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**Elemental distribution of topsoil within the Lake
Qinghai catchment, NE Tibetan Plateau and its
implication for weathering at semi-arid area**

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Abstract:

A total of 73 topsoil samples (top 30 cm) were collected from the Lake Qinghai catchment in 2009, NE Qinghai–Tibetan Plateau (QTP) to investigate geochemical patterns, identify possible sources and explore implication of chemical weathering in study region. 15 oxides and elements (CaO, Na₂O, MgO, K₂O, Al₂O₃, SiO₂, Fe₂O₃, P, Ti, Cu, Zn, Pb, Rb, Sr and Zr) were determined by X–ray fluorescence spectrometry. Enriched CaO levels were observed in alpine soil, pedocal, solonchak and aeolian sand soil whereas lost in hydromorphic and semi–hydromorphic. High Na₂O in marsh solonchak could indicate the existence of evaporates. Deficit of Cu and Zn but enrichment of Pb existed, and the accumulation of P in topsoil could be from plant uptake. Some human activities have exerted influence on virgin topsoil to some extent by GIS mapping. Implications on chemical weathering were characterized by major carbonate controlling of initial weathering stage under dry–cold climatic condition and transition between Ca, Na removal and further removal of K conditions.

Key words: topsoil types; chemical index of alteration; Lake Qinghai catchment

1. Introduction

The further development of western China during recent decades has a side effect of virgin soil in Qinghai–Tibet by the introduction of toxic metals from many human activities, such as mining (coal, potash and copper deposits) (Cao et al., 2011; Yang et al., 2013), over–grazing (Fan et al., 2010a), pastoralist settlements concentrated (Harris, 2010), Qinghai–Tibet railway transportation (Qin and Zheng, 2010; Zhang et al., 2012), highway construction (Wu et al., 2003), tourism development (Wang et al., 2011) and so on, adding natural processes, such as desertification and “black soil patch” degraded grassland (Harris, 2010), degradation of alpine ecosystems and permafrost due to climatic change (Chen et al., 2012; Wang et al., 2007; Zhang et al., 2011). Those anthropogenic or natural processes inevitably increase levels of trace element in soils. For that reason, the investigation of element geochemical behavior of virgin soil in Qinghai–Tibet can furnish useful information concerning these contamination status.

The quantitative data on trace element in topsoil are used to estimate the soil’s heavy metal concentrations (Li et al., 2012), to explore the mobility, bioavailability, and human bioaccessibility of different trace metals (Luo et al., 2012a), to obtain the fluxes of the soil heavy metal input/output pathways (Xia et al., 2013), to identify possible sources using multivariate statistical analysis, GIS mapping techniques or Pb isotopic composition analysis (Facchinelli et al., 2001; Li et al., 2004; Wong and Li, 2004), and to investigate the potential risks to ecosystem and human health (Li et al., 2014; Wei and Yang, 2010). While the levels of major elements are generally dependent on the lithology of soil parent material and pedological processes responsible for the formation of soils (Baize and Sterckeman, 2001), such as the Chemical Index of Alteration (*CIA*) based on contents of elected major elements has been used to compare the degree of soil formation (Nesbitt and Young, 1982) and

A–CN–K diagram (Al_2O_3 –($\text{CaO}^* \text{Na}_2\text{O}$)– K_2O) could reflect principal component changes of chemical weathering processes in soil (Liu et al., 2009; Yang and Rose, 2005). These methods of soil studies in recent decades have focused on urban soil (Appleton et al., 2013; Luo et al., 2012b), street dusts (Han et al., 2008; Li et al., 2001; Yang et al., 2011), agricultural and non agricultural soil (Liu et al., 2013; Sun et al., 2013), flood zone (Li and Zhang, 2010; Ye et al., 2011), human–constructed soils (Acosta et al., 2011; Wei and Yang, 2010), mine and developed areas (Li et al., 2014; Teng et al., 2010). However, limited work has been performed on contaminated/uncontaminated condition of topsoil in QTP in recent decades.

Lake Qinghai, located at the northeastern margin of QTP, lies at the transition from arid to semiarid climate zones, where harsh environment, sparse population as well as degeneration and desertification of the grassland caused by over–grazing coexist. Qinghai–Tibet railway pass along the lakeshore, and herdsman settlements are located at both sides of the Qinghai–Tibet highway. Qinghai Lake is the important wetland of the world and an important place that protect the world's biological diversity. The Rishui and Muli coalfield are located at northeast side in catchment and northwest edge of catchment, respectively (Figure 1). Those natural and anthropogenic conditions make Lake Qinghai become particularly suitable for scientific research due to its sensitivity to environment. Previous studies on Lake Qinghai focused on reconstruction of paleoenvironment and paleoclimate (Henderson and Holmes, 2009; Rhode et al., 2010), hydrological and solute budgets (Jin et al., 2010b; Xu et al., 2010), change of lake water level (Chen et al., 2012; Li et al., 2007), and investigation of ecology (Cao and An, 2010; Wang et al., 2010). However, little is known so far about the element geochemistry of soil in Qinghai Lake catchment.

The main objectives of this study are (1) to investigate the native major- and trace-element contents of topsoil types; (2) to identify possible sources of contamination and portray their spatial patterns using multivariate analyses and GIS mapping techniques; (3) to shed light on implication of chemical weathering on topsoil within the Lake Qinghai catchment. The results could be used for assessing the topsoil contaminated/uncontaminated condition and a better management of the Lake Qinghai catchment.

2. Materials and Methods

2.1. Study area and topsoil types

Lake Qinghai (36°32'–37°15' N, 99°36'–100°47' E, 3194 m a.s.l.) catchment, with a surface water area of 4260 km² and a water volume of 7.16×10¹⁰ m³, is surrounded by four mountain ranges, namely Riyue Mts to the east, Qinghai Nanshan Mts to the south, Shule south Mts to northwest, and Datong Mts to the north. Those mountains, with general elevations above 4000 m, account for ~70% of the drainage area. The climate is controlled by the Asian summer and the Westerlies with strong solar radiation with long, cold winters and short, cool summers, and frost for any time of the year (Yu and Zhang, 2008). Mean annual air temperature (MAT) (1951–2007) is ~1.2°C. Mean annual precipitation (MAP) (1951–2007) is 357 mm, but evaporation is 3–4 times higher than precipitation (LIGCAS, 1994). Bed rocks of the catchment consist of the late Paleozoic marine sedimentary rocks composed primarily of limestone and sandstones, and a small fraction of igneous rocks constituted granite, diorite and granodiorite. Quaternary loess is distributed around the lake, and seasonally frozen earth is widely distributed in the valleys of the catchment (LIGCAS, 1979).

Based on the data from China's second national soil survey, the soil types in the study region were mainly classified into six soil orders and ten soil groups shown in Figure 1. A soil classification benchmark system established on GSCC (the genetic soil classification of China), ST (Staff, 1999) and WRB (World Reference Base for Soil Resources). Alpine soil (including alpine frost desert soil, alpine meadow soil, and alpine steppe soil), pedocal (including chernozem and chestnut soil) and semi-hydromorphic soil (including mountain meadow soil) are zonal, which are affected by altitude, precipitation and relief, whereas hydromorphic (including bog soil and peat soil), solonchak (including marsh solonchak) and aeolian sandy soil are intrazonal, which are affected by relief, hydrops and aeolian dust in study area (Ma, 1997).

2.2. Sampling and chemical analyses

A total of 73 surface soil samples (0–30 cm depth, removing grass turf) were taken from Lake Qinghai catchment during 1 July–30 September 2010 (Fig. 1). About 1 kg of each soil sample was collected using a stainless steel spade and a plastic scoop, and fresh samples were contained in food bags. The coordinates of sampling locations were recorded with a differential GPS. All the samples were freeze-dried, then grounded to pass 200-mesh sieves (<74 μm) and homogenized in an agate mortar. Five grams of the powdered sample were compressed into a thin compact disc (approximate 3.2 cm in diameter). The concentrations of 15 oxides or elements in bulk topsoil (CaO, Na₂O, MgO, K₂O, Al₂O₃, SiO₂, Fe₂O₃, P, Ti, Cu, Zn, Pb, Rb, Sr and Zr) were measured by an Energy Dispersive X-Ray Fluorescence (ED-XRF) spectrometry (Epsilon 5 ED-XRF, PANalytical B. V., the Netherlands). Calibration was done by using national reference samples (15 soil samples (GSS 1–7 and 9–16) and 11 stream sediment samples (GSD 1–11). Analytical precision, as verified by replicate analyses of GSS–8, was better than 1% for major elemental oxides and better than 5%

for trace elements.

2.3. Data analyses using computer software

Raw data were stored in MS Excel, and basic statistical parameters were calculated to acquire the overall feature of the data sets. The tests for normality of the raw and transformed data were performed using SPSS 17 software, prior to multivariate analyses. To classify elements into groups that share similar geochemical features, multivariate analyses of cluster analysis (CA) and principal component analysis (PCA) were carried out using SPSS 17 software. CA was used to classify oxides/elements into groups with good correlations within the groups. The distance cluster represented the degree of association between elements. The lower the value on the distance cluster, the more significant was the association. In the PCA, the principal components were calculated based on the correlation matrix. Varimax with Kaiser normalization was used as the rotation method in the analysis. The distance measure used in CA was the Squared Euclidean distance. Spatial patterns of trace element based on interpolation of Inverse Distance Weighted (IDW) were used for ArcGIS 10.0 software. Most of maps were produced using origin 8.5 software.

3. Results and discussion

3.1. Concentrations of major and trace elements

Statistical summary of major elements (K, Na, Ca, Mg, Al, Si and Fe,) shown in their oxide formats (K_2O , Na_2O , CaO , MgO , Al_2O_3 , SiO_2 and Fe_2O_3) and trace elements (P, Ti, Cu, Zn, Pb, Rb, Sr and Zr) were presented in Table 1. The mean values of these major elements were similar to the background values of soil in Qinghai (Ma, 1997). Compared with Upper Continental Crust (UCC), CaO and MgO were enriched whereas Na_2O , K_2O , Al_2O_3 , Fe_2O_3 and SiO_2 were lower than those of UCC (Chi and Yan, 2007), corresponding to ratios

between major elements in this study and those in UCC for 1.5, 1.1, 0.5, 0.64, 0.75, 0.68 and 0.75, respectively. These were probably due to eluviation and accumulation of alkaline earth elements (CaO and MgO) inherited the dominant carbonate weathering in this region. On the other hand, the maximum loss was alkaline elements (Na₂O and K₂O) and immobile elements (Al₂O₃, Fe₂O₃ and SiO₂) were also lost to some extent during soil formation. Obviously, it was this accumulation of carbonate in processes of pedogenesis that was the main factor affecting soil element geochemistry in Lake Qinghai catchment, which was consistent with previous studies on the Tianshan Mountain area of Xinjiang (Huang and Gong, 2005) and the unpopulated Kekexili region of QTP (Huang et al., 2006).

The background values of trace elements in topsoil were important for the assessment of soil fertility and contamination status (Li et al., 2008; Teng et al., 2010; Yuan et al., 2014). Compared to the mean values of soils in Qinghai (Table 1), soils in the catchment had lower in Cu, Zn, Pb, Rb, Sr, and Zr except for Ti and P (missing P background data), corresponding to ratios between trace elements in this study and those in soils of Qinghai for 0.76, 0.68, 0.6, 0.85, 0.97, 0.97 and 1.01, respectively. First, those results obviously indicated deficit of some trace elements (such as Cu and Zn) in Lake Qinghai catchment, consistent with previous studies (Jiao.T., 2003; Suo et al., 2000). Second, compared to the mean values of UCC, a similar tendency was presented except for a higher Pb (17.39 mg/kg, corresponding to ratio of 1.02) (Table 1). A higher Pb background values in this catchment may occurred not only from mining, but also from other causes such as atmospheric deposition. Dai et. al., (2012) studied that coalfield mining may cause higher Pb contents in topsoil due to Early and Middle Jurassic (J₁₋₂) of coal-forming periods in the northwestern coal area with mean Pb concentration of 16.64 mg/kg. However, Jin et. al., (2009) thought that excess anthropogenic Pb of two short north-south sediment cores of lake after subtracting lithogenic Pb was

transferred to the lake and its sediments predominantly via the atmosphere deposition. Therefore, higher background values of Pb sources need further investigation. Third, the ratio of topsoil/UCC for P exceeded 1.0, suggesting that P was accumulated in the topsoil possibly through plant uptake but not by application of phosphate fertilizers in grassland. Moreover, P tends to be strongly absorbed by the soil colloids and to accumulate in the surface horizon (Kleinman et al., 2003). Finally, “hydrolyzate elements” such as Rb and K had a strong affinity for clay minerals but Sr and Na as “leachate elements” due to their smaller ions radius (Bowen, 1979; Ma, 1997). These differences in affinity for clay minerals would explain the observed variations.

Generally, the geochemistry patterns of major elements indicated that the change of CaO concentrations was dominant over processes of pedogenesis, while deficit of background trace elements for Cu and Zn, and enrichment of those for Pb and P existed.

3.2. Major elements in different topsoil groups

The elemental compositions normalized by UCC in each topsoil group are showed in Figure 2. Enriched CaO levels were observed in alpine soil, pedocal, solonchak and aeolian sand soil whereas lost in hydromorphic and semi-hydromorphic. Dominant carbonates (Jin et al., 2010a) in alpine soils (alpine frost desert soil ($15.4 \pm 0.4\%$) and alpine steppe soil ($10.6 \pm 0.7\%$)) distributed in high-altitude (3700~4200m), shattering and cracking under freeze-thaw and exfoliation for a year round, which may cause calcium content of topsoil equivalent to that of bedrock (ISSCAS, 1978; Ni et al., 2007). Aeolian sandy soil in low-latitude (3300~3400m) was deposited in northeast shore of lake. Previous studies suggested that aeolian sediment provenance widely originate from the Qaidam Basin in the adjacent northern QTP (An et al., 2012; Fan et al., 2010b; Qiang et al., 2010), with the dominant compositions such as $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ in lake sediments and loess over Lake Qinghai

catchment. However, CaO contents in hydromorphic and semi-hydromorphic were located in hydros easily subjected to loss in soil Freezing–thawing process (Wang et al., 2013).

Compared to the other groups, marsh solonchak had a significantly higher content of Na₂O (3.1%), probably indicating the existence of evaporates (i.e. NaCl and Na₂SO₄·10H₂O), which was consistent with a previous study identified by elemental ratios of the dissolved solute in river water within the Lake Qinghai catchment (Jin et al., 2010a).

Alpine frost desert soil and peat soil had significantly higher contents of trace elements except Sr in this study, which were may attributed to mobility of trace elements in weathering of soil, Further studies were needed to determine the reason for this enrichment.

3.3. Potential source identification by multivariate analyses

The dendrogram (cluster tree) for 15 oxides/elements was showed in Figure 3. The oxides/elements could be classified into two major groups. The first major group contained only CaO due to the dominant carbonate of bed rocks in Lake Qinghai catchment. The associations among oxides/elements in the second major group were quite complex. These oxides/elements could be further classified in three group:

Group 1: CaO, dominant carbonate weathering with carbonate areas of 15053.2 km², accounting for 59.6% of the catchment, which further verified importance of carbonate in processes of pedogenesis discussed above.

Group 2: MgO, Na₂O, SiO₂, Zr and Sr. They could be from silicate weathering with silicate areas of 5296.2 km², accounting for 20.9% of the catchment. Natural silicate minerals contained existence of Zr-bearing miners (such as ZrSiO₄). Although Sr element widely presented in carbonate, its contributions in soil also were from silicate mineral weathering (Jacobson and Blum, 2000).

Group 3: Fe_2O_3 , Zn, Cu, Pb, K_2O , Rb, Ti, Al_2O_3 and P. If further subdivided, Group 3 classified in four subgroup: Fe_2O_3 –Zn–Cu–Pb, K_2O –Rb, Ti– Al_2O_3 and P. The first subgroup indicated that trace elements (Cu, Zn and Pb) accompanied siderophile elements. The second subgroup represented alkali metals due to their affinity. The third represented bedrock composition of soils. The last subgroup indicated accumulations of nutrient P in topsoil through plant uptake.

To further investigate the relationships between oxides/elements, PCA was performed. PCA was applied to extract quantitative information for the identification of the sources of pollutants (Lu et al., 2010; Sollitto et al., 2010). Based on the loadings of the principal components (PCs) in Table 2, the 15 oxides/elements could be grouped into four PCs. The oxides/elements classification from PCA was consistent with the results from CA: PC1 from PCA and Group 3 from CA, PC2 and PC3 and Group 2, PC4 and Group 1. Notingly, Group 2 constituting two subgroup (MgO, Na_2O , SiO_2 , Zr and Sr) were divided into PC2 (MgO– Na_2O – SiO_2) and PC3 (Zr–Sr), which could indicate Zr-bearing or Sr-bearing minerals from different silicate mineral weathering in processes of pedogenesis.

3.4. Spatial distributions of trace elements by GIS mapping techniques

The geochemical mapping produced by GIS provided a reliable means of monitoring environmental conditions and identifying hot areas, especially for trace elements (Facchinelli et al., 2001; Li et al., 2004; Sun et al., 2013). The elemental concentrations were first interpolated with the IDW method. The geochemical maps that were obtained were then overlaid with other thematic maps such as road systems, rail, villages and mining sites (Rishui and Muli coalfield) using a GIS software. The geochemical maps of the selected elements, including Cu, Zn, Pb, Rb, Sr, Zr, Ti and P were illustrated in Figure 4.

Three spatial patterns were obtained from the geochemical maps in this study area. The spatial distribution maps for Cu, Zn, Pb, Rb and Ti showed similar geographical trends, corresponding to those of PC1 from PCA and Group 3 from CA discussed above, with high concentrations in northeast (representing coalfield), northwest (village and pastoralist's settlements) and west of lake (roadside settlements). Those results indicated that human activities have exerted influence on virgin topsoil to some extent in Lake Qinghai catchment. Moreover, the spatial distributions of Sr and Zr correspond to those of PC3 from PCA. High concentrations of both elements were mainly found in the north and south of lake, which could be due to different natural distributions of Sr-bearing minerals (such as SrSO₄ or SrCO₃) and Zr-bearing minerals (ZrSiO₄) in bedrocks. Furthermore the spatial distributions of P revealed higher values in the central catchment due to grass cover in alpine meadow soil and alpine steppe soil (Figure 1).

3.5. Implications on chemical weathering

The chemical index of alteration (*CIA*) could available and qualitatively indicate weathering intensity and weathering environment (Nesbitt and Young, 1982; Selvaraj and Chen, 2006). The *CIA* value was defined as:

$$CIA = \frac{Al_2O_3}{(Al_2O_3 + CaO^* + K_2O + Na_2O)} \cdot 100 \quad (\text{Molar proportions}) \quad (\text{Equation 1})$$

where CaO* represented the CaO content of silicate minerals only. In equation 1, if values of CaO outweighed that of Na₂O, m_{CaO*} = m_{Na₂O}; if CaO < Na₂O, m_{CaO*} = m_{CaO} (Nesbitt and Young, 1982). The *CIA* has been successfully applied in a large number of studies involving weathering intensity of transformation feldspars to clay minerals and other depositional environments (Hren et al., 2007; Shin et al., 2011; Wu et al., 2011).

A–CN–K diagram derived from the thermodynamic calculation of mineral stability and experiment of leaching feldspar could reflect trends and principal component changes of chemical weathering processes (Liu, 2009; Nesbitt and Young, 1984; Yang et al., 2004).

Figure 5 was a mixing plot on chemical weathering patterns such as stage, trend, environment and processes. On the one hand, the *CIA* mean value was 56.5 with the range from 44.3 to 63.9 in Lake Qinghai catchment, which indicated the preliminary weathering stage, as the world average *CIA* value 72.1 (Li and Yang, 2010). On the other hand, chemical composition of common shale in eastern China, which typically represented products of UCC weathering (Nesbitt and Young, 1982), was conceived as a final end-number (club in Figure 5) in semi-arid area. The values of loess were considered as a transition (diamond in Figure 5), and UCC are reckoned as a first source (spade in Figure 5). The direction of UCC pointing to terrigenous shale represented weathering trend of catchment. In addition, previous studies on weathering environment based on statistical analysis suggested that *CIA* values of 50–65, 65–85 and 85–100 reflected cold-dry, warm-humid and hot-damp conditions, respectively (Selvaraj and Chen, 2006). The *CIA* mean value of 56.5 indicated that the chemical weathering environment was cold and dry climate. At last, main clay minerals (potash feldspar, dolomite, illite, plagioclase, montmorillonite, kaolinite, aluminite trihydrate) were also projected at A–CN–K diagram (Chi and Yan, 2007). Data points of topsoil were paralleled to axes of the A–CN line and locate between plagioclase and montmorillonite. Those information of A–CN–K in Figure 5 evidently indicated that products of weathering remained montmorillonite and plagioclase, and failed to come up to kaolinite. In other word, the effect of decalcification and removal of Na (dissolution of plagioclase) on topsoil accompanied with deepening removal trend of K and evolution of enrichment in Al. In short, implications on chemical weathering of the Lake Qinghai catchment at semi-arid area was

characterized by major carbonate controlling of initial weathering stage under dry–cold climatic condition and transition between Ca, Na removal and further removal of K conditions.

4. Conclusions

Soil types of Lake Qinghai catchment are divided into six soil orders and 10 soil groups. Enriched CaO levels were observed in alpine soil, pedocal, solonchak and aeolian sand soil whereas lost in hydromorphic and semi–hydromorphic. High Na₂O in marsh solonchak could indicate the existence of evaporates. The ratios of trace elements to UCC indicate deficit of Cu and Zn but enrichment of Pb in topsoil. The topsoil/UCC ratios of P exceeded 1.0 indicate that the accumulation of P could be from plant uptake.

Soil geochemical patterns of elements or oxides were attributed coming from natural sources by CA and PCA analyses, but some human activities have exerted influence on virgin topsoil in Lake Qinghai catchment to some extent by GIS mapping.

Implications on chemical weathering was characterized by major carbonate controlling of initial weathering stage under dry–cold climatic condition and transition between Ca, Na removal and further removal of K conditions.

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Table 1. Chemical compositions (average concentration \pm standard deviation) of various topsoils within the Lake Qinghai catchment.

Topsoil type	N ^a		Na ₂ O (%)	K ₂ O (%)	CaO (%)	MgO (%)	Al ₂ O ₃ (%)	SiO ₂ (%)	TFe ₂ O ₃ (%)	P (mg/kg)	Ti (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Rb (mg/kg)	Sr (mg/kg)	Zr (mg/kg)
Alpine frost desert soil	3	AV ^b	1.39	2.72	15.40	2.48	12.96	55.86	5.45	905.46	3965.03	27.60	83.68	24.47	116.86	155.53	196.60
		SD ^c	0.05	0.33	0.40	0.39	0.12	1.72	0.74	169.67	422.39	5.83	12.79	3.75	13.43	35.01	18.86
		RSD ^d %	3.60	12.13	2.60	15.73	0.93	3.08	13.58	18.74	10.65	21.12	15.28	15.32	11.49	22.51	9.59
Alpine meadow soil	10	AV	1.87	2.08	7.39	2.50	11.77	47.72	3.85	768.61	3369.55	16.73	54.35	16.29	88.18	183.78	210.52
		SD	0.29	0.17	0.28	0.36	0.89	3.67	0.69	145.39	415.29	3.91	10.29	1.79	11.08	28.16	16.96
		RSD%	15.51	8.17	3.79	14.40	7.56	7.69	17.92	18.92	12.32	23.37	18.93	10.99	12.57	15.32	8.06
Alpine steppe soil	10	AV	2.22	1.80	10.59	2.00	9.92	51.38	2.69	562.11	2575.50	11.17	36.36	12.92	68.80	221.30	173.61
		SD	0.44	0.25	0.72	0.57	1.13	10.34	0.66	214.78	588.48	5.09	11.35	3.13	12.73	59.98	33.99
		RSD%	19.82	13.89	6.80	28.50	11.39	20.12	24.54	38.21	22.85	45.57	31.22	24.23	18.50	27.10	19.58
Mountain meadow soil	4	AV	2.19	2.08	3.98	3.49	11.51	50.65	3.56	630.77	3074.06	15.27	53.68	15.14	81.55	221.08	176.39
		SD	0.27	0.33	0.42	1.39	1.53	3.06	0.93	138.59	505.53	7.02	18.95	4.39	20.26	55.98	30.25
		RSD%	12.33	15.87	10.55	39.83	13.29	6.04	26.12	21.97	16.45	45.97	35.30	29.00	24.84	25.32	17.15
Chernozem	5	AV	1.85	2.06	4.36	2.79	11.59	44.64	3.85	750.00	3269.14	16.89	53.28	15.44	85.69	225.58	199.26
		SD	0.15	0.16	0.10	0.35	0.62	1.78	0.44	94.11	235.61	2.21	7.70	1.98	8.81	50.03	14.23
		RSD%	8.11	7.77	2.29	12.54	5.35	3.99	11.43	12.55	7.21	13.08	14.45	12.82	10.28	22.18	7.14
Chestnut soil	18	AV	1.80	2.27	6.46	2.46	11.50	51.11	4.02	804.01	3443.34	18.20	59.16	19.67	90.51	203.00	226.46
		SD	0.21	0.33	0.25	0.42	0.78	4.58	0.86	110.49	446.85	5.75	14.65	4.69	15.23	43.20	43.52
		RSD%	11.67	14.54	3.87	17.07	6.78	8.96	21.39	13.74	12.98	31.59	24.76	23.84	16.83	21.28	19.22
Bog soil	10	AV	2.15	2.04	2.70	1.95	9.98	60.75	2.92	617.22	2801.89	13.05	43.92	16.48	74.54	213.42	217.38
		SD	0.19	0.24	0.06	0.46	0.71	8.28	0.48	129.94	391.79	4.28	9.20	3.10	10.42	27.82	55.00
		RSD%	8.84	11.76	2.22	23.59	7.11	13.63	16.44	21.05	13.98	32.80	20.95	18.81	13.98	13.04	25.30
Peat soil	3	AV	1.61	2.87	3.44	2.26	12.86	58.56	5.29	877.15	3993.1	26.67	79.03	24.98	115.73	149.53	218.6
		SD	0.24	0.1	0.3	0.24	0.53	2.11	0.5	78.44	181.47	2.57	7.05	1.78	7.63	12.9	17.72
		RSD%	14.91	3.48	8.72	10.62	4.12	3.6	9.45	8.94	4.54	9.64	8.92	7.13	6.59	8.63	8.11

Table 1 (continued).

Topsoil type	N ^a	Na ₂ O (%)	K ₂ O (%)	CaO (%)	MgO (%)	Al ₂ O ₃ (%)	SiO ₂ (%)	TFe ₂ O ₃ (%)	P (mg/kg)	Ti (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Rb (mg/kg)	Sr (mg/kg)	Zr (mg/kg)
Marsh	2	3.08	2.35	11.56	2.57	11.38	67.09	3.7	539.62	2906.85	17.78	47.92	15.91	80.28	270.1	175.58
solonchak	SD	0.08	0.48	1.44	0.57	0.13	0.41	0.47	35.48	12.43	0.93	0.91	0.46	1.81	2.23	13.19
	RSD%	2.6	20.43	12.46	22.18	1.14	0.61	12.7	6.57	0.43	5.23	1.9	2.89	2.25	0.83	7.51
Aeolian	8	1.72	2.15	5.67	2.76	12.28	46.75	4.22	763.88	3473.71	18.42	60.6	17.54	92.87	206.72	211.95
sandy soil	SD	0.14	0.09	0.18	0.3	0.53	2.54	0.34	114.88	256.03	2.97	4.33	1.02	7.4	50.27	30.83
	RSD%	8.14	4.19	3.17	10.87	4.32	5.43	8.06	15.04	7.37	16.12	7.15	5.82	7.97	24.32	14.55
Sum	73	1.94	2.16	6.66	2.44	11.32	51.99	3.75	722.78	3226.98	16.83	54.26	17.39	86.3	204.94	206.65
	SD	0.38	0.34	3.11	0.61	1.22	7.69	0.96	167.52	560.28	5.98	15.79	4.37	16.91	46.29	39.13
	RSD%	19.59	15.74	46.7	25	10.78	14.79	25.6	23.18	17.36	35.53	29.1	25.13	19.59	22.59	18.94
	Minimum	1.34	1.41	2.62	0.8	8.12	28.67	1.61	307.14	1690.89	3.95	19.34	8.04	49.17	119.63	108.88
	Maximum	3.13	2.96	15.76	5.47	13.36	70.98	5.9	1114.5	4241.3	31.4	94.2	27.24	125.3	354.46	347.4
	Skewness	1.12	0.35	0.98	1.39	-0.65	0.31	-0.1	-0.23	-0.64	-0.06	-0.02	0.4	-0.01	0.94	0.87
Kurtosis	1.2	0.17	0.91	7.72	-0.31	0.72	-0.15	0.01	0.22	0.12	0.06	-0.17	0.03	0.99	2.49	
Upper Continental Crust ^e		3.9	3.37	4.2	2.22	15.19	77	5		3000	25	71	17	112	350	190
Soils in Qinghai ^f		1.68	2	5.31	1.97	11.52		4.07		3200	22.2	80.3	29	102	212	214
Ratio to soils	UCC	0.5	0.64	1.59	1.1	0.75	0.68	0.75		1.08	0.67	0.76	1.02	0.77	0.59	1.09
	Qinghai	1.15	1.08	1.25	1.24	0.98		0.92		1.01	0.76	0.68	0.6	0.85	0.97	0.97

^a N=sampling number, ^b AV= average concentration, ^c SD= standard deviation, ^d RSD= relative standard deviation.

^e data from abundance of chemical elements of the Upper Continental Crust (UCC): a new table (Taylor, 1964).

^f data from soil in Qinghai (in Chinese) (Ma, 1997).

Table 2. Rotation component matrix of oxides and trace elements within the Lake Qinghai catchment.

Oxides	Component loadings				Extraction
	PC1	PC2	PC3	PC4	
Na ₂ O	-0.45	0.61	-0.34	-0.07	0.689
K ₂ O	0.94	-0.24	0.08	0.02	0.948
CaO	0.06	-0.01	0.13	0.88	0.801
MgO	0.31	0.71	-0.42	0.16	0.807
Al ₂ O ₃	0.84	0.31	0.15	0.02	0.818
SiO ₂	0.12	0.95	-0.06	0.05	0.924
TFe ₂ O ₃	0.95	0.17	0.17	0.02	0.964
P	0.62	0.41	0.39	-0.01	0.700
Ti	0.86	0.23	0.32	0.17	0.928
Cu	0.96	0.08	0.04	-0.04	0.925
Zn	0.97	0.13	0.14	0.03	0.986
Pb	0.92	-0.19	0.15	0.10	0.907
Rb	0.97	0.04	0.15	-0.04	0.973
Sr	-0.33	0.09	0.82	0.05	0.794
Zr	0.20	0.06	0.62	0.52	0.700
Initial eigenvalues	7.905	2.078	1.632	1.249	
% variance	52.7	13.854	10.878	8.325	
Cumulative %	52.7	66.554	77.432	85.757	

Extraction method: principal component analysis.

Rotation method: Varimax with Kaiser normalisation. Rotation converged in 5 iterations.

Figure captions:

Figure 1. Topsoil types and distribution of sampling sites within the Lake Qinghai catchment.

Figure 2. Elemental compositions of topsoil groups normalized by Upper continental Crust.

Figure 3. Dendrogram of the cluster analysis of topsoils based on oxides/elements concentrations (n=73).

Figure 4. Spatial distribution of Cu (a), Zn (b), Pb (c), Rb (d), Sr (e), Zr (f), Ti (g) and P (h), respectively, in topsoil within the Lake Qinghai catchment.

Figure 5. Mixing plots between A–CN–K of topsoil chemical elements (the arrow indicating chemical weathering trend) and ranks/orders of *CIA* index indicating chemical weathering environment in topsoil within the Lake Qinghai catchment.

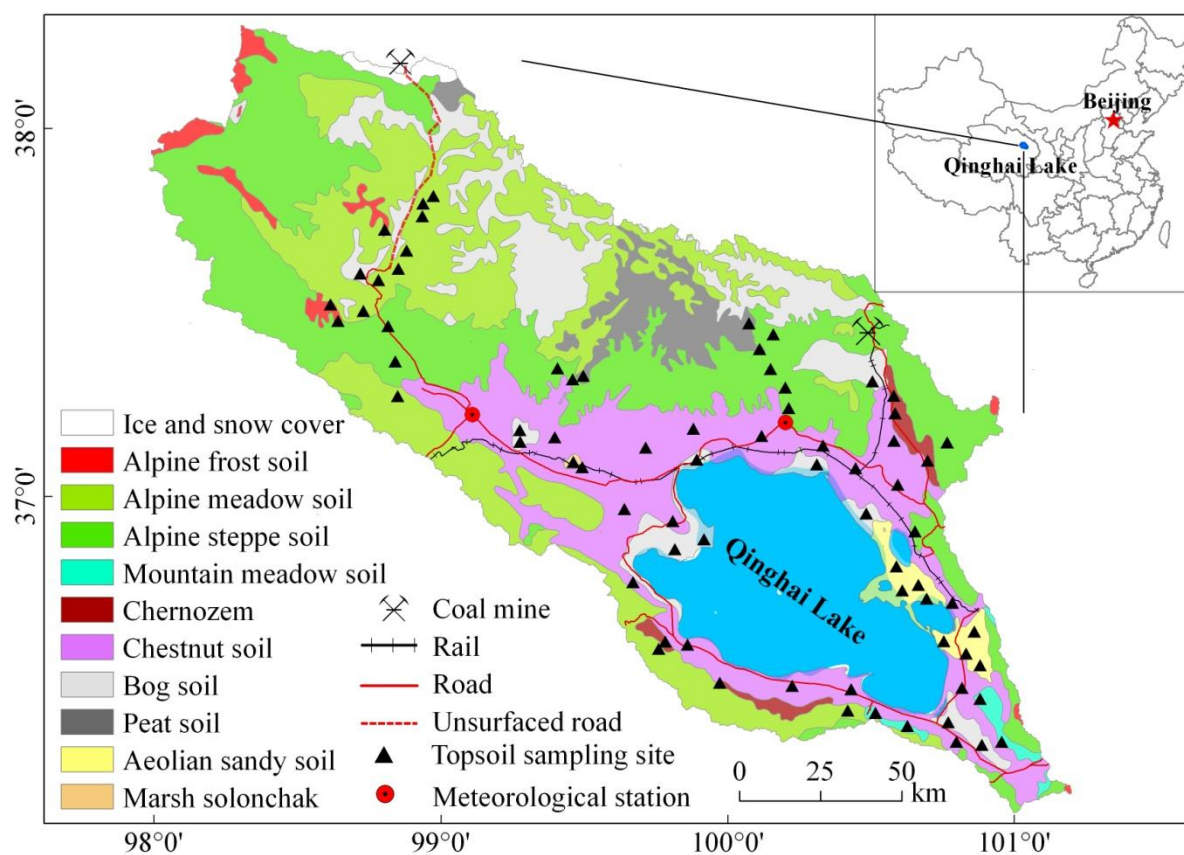


Figure 1

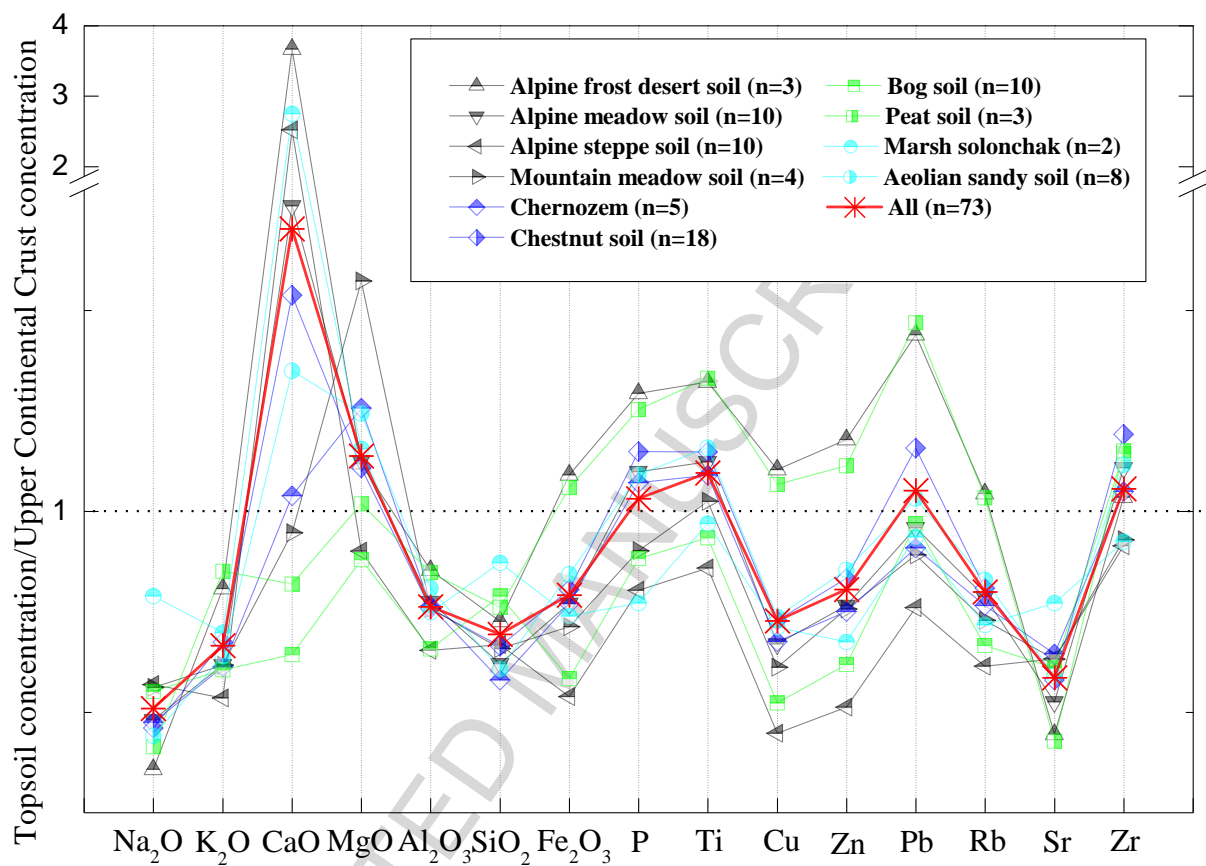


Figure 2

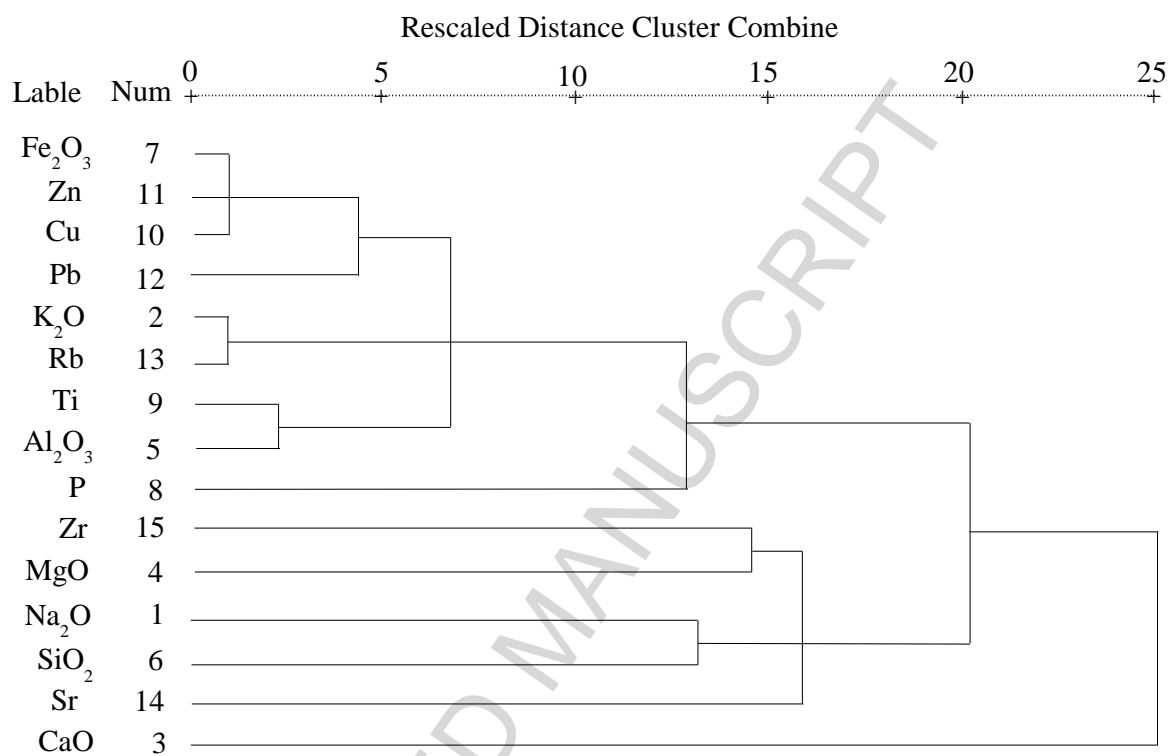


Figure 3

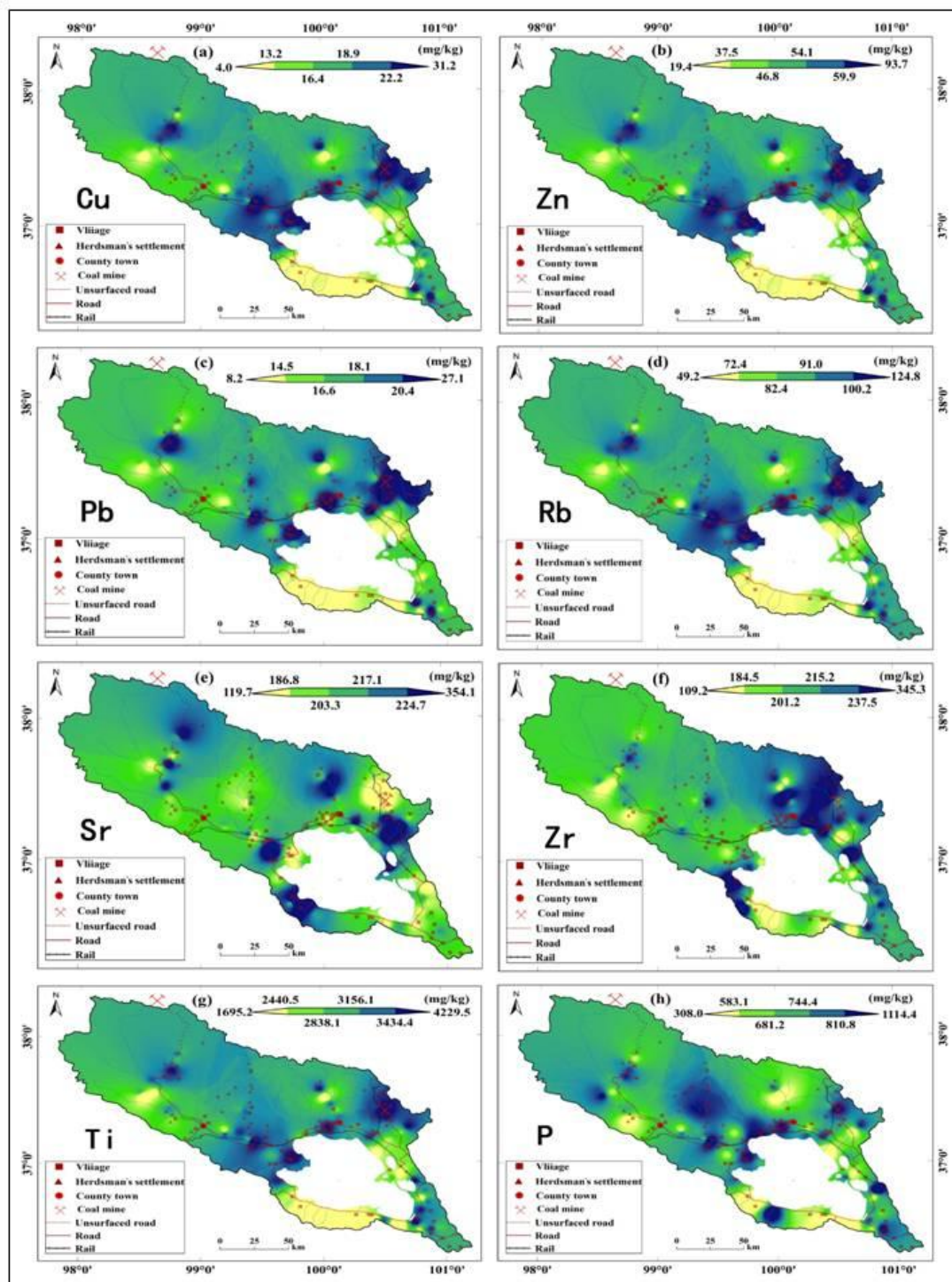


Figure 4.

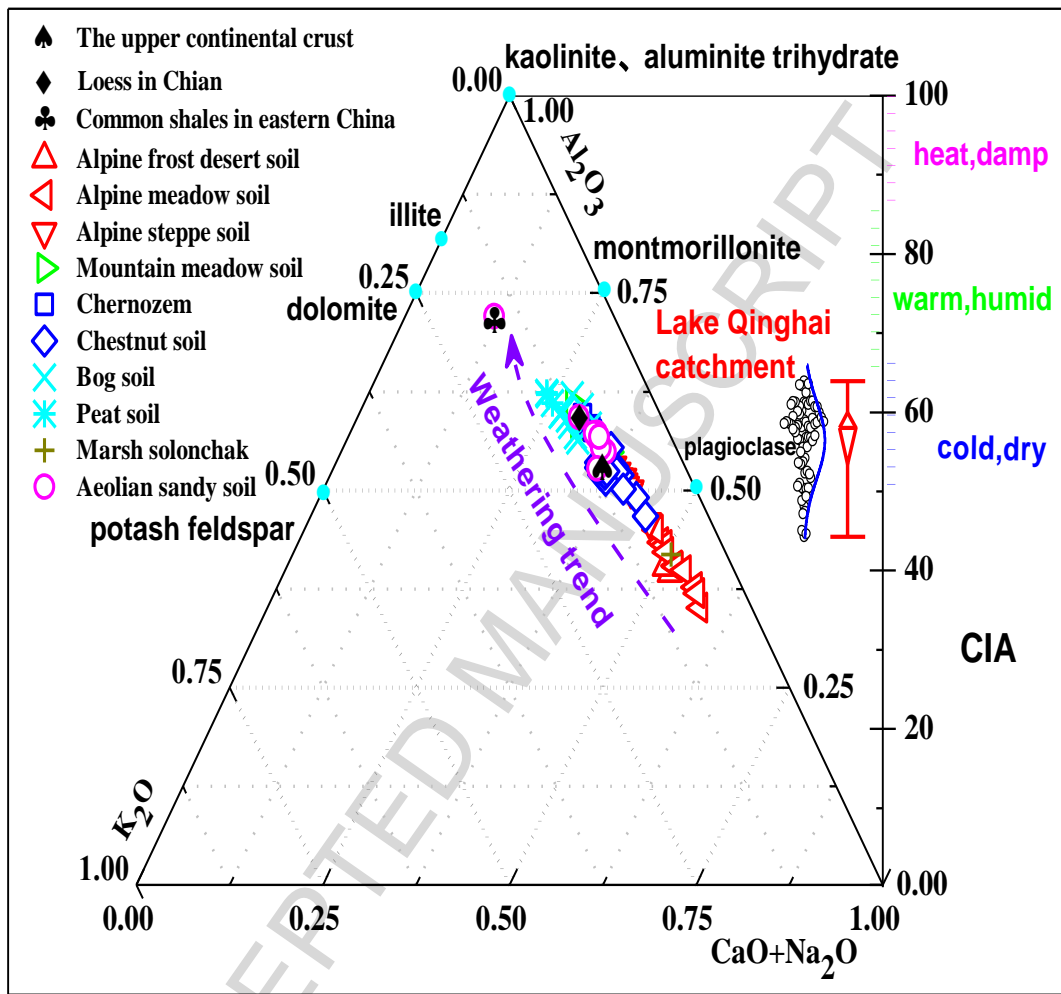


Figure 5

Highlights

- ◆ A major carbonate control of the primary weathering stage under cold-dry climatic conditions was shown.
- ◆ Deficiency of Cu and Zn but enrichment of Pb and P were existed.
- ◆ Some human activities have exerted influence on virgin topsoil to some extent.