

Strontium isotopic and elemental characteristics of calcites in the eolian dust profile of the Chinese Loess Plateau during the past 7 Ma

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Strontium isotopic ratios, calcium and strontium contents of calcites in the eolian dust profile during the last 7 Ma at Lingtai were systematically studied. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites change with three secondary fluctuations in the Quaternary loess-paleosol sequence: slight fluctuations from L_{33} to S_{15} , a slight increase from L_{15} to L_6 , and a dramatic decrease from S_5 to L_1 . They are usually lower in the Quaternary loess than in the interstratified paleosols. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites in the Tertiary red clay are relatively stable, mostly higher than in the Quaternary loess and paleosols. Ca^{2+} and Sr^{2+} contents of calcites are relatively high in the Quaternary loess and the Tertiary red clay but low in the Quaternary paleosols. Sr^{2+} is well correlated with Ca^{2+} , and can thus be an effective tracer for Ca^{2+} .

High contents of Ca (Sr) in the Tertiary red clay show that carbonates were poorly leached out of the Tertiary red clay. Like Ca contents, Ca/Sr ratios in the Tertiary red clay are close to those in the Quaternary loess. Elemental ratios and contents have different variations from the Sr isotopic ratios of calcites in the Lingtai profile, implying that isotopic ratios were better proxies for climate change than elemental ratios and contents. Primary carbonate and silicate comprised two endmembers determining the range of the Sr isotopic ratios of calcites, and chemical weathering was an inner driver to induce strontium isotopic variations of calcites in the eolian dust profile. Our isotope data indicate that chemical weathering was strongest in the Tertiary red clay, the second in the Quaternary paleosols, and weakest in the Quaternary loess. Strontium isotopic variations of calcites are in a good agreement with pedogenic characteristics in the Lingtai profile, broadly consistent with a proxy of the summer monsoon— $\text{Fe}_2\text{O}_3(f)/\text{Fe}_2\text{O}_3(t)$ ratios, and correlate with variations of $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios in the Lingtai profile and the dust flux in ODP885/886 during the late Cenozoic. Strontium isotopic variations of calcites are different from the magnetic susceptibility records in the Lingtai profile, further demonstrating that magnetic susceptibility of the Tertiary red clay could not reliably indicate the Tertiary summer monsoon.

As a result, strontium isotopic characteristics of calcites in the Lingtai profile indicate that the Quaternary summer monsoon had a glacial-interglacial alternation and weakened with large-amplitude oscillations since 0.5 Ma B.P., and also reveal that the Tertiary summer monsoon was more stable and overall stronger than the Quaternary, nevertheless, similar climates to those in the Tertiary probably occurred during a few paleosol developments of the Quaternary.

Keywords: Chinese Loess Plateau, the eolian dust profile, strontium isotope of calcite, chemical weathering, the East Asian summer monsoon

INTRODUCTION

The entire loess-paleosol sequences in the Chinese Loess Plateau provide well documented records of paleoclimate changes in the past about 2.5 Ma (Liu, 1985). Many physical, chemical, and biological proxies reflecting climate change have been established. For example, magnetic susceptibility is a classical proxy for the East Asian summer monsoon, whereas grain size mainly reflects the winter monsoon variation. These proxies provide very significant evidence for us to understand the

East Asian monsoon evolution and its inner relationships with global changes (Liu, 1985; An *et al.*, 1991, 2001; Chen *et al.*, 1999; Ding *et al.*, 2001a; Gu *et al.*, 1997; Guo *et al.*, 2002; Han *et al.*, 1997; Lu *et al.*, 2001).

In recent years, red clay deposits underlying the Quaternary loess-paleosol sequences have attracted increasing interest (Miao *et al.*, 2004; Ding *et al.*, 1999, 2001b; Guo *et al.*, 2004; Gylesjö and Arnold, 2006). Previous studies showed that the Tertiary red clay has the same origin as the Quaternary wind-blown loess and paleosols (Guo *et al.*, 2002; Ding *et al.*, 1998). Thus, the climate history registered in eolian deposits of the Chinese Loess Plateau was extended down to more than 7 Ma (Guo *et al.*, 2002; Ding *et al.*, 1999). It is still controversial

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whether magnetic susceptibility is reliable in registering the summer monsoon evolution of the Tertiary red clay record, although magnetic susceptibility was a classical proxy indicating the Quaternary summer monsoon (An *et al.*, 1991). Some authors considered that magnetic susceptibility could be still used as a good proxy reflecting the Tertiary summer monsoon, though it was much lower in the Tertiary red clay than in the Quaternary loess-paleosol sequence (An *et al.*, 2001; Sun *et al.*, 1998). Others argued that magnetic susceptibility of the Tertiary red clay was not reliable in tracing the Tertiary summer monsoon due to substantial gleying (Ding *et al.*, 1999, 2001a). Very limited indices have been suggested as indicators of the summer monsoon in the past 7 Ma. In order to reconstruct the long-term evolutionary history of the summer monsoon during the late Cenozoic, it is important to present new and reliable proxies for the summer monsoon from the loess-paleosol-red clay sequences in the Chinese Loess Plateau.

Primary and secondary carbonates are two kinds of carbonate minerals in soils (Liu, 1985). Primary carbonates are generated from parent rocks, and their mineralogical and geochemical features are not altered in the process of soil developments. Secondary carbonates are developed in soils due to chemical weathering, and thus contain information on primary carbonate dissolution and silicate weathering. In general, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are distinctly different between primary carbonates and silicates in soils. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of secondary carbonates mainly depend on the contributions from primary carbonates and silicates. In recent years, a great progress has been made on the geochemical cycle of soils and chemical weathering using the method of strontium isotope tracing (Quade *et al.*, 1995; Capo *et al.*, 1998; Capo and Chadwick, 1999; Van der Hoven and Quade, 2002; Chiquet *et al.*, 1999; Stewart *et al.*, 1998; Yokoo *et al.*, 2001, 2004). Therefore, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of soil carbonate may be a good proxy indicating chemical weathering.

Thick and continuous eolian deposits possess common features of soils, and contain abundant carbonates (Liu, 1985). These carbonates are mainly secondary calcites (Wen, 1989; Chen *et al.*, 1997). Most eolian carbonates from source areas were probably altered after they were precipitated in the Chinese Loess Plateau. Thus, carbonates in eolian deposits perhaps record much information on paleoclimate and paleoenvironment. In recent decades, researchers have mainly investigated carbonate contents and C and O isotopes in carbonates from eolian dust profiles to explore the evolutions of paleotemperature, paleoprecipitation and the East Asian summer monsoon (Han *et al.*, 1997; Ding and Yang, 2000; Rao *et al.*, 2006; Li *et al.*, 2007). However, only a few pioneers studied chemical weathering associated with the East Asian summer monsoon in the Chinese Loess Pla-

teau using the method of strontium isotope tracing. For example, Chen *et al.* (1997) concluded that chemical weathering was an important influence on $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of secondary carbonates in eolian deposits. Liu *et al.* (1999) showed that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonates in the Luochuan profile reflected chemical weathering and paleoclimate change. Yang *et al.* (2000) suggested calcite Sr isotopic ratio was a good proxy of chemical weathering indicating the summer monsoon through the investigation of the high-resolution Sr isotopic record in the Luochuan $S_0-L_1-S_1$ sequence. These studies mainly focused on the upper sections of the Quaternary eolian dust profiles. However, strontium isotopic compositions of carbonates and related paleoclimate change in the lower part of the Quaternary eolian dust profiles and the Tertiary red clay are poorly understood. One should note also that the methods of sample preparation for Sr measurements are variable in different investigations. Liu *et al.* (1999) extracted carbonates from eolian deposits with 0.8M HCl solution. However, the 0.8M HCl solution can also partially dissolve silicates (Yang *et al.*, 2000), thus strontium isotopic ratios of carbonates dissolved by this media were probably biased by dissolution of silicate minerals. Chen *et al.* (1997) and Yang *et al.* (2000) used 0.5M HOAc to dissolve carbonates in the eolian dust profiles. Their experiments showed that the 0.5M HOAc solution only dissolved calcite but did not destroy dolomite and silicates. As secondary calcites are dominant carbonates in eolian deposits of the Chinese Loess Plateau, the 0.5M HOAc solution is a very good chemical media in secondary carbonate extraction from eolian deposits.

In this paper, we investigate strontium isotopic characteristics and calcium and strontium contents of calcites in the Lingtai loess-paleosol-red clay sequence of the Chinese Loess Plateau during the past 7 Ma, and attempt to establish a new and reliable long-term proxy of chemical weathering associated with the East Asian summer monsoon in the late Cenozoic.

SAMPLES AND METHODS

Eolian deposits in the Chinese Loess Plateau cover about 440,000 km², accounting for 72.4% of the total area of eolian deposits throughout China. Loess materials gradually decrease in grain size southeastwards in the Chinese Loess Plateau with three zones of sandy loess, loess and clayey loess (Liu, 1985). The standard eolian deposit consists of the Holocene loess, the late Pleistocene Malan loess, the middle Pleistocene Lishi loess, the early Pleistocene Wucheng loess, and the Tertiary red clay, usually >100 m thick (Liu, 1985).

The Lingtai profile (35°04' N, 107°33' E), located in Renjiapo village 13 km south of Lingtai county, Gansu province (Fig. 1), is a typical loess-paleosol-red clay se-

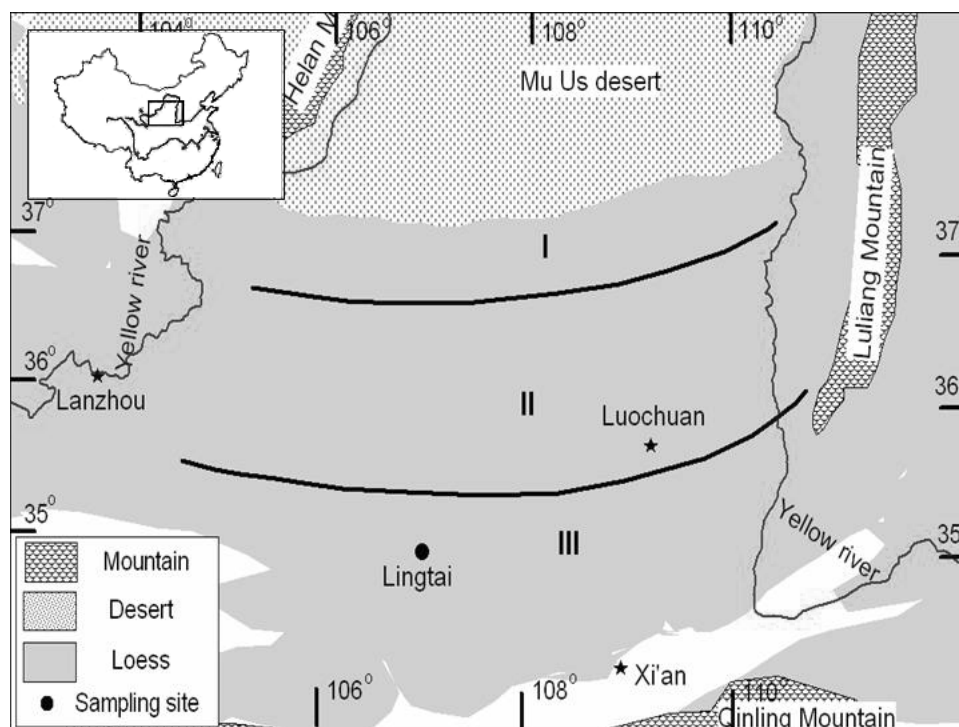


Fig. 1. Location of the Lingtai eolian dust profile. Note: Zone I, Sandy loess; Zone II, Typical loess; Zone III, Clayey loess.

quence in the Chinese Loess Plateau (Ding *et al.*, 1999). The Quaternary loess-paleosol sequence is about 175 m thick and the underlying Tertiary red clay is about 130 m thick. The Tertiary red clay accumulated on the Mesozoic sandrocks from about 7 Ma B.P. to 2.6 Ma B.P. (Ding *et al.*, 1999). The Tertiary red clay is obviously redder than the Quaternary loess and paleosol. There are also plenty well-developed calcic nodule horizons but few unaltered layers like the loess in the Tertiary red clay. The Tertiary red clay experienced different extent of weathering-pedogenesis. Overall, its weathering-pedogenesis is generally stronger than that of the Quaternary paleosol. Pedostratigraphy, magnetic susceptibility, grain size, mineralogy, and geochemistry of the Lingtai profile have been investigated in detail (Ding *et al.*, 1999, 2001a; Gylesjö and Arnold, 2006; Gu *et al.*, 1999; Sun and An, 2002). Previous data are helpful for this study. At present, annual mean temperature and rainfall are 9.1°C and 600 mm respectively at Lingtai (Ding *et al.*, 2001a).

A typical sample was taken from each layer from L₁ to L₃₃ in the Lingtai profile. In addition, 9 samples were collected from the Tertiary red clay of this profile. All the samples were gently crushed by a hammer and ground in an agate mortar to a size-fraction of <80 mesh. 1 gram of each sample was added to a Teflon container and treated with 40 ml 0.5M acetic acid solution at room temperature for 8 hours. Then, its leachate was obtained by using a quantitative filter for Sr isotopic analysis and

compositional measurements of Ca and Sr. Sr was separated by standard ion-exchange techniques, and its isotopic ratio was measured on a VG354 Mass Spectrometer at the Center of Modern Analysis, Nanjing University. The Sr isotopic ratio was normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. The reproducibility and accuracy of Sr isotopic runs were routinely checked by running Standard Reference Material NIST 987. The $^{87}\text{Sr}/^{86}\text{Sr}$ for the NIST 987 was 0.710287 ± 0.000012 (2σ , $n = 15$) during this experiment. The analytical blank was 1 ng and negligible for the determination of Sr isotopic compositions. Ca and Sr contents were determined by Atomic Absorption Spectrometry with a relative uncertainty of 2%. In addition, magnetic susceptibility of the Lingtai profile was determined by using the BartingtonMS2 in Institute of Earth Environment, CAS, China.

RESULTS AND DISCUSSION

Sr isotopic ratios and Ca, Sr contents in calcites

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and Ca and Sr contents in calcites of the Lingtai eolian dust profile are listed in Table 1 and are plotted in Fig. 2. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in calcites range from 0.710433 to 0.711369 with an average of 0.71099 for the Quaternary loess, a range of 0.710968 to 0.711683 with a mean of 0.711313 for the Quaternary paleosols, and a range of 0.711377 to 0.711668 with an average of 0.711517 for the Tertiary red clay. In the Lingtai eolian

Table 1. Sr isotopic ratios, calcium and strontium contents of calcites in the Lingtai eolian dust profile during in the 7 Ma

Lingtai	Depth (m)	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr^{2+} (ppm)	Ca^{2+} (ppm)	Lingtai	Depth (m)	$^{87}\text{Sr}/^{86}\text{Sr}$	Sr^{2+} (ppm)	Ca^{2+} (ppm)
L01	5.2	0.711011 ± 14	37.7	34087	S19	103.6	0.711333 ± 18	11.5	4193
S01	12.6	0.711495 ± 10	8.1	2909	L20	104.4	0.710986 ± 17	42.9	54227
L02	15.9	0.710496 ± 11	34.7	30593	S20	105.8	0.711312 ± 18	15.0	7689
S02	21.1	0.711099 ± 19	13.6	2411	L21	106.4	0.710772 ± 18	40.2	45209
L03	25.3	0.710481 ± 15	36.3	32318	S21	108.6	0.711338 ± 7	7.6	2112
S03	26.6	0.711161 ± 18	15.3	2234	L22	109.4	0.711369 ± 12	21.3	19804
L04	30.4	0.711013 ± 18	22.3	23339	S22	110.6	0.711406 ± 14	10.4	4176
S04	33.5	0.711295 ± 13	14.4	1221	L23	112.6	0.711194 ± 11	25.2	29054
L05	35.3	0.711241 ± 10	13.5	1897	S23	113.2	0.711471 ± 13	23.8	32340
S05	40.4	0.711683 ± 14	10.3	1826	L24	118.6	0.710958 ± 18	47.9	21383
L06	47.6	0.711017 ± 11	8.5	2107	S24	120.0	0.711214 ± 19	15.9	6051
S06	50.6	0.711584 ± 18	8.7	1886	L25	122.2	0.711056 ± 15	20.6	14866
L07	53.8	0.710997 ± 19	19.2	16336	S25	126.0	0.711312 ± 7	15.9	7296
S07	55.2	0.711426 ± 13	9.5	2350	L26	129.0	0.711148 ± 17	34.9	27735
L08	57.4	0.711330 ± 14	12.3	2021	S26	131.6	0.711269 ± 12	14.8	7309
S08	59.1	0.711413 ± 12	12.2	1796	L27	134.8	0.710860 ± 13	27.0	18825
L09	66.1	0.710744 ± 16	34.0	52636	S27	140.6	0.711145 ± 20	15.4	8273
S09	68.3	0.711282 ± 16	12.2	1442	L28	141.8	0.711233 ± 13	40.2	44345
L10	71.5	0.710757 ± 17	20.2	17600	S28	142.2	0.711136 ± 13	36.9	58346
S10	72.9	0.710968 ± 10	13.3	2710	L29	144.2	0.710777 ± 14	41.6	15423
L11	74.2	0.711292 ± 19	11.3	2109	S29	145.2	0.711277 ± 18	15.9	5830
S11	75.6	0.711356 ± 16	10.9	1665	L30	146.4	0.711267 ± 21	21.6	11199
L12	76.8	0.711272 ± 8	10.8	2096	S30	147.4	0.711276 ± 15	18.1	7117
S12	77.6	0.711282 ± 11	12.1	1202	L31	149	0.711234 ± 13	28.9	33328
L13	79.0	0.710843 ± 12	26.4	18079	S31	151.2	0.711422 ± 16	22.3	15902
S13	81.4	0.711437 ± 19	11.9	2015	L32	155.4	0.710979 ± 16	37.2	24950
L14	82.8	0.711317 ± 14	16.6	3645	S32	162	0.711375 ± 9	19.8	8904
S14	84.0	0.711380 ± 14	11.8	2285	L33	165.6	0.711031 ± 17	43.4	34446
L15	87.5	0.710433 ± 12	59.2	35174	RC-1	209	0.711668 ± 17	45.7	43672
S15	90.6	0.711172 ± 15	14.7	2761	RC-2	212	0.711575 ± 17	43.3	68870
L16	92.2	0.710634 ± 18	48.7	89971	RC-3	221.4	0.711497 ± 20	27.7	8770
S16	96.0	0.711317 ± 16	27.5	18491	RC-4	234	0.711552 ± 19	32.8	9913
L17	97.6	0.711203 ± 13	33.4	29102	RC-5	246.8	0.711412 ± 15	38.2	26665
S17	98.6	0.711223 ± 14	18.9	7558	RC-6	254	0.711377 ± 16	27.7	7200
L18	99.8	0.710900 ± 15	37.2	37675	RC-7	267.6	0.711413 ± 12	41.8	33347
S18	100.8	0.711143 ± 16	19.5	8827	RC-8	279.6	0.711526 ± 8	62.1	47701
L19	102.2	0.710831 ± 10	40.7	37205	RC-9	282.8	0.711633 ± 11	88.7	99845

Note: L, the Quaternary loess; S, the Quaternary paleosol; RC, the Tertiary red clay.

dust profile, variations in the Sr isotopic ratios of calcites have several significant features as follows. 1) The majority of the Quaternary loess layers have lower Sr isotopic ratios than the interstratified paleosols, except for some loess layers e.g., L₂₂ and L₂₈. 2) There are three stages of strontium isotopic variations of calcites in the Quaternary profile at Lingtai. Firstly, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios fluctuate with a relatively small amplitude between L₃₃ and S₁₅. Secondly, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios display slightly wide fluctuations and gradually increase from L₁₅ to L₆. Finally, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios gradually decrease with large-amplitude oscillations from S₅ to L₁. 3) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are relatively constant in the Tertiary red clay and generally higher than those in the Quaternary loess and paleosols. Only a few Quaternary paleosols such as S₁, S₅ have the Sr isotopic ratios close to those in the Tertiary red clay.

Ca contents in calcites range from 1897 to 89971 ppm with a mean of 26145 ppm for the Quaternary loess, from 1202 ppm to 58346 ppm with a mean of 7535 ppm for the Quaternary paleosols, and from 7200 ppm to 99845 ppm with a mean of 38442 ppm for the Tertiary red clay. Sr contents in calcites range from 8.5 to 59.2 ppm with a mean of 30 ppm for the Quaternary loess, from 7.6 ppm to 36.9 ppm with a mean of 15.3 ppm for the Quaternary paleosols, and from 27.7 ppm to 88.7 ppm with a mean of 45 ppm for the Tertiary red clay. Ca contents are directly related to calcite contents in eolian deposits. Calcite contents can be calculated through calcium contents (Fig. 2). Calcite contents vary from 0.3% to 25% in the Lingtai profile. Calcite contents correlate with carbonate contents measured by Sun and An (2002) in the Lingtai profile and are broadly similar to calcite contents in the

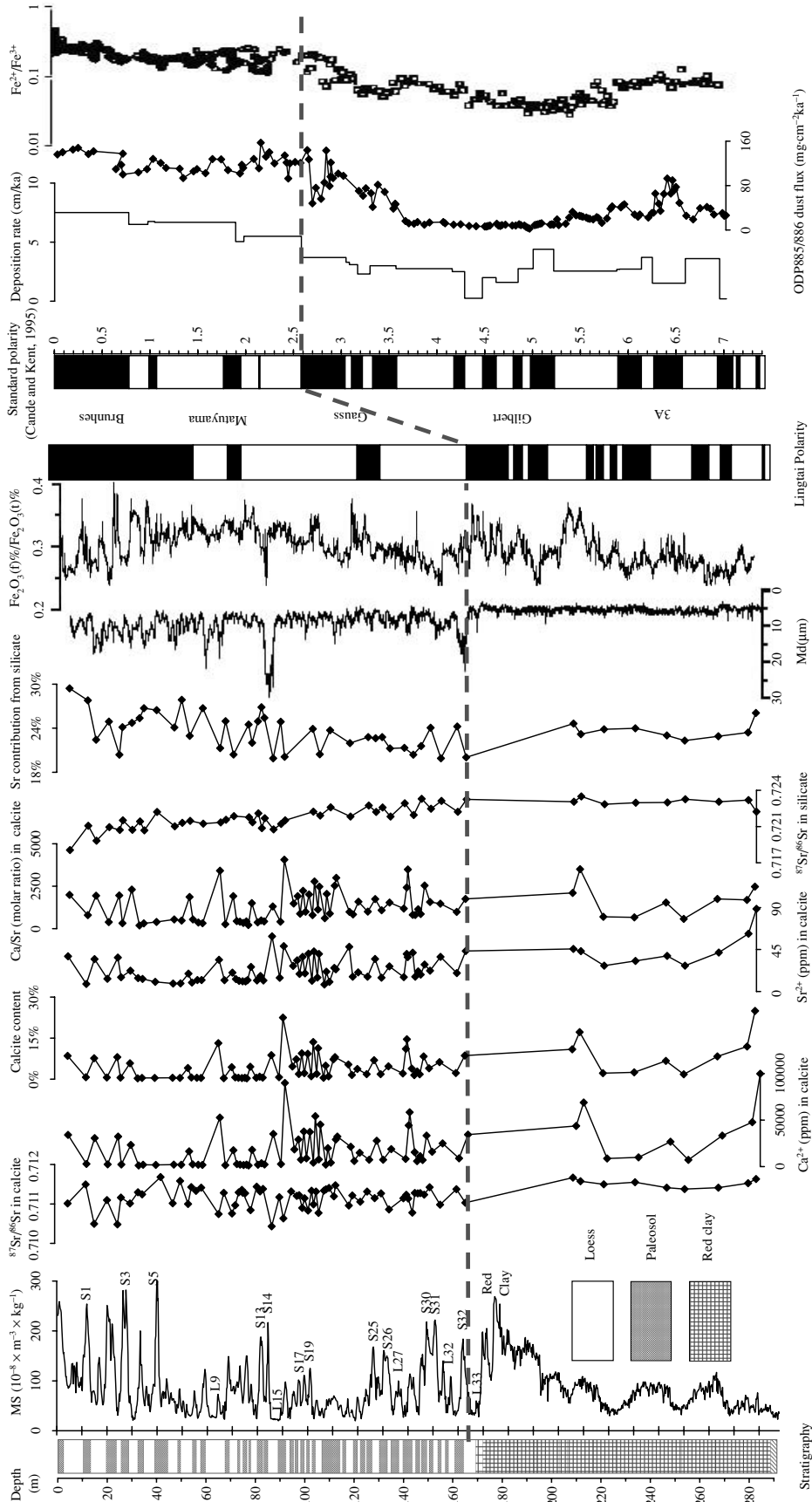


Fig. 2. Variations in Sr isotope ratios, Ca and Sr contents, Ca/Sr molar ratios of calcites, calcite contents, Sr contribution from silicate weathering, magnetic susceptibility, grain size ($Fe_2O_3(f)/Fe_2O_3(t)$ ratios (Ding et al., 2001a), $Fe_2O_3(f)/Fe_2O_3(t)$ ratios (Ding et al., 2001a), depositional rate (Sun and An, 2002) and Fe^{2+}/Fe^{3+} (Gu et al., 1999) in the Lingtai profile, and dust flux in ODP885/886 (Rea et al., 1998) during the late Cenozoic.

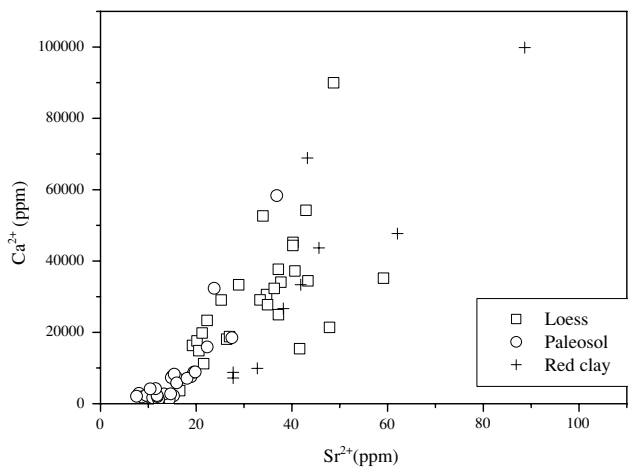


Fig. 3. Correlation between calcium and strontium in calcite.

Chaona profile at Lingtai measured by Chen *et al.* (2007). Calcite and Ca, Sr contents in this study change with several typical features in the Lingtai profile. Firstly, Calcite and Ca, Sr contents are usually lower in paleosols than in the loess and the red clay (Figs. 2 and 3), except a few paleosols such as S₂₃ and S₂₈. Secondly, they have an oscillatory increase in content from the top to the bottom of the eolian dust profile (Fig. 2). Thirdly, Ca content changes similar to Sr content in the profile, and both have a good correlation with the correlation coefficient r of 0.91 (Fig. 3); Sr can thus be an effective indicator tracing Ca.

Geochemical significance of Ca and Sr in calcites

The Quaternary loess and paleosols, and the Tertiary red clay in the Chinese Loess Plateau are of eolian origin (Guo *et al.*, 2001, 2004; Ding *et al.*, 1998), originating from the desert and Gobi areas of the northwestern China (Liu, 1985; Rao *et al.*, 2006). Figure 4 is a sketch map of the eolian material cycle in the northwestern China. Wind-blown primary carbonates and silicates accumulated in the Chinese Loess Plateau. After precipitation, primary carbonate chemically reacted with HCO_3^- from rainfall, and was finally dissolved as soluble $\text{Ca}(\text{HCO}_3)_2$ species in the soil solution. In the mean time, some primary silicates perhaps released a small amount of Ca^{2+} and Sr^{2+} into the soil solution after they experienced the process of hydrolyzation or reacted with HCO_3^- and organic acids released by plants. Ca^{2+} (Sr^{2+}) and HCO_3^- were partly leached out or moved down in the soil. Secondary carbonates were formed when ion concentrations changed from the unsaturated state to the saturated state with decreasing of water content or increasing alkalinity in soil solution. In general, strontium substitutes isomorphously for calcium in the structures of secondary carbonates due

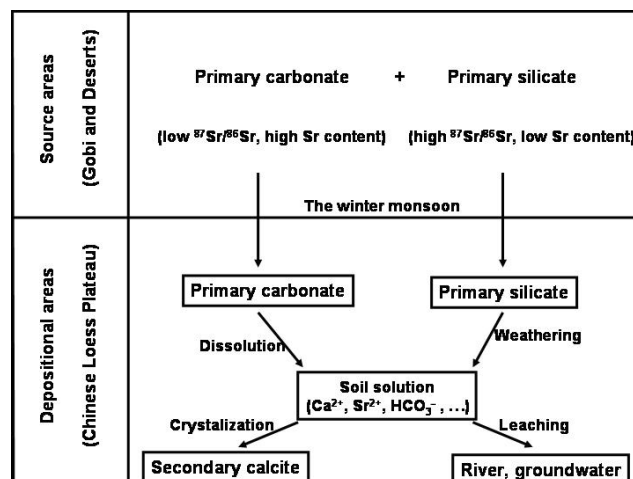


Fig. 4. Cycle of eolian materials in Northwest China.

to the similar ionic radius of strontium and calcium. During the surficial cycle of carbonates (Fig. 4), the contents of residual carbonates were related to the local rainfall in the eolian dust profile. In other words, the leaching intensity of carbonates, actually reflecting the local rainfall in the history of eolian deposits, is thus usually used to indicate the summer monsoon variation (Liu, 1985; Wen, 1989; Sun and Zhao, 1991).

Variations of Ca contents in calcites, which are consistent with those of carbonate and calcite contents measured by Sun and An (2002) and Chen *et al.* (2007), are inversely correlated to magnetic susceptibility and pedogenic intensities by field observations in the Quaternary loess-paleosol sequence (Ding *et al.*, 2001a). Ca contents in calcites actually mirror secondary calcite contents in the eolian dust profile and are thus a good proxy for the Quaternary summer monsoon. Sr also has the same function as Ca in calcite because of a good correlation between Sr and Ca. It is worth noting that calcite (or Ca) contents are low in the Quaternary paleosols and high in the Quaternary loess. It is very likely that most primary carbonates in the Quaternary paleosols were leached to form calcic nodules in the bottom of the Quaternary paleosols under warm and humid climates. However, few calcites were seldom *in situ* products after primary carbonate dissolution in the Quaternary loess under cold and dry climates. Consequently, variations of calcite (or Ca) contents in the Quaternary loess-paleosol sequence merely indicate large-scale climate changes such as glacial and interglacial climates.

Compared with the Quaternary loess and paleosols, the Tertiary red clay contains much more calcites, calcium and strontium. This phenomenon is universal in the Chinese Loess Plateau. Chen *et al.* (2007) suggested that a large number of calcites existing in the Tertiary red clay

of the Chaona profile at Lingtai were due to the little rainfall and the weak summer monsoon at that period. However, the interpretation does not agree with field observations that there was a high degree of pedogenetic development, abundant Fe–Mn films and calcic nodules in the Tertiary red clay (Chen *et al.*, 2007). Other authors considered that there was a sign of groundwater activity in the bottom of the Tertiary red clay in the Chinese Loess Plateau (Guo *et al.*, 2001). However, they did not provide sufficient evidence to interpret how much the groundwater impacted carbonates at the bottom of the Tertiary red clay. We conclude that high contents of carbonates in the Tertiary red clay were mainly a result of primary carbonate redistribution by strong chemical weathering. There are several reasons as follows: 1) In general, carbonates are mainly in the fine fractions of eolian deposits (Wang *et al.*, 2005), and the Tertiary red clay is much finer in grain size than the Quaternary loess and paleosols (Fig. 2). Thus, the Tertiary red clay should have higher abundant primary carbonates from source areas than the Quaternary loess and paleosols when they were accumulated in the Chinese Loess Plateau. 2) Ca/Sr molar ratio is usually high in the primary carbonate and low in the primary silicate (Capo *et al.*, 1998; Liu, 2002; Banner, 2004). Variations in Ca/Sr molar ratios mainly indicate relative contributions to secondary calcites from primary carbonate leaching and silicate weathering in eolian deposits (Fig. 2). Carbonates were dissolved but few leached and silicate weathering was weak, thus there were high Ca/Sr molar ratios in the Quaternary loess during the glacial periods with cold and dry climates. However, carbonates were mostly leached and silicate weathering was relatively strong, thus there were low Ca/Sr molar ratios in the Quaternary paleosols during the interglacial periods with humid and warm climates. Ca/Sr molar ratios and contents of calcites have similar variations in the Quaternary loess-paleosol sequence although the mechanisms of their variations are different (Figs. 2 and 5). Our data show that calcite contents and Ca/Sr molar ratios in the Tertiary red clay are close to those in the Quaternary loess but higher than those in the Quaternary paleosols and further imply that the leaching percentage of carbonates and relative contributions of silicate weathering to secondary calcites are perhaps very small in the Tertiary red clay (Fig. 5). Nevertheless, our data cannot reveal that chemical weathering of the Tertiary red clay was weaker than that of the Quaternary paleosols because weathering-pedogenesis of the Tertiary red clay was in fact stronger than that of the Quaternary paleosol through detailed field investigations of the Lingtai profile (Ding *et al.*, 1999). 3) There were cold-dry and warm-humid climate cycles during the Tertiary red clay development as well as during the formation of the Quaternary loess-paleosol sequence. Nevertheless, differences between

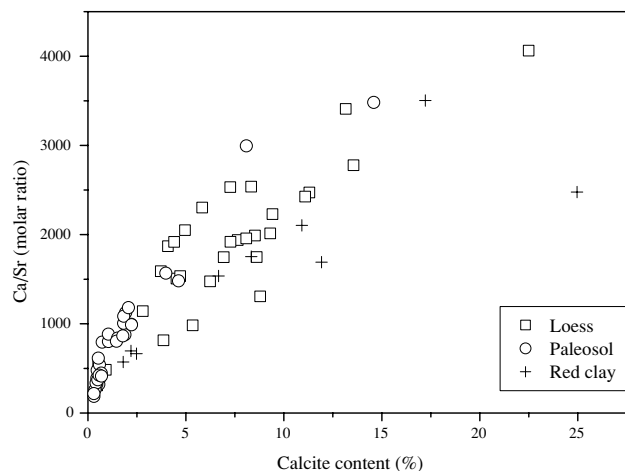


Fig. 5. Plot of Ca/Sr molar ratios in calcites vs. calcite contents.

cold-dry and warm-humid climates during the Tertiary red clay developments were smaller than during the formations of the Quaternary eolian deposits. Under a relatively dry-cold climate of the Tertiary, secondary carbonates occurred in different positions of a sub-layer of the Tertiary red clay after primary carbonate dissolution due to little rainfall. Subsequently, the interstratified sub-layer was developed under a relatively humid-warm climate of the Tertiary. Carbonates were mostly transported to form calcic nodules or cementations in the bottom of the interstratified sub-layer or within the underlying sub-layer after primary carbonate dissolution with sufficient rainfall. However, dissolved carbonates were not transported down long distances in the Tertiary red clay because clay minerals are main silicate minerals of the Tertiary red clay (Gylesjö and Arnold, 2006) and are relatively waterproof. 4) Sedimentation rate of eolian dust was lower during the Tertiary red clay development than during the Quaternary loess or paleosol formations (Fig. 2), thus sedimentation thickness of eolian dust was thinner for the Tertiary red clay than for the Quaternary loess and paleosols in the same interval. Multi-cycles of eolian depositions ultimately evolved into the present relief sceneries of the Tertiary red clay under the process of post-geologic compression and concretion (Ding *et al.*, 1999).

Thus, high contents of calcites in Tertiary red clay are not suitable to characterize the Tertiary climates.

Influences on strontium isotopic variations of calcites

Strontium in calcites of eolian deposits mainly came from primary carbonate dissolution and primary silicate weathering (Fig. 4). Thus, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites in the Chinese Loess Plateau were mainly influenced by two factors. The first are the source rocks of eolian deposits

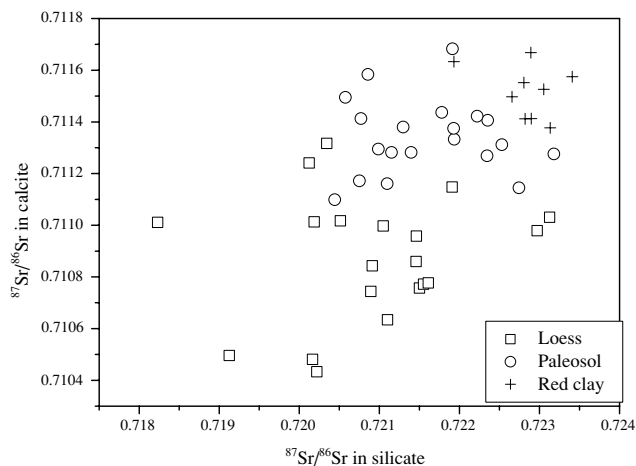


Fig. 6. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ in calcite vs. $^{87}\text{Sr}/^{86}\text{Sr}$ in silicate.

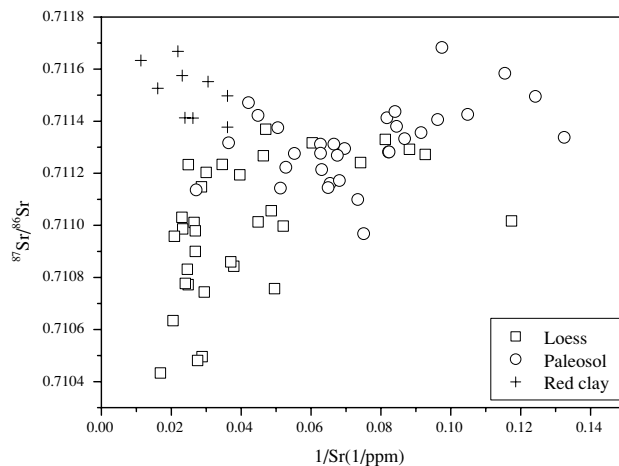


Fig. 7. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ in calcites.

and the second is chemical weathering in the Chinese Loess Plateau.

Source rocks of eolian deposits might be considered to consist of primary carbonate and silicate from the northwestern areas of China. Marine carbonate strata of various periods are widespread in Northwest China and have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7068 to 0.7092 (Palmer and Elderfield, 1985; Capo and DePaolo, 1990; Banner, 2004), which are lower than $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in calcites of the Lingtai profile. Primary carbonates accumulated in the Chinese Loess Plateau originated from marine strata in the northwestern areas, thus have low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with high Sr contents. Primary silicates accumulated in the Chinese Loess Plateau include feldspars (mainly albite, anorthite, and K-feldspar) and clay minerals (Liu, 1985). Illite dominates the clay minerals, whereas vermiculite, kaolinite, smectite and mica are minor. Minerals (anorthite, K-feldspar, illite, vermiculite, smectite and mica) contain strontium due to isomorphous substitution of Sr for Ca and radiogenic ^{87}Sr by the decay of ^{87}Rb substituting for K (Capo *et al.*, 1998). Primary silicates of eolian deposits commonly have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios with low Sr contents (Nakai *et al.*, 1993; Asahara *et al.*, 1995; Yang *et al.*, 2001; Svensson, 2002; Yokoo *et al.*, 2004). In fact, primary carbonate with high Sr content and low Sr isotopic ratio, and primary silicate with low Sr content and high Sr isotopic ratio are two endmembers controlling the range of the Sr isotopic ratios of calcites in eolian deposits.

Wang *et al.* (2007) reported that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of silicates vary from 0.7182 to 0.7234 in the Lingtai profile, which are higher than those of calcites in this study. We suggest that their Sr isotope data can represent Sr isotopic compositions of primary silicates in the Lingtai profile. There are two reasons as follows: 1) In general, there was distinct strontium isotopic composition of the sili-

cate rock between after and before chemical weathering due to differential weathering of minerals (Bullen *et al.*, 1997). However, chemical weathering of the Chinese Loess Plateau was so weak that it only leached soluble elements such as Ca and Na (Chen *et al.*, 1997, 2001). Mineralogical studies also showed clay minerals of the Quaternary were of clastic origin in the Chinese Loess Plateau (Ji *et al.*, 1999; Gylesjö and Arnold, 2006; Kalm *et al.*, 1996). Only tiny silicates were chemically weathered in paleosol S₅ which had the highest pedogenic intensity among the Quaternary paleosols (Han *et al.*, 1998). In addition, it was observed through the electronic microscope that a very tiny authigenic mineral—attapulgitite occurred only in the Tertiary red clay (Xie *et al.*, 2005). So, chemical weathering of very tiny silicates did not clearly alter Sr isotopic compositions of silicates in eolian deposits. 2) Wang *et al.* (2007) extracted silicate fractions of eolian deposits by using 0.5M acetic acid solution. 0.5M acetic acid solution only dissolves calcite but does not destroy clastic minerals such as dolomite and silicate in eolian deposits (Yang *et al.*, 2000). Nevertheless, dolomite contents are very low in eolian deposits (Liu, 1985; Wen, 1989). Thus, silicate fractions (0.5M acetic acid-insoluble materials) in Wang *et al.* (2007) basically represent primary silicates accumulated in the Chinese Loess Plateau from source areas.

It is especially worth noticing that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of silicates (Wang *et al.*, 2007) correlate with those of calcites in the Lingtai profile (Fig. 6). Strontium isotopic variations of silicates seemed to be an important influence on strontium isotopic variations of calcites.

Sr containing silicate minerals are mainly feldspars in the Quaternary loess with coarse grain sizes, feldspars and clay minerals in the Quaternary paleosols with finer grain sizes, and clay minerals in the Tertiary red clay with the finest grain sizes (Liu, 1985; Gylesjö and Arnold,

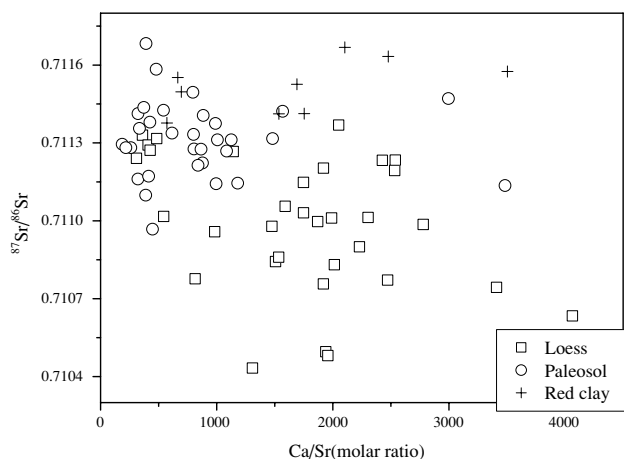


Fig. 8. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Ca/Sr in calcites.

2006; Ding *et al.*, 2001a). Moreover, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of silicates are the highest in the Tertiary red clay, the second in the Quaternary paleosols, and the lowest in the Quaternary loess (Wang *et al.*, 2007). It is thus inferred that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of eolian clay minerals are higher than those of eolian feldspars, which is also supported by previous results (Rao *et al.*, 2006). Chemical weathering of the Quaternary loess was evidently too weak to leach carbonates and destroy feldspars under cold and dry climates in glacial periods. Thus, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites were low due to much Sr from primary carbonates and little Sr from silicates in the soil solution of the Quaternary loess (Figs. 2, 7 and 8). In general, feldspars are more prone to chemical weathering than clay minerals in surface processes. If the Quaternary paleosol experienced the same weak chemical weathering as the Quaternary loess, feldspars could not be eroded, and clay minerals with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could be completely unaltered in the Quaternary paleosol. Furthermore there could be more carbonates in the Quaternary paleosol than in the loess because of more primary carbonates in finer eolian dust when it accumulated in the Chinese Loess Plateau. Thus, there should be lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites in the Quaternary paleosol than in the Quaternary loess, but higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of silicates in the Quaternary paleosol. In fact, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites were obviously higher, and calcite contents and Ca/Sr ratios were lower in the Quaternary paleosol than in the Quaternary loess (Figs. 2, 7 and 8). Therefore, chemical weathering was stronger in the Quaternary paleosol than in the Quaternary loess, which agrees with climatic and pedogenetic characteristics of the Quaternary paleosol development (Liu, 1985; Ding *et al.*, 1999, 2001a).

By analogy, clay minerals could be unaltered even if carbonates were subject to multiple alternations of disso-

lution and crystallization in the Tertiary red clay if the Tertiary red clay suffered from the same weak chemical weathering as the Quaternary loess. Thus, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites in the Tertiary red clay should be as low as in the Quaternary. In fact, there were overall higher Sr isotopic ratios of calcites in the Tertiary red clay compared with the Quaternary loess and paleosol (Figs. 2, 7 and 8). Therefore, clay minerals were undoubtedly eroded to release a little Sr with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios by strong chemical weathering in the Tertiary red clay. Previous studies showed that authigenic attapulgite occurred in minor quantities in the Tertiary red clay but not in the Quaternary eolian deposit, though trivial plagioclases were chemically eroded in the Quaternary eolian deposits (Liu *et al.*, 2002; Xie *et al.*, 2005), and also demonstrated that chemical weathering of the Tertiary red clay was stronger than that of the Quaternary loess and paleosol. High calcite contents and Ca/Sr molar ratios in the Tertiary red clay indicated the low leaching percentage of carbonates and relatively few Sr contributions of primary silicates to secondary calcites, but high Sr isotopic ratios of Sr released from clay minerals could result in overall higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites in the Tertiary red clay than in the Quaternary loess and paleosol (Figs. 7 and 8), which implies isotopic compositions are more sensitive to climatic and environmental changes than element contents and elemental ratios.

If post-geologic compression-concretion and carbonate leaching from the overlying sub-layer are not considered, the relief scenery of the single sub-layer of the Tertiary red clay would be roughly similar to that of the single soil layer of the Quaternary (e.g., S_1) (Liu, 1985). That is to say, abundant carbonates should occur in the bottom but sparsely in the upper or middle of the single sub-layer of the Tertiary red clay. Thus, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of calcites within the assumed sub-layer should be higher than those of the single sub-layer that experienced the effect of carbonate leaching from the overlying sub-layer and the post-geologic compression-concretion. This conclusion suggested that silicate weathering in the Tertiary red clay was in fact stronger than that indicated by isotopic data measured in this study.

In a word, strontium isotopic variations of silicates were not a predominant inducement of strontium isotopic variations of calcites. However, chemical weathering was really an inner driver for strontium isotopic variations of calcites in the Lingtai profile since 7 Ma B.P. The Sr isotopic ratios of calcites are thus undoubtedly an effective tool to measure the chemical weathering intensity of the Chinese Loess Plateau.

Quantifying Sr contribution of eolian silicate weathering to calcite

Mineralogical and geochemical studies showed that

chemical weathering was very weak, so that it only resulted in carbonate dissolution without appreciably altering silicate minerals in the Chinese Loess Plateau (Chen *et al.*, 1998; Han *et al.*, 1998; Ji *et al.*, 1999; Kalm *et al.*, 1996; Liu *et al.*, 2002; Xie *et al.*, 2005). However, chemical weathering of the Chinese Loess Plateau has not been quantified using Sr isotope methodologies.

Primary carbonate and silicate from source areas are two endmembers of strontium isotopic variations of calcites in the Lingtai profile. Relative Sr contributions of two endmembers to calcites changed with the intensity of weathering-pedogenesis in the Chinese Loess Plateau. Here, Sr contributions of silicate weathering to calcites in the Lingtai profile during the last 7 Ma were calculated by using the mass balance equation of Sr isotope. The equation was $^{87}\text{Sr}/^{86}\text{Sr}_{\text{CA}} = X \cdot ^{87}\text{Sr}/^{86}\text{Sr}_{\text{SI}} + (1 - X) \cdot ^{87}\text{Sr}/^{86}\text{Sr}_{\text{MC}}$, where X was relative content, SI was silicate, CA was calcite of eolian deposits, and MC was marine carbonate. The Sr isotopic data of Wang *et al.* (2007) can represent those of the high endmember (namely, eolian silicates) for strontium isotopic variations of calcites in the Lingtai profile according to the detailed analyses in Subsection "Influences on strontium isotopic variations of calcites". The low endmember was marine carbonate. Its $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.708 (the mean Sr isotopic ratio of Phanerozoic seawater) was assumed to be basically constant in the past 7 Ma (Faure and Hurlly, 1965). Therefore, as shown in Fig. 2, less than 30% Sr in calcites came from eolian silicate weathering in the Quaternary loess-paleosol sequence and the Tertiary red clay during the past 7 Ma in term of the mass balance equation.

The Sr isotopic ratios of calcites—a good proxy for the East Asian summer monsoon in the late Cenozoic

The intensity of weathering-pedogenesis mainly depended on the summer temperature and rainfall in the Chinese Loess Plateau. The most prominent characteristic of the East Asian summer monsoon was that the related climate was both humid and warm in the same season. Thus, the intensity of weathering-pedogenesis in the Chinese Loess Plateau was closely associated with the East Asian summer monsoon.

Being synchronized with the variation of magnetic susceptibility, the Sr isotopic ratios of calcites decreased with wide fluctuations from S_5 to L_1 of the Lingtai profile as well as the Luochuan profile (Rao *et al.*, 2006). Temporal strontium isotopic variations of calcites corresponded to the climatic evolution of the central Loess Plateau (Cheng and Xie, 1993), indicating a clear decrease in the East Asian summer monsoon since 0.5 Ma B.P.

Magnetic susceptibility of the Quaternary profile below S_5 at Lingtai shows two secondary small-amplitude oscillations: one in the lower Lishi Loess ($L_{15} \rightarrow L_6$) and the other in the Wucheng Loess ($L_{33} \rightarrow S_{15}$). In both the

oscillations, magnetic susceptibility oscillates with the decreasing amplitude and gradually decreases towards the respective values of the lower Lishi Loess and the Wucheng Loess (Fig. 2). The paleosols below S_5 are closely spaced except for some thick intervening loess layers, such as L_9 , L_{15} , L_{24} , L_{27} , and L_{32} . The Sr isotopic ratios of calcites are low in the thick loess layers and are uniform in soils between the thick loess layers. Like the two oscillations seen in magnetic susceptibility, the Sr isotopic ratios of calcites also have two secondary fluctuations in the Quaternary profile below S_5 : one in the lower Lishi Loess ($L_{15} \rightarrow L_6$), the other in the Wucheng Loess ($L_{33} \rightarrow S_{15}$). However, strontium isotopic variations do not mirror changes in magnetic susceptibility in the two units. The values of magnetic susceptibility of the paleosols between S_5 and L_9 are very low, despite the high degree of pedogenetic development of the paleosols (Ding *et al.*, 1999). However, the Sr isotopic ratios of calcites are consistently high in this part (Fig. 2), thus being in concordance with soil micromorphological observations (Ding *et al.*, 1999). The Sr isotopic ratios of calcites in the paleosols between L_{27} and L_{32} , however, do not show high values, which is inconsistent with both the susceptibility record and soil micromorphological observations. Ding *et al.* (2001a) discovered the same phenomenon when they explored the Fe_2O_3 ratio record of the Lingtai profile. At present, the cause for this is unknown (Ding *et al.*, 2001a). Nevertheless, being roughly similar to magnetic susceptibility, the Sr isotopic ratios of calcites in the Quaternary profile change in correspondence to loess-paleosol alternations, which is generally high in paleosols and low in the loess (Table 1, Fig. 2).

Compared with the Quaternary loess and paleosols, the Tertiary red clay is overall smaller in grain size (Fig. 2) and redder in color than the Quaternary paleosols. In addition, clay coatings and Fe–Mn films were well developed, and the loess layers similar to the Quaternary loess were seldom observed in the Tertiary red clay (Ding *et al.*, 1999, 2001a). In short, the intensity of weathering-pedogenesis of the Tertiary red clay was not lower than that of the Quaternary paleosols, indirectly implying the relatively weak winter monsoon during the Tertiary in the Chinese Loess Plateau. However, the magnetic susceptibility record in the Tertiary red clay shows markedly low values except for the uppermost part, which is inconsistent with the soil characteristic of the Tertiary red clay (Ding *et al.*, 1999). The Sr isotopic ratios of calcites in the Tertiary red clay vary uniformly and are close to those of a few Quaternary paleosols, but are obviously higher than those of the loess and other paleosols of the Quaternary. Sr isotopic characteristics are consistent with variations of pedogenic intensities, which further demonstrates that the intensity of weathering-pedogenesis was

overall higher in the Tertiary red clay than in the Quaternary and also implies that a few Quaternary paleosols were perhaps subject to similar pedogenic intensities to the Tertiary red clay.

Ding *et al.* (1999, 2001a) interpreted the cause of low magnetic susceptibility in the Tertiary red clay on the basis of detailed investigations on pedostratigraphy and geochemistry of the Lingtai profile, and then pointed out that magnetic susceptibility was not reliable in registering the summer monsoon variations of the red clay record, and further put forward a good proxy indicating the East Asian summer monsoon evolution in the late Cenozoic— $\text{Fe}_2\text{O}_3(f)/\text{Fe}_2\text{O}_3(t)$ (Ding *et al.*, 1999; 2001a). The Sr isotopic features are roughly similar to the Fe_2O_3 ratio record in the Lingtai profile after 7 Ma B.P. (Fig. 2). However, the $\text{Fe}_2\text{O}_3(f)/\text{Fe}_2\text{O}_3(t)$ values are very variable, although they are not low in the Tertiary red clay, which is different from small variations of the Sr isotopic ratios of calcites. There are two possible interpretations. One is that the Sr isotope record at low resolution only reflects large-scale climate change, due to our large incremental sampling in the Tertiary red clay; thus this would not improve on the high-resolution Fe ratio record. The other is that the $\text{Fe}_2\text{O}_3(f)/\text{Fe}_2\text{O}_3(t)$ values, which may comprise some undiscovered factors, could not be better than the Sr isotopic ratios of calcites in determining chemical weathering and the summer monsoon in the Chinese Loess Plateau. Fortunately, strontium isotopic variations of calcites in the Lingtai profile correspond well with $\text{Fe}^{2+}/\text{Fe}^{3+}$ variations in the Lingtai profile and the dust flux in ODP885/886 (Fig. 2). $\text{Fe}^{2+}/\text{Fe}^{3+}$ values are a measure of the intensity of Fe-containing mineral weathering in eolian deposits. Lower $\text{Fe}^{2+}/\text{Fe}^{3+}$ values represent higher oxidation intensity of Fe-containing minerals in eolian deposits, namely, higher weathering intensity, thus indicating the stronger summer monsoon (Gu *et al.*, 1999). In contrast, higher $\text{Fe}^{2+}/\text{Fe}^{3+}$ values in eolian deposits reflect the weaker summer monsoon. The variation of dust flux in ODP885/886 actually mirrors the aridity intensity of the East Asian regions. The larger dust flux in ODP885/886 shows the higher aridity intensity of the East Asian regions whereas the less dust flux in ODP885/886 indicates the lower aridity intensity of the East Asian regions (Rea *et al.*, 1998). The $\text{Fe}^{2+}/\text{Fe}^{3+}$ values in the Lingtai profile and the dust flux in ODP885/886 gradually increased since 7 Ma B.P. Both changed constantly in the Tertiary, which is obviously lower than in the Quaternary. The results of $\text{Fe}^{2+}/\text{Fe}^{3+}$ values and the dust flux show that the Tertiary red clay was developed under conditions of the weaker aridity and the relatively stronger summer monsoon, whereas the Quaternary loess-paleosol sequence formed under the condition of the stronger aridity and the weaker summer monsoon, and further reveal that the aridity intensity of the East Asian regions increased since the on-

set of the late Cenozoic. Therefore, our Sr isotope data support the conclusions of Ding *et al.* (2001a, b): the summer monsoon in the Chinese Loess Plateau was overall stronger and more stable in the Tertiary than in the Quaternary, so that there were generally warmer and more humid climates in the Tertiary than in the Quaternary. Nevertheless, similar climates to the Tertiary probably occurred during the developments of a few Quaternary paleosols. The Sr isotopic ratios of calcites in the eolian dust profile can thus be regarded as a good proxy reflecting the long-term East Asian summer monsoon evolution in the late Cenozoic.

CONCLUSIONS

Through investigating Sr isotopic and elemental characteristics of calcites in the Lingtai eolian dust profile of the Chinese Loess Plateau during the last 7 Ma, we draw the following conclusions:

1) Ca/Sr molar ratios, Ca^{2+} and Sr^{2+} contents are lower in the Quaternary paleosols but higher in the Quaternary loess and the Tertiary red clay. High and low fluctuations of three parameters in the Quaternary loess-paleosol sequence mirror the East Asian summer monsoon evolution on a large scale. Their high values in the Tertiary red clay were a result of primary carbonate redistribution, but cannot be used to infer the weak summer monsoon at that period.

2) The Sr isotopic ratios of calcites are usually lower in the loess than in interstratified paleosols during the Quaternary. The Sr isotopic ratios of calcites in the Tertiary red clay are relatively stable, and overall higher than those in the Quaternary loess and paleosols. Nevertheless, a few paleosols of the Quaternary have calcites with Sr isotopic ratios close to the Tertiary red clay. Primary carbonate and silicate are two endmembers of strontium isotopic variations of calcites. Chemical weathering is really an inner driver to induce the strontium isotopic variation of calcite. Sr isotope data of calcites show that chemical weathering was strongest in the Tertiary red clay, moderate in the Quaternary paleosols, and weakest in the Quaternary loess. Our result from isotopic mass balance calculations suggests that less than 30% of Sr in calcite came from eolian silicate weathering in the Lingtai profile.

3) Strontium isotopic variations of calcites are in a good agreement with post-pedogenic characteristics in the Lingtai profile, broadly consistent with a proxy for the summer monsoon— $\text{Fe}_2\text{O}_3(f)/\text{Fe}_2\text{O}_3(t)$ ratios established by Ding *et al.* (2001a), and also identical to variations of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratios in the Lingtai profile and the dust flux in the ODP885/886 during the late Cenozoic. Thus, the Sr isotopic ratio of calcite can be regarded as a good proxy indicating the summer monsoon. However, stron-

tium isotopic variations of calcites are different from the magnetic susceptibility records from the Lingtai loess-paleosol-red clay sequence, demonstrating that magnetic susceptibility of the red clay was not a reliable proxy for chemical weathering and monsoon evolution of the Tertiary.

4) Sr isotopic characteristics of calcites in the Lingtai eolian dust profile during the late Cenozoic indicate that the Quaternary summer monsoon had a glacial-interglacial alternation and weakened with a large-amplitude oscillation since 0.5 Ma B.P. in the Chinese Loess Plateau, and also reveal that the Tertiary summer monsoon was more stable and broadly stronger than the Quaternary, nevertheless, similar climates to the Tertiary probably occurred during a few paleosol developments of the Quaternary.

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