg, Ti and siderophile elements such as Cr, Ni, Co, etc. (Figs. 2 and 3). As for REE compositional characteristics, loess of China is quite different from the lower and bulk crust, the former being characterized by relative enrichment of LREE and remarked Eu depletion and the latter by relatively depletion of LREE with almost no Eu depletion observed in the bulk crust but pronounced Eu enrichment in the lower crust (Fig. 5). The chemical differences mentioned above truly reflect that there are considerable differences in composition between loess of China and the lower and bulk crust, indicating that loess of China contains mainly the loess-forming material from the upper continental crust, while the lower and bulk crust contain relatively high amounts of deep crustal material. That is why loess of China is relatively rich in lithophile and poor in siderophile elements while the lower and bulk crust is relatively rich in siderophile elements and poor in lithophile elements.

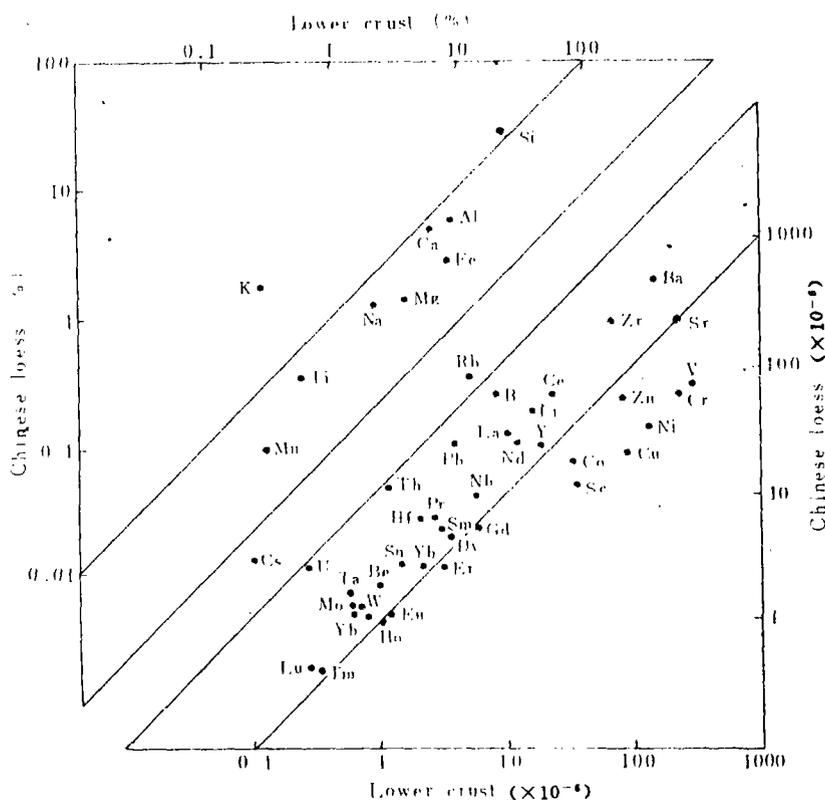


Fig. 2 Comparison of the chemical composition of loess of China with that of the lower crust

By comparing the chemical composition of loess of China with that of the upper crust (Taylor and McLennan, 1985), we can see that there are surprisingly significant similarities between them (Fig. 4). As compared with the upper crust, the most majority of the elements in loess of China are close to each other in contents and some elements, such as Mg, Ti, La, Ce, U, etc., are even identical to each other in abundance except that Ca and B are relatively high and Na and Nb relatively low. In regard to the REE compositional characteristics, the REE distribution patterns in loess of China are parallel to, or even approximate to, those of the upper crust, with no difference for the extent of Eu depletion (Fig. 5). Higher content of Ca in loess of China may be due mainly to more carbonate minerals (mainly calcite) contained in loess material. Relative enrichment of B in loess of China may be attributed to the strong adsorbing capability of clay minerals. The loss of Na as a result of leaching during the process of pedogenesis is a reasonable explanation of relatively low Na content in loess of China (Liu Tungsheng *et al.*, 1985; Wen Qizhong *et al.*, 1989). Generally, there is almost no difference in average chemical composition between loess of China and the upper continental crust (Taylor and McLennan, 1985), demonstrating that loess of China is the typical representative of average natural samples of the exposed upper continental crust (Taylor and McLennan, 1985).

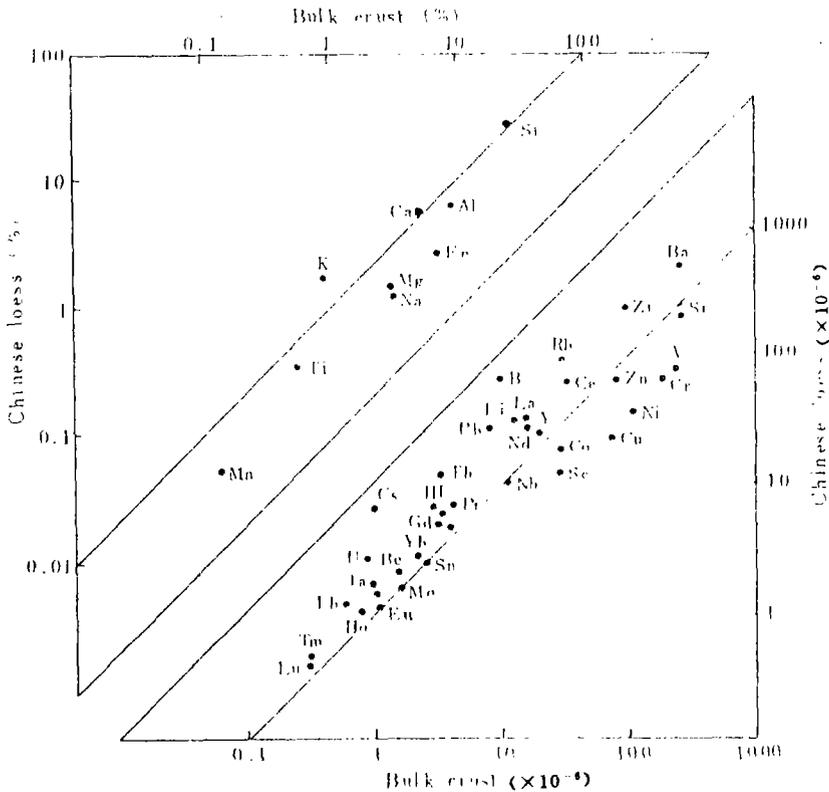


Fig. 3 Comparison of the chemical composition of loess of China with that of the bulk crust

Conclusions

1. Relatively precise average chemical composition data for loess of China have been obtained by extensive sampling and precise analysis of the Malan loess distributed in the area along the middle reaches of the Yellow River in China and by using the mass-weighted average calculating method.

2. The composition characteristics of trace elements in loess of China are similar to those of major elements, i. e. , the content of most trace elements are of slight variation, but show regular variations with respect to their regional distribution. For example, such elements as Zn, Cu, Co, Ni, V, Li, Rb, Cs, REE, etc. , display a tendency of increasing in the order of clayey loess → loess → sandy loess, while Ta, Mo, Sr etc. show an opposite tendency . Evidence suggests that the principal factors governing the variation in trace element contents in loess of China are the mineral composition and the particle size composition.

3. Significant differences are noticed in average chemical composition between loess of China and the lower and bulk crust, the former being relatively rich in K, Si and LIL elements, while the lower and bulk crust is rich in Fe, Mg, Ti and siderophile elements. Loess of China is characterized by relative enrichment of LREE and remarked Eu depletion

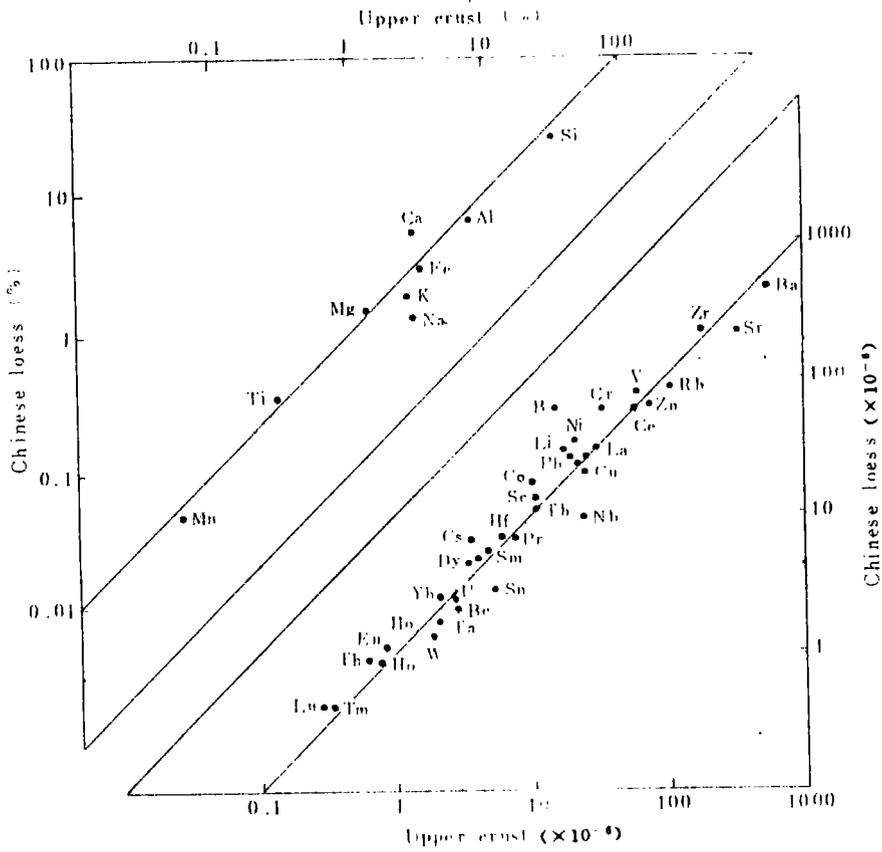


Fig. 4 Comparison of the chemical composition of loess in China with that of the upper crust

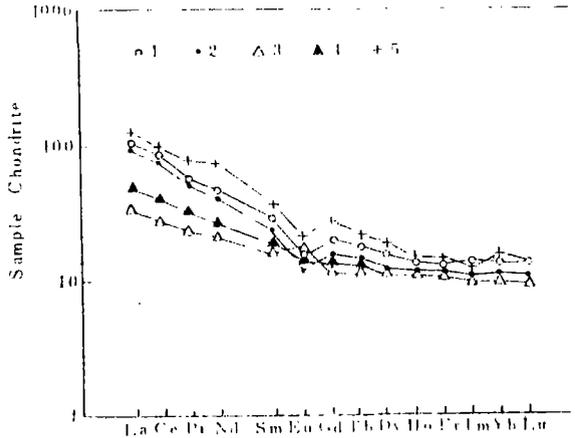


Fig. 5 The REE distribution patterns in loess of China as well as in other crustal materials
 1=loess of China (this paper); 2=upper crust (Taylor and McLennan, 1985);
 3=lower crust (Taylor and McLennan, 1985); 4=bulk crust (Taylor and McLennan, 1985);
 5=continental crust of China (Li Tong, 1994)

whereas the lower and bulk crust is relatively poor in LREE with no Eu depletion observed in the bulk crust and remarked Eu enrichment in the lower crust. It is indicated that loess

of China is typically representative of the upper crustal material.

4. Much similarity is noticed in average chemical composition between loess of China and upper continental crust. In the loess of China Ca and B are relatively high and Na, Nb are relatively low, and the majority of the rest elements are close to one another, some elements such as Mg, Ti, La, Ce and U even identical to one another with respect to their contents. In regard to REE compositional characteristics, the REE distribution patterns in loess of China are parallel to, or even close to, those of the upper crust with no deviation in extent of Eu depletion. Therefore loess of China not only provides the ideal average natural samples of exposed upper continental crust, but also presents an average chemical composition of upper continental crust.

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