Dear, editor Ran Feng,

We have carefully revised and edited the manuscript entitled " Late Miocene-Pliocene climate evolution recorded by the red clay covered on the Xiaoshuizi planation surface, NE Tibetan Plateau" based on the valuable comments and suggestions from three anonymous reviewers. Below please find the detailed responses. In addition, other major modifications are also listed.

Responses to comment 1

I think the manuscript needs to present the geochemistry data versus stratigraphic depth, in addition to just age. There also needs to be more discussion on the relationship between sedimentation rate and pedogenesis. For example, it would be helpful if Figure 3 was plotted vs. depth and there was also a column that plots sedimentation rate, and the presence of nodule horizons. This is important because the interval between 4.5 and 4.3 Ma, for example, shows a strong increase in magnetic evidence for pedogenesis and also coincides with a noticeable drop in deposition rate. Therefore, it needs to be discussed if this increase in pedogenesis was driven solely by wetter conditions, or was there also more time for soil formation and leaching of Ca. I do think more stratigraphic context will help some of the arguments presented in the text. For example, upon my initial reading of the text and figure, the division into the 2 primary intervals placed at 4.8 Ma seemed somewhat arbitrary looking at figure 3 (i.e. why not 4.6 or 5.1). But it makes much more sense in terms of the large decline in sedimentation rate around 4.8, which accompanied by the deposition of a carbonate nodule layer, and then the noted increase up-section in nodule horizons underlaying leached zones. Also with deposition of loess being connected to regional wind patterns, is it significant that there was a notable _200 kyr drop in sedimentation rates before a shift to generally wetter/more seasonal conditions?

Our response: Many thanks for your valuable suggestions. We would take these suggestions and use new figure to replace the Fig 3, and we would add a brief statement "Profiles of the various proxies are illustrated in Fig 3 and there is an obvious difference in the character of the fluctuations above and below the depth of 16.5 m (~4.8 Ma). Above 16.5 m, the carbonate content fluctuates at a lower level but with greater amplitude, and the magnetic susceptibility also fluctuates at a greater amplitude. In addition, the CV of most of the records is greater above the boundary than below (Table 1). This suggests that the climate became more humid and variable after 4.8 Ma. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred (Li et al., 2017). Thus, the red clay sequence was divided into two intervals: *Interval Ⅰ* (6.7-4.8 Ma) and *Interval Ⅱ (*4.8-3.6 Ma). The characteristics of the individual proxy records are describe in detail below" in front of line 174. We will also add "We use the coefficient of variation (CV) to measure the variability of the records. The higher the CV, the more variable the record. The CV is defined as: $\mathrm{CV} = 100 * \frac{\mathrm{Standard\ deviation}}{\mathrm{Mean}}$" at the end of chapter 3 (line 172).

I am somewhat confused by the explanation of K/Al ratios as a weathering proxy (lines 238-245). With time, Al can mobilize and become depleted at the top of a paleosol and enriched down profile. And in certain situations, you might expect K to be enriched at the soil surface, due to its biological importance. So, within the same well developed soil, you might expect a higher K/Al ratio at the top, and a lower ratio deeper in the profile. This is never plotted, so it might be worth eliminating this text?

The various magnetic susceptibility terms are well described in the discussion, but I think it would help readers if at least some of this information was moved up to either the results or methods. This would help provide context to all of the values presented in the results.

Our response: We would consider removing the K_2O/Al_2O_3 ratio and modify the statement "In addition, previous…" in lines 238-252 as "In addition, the K_2O/Na_2O ratio is used to evaluate the clay content in loess and is also a measure of plagioclase weathering, avoiding biases due to uncertainties in separating carbonate Ca from silicate Ca (Liu et al., 1993; Buggle et al., 2011). Na_2O is mainly produced by plagioclase weathering and is easily lost during leaching as precipitation increases. By contrast, K_2O (mainly produced by the weathering of potash feldspar) is easily leached from primary minerals and is then absorbed by secondary clay minerals with ongoing weathering (Yang et al., 2006; Liang et al., 2013). In the arid and semi-arid regions of Asia, K_2O is enriched in palaeosols compared to loess horizons (Yang et al., 2006). Thus, high K_2O/Na_2O ratios are indicative of intense chemical weathering. " We would also remove "The K_2O/Al_2O_3 ratio also increased rapidly at about 4.8-4.7 Ma and maintained relatively high values after 4.7 Ma. This may indicate that the overall weathering intensity was sufficient to produce secondary clays, resulting in a spike in K_2O concentration" in lines 409-312. In lines 287-288, "Morlet wavelet transform analysis of both carbonate content and χ_{pedo} show that the orbital signal increases since 4.8 Ma (Fig. 5 d)."

Minor suggestions:

Line 57: suggest "occurring" or "underway" instead of "ongoing"

Our response: We would modify "ongoing" as "occurring".

Line 76: suggest "supplied" instead of "prepared"

Our response: Thank you for suggestion. We consider remove the sentence.

Lines 75-88: I'm guessing the sentence beginning with "Make clear…" on line 78 was accidentally left in as a comment, which I still think needs to be addressed. I think I understand what the authors are going for within the paragraph, but I think the logic can be expressed more clearly. The strength/onset of the Asian monsoon is linked to these globally significant events (Tibetan uplift, northern hemisphere ice, etc). Therefore, by constraining paleoclimate across the Chinese Loess Plateau not only does this improve our understanding of regional climate, but it can also provide insight about the paleomonsoon, and therefore changes in the global climate system during the Pliocene.

Our response: Many thanks for your suggestions. We would modify statement as "East Asia is one of the key regions for studying the aridification of the Asian interior and the Asian monsoon evolution which is tightly linked to the uplift of the TP, the regional climate change and global temperature and ice volume evolution (An et al., 2001; Ding et al., 2001; Li et al., 2008; Clift et al., 2008; Nie et al., 2014; Ao et al., 2016; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014)" and add "Therefore, determining the climatic conditions of the NE TP during the early Pliocene not only improves our understanding of the regional climate change, but also provides insights into the responses of the palaeo-EASM and westerlies to TP uplift and changes in the global climate system at this time." before line 111.

Line 96: suggest removing “condition” and changing “aridification process” to “regional aridification”

Our response: We would modify “ a dry climate condition” as “dry climatic conditions”and modify “however, aridification process was interrupted by a long interval of wet climate” as “but generally wet climatic conditions”.

Line 104: change “to be” to “that”, and I think it would be helpful for the future readers not just to say “gleying”, but instead state briefly what that means (waterlogging, and iron reduction) and why it matters for the magnetic susceptibility record.

Our response: We would modify “It’s thought to be substantial gleying resulted from large amount precipitation which made magnetic susceptibility invalid over this period” was replaced as “It is thought that waterlogging and iron reduction resulting from high precipitation significantly affected the climatic significance of magnetic susceptibility records during this period”.

Line 105-106: This sentence does not make sense. Are you trying to say that climate in this region is influenced by the strength of both the westerlies and the monsoon, and that those two factors may not be directly related?

Our response: We would remove the statement.

Lines 114-115: What makes the XSZ red clay different geomorphologically?

Our response: The Xiaoshuizi peneplain of the Maxian mountain occupies a critical transition position between the high-altitude TP and the low North China Craton (Li et al., 2017). The obvious difference between Xiaoshuizi deposit and the red clay in the Chinese Loess Plateau is the modern altitude, and this exactly results from the special geographical position of NE Tibetan Plateau.

Line 118: suggest “are” instead of “have been”

Our response: We would modify “have been” as “are”

Line 121: This sentence is slightly off.

Our response: We would modify it as “Finally, the regional climate evolution and its possible mechanisms have been further discussed.”

Line 133: suggest “reconstruct and discuss” instead of “discuss ”

Our response: We would modify "discuss" as "reconstruct and discuss"

Line 133-134: not sure exactly what is meant here. Is the XSZ core characterized by more continuous deposition and records a longer time interval than the Shangyantan core?

Our response: Yes, SYT core is only covered the age from 6.4-4.2 Ma.

Line 136: capitalize China

Our response: We would modify it.

Lines 137-138: Not sure what is mean by the sentence beginning with "The East Asian Monsoon." Are you trying to explain how these two factors together control climate at the study site. This could be elaborated.

Our response: The means of this sentence is similar to statement of lines 127-128. We would remove it.

Line 144: Where in the section is the increase in gravel? From the strat column it looks like it is at the base. Say this in-text.

Our response: We would add "at the base (Fig. 1b)" after "…gravel content" in line 144.

Lines 145-147: Clarify if most carbonate horizon are overlain by a brownish red-layer, or if the carbonate zone in its entirety underlies a larger brownish-red layer. Lines 148-150: It's not clear as written if carbonized root channels have more abundant Fe-Mn staining.

Our response: We would modify "is impregnated with" as "contains numerous" and modify "horizons containing" in line149 as "the".

Line 168: Is all of the remaining Ca in silicate minerals? Won't a lot of it be loosely bound to clay minerals in the soils? Also, the correction for Phosphorous also needs to be explained. I'm guessing you are assuming some component of Ca-bearing phosphate minerals, but what is the basis for this assumption.

Our response: Thanks for your questions and suggestions. No, not all of remaining Ca in silicate minerals and the Ca bound to clay minerals is also included. Silicate-bound CaO* is obtained, in theory, by the simple equation (Fedo et al., 1995): CaO*(mol) = CaO(mol) –CO_2(calcite mol) − 0.5 CO_2(dolomite mol) − 10/3 P_2O_5 (apatite mol). It generally calculated based the assumption that all P_2O_5 is associated with apatite and all inorganic carbon is associated with carbonates. It may neglect the Ca bound to clay minerals and overestimate the component of Ca-bearing phosphate minerals (Garzanti and Resentini., 2016). The reason we use the equation to calculate the values is that we try to expel the possibility the variation of Sr is determined by the bound of secondary carbonate, but not by weathering intensity. For Sr can substitute Ca in secondary carbonates (Reeder et al., 2006; Buggle et al., 2011). We will modify statement "The molar content of silicate Ca (CaO*) was calculated using the following equation:" as "Silicate-bound CaO (CaO*) can be estimated, in principle, by the equation: CaO*(mol) = CaO(mol) – CO_2(calcite mol) − 0.5 CO_2(dolomite mol) − 10/3 P_2O_5(apatite mol) (Fedo et al., 1995). It is generally calculated based on the assumption that all the P_2O_5 is associated with apatite and all the inorganic carbon is associated with carbonates Thus, the CaO* of the XSZ red clay was calculated using the following equivalent equation" .

Line 199: What do you mean by durations? Are you saying there are some thicker intervals of high magnetic susceptibility?

Our response: Yes, it means the interval of strong pedogenesis sustained longer.

Line 256: space between "susceptibility" and "of"

Our response: We would correct it.

Line 257: suggest removing "two"

Our response: We would remove "two".

Line 314: Spelling of "Multiproxy"

Our response: We would modify it.

Line 317-318: suggest "a significant change is recorded by most of the proxies that

occurred"

Our response: We would modify "we observe that a significant change recorded by the most of the multiproxy (carbonate, Rb/Sr, K_2O/Al_2O_3, χ_{pedo}) occurred near 4.8-4.7 Ma" as "there is a significant change in most of the proxies (carbonate, Rb/Sr, K_2O/Na_2O and χ_{pedo}) near 4.8 Ma".

Line 318: K/Al is not plotted, but K/Na is plotted. Based on the comment above, I think this is probably a better choice.

Our response: We would modify "K_2O/Al_2O_3" as "K_2O/Na_2O".

Line 327: suggest "relatively" instead of "relative" and "and" instead of "which"

Our response: We would modify "relative" as "relatively" and modify "which" as "and".

Line 328: Not sure what this sentence is trying to say.

Our response: This sentence may be redundancy. We would remove "when these proxies detailed climate changes especially when climate is relative wet".

Line 329: I suggest clarifying the beginning of this sentence to say something along the lines of "Carbonate content becomes more variable after 5.5 Ma, which is…"

Our response: We would modify the sentence "It is evident that the carbonate content decreases with increased variation amplitude after 5.5 Ma" as "Carbonate content becomes more variable after 5.5 Ma, which is…"

Line 333: spelling of "indices"

Our response: We would correct it.

Line 345: suggest "central and eastern" instead of "hinterland of the"

Our response: We would modify "hinterland of the" as "central and eastern".

Line 377: suggest rewording the sentence beginning with: "Look around the globe,.."

Our response: We would modify the sentence of lines 376-377 as "A sustained cooling occurred in both hemispheres during late Miocene and the cooling culminated between 7 and 5.4 Ma (Herbert et al., 2016).”

Line 415: I’m not sure what “humid toward arid direction” means

Our response: It means climate tended to become dry. We would modify the sentence as “During 3.9-3.6 Ma, precipitation decreased, and weathering and pedogenic intensity also weakened”.

Line 521: suggest “provides the opportunity constrain and discuss..”

Our response: We would modify it as “provides the opportunity to elucidate the history of …”

Line 526: again suggest “central and eastern” instead of “hinterland of the”

Our response: We would modify “hinterland of the” as “central and eastern”.

Line 531: suggest removing “obviously”

Our response: We would remove “obviously”.

Figure 1: I think it would help if you put a larger non-circle shape on panel A corresponding to the study site. Then you can remove the Xiashuizi label, which slightly obscures the vector. Then, match this symbol on panel C You are missing the white reversals between C3n.1n, C3n.2n, and C3n.3n on the Polarity plot for the XSZ section. These were included in the age model presented in Li et al. (2017). What do the black bars on the lithology column represent.

Our response: Thank you for suggestions and pointing faults out. We have not noticed it in Fig. 1b. There is something wrong with this figure when we convert it into PDF format. Some thin white rectangles are missed. The black bars on the lithology column were the thin white rectangles representing the carbonate nodule layer. We would give the new figure (Fig 1).

Figure 2: I think it would help if the line thicknesses were slightly thinner.

Our response: You mean figure 3? We would modify it.

Responses to comment 2

Spelling and Grammar:

I have not edited this manuscript for spelling and grammar. I strongly encourage the authors to seek assistance from a very proficient or native English speaker. Also, please review the manuscript for organizational mistakes (e.g. Figures 2 and 3 are not cited in the text; incorrect citations).

Our response: Thanks for your suggestions. We would take consideration in the revised version and we would add"(Fig. 2)" after "yellowish clay layers" and add "(Fig. 2b)" after "…horizons" and cite Figure 3 in chapter 4(Results).

Statistics:

The authors need to provide more information about the magnetostratigraphic ages. What is the temporal resolution of the records? What are the temporal uncertainties? Can the records accurately resolve all the cycles you discuss (e.g. precession)? Does variable deposition rate impact the signals?

Our response: The average temporal resolution of records is 3.8 kyr. The resolution of records for detecting the precession signal needs to be 4 kyr or less (Luo et al., 2017). 80 % of sampling intervals satisfied the requirement with the resolution. Thus, the records can theoretically document the eccentricity and obliquity cycle of entire period and document the precession cycle of 80 % period. The variable deposition rate does impact on the conservation of the signals especially for precession signal.

How did the authors decide that 4.8 Ma was the appropriate transition point? It seems arbitrary to me. I see no clear transition in Figure 3. Are the two periods (6.7-4.8 Ma and 4.8-3.6 Ma) statistically distinct?

Our response: Figure 3 may not show the distinct of two periods clearly enough due to variable deposition. Thus, we present figure of records versus stratigraphic depth (Fig 1s). Synthesized the values and variations of the carbonate content, elements content and magnetic susceptibility, a transition period is presented at 16.5-15 m (4.8-4.6 Ma). There is an obvious difference in the character of the fluctuations above and below the depth of 16.5-15 m. For example, above the 16.5 m, the carbonate content fluctuates at a lower level but with larger amplitude accompanied by the noted increase in nodule horizons underlaying leached zones in the field, and the magnetic susceptibility also fluctuates at greater amplitude. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred. Thus, we define the 4.8 Ma as the transition point.

The average value and coefficient of variation of the records during two periods (6.7-4.8 Ma and 4.8-3.6 Ma) have been given in Tables 1s. The coefficient of variation (CV) is defined as:

$$CV = 100 * \frac{\text{Standard deviation}}{\text{Mean}}$$

The higher the CV is, the more changeable the record is. It shows the average value and CV of the most records show the obvious difference between two periods and most of the records are more changeable during 4.8-3.6 Ma than 6.7-4.8 Ma.

I find the signal filtering in Figure 5 questionable. First, the authors filter the data at frequencies with insignificant power (e.g. the 100 kyr filtering of carbonate content). Further, the most significant signals exist at frequencies that are difficult to explain, which the authors dismiss, and many of the discussed signals are barely significant at 90% confidence. The wavelet plots highlight the limited signal strength. Even if the filtered signals are sound, the filtered signals changes do not well align with the benthic d^{18}O record.

Our response: The reason we filtered the carbonate at 100 kyr is that we observed that fluctuations of $CaCO_3$ and weathering indices agree well with eccentricity orbital variations at 4.8-3.9 Ma (Fig 1s-c). We perform the spectral analysis for carbonate content in two periods (6.7-4.8Ma and 4.8-3.6 Ma) respectively. It shows 100 kyr, 41 kyr and 21 kyr periodic signals of carbonate are significant in the period of 4.8-3.6 Ma (Fig 1s). However, most of the orbital periodic signals are insignificant in the period of 6.7-4.8 Ma.

As for non-orbital periodic signals, we have not found the driving force and the signals recorded by carbonate content are different from χ_{pedo}. It may indicate non-orbital periodic signals are fake and more significant non-orbital periodic signals of carbonate content are relate to the dissolution-reprecipitation process of carbonate. Thus, we do not filter the records at these frequencies. We consider removing wavelet plots.

Interpretation:

The potential drivers of the climate signals are often overstated. Connections are made with limited support. Many of the mechanisms discussed are still debated, particularly the Isthmus of Panama hypothesis and timing of Tibetan Plateau uplift. At the least, the authors need to do a better job citing recent literature and discussing the remaining uncertainties. Also, many of the citations are not primary sources for the associated statements.

Our response: Thank you pointing it out. We would pay special attention to these problems in the revised version.

Specific Comments:

Line 51: Earth's orbital went through many cycles over this period, so the "orbital configuration statement does not make much sense.

Our response: We would remove the statement "(ii) orbital configuration".

Lines 51-53: These statements, such as "comparable temperatures in the tropic region", require citations.

Our response: We would add the citations "(Herbert et al., 2010, 2016)".

Line 65: Please clarify the link between mean tropical Pacific east-west gradient and ENSO.

Our response: We would modify the statement of line 65 as "…and low east-west sea surface temperature gradient in the tropical Pacific during this interval is believed to have given rise to a permanent El Nino Southern Oscillation."

Line 68: The timing of uplift of the Tibetan Plateau is heavily debated…

Our response: Sorry, the expression is misleading. What we would like to express is the uplift of the Tibetan Plateau was still underway.

Line 70: Lunt et al. (2008) is not a direct source for the closure of the Isthmus of Panama. More recent works debate the timing of closure (e.g. Bacon et al., 2015;

O'Dea et al., 2016).

Our response: Thank you for pointing it out. We would modify it as "(Keigwin et al., 1978; O'Dea et al., 2016)".

Line 72: This statement is also not well supported. For example, Lunt et al. (2008), who are cited earlier, found closure of the Panama seaway to have little influence on NH glaciation. In general, the authors need to update their citations and discuss the Literature more thoroughly. These ideas are far from settled, yet they are presented as facts.

Our response: Thank you for pointing these faults out. We would remove the statement

Line 80-82: Citation?

Our response: We would remove the statement.

Line 85: "Arctic volume" means "Arctic ice volume"?

Our response: Yes, we would correct it.

We would modify the statement of lines 68-88 as "Meanwhile, the episodic uplift of the TP (Li et al., 2015; Zheng et al., 2000; Fang et al., 2005a, 2005b) and gradual closing of the Panama seaway (Keigwin et al., 1978; O'Dea et al., 2016) were underway. The former substantially influenced the palaeoclimate change (An et al., 2001; Ding et al., 2001; Liu et al., 2014) and the later resulted in reorganization of the global thermohaline circulation (Haug et al., 1998, 2001)."

Lines 105-106: This statement does not make sense.

Our response: Thank you for pointing it out. We would remove the statement.

Lines 136-140: Sources for these data?

Our response: We would modify the statement of lines 136-138 as "The mean annual temperature during 1986-2016 was ~7.0 ℃ and the annual precipitation was 260-550 mm. Most (80%) of the precipitation is in summer and autumn. (The data were obtained from the National Meteorological Information Center (http://data.cma.cn/) of the Chinese Meteorological Administration (MCA)"

Line 154: This requires more detail.

Our response: We would remove the statement in lines 153-155 and add "Each sample age was estimated using linear interpolation to derive absolute ages, constrained by our previous magnetostratigraphic study (Fig. 1b). The average temporal resolution of the records is 3.8 kyr. Some 80 % of the sequence has a sampling resolution of 4 kyr or less" at the end of the chapter 3.

Line 175-182: How did you decide on these intervals? Did you test that they are statistically distinct?

Our response: We would add a brief statement "Profiles of the various proxies are illustrated in Fig 3 and there is an obvious difference in the character of the fluctuations above and below the depth of 16.5 m (~4.8 Ma). Above 16.5 m, the carbonate content fluctuates at a lower level but with greater amplitude, and the magnetic susceptibility also fluctuates at a greater amplitude. In addition, the CV of most of the records is greater above the boundary than below (Table 1). This suggests that the climate became more humid and variable after 4.8 Ma. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred (Li et al., 2017). Thus, the red clay sequence was divided into two intervals: *Interval Ⅰ* (6.7-4.8 Ma) and *Interval Ⅱ (*4.8-3.6 Ma). The characteristics of the individual proxy records are described in detail below" in front of "Carbonate content" in line 174. We will also add "We use the coefficient of variation (CV) to measure the variability of the records. The higher the CV, the more variable the record. The CV is defined as:

$$\mathrm{CV} = 100 * \frac{\text{Standard deviation}}{\text{Mean}},"$$

at the end of chapter 3(line 172).

Line 224-226: How are you sure that it relates to monsoon strength? Could it be seasonal or evaporative changes?

Our response: We agree with you. However, on the condition moisture is carried by the monsoon and the monsoon is strong enough, $CaCO_3$ could indicate the monsoon strength (Fang et al., 1999; Sun et al., 2010).

Lines 235-237: Both statements are significant at 99% confidence?

Our response: The correlation between Sr and CaO* (silicate CaO) is significant at 99% confidence, while the correlation between Sr and $CaCO_3$ is not significant.

Lines 282-286: Are you sure these signals are real? If so, how might you explain the cycles not related to orbital variability?

Our response: The questions are really worth pondering. Firstly, our chronology is reliable. Secondly, all sampling intervals of XSZ red clay satisfies requirement to detect eccentricity and obliquity signals and 80 % of sampling intervals satisfies requirement to detect the precession signal. Thirdly, three orbital periodic signals were also detected in the other sites of the CLP from late Miocene to early Pliocene, which means changes of orbital parameters really had impact on climate of the CLP (Han et al., 2011; Li et al., 2008). Thus, 100 kyr, 41 kyr and 21 kyr periodic signals recorded by XSZ red clay are probably true.

Changes of Earth orbital parameters would dynamically lead to the variation of the climate. However, the change of Earth orbital parameters is just one of forcing factors and other factors (some internal process or feedback) could magnify or cover the orbital forcing, which means the climate changes probably show non-linear response to orbital forcing. In this specific case, it might be the expansion of the palaeo-EASM that enhanced the orbital periodic signals of XSZ red clay between 4.8 and 4.1 Ma. As for short cycles, the power of these cycles would be weakened by the low and uneven sedimentation accumulation rate (Luo et al., 2017). Meanwhile, the age model has not been astronomically tuned. Thus, it’s hard to completely match the filtered 41 kyr and 21 kyr components with the lagged obliquity and precession in phase and amplitude even these signals are real. Our results resemble to those of Han (2011) and Tian (2002) that three orbital periodic signals were significant while records and orbital variability were less matched from late Miocene to early Pliocene.

Lines 294-295: Doesn’t this “incomplete nature of the red climate time series” impact all of the frequency analyses? How can you distinguish real and fake signals?

Our response:

The incomplete nature of the climate time series would also impact on the conservation of the signals especially for precession signal. At least to date, we have not found the driving force yielding these non-orbital periods. Thus, these non-orbital periodic signals are probably random or fake.

Line 302: I believe that a 23 kyr filter makes more sense for the climate response to orbital change.

Our response: The 21kyr filtered component is filtered at 18-24kyr. The 23kyr filtered component was included.

Line 304: What record? Lisiecki and Raymo (2005)?

Our response: The data was the filtered components of the $\delta^{18}O$ record (Zachos et al., 2001) at the 21-kyr, 41-kyr, and 100-kyr bands.

Line 306: I do not observe this in the filtered record…Is this change significant? How much do these filter components contribute to the complete signal?

Our response: This shift may be not obvious in the 100-kyr filtered components but obvious in 41-kyr and 21-kyr filtered components especially in 41-kyr filtered components. We don't know how to measure the contribution. However, fig 1s shows 100 kyr, 41 kyr and 21 kyr periodic signals of carbonate content in the interval of 4.8-3.6 Ma are more significant than the interval of 6.7-4.8 Ma.

Line 309-310: Where is this shown? The 41 kyr signal in the benthic records do not well align with the data.

Our response: The shift may be not obvious in Fig 5 where we put all filtered curves together. Fig 4s shows 41 kyr signal in the benthic record and XSZ records enhanced between about 4.8 and 4.1 Ma. In my opinion, three curves have shown some similarities during the period of 4.8-3.6 Ma, with larger oscillation at the intervals of 4.7-4.4 Ma and 4.2-3.9 Ma, and damped oscillation at the interval of 3.9-3.6 Ma. On the other hands, the record has its own climatic significance and limitation, and even the 41 kyr filtered curves of $CaCO_3$ and χ_{pedo} show difference. Thus, the differences of the 41 kyr signal in benthic records and XSZ records are reasonable.

Lines 317-319: I see no clear changes in the records. You need statistical support.

Our response: Tables 2s has shown that from the period of 6.7-4.8 Ma to 4.8-3.6 Ma, average value of

$CaCO_3$ decreased, weathering proxies and magnetic susceptibility increased. CV of the most proxies increased.

Line 361: ODP source?

Our response: Yes, ODP 1148.

Line 368: "…roughly parallel…" I do not see a correlation. Please quantify.

Our response: We would add "χ_{pedo} shows a significant positive relationship with $\delta^{18}O$ at 80 % confidence interval (Fig. 4f)" after "pedogenesis proxies roughly parallel to the stacked deep sea benthic foraminiferal oxygen isotope curve" in lines 368-369. We would also add the fig 4f.

Line 384: This is possible but not necessarily the case.

Our response: Thank you for pointing it out. We would modify "would have resulted" as "could result"

Lines 392-393: Cooler air can hold less vapor, but this statement is an extreme simplification.

Our response: We would modify the statement of lines 391-393 as "However, moisture sources for the westerly flow are distant from the CLP (Nie et al., 2014), and only a relatively small amount of moisture was carried to the CLP, resulting in a dry and stable climate in the XSZ region."

Lines 402-403: You record captures seasonal variability?

Our response: Research on migration process of carbonate indicated seasonally wet/dry climate is a key factor in driving carbonate dissolution and reprecipitation, and strong seasonally biased precipitation enhances the leaching process and produces thick leached horizons (Rossinsky and Swart, 1993; Zhao, 1995, 1998). We would add this statement before "The emergence of…"

Lines 469-471: Citation?

Our response: We would add the citations "(Keigwin et al., 1978; O'Dea et al., 2016)".

Line 480: Why global moisture and not local moisture?

Our response: It referred to moisture at high northern latitudes. We would remove sentence.

Lines 484-487: This does not make sense.

Our response: We would remove the statement.

Lines 491-492: Are you talking about regional or global albedo?

Our response: It's reduced ice albedo at high northern latitudes. We would add "at high northern latitudes" after "…reduced ice albedo".

Lines 492-495: Citation?

Our response: We would add the citations "(Chang et al., 2011; Sun et al., 2015)".

Lines 497-498: Could this discrepancy relate to differences between short term variability and the mean climate state?

Our response: Yes, it's one possibility.

Line 502: "We noticed"? You mean the authors of these other publications noticed?

Our response: The expression is inappropriate. We would modify it as "Several crucial changes linked with the summer monsoon occurred: There was a vast expansion of the western Pacific warm pool into subtropical regions in the early Pliocene (Brierley et al., 2009; Fedorov et al., 2013), and temperatures at the edge of the warm pool showed a warming trend of ~2℃ from the latest Miocene to the early Pliocene (Karas et al., 2011)".

Lines 502-506: How close are these events in time?

Our response: All of these events started at 5.2-4.8 Ma and developed at ~4.6 Ma.

Figures:

Figure 1a: The winds do not look correct. Also, 850 hPa winds do not exist over the Plateau

Our response: Thank you for pointing it out. We would correct it and provide new figure (Fig 1).

Figure 2 and Figure 3 are not cited in the text.

Our response: We would cite the Figure 2 at the end of sentence "…clay is composed of brownish red and yellowish clay layers” in line 145 and Figure 3 in chapter 4(Results).

Figure 3: It is difficult to see how the axes align with the lines

Our response: We would use new figure 3 to replace the figure 3

Figure 5d: Do the black lines represent significance?

Our response: Yes, these lines are the 95% confidence limit line. We would provide new figure (Fig 5).

Responses to comment 3

Major concerns:

1) The introduction part is not well written as there are many ambiguity and in accuracy (see detailed comments below). This section needs significant reworking.

2) The authors seem to preferentially pick 4.8 Ma as the boundary between the two climate intervals. However, most of the proxies exhibited in Fig. 3 seem has a distinct change at 4.6 Ma, but not 4.8 Ma, e.g., Al_2O_3, K_2O, as well as the three magnetic susceptibility plots. In addition, for the grain size and carbonate content plots, there is no apparent difference below and above 4.8 Ma.

3) This manuscript is generally good written in English, but additional efforts are required to polish the language.

Our response: Thanks for your valuable suggestions. We would rework the introduction and would modify and polish the language. We would explain how we defined the boundary later.

Line-to-line comments:

L1-2: I found the title is kind of misleading. The authors emphasize the Tibetan Plateau as the location of their section. However, throughout the manuscript, the Xiaoshuizi section is compared with other sections on the Chinese Loess Plateau, and reflects nothing of the Tibetan Plateau evolution. So it would be more appropriate to emphasize the location as the “western Chinese Loess Plateau”.

Our response: It's a very good question. The reason why we emphasize the NE Tibetan Plateau is that it significantly represents the location of the Xiaoshuizi planation surface. It locates the transition zone from the Tibetan Plateau to the Chinese Loess Plateau. The obvious difference between Xiaoshuizi deposit and the red clay in the Chinese Loess Plateau is the modern altitude, and this exactly results from the special geographical position of NE Tibetan Plateau. Compared with other sections on the Chinese Loess Plateau is the main method to address the evolution of palaeo-circulation over the Xiaoshuizi planation from late Miocene to early Pliocene.

L49: one of the most intensively studied intervals of what? Climate I assume?

Our response: Thank you for pointing it out. We would add "on climate change research" at the end of the sentence.

L51: in line 41, the authors state closure of the Panamanian Seaway at 4.8 Ma, and it seems that the seaway closure has significant climate effects. Thus, it would be inappropriate to state here that the Zanclean is similar as present due to similar land-sea distribution.

Our response: Thank you for pointing it out. We would remove "(i) land-sea distribution".

L52-53: references for "comparable temperatures in the tropical region" need to be added.

Our response: We would add the citations "(Herbert et al., 2010, 2016)".

L54: Zanclean is a period from cold to warm?

Our response: The statement may be inappropriate. We would remove it.

L66-67: wired transition from the previous sentence. Not consistent.

Our response: We would modify it as "whether permanent El Nino–like conditions were sustained during the Pliocene is still controversial."

L68: This is at least not accurate, if not wrong. Numerous studies have demonstrated that surface uplift of the Tibetan Plateau is stepwise and spatially diachronous. See reviews of Tapponnier et al., 2001, Wang et al., 2014 and many others. The south-central parts of the Tibetan Plateau were

uplifted much earlier than the Zanclean, e.g., Paleogene. In the northern Tibetan Plateau, although there might be tectonic deformation in the margins of the Plateau (Li et al., 2015), the major part of the northern Plateau is probably uplifted during the Miocene, as evidenced by numerous other evidence, see review of Yuan et al., 2012. While it's OK to stick on the authors' own preference, it's necessary to discuss/reflect other research progress.

Our response: Thank you for pointing it out. What we would like to express is the uplift of the Tibetan Plateau was still underway. We would modify the statement of lines 68-88 as "Meanwhile, the episodic uplift of the TP (Li et al., 2015; Zheng et al., 2000; Fang et al., 2005a, 2005b) and gradual closing of the Panama seaway (Keigwin et al., 1978; O'Dea et al., 2016) were underway. The former substantially influenced the palaeoclimate change (An et al., 2001; Ding et al., 2001; Liu et al., 2014) and the later resulted in reorganization of the global thermohaline circulation (Haug et al., 1998, 2001)".

L72: 3 Ma or 2.6 Ma? Be accurate.

Our response: It's 2.6 Ma. We would correct it.

L75: first appearance of ASM in the main text, need to define first. In addition, for summer monsoons in Asia, there is the East Asia Summer Monsoon and the South Asia (India) Summer Monsoon. Which one do you mean? I assume East Asia Summer Monsoon?

Our response: Thank you for pointing it out. We would correct it. Actually, the South Asia Summer Monsoon also put an impact on the XSZ. However, the impact is not as significant as that put by East Asia summer Monsoon. We would modify it.

L76-77: In the abstract, the authors consider the ASM as moisture carrying, but the Westerlies as moisture lacking. So it's not appropriate to list them together. In addition, moisture transport is short-time climate condition, how could it cause long-term glaciation?

Our response: Thank you for pointing it out. We would rework this part.

L82: "warm and wet" climate yield "wet" climate? Definitely!

Our response: Thank you for pointing it out. We would remove the sentence.

L84: a weakened summer monsoon of where? Globally or East Asia only?

Our response: It is East Asia Summer Monsoon. We would remove sentence.

L89-91: onset of interior Asian aridification since the late Miocene? This is totally unjustified. Numerous studies indicate much earlier onset of Asian interior aridification, e.g., since 22 Ma (Guo et al., 2002), or much earlier at Eocene-Oligocene transition (Dupont-Nivet et al., 2007), or late Eocene (Bosboom et al., 2014).

Our response: We would modify the "..onset of interior Asian aridification related to the uplift of the

L103-105: is this phenomenon also observed in other studies?

Our response: Yes, pollen assemblages at Chaona indicate a considerably warmer and more humid climate from 4.61-4.07 Ma which was not consistent with that the low magnetic susceptibility values (Ma et al., 2005).

L107-108: what inconsistent? Need to clarify. For the evidence listed above, it's necessary to point out which region is dominated by westerlies, which is dominated by ASM.

Our response: We would add "where climate is dominated by East Asia Monsoon," after "In eastern and central CLP," in line 94.

L110: why the western CLP is especially important? Need to give reasons here.

Our response: We would rework this part. And modify statement of lines 105-110 as "In addition to the East Asian Monsoon, the westerlies also had an impact on climate of East Asia. However, patterns of climate change in westerlies dominated regions were different from the eastern and central CLP during the early Pliocene. Geochemical, stratigraphic and pollen evidence from the Qaidam and Tarim basins has demonstrated that aridification had intensified since the early Pliocene (Fang et al., 2008; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014). Although the general climatic trends of the main CLP and northern TP during this period were well recorded, palaeoclimatic change in the NE TP which is at the junction of the westerlies and monsoonal influences remains unclear. Therefore, determining the climatic conditions of the NE TP during the early Pliocene not only improves our understanding of the regional climate change, but also provides insights into the responses of the palaeo-EASM and westerlies to TP uplift and changes in the global climate system at this time."

L126-127: rejuvenated at what time?

Our response: The tectonic movement of the Pre-Sinian formed the inverse anticlinorium and several faults arranged as en echelon (or parallel) pattern, which lay the foundation for outline of Maxianshan (Li et al., 1990). The planation surface research indicates the tectonic movement since late Miocene made the area uplift with a great amplitude (Li et al., 2017; Ma et al., 2016).

L175-182: what are the criteria to divide the carbonate content plot into 6.7-4.8 Ma and 4.8-3.6 Ma. I do not see apparent difference between these two subdivisions. For the 6.7-4.8 Ma interval, the carbonate content is 3.8-39.2.The 6.0-5.5 interval, with much smaller amplitude of fluctuation, seems to be more different from the other time intervals.

Our response: Figure 3 may not show the distinct of two periods clearly enough due to variable deposition. Thus, we present figure of records versus stratigraphic depth (Fig 1s). Synthesized the values and variations of the carbonate content, elements content and magnetic susceptibility, a transition period is presented at 16.5-15 m (4.8-4.6 Ma). There is an obvious difference in the character of the fluctuations above and below the depth of 16.5-15 m. For example, above the 16.5 m, the carbonate content fluctuates at a lower level but with larger amplitude accompanied by the noted increase in nodule horizons underlaying leached zones in the field, and the magnetic susceptibility also fluctuates at greater amplitude. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred. Thus, we define the 4.8 Ma as the transition point.

The average value and coefficient of variation of the records during two periods (6.7-4.8 Ma and 4.8-3.6 Ma) have been given in Tables 1s. The coefficient of variation (CV) is defined as:

$$CV = 100 * \frac{\text{Standard deviation}}{\text{Mean}}$$

The higher the CV, the more changeable the record. It shows the average value and CV of the most records show the obvious difference between two periods and most of the records are more changeable during 4.8-3.6 Ma than 6.7-4.8 Ma.

We would explain it in revised version.

L185-187: looking at Fig. 3, it's pretty hard to determine whether two plots are of similar trend, or opposite trend. I would suggest to provide statistical evaluation to help readers understand the similarity between plots.

Our response: Would add table 2 in the revised version.

L188: provide the ranges of Al_2O_3 and K_2O for the two time intervals. L189: why choose 4.8 Ma as the boundary? The values between 4.8-4.6 seem be more similar as the 6.7-4.8 Ma interval.

Our response: Fig1s shows 16.5-15m (corresponding to 4.8-4.6 Ma) is a transition period. During this period, K_2O and Rb increased while CaO, Na_2O and Sr decreased. The transition period means climate translates from one condition to another. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred. Thus, we define the start of the transition period (4.8 Ma) as the transition point.

We would modify the statement of lines 184-191 as "The XSZ red clay consists mainly of SiO_2, Al_2O_3, CaO and Fe_2O_3 with low concentrations (<5%) of MgO, K_2O, Na_2O, Sr, Rb and Ba (Table 1). During Interval Ⅰ, K_2O ranges from 1.9-3.3% with an average content of 2.6%. Na_2O ranges from 0.14-1.52% with an average content of 1.2%. Rb ranges from 80-125 ppm with an average content of 103.9 ppm. Sr ranges from 150-252 ppm with an average content of 211.7 ppm. During Interval Ⅱ, K_2O ranges from 2-3.7% with an average content of 3%. Na_2O ranges from 0.94-1.54 % with an average content of 1.23%. Rb ranges from 74-134 ppm with an average content of 109.9 ppm. Sr ranges from 141-281 ppm with an average content of 214.6 ppm. The variations in CaO show the same trend as carbonate content. The variations of Rb and K_2O are synchronous and roughly opposite to that of CaO. The changes of Sr show some similarity with magnetic susceptibility before 4.8 Ma but with CaO after 4.8 Ma. Accordingly, table 2 indicates CaO has positive correlation with $CaCO_3$ and Sr while negative correlation with other elements. The variations in CaO, K_2O, Sr and Rb content during 4.8-3.6 Ma are greater than those during 6.7-4.8 Ma, which is also indicated by the CV of these elements (Table 1) ."

L193: similar question, why group values between 6.7-4.8 together, but not include values between 4.8-4.6, which exhibit more similarities as the 6.7-4.8 Ma interval, which are of lower values and smaller amplitude of variation.

Our response: Fig1s shows magnetic susceptibility start to increase from 16.5 m (4.8 Ma).

L204: there is no difference between these two intervals.

Our response: >40 um content is a proxy for winter monsoon strength. <2um content partly adheres to coarser silt and sand particles. Thus, we do not take two contents into consideration here.

L206: in Fig. 3, it shows >40 um.

Our response: It's >40 um. We would correct ">43 um" as ">40 um".

L251: I have a question here, maybe very basic in your discipline. If one wants to use K_2O/Na_2O values to determine the intensity of chemical weathering, a pre-assumption is that before weathering, all the samples have similar K_2O/Na_2O values. Right? How about if the original K_2O/Na_2O values are different? This question might also exist for other chemical proxies used here.

Our response: It's really a good question. Previous studies have indicated the rare earth element distribution patterns of both the loess and red clay are identical to those of upper continental crust (Ding et al., 2001; Jahn et al., 2001). It suggested the initial geochemical composition of well mixed loess and red clay is similar. Thus, changes in K_2O/Na_2O and Rb/Sr ratios are mainly determined by post-depositional weathering.

L287-288: Could you please explain this in more detail? Which feature in Fig. 5d denotes orbital signal increase since 4.8 Ma? As far as I can infer from Fig. 5d, in the carbonate content plot, the orbital parameters increase since 4.9-5.0 Ma. While, in the Xpedo plot, it seems the increasing timings are diachronous for different orbital parameters.

Our response: Thank you for pointing it out. The explanation for plot Fig 5d may be not appropriate. We consider removing the wavelet plots and the statement "Furthermore, Morlet wavelet transform analysis of both carbonate content and χpedo show that the orbital signal increases since 4.8 Ma (Fig. 5 d)" in lines 286-288.

L292-295: Here the authors propose that the carbonate content and Xpedo signals reflect incomplete preservation of paleoclimate signals. Then the question is if the original paleoclimate

signals are incomplete, how would you use these records to predict paleoclimate changes?

Our response: It involves scale problem. These records cannot document the millennial-scale climate change completely but can document palaeoclimate changes in ten thousand scale. The reason why we said the signals are incomplete is that 20% of sample intervals are not satisfied with the requirement for detecting the precession signal (with the resolution 4 kyr or less).

L308-312: According to the authors' statement, the rapid change from 6.7-4.8 Ma low amplitude to 4.8-4.1 Ma large amplitude is observed in all the three orbital parameters. But for the benthic foraminiferal d^{18}O record, similar change is only observed in the 41-kyr component. Why? This does not read like strong evidence to infer that the wet-dry oscillations were driven by changes in ice volume or global temperature. An associated question would be if the authors do not consider solar radiation intensity is the cause of the wet-dry cycles, but ice volume or global temperature, then what's the cause of ice volume and global temperature changes? Isn't solar radiation intensity a driving factor?

Our response: "This may mean that the increased contrast in wet-dry oscillations at the XSZ site was not driven directly by changes in solar radiation intensity but rather was linked with changes in ice volume or global temperature."(lines 310-312). Sorry, the sentence is an ambiguous or misleading expression. It's the enhancement for wet-dry contrast not wet-dry oscillation, which was linked with changes in ice volume or global temperature. We would correct it. Changes of Earth orbital parameters (linked to solar radiation intensity) would dynamically lead to the variation of the climate including changes in global temperature, ice volume and also wet-dry cycles of XSZ section. However, the change of Earth orbital parameters is just one of forcing factors and some internal process or feedback could magnify or cover the orbital forcing, which means the climate changes probably show non-linear response to orbital forcing (solar radiation intensity). In this specific case, it might be the expansion of the palaeo-EASM that enhanced the orbital periodic signals of XSZ red clay between 4.8 and 4.1 Ma.

In addition, for our records, the most significant change is also observed in 41kyr filtered components. The remarkably increased amplitude of the 41kyr filtered components from XSZ and the deep sea δ^{18}O record at about 4.8 Ma indicating common changes may have synchronously amplified the response of δ^{18}O record and XSZ wet-dry oscillations to obliquity forcing. The variation of deep sea δ^{18}O related to the changes in global temperature and ice volume (Zachos et al., 2001). The increased wet-dry oscillation of XSZ related to the expansion of palaeo-EASM. Thus, the expansion of palaeo-EASM may be related to changes in global temperature and ice volume. It is not the evidence but just one possibility.

L317-318: I find this conclusion hard to believe. For the carbonate content signal, the authors state that they record incomplete paleoclimate signal (see comments for L292-295). For the K_2O/Na_2O and Rb/Sr record, a more apparent change seems to be at 4.6 Ma. If higher carbonate content represents dry climate, and lower carbonate content represents humid climate, compared with 6.7-4.8 Ma, the 4.8-3.6 Ma would have more humid period, but also much drier period, because the 4.8-3.6 Ma has larger variability. While, I did not see a clear wetting trend.

Our response: Firstly, as mentioned above, palaeoclimate signal is incomplete in millennial scale. In ten thousand scale, it is complete. Secondly, carbonate content averaged with 13.8% during the interval of 4.8-3.6 Ma and 17.4% during the interval of 6.7-4.8 Ma, which indicate climate became wetter after 4.8 Ma. In detail, during the interval of 4.8-3.6 Ma, the carbonate content fluctuates with greater amplitude but at a lower level and leached horizons is thicker than the interval of 6.7-4.8 Ma, which means leaching process enhanced after 4.8 Ma. Thirdly, the similar phenomenon was also observed in Xijin loess-paleosol series that in loess layers carbonate has a high average content with small fluctuation amplitude while in paleosol layers carbonate has a low average content with large fluctuation amplitude (Ye, 2017).

L363-364: This is a false statement. Even at present, the Tibetan Plateau cannot block the Westerlies completely. The Westerlies can travel to the northeastern Tibet through valleys in the Tianshan.

Our response: Thank you for pointing it out. We would remove the statement.

L368: which plots are pedogenesis proxies? Cite the specific plots here. "roughly"? how rough? Better to give a quantitative value.

Our response: We would add "χ_{pedo} shows a significant positive relationship with $\delta^{18}O$ at 80 % confidence interval (Fig. 4f)" after "pedogenesis proxies roughly parallel to the stacked deep sea benthic foraminiferal oxygen isotope curve" in lines 368-369. We would also add the fig 4f

L391-392: is there evidence to suggest reduced amount of atmospheric water vapor? Weakening of the palaeo-ASM and dominance of Westerlies can explain the aridity. This does not necessarily need reduced amount of atmospheric water vapor.

Our response: Thanks for your suggestion. We would modify the statement of lines 391-393 as "However, moisture sources for the westerly flow are distant from the CLP (Nie et al., 2014), and only a relatively small amount of moisture was carried to the CLP, resulting in a dry and stable climate in the XSZ region."

L469: "extremely wet"? wetter than any other period?

Our response: The expression is inappropriate. We would modify "As mentioned above, the extremely wet climate across the CLP was synchronous with the gradual closure of the Panama Seaway, which led to a larger reorganization of the global thermohaline circulation pattern" as "The occurrence of humid climate across the CLP was synchronous with the gradual closure of the Panama Seaway (Keigwin et al., 1978; O'Dea et al., 2016)."

L528-530: I probably missed it, but how could your records reflect seasonality of precipitation? Which proxy records seasonal signals?

Our response: Research on migration process of carbonate indicated seasonally wet/dry climate is a key factor in driving carbonate dissolution and reprecipitation, and strong seasonally biased precipitation enhances the leaching process and produces thick leached horizons (Rossinsky and Swart, 1993; Zhao, 1995, 1998). The emergence of high-frequency cycles of carbonate eluviation-redeposition and thicker leached horizons indicates that seasonal precipitation increased during the interval of 4.8-3.6 Ma.

L532: why the strongest summer monsoon is between 4.6-4.25 Ma? What are the possible reasons for the decreasing strength after 4.25 Ma?

Our response: From 4.60-4.25 Ma, pedogenesis and weathering intensity of XSZ reached a maximum, as did precipitation intensity, which is manifested by the enhanced eluviation and carbonate accumulation. These evidences indicate the strength of summer monsoon is strongest from 4.60-4.25

Ma. Meanwhile, the temperatures of both high northern latitude and subtropic Pacific were relatively high, which may be responsible for enhancement of the palaeo-EASM. On the other hand, input of ice raft debris into subarctic northwest Pacific increased from 4.25 to 4.1 Ma which indicates temperature of the high northern latitudes decreased. Temperature at subtropic Pacific also decreased after 4.0 Ma. The decreased temperature of high northern latitude and subtropic Pacific may be the reason for the decreasing strength of palaeo-EASM after 4.25 Ma (Fig. 6).

Figures:

Fig. 1: a, the present outline is too large, the wind vectors are too small to see. It's better to show a smaller region with more details; e.g., regions between 10N-50N, 70E-130E. c. highlights the Xiaoshuizi section. Hard to find now.

Our response: Thank you for suggestions. We would modify it. (Fig. 1)

Fig. 2: These photos exhibit very few useful information.

Our response: These photos visually exhibit information about Xiaoshuizi planation surface and red clay.

Fig. 3: Between 4.8-4.6 Ma, most plots show a weird shape. Is this because there are limited samples compared with other time intervals?

Our response: Yes, it is. We would use new figure 3 to replace the figure 3

Fig. 5: apparently the authors need to provide more information in the caption about their plots. For example, Fig. 5d, what does the color mean? What does the black curve represent? Also, the horizontal age scale is better to use Ma, but not ka, as Ma is used throughout the manuscript. In Fig. 5a-b, there are other strong periodicities denoted. How about these periodicities in Fig. 6d?

Our response: We would modify it. (Fig. 5)

Fig. 6. It will be better to arrange all the proxies with the same logic, e.g., left-wet, right-dry.

Our response: The reason why we put the benthic foraminiferal $\delta^{18}O$ record with different logic from other records is that we would like to show the similarity of benthic foraminiferal $\delta^{18}O$ record and χ_{pedo}

curve during 6.7 to 4.8 Ma.

Other Modifications:

1. Modifications in abstract

The mentioned line number refers to that in the discussion manuscript. **In lines** 24-27, “As an analogue for predicting the future climate, Pliocene climate and its driving mechanism attract much attention for a long time. Late Miocene-Pliocene red clay sequence on the main Chinese Loess Plateau (CLP) has been widely applied to reconstruct the history of interior aridification and Asian monsoon climate.” was replaced with “The Pliocene climate and its driving mechanisms have attracted substantial scientific interest because of its potential as an analog for near-future climates. The late Miocene-Pliocene red clay sequence of the main Chinese Loess Plateau (CLP) has been widely used to reconstruct the history of interior Asian aridification and Asian monsoon” **In line** 27, “the typical” was removed. **In line** 28, “the” and “(TP)” were added before and after “…Tibetan Plateau…” respectively and “Recently,” was replaced with “A”. **In line** 29, “ has been found” was modified as “sequence was recently discovered”. **In line** 30, “Tibetan Plateau (TP)” was modified as “TP”. **In lines** 30-32, “To reconstruct the late Miocene-early Pliocene climate history of NE Tibetan Plateau and to assess the regional differences between the central and western CLP, multiple climatic proxies were analyzed from the XSZ red clay sequence” was replaced with “In this study, we analyzed multiple climatic proxies from the Xiaoshuizi red clay sequence to reconstruct the late Miocene-early Pliocene climate history of the NE TP and to assess regional climatic differences between the central and western CLP”. **In line** 33, “occurrence of” was added before “...minimal weathering…” and “from 6.7 to 4.8 Ma” was modified as “during 6.7-4.8 Ma”. **In line** 34, “implicate” was modified as “indicated” and “sustained” was removed. **In line** 35, “paleo-Asian Summer Monsoon (ASM)” was modified as “palaeo-East Asian Summer Monsoon (EASM)” and “instead” was modified as “that”. **In line** 36, “condition” was modified as “conditions”. **In line** 37, “the interval of” was removed. **In line** 38, “increasing” was modified as “an increase in”, “Thus, we” was replaced with “We” and “obvious” was removed. **In line** 39, “climate transition near 4.8 Ma to the paleo-ASM expansion” was replaced with “climatic transition near 4.8 Ma to the expansion of the palaeo-EASM”. **In line** 40, “vast” was removed. “the subtropical regions and water" was replaced with "subtropical regions and the" . **In line** 41 "freshening in" was replaced with "freshening of". **In line** 43, "carried" was replaced with "transported" and "Tibetan Plateau" was replaced with "TP". **In line** 44, "Xiaoshui Peneplain" was replaced with "Xiaoshuizi Planation surface" and "palaeo-ASM" was modified as "palaeo-EASM".

2. Modifications in introduction

In line 49, "on climate change research" was added after "…pre-Quaternary". **In lines** 50-51, "it is analogous to the present day" was replaced with "often used as an analogue for near-future climate conditions" and " (i) land-sea distribution, (ii) orbital configuration, (iii)" was removed. **In line** 52, "(Raymo et al., 1996; Fedorov et al., 2013)" was modified as "(Tripati et al., 2009; Pagani et al., 2010)" and "(iv)" was removed. **In line** 53, "(Herbert et al., 2010, 2016)" was added after "…tropic region". Statement of **lines** 53-55 was removed. **In line** 56, "...unique and some crucial transitions of the" was modified as "markedly different from today and several critical changes in". **In line** 57 "undergoing" was modified as "occurring (Haug et al., 1998, 2005; Lawrence et al., 2006; Chaisson and Ravelo, 2000)" , "For example, the early-Pliocene global mean temperature was approximately 4 ℃ warmer (Brierley and Fedorov, 2010) and the sea levels estimated to have been ~25 m higher than today (Dowsett et al., 2010)" was added before "Temperatures at…" and "the" was removed. The sentence of **lines** 59-61 was replaced with "The zonal and meridional sea surface temperature gradients in the Northern Hemisphere was weak and gradually changed toward a modern much more pronounced spatial temperature contrasts (Fedorov et al., 2013； Brierley et al., 2009, 2010)". **In line** 62, "an "equable" climate" was replaced with "weaker meridional circulation". **In line** 63, "Abbot and Tziperman., 2008" was replaced with "Brierley et al., 2009, 2010" and "the" was modified as "and low". **In lines** 64-65 "is also believed to be low, which is tightly linked with" was replaced with "is believed to have given rise to a". **In lines** 66-67, "debate persists on" was removed and "is still controversial" was added after "Pliocene". The statement of **lines** 68-88 was replaced with "Meanwhile, episodic uplift of the TP (Li et al., 2015; Zheng et al., 2000; Fang et al., 2005a, 2005b) and gradual closing of the Panama seaway (Keigwin et al., 1978; O'Dea et al., 2016) were underway. The former substantially influenced the palaeoclimate change (An et al., 2001; Ding et al., 2001; Liu et al., 2014) and the later resulted in reorganization of the global thermohaline circulation (Haug et al., 1998, 2001). Together these observations imply a structural change in global climate from the early Pliocene to present. We have to ask what the regional climate like under such special climatic and tectonic settings." The sentence of **lines** 89-91 was replaced with "East Asia is one of the key regions for studying the aridification of the Asian interior and the Asian monsoon evolution which is tightly linked to the uplift of the TP, the regional climate change and global temperature and ice volume evolution (An et al., 2001; Ding et al., 2001; Li et al., 2008; Clift et al., 2008; Nie et al., 2014; Ao et al., 2016; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014). Previous research has revealed that the red clay was widely deposited since the late Miocene across the CLP, indicating that the Asian aridification related to the uplift of the TP enhanced". Statement of **lines** 92-94 was removed. **In line** 94, "the" was added after "in" and "where climate is dominated by East Asian Monsoon" was added after "CLP". **In line** 95, "also" was removed. **In lines** 96-97, "a dry climate condition during late Miocene" was replaced with "dry climatic conditions during the late Miocene" and "however, aridification process was interrupted by a long interval of wet climate" was replaced with "but generally wet climatic conditions". **In line** 99, "of" was replaced with "from". **In line** 100, "reveal" was replaced with "indicate". **In line** 101, "monsoon system" was modified as "summer monsoon intensity". **In line** 103-105, "It's thought to be substantial gleying resulted from large amount precipitation which made magnetic susceptibility invalid over this period" was replaced as "It is thought that waterlogging and iron reduction resulting from high precipitation significantly affected the climatic significance of magnetic susceptibility records during this period". Statement of **lines** 105-110 was replaced with "In addition to the East Asian Monsoon, the westerlies also had an impact on climate of East Asia. However, patterns of climate change in westerlies dominated regions were different from the eastern and central CLP during the early Pliocene. Geochemical, stratigraphic and pollen evidence from the Qaidam and Tarim basins has demonstrated that aridification had intensified since the early Pliocene (Fang et al., 2008; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014). Although the general climatic trends of the main CLP and northern TP during this period were well recorded, palaeoclimatic change in the NE TP which is at the junction of the westerlies and monsoonal influences remains unclear. Therefore, determining the climatic conditions of the NE TP during the early Pliocene not only improves our understanding of the regional climate change, but also provide insights into the responses of the palaeo-EASM and westerlies to TP uplift and changes in the global climate system at this time." Statement of **lines** 111-114 was modified as "Continuous red clay sequence was recently discovered on the uplifted Xiaoshuizi (XSZ) planation surface in the NE TP and has been dated via high-resolution magnetostratigraphy analysis (Li et al., 2017).” The sentence of **lines** 114-117, was modified as “The distinctive geomorphological and climatic characteristics of the XSZ red clay sequence differentiates it from the main CLP red clay, and provides the opportunity to reveal the late Miocene-early Pliocene climate history of the NE TP and to discuss the climatic differences between the central and western CLP”. Statement of “multiple climatic proxies have been applied in the Xiaoshuizi…” **lines** 118-120, was modified as “we measured multiple climatic proxies from the late Miocene-Pliocene XSZ red clay core and then the detailed history of precipitation, chemical weathering and pedogenesis during 6.7-3.6 Ma are reconstructed”. **In line** 121, “and” was modified as “evolution and its” and “mechanism” was modified as “mechanisms”.

3. Modifications in Regional background

In line 124, “locates” was modified as “is located”. **In line** 25, “the” was removed. **In line** 25, “Maxianshan” was modified as “Maxian”. **In line** 131, “covered on” was modified as “covering”. **In line** 132, “peneplain” was modified as “planation surface”. **In lines** 132-134, “here we choose the Xiaoshuizi core to discuss the regional climate because of its continuous deposit and whole timescale relative to the Shangyaotan core mentioned in Li et al (2017)” as “Here, we use the Xiaoshuizi drill core to reconstruct and discuss the regional climate during the Miocene-Pliocene. The long, continuous well-dated record of the drill core is superior to that of the Shangyaotan core mentioned in Li et al. (2017)”. **In line** 136, “china, and the Tibetan Plateau” was modified as “China, and the TP” and “The East Asian Monsoon system and the westerly circulation operate together ” was removed.

4. Modifications in material and methods

In line 144 “at the base (Fig. 1b)” was added after “…gravel content”. **In line** 145, “(Fig. 2)” was added after “yellowish clay layers” and “impregnated with many” was modified as “contains numerous”. **In line** 147, “..layer; there are” was modified as “layer. There are also”. **In line** 148, “snail fossil” was modified as “fossil snail shell”. **In line** 149, “horizons containing” was removed. **In line** 150, “over the Xiaoshuizi”, was modified as “across the XSZ”. **In line** 151, “all of which are” was modified as “both are, ” and “many” was modified as “numerous”. **In line** 152, “(Fig. 2b)” was added after “…horizons” and “Grain-size” was modified as “Samples for grain-size” and “samples” was modified as “measurements”. **In line** 153, “while” was modified as “and”. The sentence of **lines** 153-155 was removed. **In line** 157, “(χ)” was removed. **In line** 161, “using” was modified as “via X-ray fluorescence using a”. **In line** 162, “first, the bulk sample was” was modified as “Bulk samples were”. **In line** 163, “…, then each sample was” was modified as “ and then”, “, and ” was modified as “;” and “about” was modified as “~”. **In line** 166, “finished” was modified as “conducted”. **In line** 167, “The molar content of silicate Ca (CaO*) was calculated using the following equation” was modified as “Silicate-bound CaO (CaO*) can be estimated, in principle, by the equation: CaO*(mol) = CaO(mol) – CO_2(calcite mol) − 0.5 CO_2(dolomite mol) − 10/3 P_2O_5(apatite mol) (Fedo et al., 1995). It is generally calculated based on the assumption that all the P_2O_5 is associated with apatite and all the inorganic carbon is associated with carbonates Thus, the CaO* of the XSZ red clay was calculated using the following equivalent equation”. **In line** 171 statement of “We use the coefficient of variation (CV) to measure the variability of the records. The higher the CV, the more variable the record. The CV is defined as:

$$CV = 100 * \frac{\text{Standard deviation}}{\text{Mean}}$$

Each sample age was estimated using linear interpolation to derive absolute ages, constrained by our previous magnetostratigraphic study (Fig. 1). The average temporal resolution of the records is 3.8 kyr. Some 80 % of the sequence has a sampling resolution of 4 kyr or less.” was added.

5. Modifications in results

Statement of “Profiles of the various proxies are illustrated in Fig 3 and there is an obvious difference in the character of the fluctuations above and below the depth of 16.5 m (~ 4.8 Ma). Above 16.5 m, the carbonate content fluctuates at a lower level but with greater amplitude accompanied by the noted increase in nodule horizons underlaying leached zones in the field, and the magnetic susceptibility also fluctuates at greater amplitude. In addition, the CV of most of the records is greater above the boundary than below (Table 1). This suggests that the climate became more humid and variable after 4.8 Ma. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred (Li et al., 2017). Thus, the red clay sequence was divided into two intervals: *Interval* Ⅰ (6.7-4.8 Ma) and *Interval* Ⅱ (4.8-3.6 Ma). The characteristics of the individual proxy records are described in detail below.” was added before **line** 174. **In lines** 175-176, “According to the fluctuations in carbonate content, the red clay sequence was divided into two intervals: *Interval* - Ⅰ is from 6.7-4.8 Ma, during which…” was modified as “During *Interval* Ⅰ,”. **In line** 177, “with an average of 17.4%;” was modified as “and has a high average value (17.4%)” and “the amplitude of fluctuations is small” was modified as “the carbonate content contrast between leach layers and accumulation layers is generally low”. **In line** 178, “(Fig. 3)” was added after “upwards” and “From 5.4-4.9 Ma, the carbonate content” was modified as “From 29-16.5 m, the”. **In line** 179, “6.7-5.4 Ma” was modified as “6.7-5.5 Ma” and “*Interval* -Ⅱ is from 42-29 m, during which…” was modified as “During *Interval Ⅱ*,”. **In line** 180, “fluctuates from 1.6-39.1% with an average of 13.8%” was modified as “fluctuations have a large amplitude (from 1.6-39.1%) but a low average value (13.8%).” **In line** 181, “From 4.8-3.9 Ma” was modified as “From 16.5-4.5 m ”. **In lines** 185-186, “The variations in Al_2O_3 and K2O are synchronous and roughly opposite to that of CaO” was replaced with “During *Interval Ⅰ*, K_2O ranges from 1.9-3.3% with an average content of 2.6%. Na_2O ranges from 0.14-1.52% with an average content of 1.2%. Rb ranges from 80-125 ppm with an average content of 103.9 ppm. Sr ranges from 150-252 ppm with an average content of 211.7 ppm. During *Interval Ⅱ*, K_2O ranges from 2-3.7% with an average content of 3%. Na_2O ranges from 0.94-1.54 % with an average content of 1.23%. Rb ranges from 74-134 ppm with an average content of 109.9 ppm. Sr ranges from 141-281 ppm with an average content of 214.6 ppm.” The statement of **lines** 187-191was replaced with “The variations of Rb and K_2O are synchronous and roughly opposite to that of CaO. The changes of Sr show some similarity with magnetic susceptibility before 4.8 Ma but with CaO after 4.8 Ma. Accordingly, table 2 indicates CaO shows positive correlation with $CaCO_3$ and Sr, while negative correlation with other elements. The variations in CaO, K_2O, Sr and Rb content during 4.8-3.6 Ma are greater than those during 6.7-4.8 Ma, which is also indicated by the CV of these elements (Table 1).” “Magnetic susceptibility also shows pronounced differences between the two intervals (Fig. 3).” was added at start of **line** 193 and “changes” was modified as “ranges”. **In line** 195, “whilst” was modified as “and” and “fluctuates” was modified as “ranges”. **In line** 199, “larger” was modified as “higher” and “…; the amplitudes and durations” was modified as “... The amplitudes”. **In line** 200, “of the three” was modified as “in the three” and “and longer” was removed. **In line** 201, “From 4.8-4.7 Ma, 4.6-4.25 Ma and from 4.1-3.9 Ma” was modified as “From 16-15 m, 13-11 m and 7-5 m”. **In line** 202, “…the values of the three parameters are high, and they exhibit peaks from 4.6-4.25 Ma” was removed. **In line** 203, “Grain-size analysis” was modified as “Grain size”. **In line** 205, “about 5 Ma, 4.6 Ma and 4.2 Ma” was modified as “about 15m, 12m and 6m”. **In line** 206, “>43um” was modified as “>40um” and “Winter Monsoon” was modified as “winter monsoon”. **In line** 207, “, as well as to other proxies described above” was added after “…clay content” and “>43um curve” was modified as “variation of the >40 μm fraction”. **In line** 208, “while” was modified as “whereas”. **In line** 209, “long-duration” was modified as “lower frequency”.

6. Modifications in discussions

In line 212, “explanation” was modified as “interpretation”. **In line** 213, “varying” was modified as “changing”. **In line** 214, “in responses to changes in precipitation and evaporation intensity” was added after “…deposited”. **In line** 215, “sequence on the CLP records” was modified as “sequences of the CLP”. **In line** 218, “the” was added before “carbonate” and “while” was modified as “whereas”. **In line** 224, “So” was modified as “Thus,”. **In line** 225, “studying” was modified as “characterizing”. **In line** 227, “i.e.,” was modified as “e.g.” . **In line** 230, “while” was modified as “whereas” and “its” was added after “due to”. modify the statement “In addition, previous…”. The statement of **lines** 232-234 was modified as “Sr may substitute for Ca in carbonates, which may limit the environmental significance of the Rb/Sr ratio”. **In lines** 235-237, “…in the XSZ section, while the correlation between Sr and CaCO3 is not significant (99% confidence interval)” was replaced with “at the 99% confidence interval, while the correlation between Sr and $CaCO_3$ is not significant. This means that the variation of Sr is determined by weathering intensity.” **In lines** 237-238, “in our studied samples” was added after “…speculate that” and “in our studied samples (Fig. 4 e and f).” was modified as “(Fig. 4 d and e)”. **In lines** 238-252, the statement of “In addition, previous study…” was modified as “In addition, the K_2O/Na_2O ratio is used to evaluate the clay content in loess and is also a measure of plagioclase weathering, avoiding biases due to uncertainties in separating carbonate Ca from silicate Ca (Liu et al., 1993; Buggle et al., 2011). Na_2O is mainly produced by plagioclase weathering and is easily lost during leaching as precipitation increases. By contrast, K_2O (mainly produced by the weathering of potash feldspar) is easily leached from primary minerals and is then absorbed by secondary clay minerals with ongoing weathering (Yang et al., 2006; Liang et al., 2013). In the arid and semi-arid regions of Asia, K_2O is enriched in palaeosols compared to loess horizons (Yang et al., 2006). Thus, high K_2O/Na_2O ratios are indicative of intense chemical weathering. ”. **In line** 253, “the” was added before “clay (<2 μm)”. **In line** 254, “the ASM” was modified as “EASM”. **In line** 255, “Eolian” was modified as “Aeolian”. **In line** 258, “Grain size” was modified as “The grain-size”. **In line** 259, “confining” was removed , “and” was modified as “to” and “grain size” was modified as “size range”. **In line** 260, “proven to be steady” was modified as “shown to be constant” and “χfd can detect” was modified as “Thus, χ_{fd} can be used”. **In lines** 261-262, “can measure” was modified as “is a measure of”. **In line** 263, “Figure 4A” was modified as “Figure 4a”. **In line** 264, “mostly” was modified as “mainly”. **In**

line 265, “eolian” was modified as “aeolian”. **In lines** 266-267, “..of the red clay on the XSZ planation surface reflects” was modified as “primarily reflects”. The statement of “We use this method…” **in lines** 269-271 was modified as “…, which we use to extract the lithogenic (χ_0) and pedogenic magnetite/maghemite (χ_{pedo}) components. In this study, pedogenic magnetite/maghemite accounts for 11% of the susceptibility ($\chi_{pedo} = \chi_{fd}$ / 0.11).” **In line** 272, “Sun et al., 2006” was modified as “Sun and Huang, 2006b” **In line** 276, “the” was removed. **In line** 277, “is proposed to” was modified as “can be use”. **In line** 278, “between the” was modified as “of”. **In line** 280, “(Fig 6)” was added after “clay”.

In line 281, the first “domain” and “the” were removed. **In line** 283-285, “ky” was modified as “kyr”. “Morlet wavelet transform analysis of both carbonate content and χpedo show that the orbital signal increases since 4.8 Ma” was modified as “the fluctuations in $CaCO_3$, weathering and pedogenesis indices agree well with orbital eccentricity variations during 4.8-3.9 Ma (Fig. 5). Three orbital periodic signals were also detected in the other sites of the CLP from late Miocene to early Pliocene, which means changes of orbital parameters really had impact on climate of the CLP (Han et al., 2011)”. **In line** 289, “As for the non-orbital cycles,” was removed and “these” was modified as “non-orbital cycles”. **In line** 290, the second “the” was removed. **In line** 291, “deposition” was modified as “depositional” and “degrees of” was added before “pedogenesis”. Statement of **lines** 292-295 was replaced with “In the XSZ section, deposition rate was low and uneven, which potentially resulted in the incomplete preservation of the paleoclimatic signal, especially for short precession cycles. Meanwhile, pedogenic and post-depositional compaction would also weaken the orbital signals and produce spurious cycles”. Statement of **lines** 297-299 was modified as “Therefore, we speculate that uneven and low deposition rates combined with compaction and leaching processes may weaken the orbital signals and be responsible for presence of non-orbital cycles in XSZ section”. **In line** 304, “foraminiferal” was removed and “Our” was modified as “The”. **In lines** 305-306, “(especially the 41-kyr component)” was added after “components”, “two” was removed and “…change rapidly from very low amplitude from 6.7-4.8 Ma to a much larger amplitude from 4.8-4.1 Ma” was modified as “changes from a low amplitude during 6.7-4.8 Ma to a relatively high amplitude during 4.8-3.9 Ma”. **In line** 306, “earth” was modified as “Earth”. **In line** 310, “This means that the increased contrast in wet-dry oscillations” was modified as “This may mean that the enhancement for wet-dry contrast”.

In line 314, “Multiporxy evidence for the dry climate during the interval of 6.7-4.8 Ma” was modified as “Multi proxy evidence for a dry climate during 6.7-4.8 Ma”. **In line** 315, “Based on the previous mentioned…” was modified as “We used the aforementioned” and “…, we” was modified as “to”. **In lines** 316-317, “peneplain, NE Tibetan Plateau” was modified as “planation surface”, “ and Table 3” was added after “Figure 6”, “we observe that” was modified as “there is” and “recorded by” was modified as “in”. **In line** 318, “K_2O/Al_2O_3” was replaced with “K_2O/Na_2O” and “occurred” was removed. **In line** 319, “was generally” was modified as “can be”. **In line** 321, “..,K_2O/Al_2O_3” was removed, “also” was added before “support” and “occurrence of” was added before “weak chemical”. **In line** 322, “Importantly” was modified as “Notably,” and “with” was modified as “to”. **In line** 324, “intensity” was removed. **In line** 325, “which” was removed and “supports the” was modified as “support the occurrence of”. **In line** 326, “the” was modified as “an”, “Thus, during this interval the Xiaoshuizi climate was relative arid” was replaced with “the climate at the XSZ site during this interval was relatively arid”. **In line** 327, “which” was removed and “pedogenesis” was modified as “pedogenic”. **In lines** 328-329, “when these proxies detailed climate changes especially when climate is relative wet” was replaced with “between the carbonate and pedogenic indexes”. **In line** 331, “may be” was modified as “is possible that”. **In line** 332, “which” was modified as “since 5.5 Ma” and “since 5.5 Ma” at the end of sentence was removed. **In lines** 333-335, the sentence of “However, from…” was modified as “However, the pedogenic indexes indicate that the generally arid climate was interrupted by two episodes of enhanced pedogenesis, at 5.85-5.7 Ma and 5.5-5.35 Ma”. **In line** 335, “different” was modified as “differences in the”. **In line** 337, “a record of mollusks” was modified as “a coeval mollusk record” and “that” was added after “showed”. **In line** 338, “dominating” was modified as “dominated” , “document the” was modified as “indicates that” and “climate condition on…” was modified as “climatic conditions occurred in…”. **In line** 339, “the” was added after “during”. **In line** 340, “During this interval” was modified as “coeval”. **In line** 342, “obvious” was modified as “principal”, “the Xiaoshuizi” was modified as “at XSZ the” and “is relative” was modified as “was relatively”. **In line** 343, “the” was added before “central”. **In line** 344, “obvious” was removed, “instance” was modified as “example” and “at” was added before “6.2-5.8 Ma”. **In lines** 345-346, “…in the hinterland of the CLP, but are not recorded by the Xiaoshuizi magnetic susceptibility” was replaced with “in the central and eastern CLP, but are absent in the magnetic susceptibility record from XSZ” and “It is worth noting that” was replaced with “Notably,”. **In line** 347, “the” before “Dongwan” was removed before “late Miocene”. **In line** 349, “records” was added after “χpedo”, “are” was modified as “was” and “from” was modified as “from”. **In line** 350, “the” was added before “Summer” and “Index” was modified as “index”. **In line** 353, “6.7-5.2” was modified as “6.7-4.8”. **In lines** 353-354, “The only difference is that the climate in the CLP hinterland fluctuated more significantly than that of the Xiaoshuizi red clay” was modified as “However, the only difference was that the climate in the central and eastern CLP fluctuated more substantially than was the case in the vicinity of the XSZ red clay section”. **In line** 355, “particularly” was modified as “especially”, “western CLP” was removed and “oscillations” was replaced with “climatic oscillations in the western CLP”. **In line** 356, “that” was added after “indicate”, “ASM” was modified as “EASM” and “on” was modified as “in”. **In line** 357, “decreased” was modified as “decreases”. **In line** 360, the first “the” was removed and “The weak palaeo-ASM” was modified as “A weak palaeo-EASM”. **In line** 361, “has been” was modified as “was” and “from” was modified as “in”. **In line** 362, “we deduce that the Asian monsoon” was modified as “we infer that the palaeo-EASM”. **In line** 363, “put a small impact on the Xiaoshuizi climate” was replaced with “had only a minor impact on the climate in the study region.” **In lines** 363-365“during late Miocene, the TP was not intensively uplifted and thus it could not block the westerlies completely (Li et al., 2015)” was removed, “Previous” was modified as “previous” and “suggestion” was modified as “indicated”. **In line** 367, “This means” was modified as “and thus”. **In line** 368, “pedogenesis” was modified as “the variation of the pedogenic” and “parallel to” was modified as “parallels to that of”. **In line** 369, “.., that χ_{pedo} shows a significant positive relationship with $\delta^{18}O$ at 80 % confidence interval (Fig. 4 f).” was added after “(Fig. 6)”. **In line** 370, “pedogenesis” was modified as “pedogenic” and “if the precipitation” was modified as “to conclude that precipitation in the study area”. **In line** 371, “palaeo-ASM. Thus, we speculate from 6.7 to 4.8 Ma, the precipitation” was modified as “palaeo-EASM and thus, we speculate that from 6.7-4.8 Ma precipitation”. **In line** 372, “ASM” was modified as “EASM” and “the climate of our study region” was modified as “regional climate”. The sentence of **lines** 376-377 was replaced with “A sustained cooling occurred in both hemispheres during late Miocene and the cooling culminated between 7 and 5.4 Ma (Herbert et al., 2016).”**In line** 379, statement of “In the Northern Hemisphere, transient glaciations appeared when the cooling culminated (Herbert et al., 2016)” was added before “Records”. **In line** 380, “northern” was modified as “Northern” and “show” was modified as “indicate”. **In line** 382, “In” was modified as “During” and “the” was modified as “a”. **In line** 384, “would have resulted” was modified as “could result”. **In line** 385, “ASM in the late Miocene” was modified as “EASM”. **In line** 386, “(Herbert et al., 2016),” was added after “gradient”. **In line** 388, “was” was modified as “is”. **In lines** 391-392, “Global cooling and the growth of polar ice-sheets reduced the amount of atmospheric water vapor; thus, relatively little moisture was carried by the westerlies, producing…" was replaced with "However, moisture sources for the westerly flow are distant from the CLP (Nie et al., 2014), and only a relatively small amount of moisture was carried to the CLP, resulting in…" **In line** 394, "the" was added before "dry climatic condition".

In line 395, "enhanced" was modified as "pronounced" and "the interval of " was removed. **In line** 396, "available" was removed. **In line** 397, "Xiaoshuizi climate turns into humid condition from previous arid climate" was modified as "previously arid climate of the XSZ area became humid". **In line** 399, "the interval of " was removed. **In line** 400, "obvious" was removed, "observed from 4.8 to 3.9 Ma. The carbonate…" was replaced with "evident during 4.8-3.9 Ma; the carbonate". **In line** 401, "30%" was replaced with "20%". **In line** 402, "Research on migration process of carbonate indicated seasonally wet/dry climate is a key factor in driving carbonate dissolution and reprecipitation, and strong seasonally biased precipitation enhances the leaching process and produces thick leached horizons (Rossinsky and Swart, 1993; Zhao, 1995, 1998)" was added before "The emergence…" **In line** 403, "was" was removed. **In line** 407, "enhanced" was removed. **In line** 408, "From 4.8 to 3.9 Ma, high" was replaced with "High" and "and the" was replaced with "from 4.8-3.9 Ma and" .**In lines** 409-412, "pedogenesis" was modified as "pedogenic", "The K2O/Al2O3 ratio also increased rapidly at about 4.8- 4.7 Ma and maintained relatively high values after 4.7 Ma. This may indicate that the overall weathering intensity was sufficient to produce secondary clays, resulting in a spike in K2O concentration" was removed and "reach the" was replaced with "reached a". **In line** 413, "…as was precipitation intensity, which was manifested by…" was replaced with "..as did precipitation intensity, which is manifested by the…". **In line** 414, "From 3.9 to 3.6Ma" was replaced with "During 3.9-3.6 Ma" and "then" was removed. **In line** 415, "pedogensis intensity weakened" was replaced with "pedogenic intensity also weakened" and ".., which may indicate that the Xiaoshuizi climate is generally humid toward arid direction" was removed. The sentence of **lines** 415-417 was replaced with "Consistent with the records of the XSZ section, mollusk records from Dongwan also indicate the occurrence of warm and humid conditions in the western CLP during the early Pliocene." **In line** 419, "the" was added before "early Pliocene". The sentence of **lines** 419-422 was modified as "Magnetic susceptibility records from the central and eastern CLP are similar to that from the XSZ section in that both the magnitude and the variability are high during 4.8-3.6 Ma" and "enhancement of" was modified as “increased”. **In line** 423, “Obviously” was replaced with “Evidently”. **In line** 424, “from 4.6-4.25 Ma in the XSZ section, the χlf” was replaced with “during 4.60-4.25 Ma in the vicinity of the XSZ section, the magnetic susceptibility”. The sentence of **lines** 425-428 was modified as “However, a record of Fe_2O_3 ratio from Lingtai reveals extremely high values, corresponding to the presence of abundant clay coatings, during 4.8-4.1 Ma and this interval was interpreted as experiencing the strongest EASM intensity in the CLP since 7.0 Ma”. **In line** 430, “considerably” was replaced with “substantially”. The sentence of **lines** 431-432 was replaced with “These various **lines** of evidence indicate that during 4.60- 4.25 Ma the climate was warm and humid in the central CLP”. **In line** 438, “the” was added before “early Pliocene”. **In line** 439, “the” was added before “hematite/goethite”. **In line** 440, “Smectite/Kaolinite ratio there shows” was replaced with “the smectite/kaolinite ratio indicates” and “about” was modified as “~”. **In line** 441, “which indicate the enhancement of palaeo-ASM” was modified as “and thus the enhancement of the palaeo-EASM”. The sentence of **lines** 441-443 was replaced with “Therefore, we regard the climatic change evident in XSZ section as the result of the expansion of the palaeo-EASM”. **In line** 444, “XSZ” was replaced with “the XSZ section”. **In line** 445, “palaeo-ASM may be” was replaced with “the palaeo-EASM may have been”. **In lines** 446-447, “decreasing input of ice raft debris into” was modified as “a decrease in the input of ice-rafted debris to the sediments of the”. **In lines** 447-448, “palaeo-ASM during early..” was modified as “the palaeo-EASM during the early”. **In lines** 450-452, “eastern equatorial Pacific” was replaced with “Eastern Equatorial Pacific” and “These coincides imply that phases of enhanced precipitation may be correlated” was replaced with “This coherence between the record of the XSZ section and marine records implies that phases of enhanced precipitation were correlative”.

In line 453, “mechanism for the paleo-ASM” was replaced with “driver of palaeo-EASM”. **In line** 454, “the” was added before “uplift”. **In line** 455, “The” was removed. **In lines** 456-457, “ASM initiation, having strengthened ASM intensity and changed the shape of the precipitation band in East Asia” was replaced with “EASM in terms of its initiation and strength as well as changing the distribution of the band of high precipitation in East Asia” and “more” was removed. **In line** 465, “very small from” was replaced with “minor from the”. **In line** 466, “the” was added before “middle”. The sentence of **lines** 465-467 was replaced with “Therefore, we speculate that uplift of the TP was not the major cause of the expansion of the palaeo-EASM at ~4.8 Ma.” The sentence of **lines** 469-471 was replaced with “The occurrence of humid climate across the CLP was synchronous with the gradual closure of the Panama

Seaway (Keigwin et al., 1978; O'Dea et al., 2016)". **In line** 471, "the" before "freshening" was removed. **In line** 477, "In particular" was replaced with "Notably". The sentence of "This in turn…" **in lines** 469-471 was removed. **In line** 483, "Arctic" was added before "indicate". **In line** 484, "at present" was replaced with "today". The sentence of "Therefore, even…" **in lines** 484-487 was replaced with "This warmth is also confirmed by other records from high northern latitude regions: diatom abundances and assemblages, pollen data, magnetic susceptibility and sedimentological evidence from Siberia all indicate that the climate was warm and wet in the early Pliocene (Memb B. D. P., 1997, 1999)" and "In contrast, the" was replaced with "The". The sentence of **lines** 489-490 was replaced with "…, and thus the land-ocean thermal contrast was intensified." **In line** 491, "reduced planetary albedo" was replaced with "a reduced ice albedo at high northern latitudes" and "This large land-ocean thermal contrast was essential for enhancing the palaeo-EASM" was added before "On the…" **In line** 494, "(Chang et al., 2011; Sun et al., 2015)" was added after "northward" and "This" was modified as "…, which". **In line** 495, "ASM" was replaced with "palaeo-EASM". **In line** 496, "indicated" was replaced with "shows that" and "at" was replaced with "in". **In line** 497, "It seems to be discrepancy with" was modified as "This appears to be contradictory to the case of the" and "cases" was removed. **In line** 498, "of" was replaced with "in". **In line** 499, "sea-air interaction during early Pliocene is…" was replaced with "that the nature of sea-air interactions during the early Pliocene was…" **In line** 500, "From 4.8 to 4.0 Ma, the thermahaline" was replaced with "From 4.8-4.0 Ma, the thermohaline". **In line** 501, "Chaisson et al., 2000" was modified as "Chaisson and Ravelo, 2000". **In line** 502, "Some" was replaced with "several", "the" was added before "summer" and "We noticed" was replaced with "…: There was". **In line** 503, "occurred in early" was replaced with "in the early". **In line** 504, "….Temperatures" was replaced with "…, and temperatures". **In line** 505, "show" was modified as "showed". **In line** 506, "The thermal" was replaced with "This enhanced thermal". **In lines** 507-508, "In modern times, when the north of western pacific warm pool was" was replaced with "Today, when the northern part of the western pacific warm pool is", the first "the" was removed and "Philippine was" was replaced with "Philippine is". **In line** 509, "Subsequently" was replaced with "…; and subsequently" and "shifted" was replaced with "shifts". **In line** 510, "was" was replaced with "is". The sentence of **lines** 511-512 was replaced with "Further research is needed to determine if this was also the case during the early Pliocene", "the" was added before "warming" and "seawater" was removed. **In line** 511, "Wang et al., 2000;" was removed. **In line** 513, "subtropic" was replaced with "the subtropical” and “been more readily evaporated” was replaced with “promoted increased evaporation”. **In line** 514, “palaeo-ASM leading to” was replaced with “palaeo-EASM, resulting in”. **In line** 515, “Thus, we deduce it may be” was replaced with “In conclusion, we infer that the”. **In line** 516, “the subtropical” was replaced with “subtropical” and “freshening of” was replaced with “the freshening of the”. **In line** 517, “palaeo-ASM during” was replaced with “palaeo-EASM during the”.

7. Modifications in conclusions

In lines 520-522, “Continuous late Miocene-Pliocene red clay preserved on the representative planation surface in NE Tibetan Plateau provides particular opportunity to discuss the Asian monsoonhistory. Multi-proxy records from the XSZ planation surface in the western CLP,…” was modified as “The continuous late Miocene-Pliocene red clay sequence preserved on the planation surface in the NE Tibetan Plateau provides the opportunity to elucidate the history of the Asian monsoon in the western CLP. Multi-proxy records from the XSZ section,…” **In line** 524, “the XSZ records indicate that” was removed. **In line** 525, “over the XSZ section” was added after “precipitation”. **In line** 526, “the hinterland of the” was replaced with “the central and eastern CLP” and “ASM” was replaced with “EASM”. **In line** 527, “during this interval” was replaced with “at this time” and “the XSZ records” was replaced with “the records from the XSZ section”. **In line** 528, “From 4.8 and 3.6 Ma, the” was replaced with “The”. **In line** 532, “the interval of 4.6-4.25 Ma” was replaced with “4.60-4.25 Ma” and “palaeo-ASM” was replaced with “the palaeo-EASM”. **In line** 533, “region” was added after “Arctic”, “the vast” was replaced with “A vast” and “into the” was replaced with “into”. **In line** 534, “water in” was removed. **In line** 535, “the” was added before “early Pliocene”.

8. Modifications in references

The citation style was changed. References **in line** 550-551, 581-582, 586-587, 662-663, 672-673 674-676 and 710-711 was removed. The following references were added:

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9. **Modifications in tables and figures**

Figure 1, 3, 4 and 5 was replaced with new figures. Table 1 was replaced with new table1 and table 2 and table 3 were added.

References cited in the Response:

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Hopefully the revised version is now satisfactory for publication in Climate of the Past.

Best Regrads,

Jijun Li

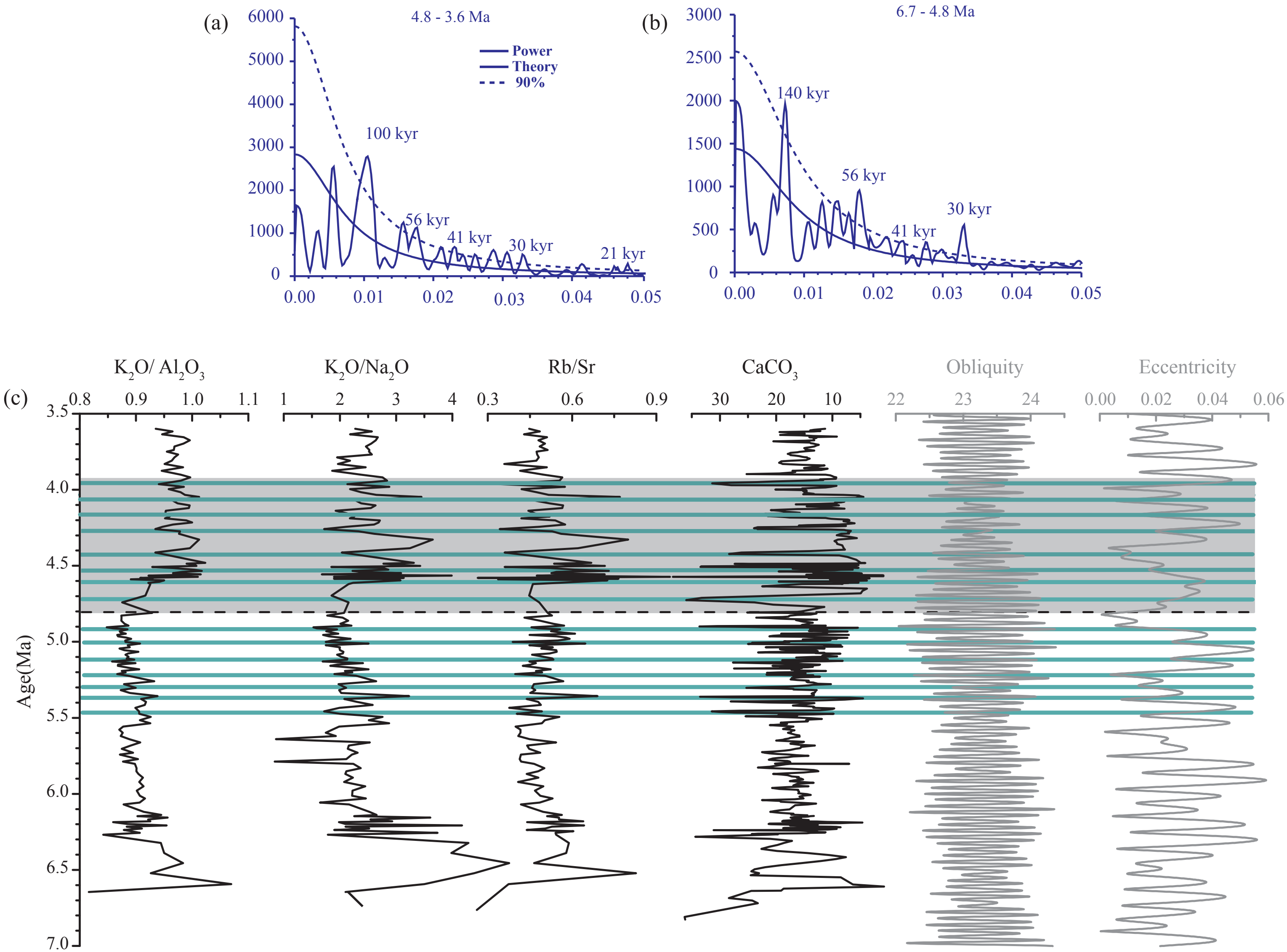

Fig. 1s. Spectrum analysis of carbonate content during the period of (a) 4.8-3.6 Ma (b) 6.7-4.8 Ma on original paleomagnetism chronology. (d) Carbonate and chemical weathering intensity fluctuations linked to eccentricity and obliquity orbital variations at 4.8–3.9 Ma.

Late Miocene-Pliocene climate evolution recorded by the red clay covered on the Xiaoshuizi planation surface, NE Tibetan Plateau

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Abstract

The Pliocene climate and its driving mechanisms have attracted substantial scientific interest because of its potential as an analog for near-future climates. The As an analogue for predicting the future climate, Pliocene climate and its driving mechanism attract much attention for a long time. Llate Miocene-Pliocene red clay sequence ofn the main Chinese Loess Plateau (CLP) has been widely used applied to reconstruct the history of interior Asian aridification and Asian monsoon. climate. However, the typical red clay sequences deposited on the planation surface of the Tibetan Plateau (TP) are rare. A Recently, continuous red clay sequence was recently discovered has been found on the uplifted Xiaoshuizi (XSZ) peneplain planation surface in the Maxian Mountains, northeastern (NE) Tibetan Plateau (TP). In this study, we analyzed multiple climatic proxies from the XSZ red clay sequence tTo reconstruct the late Miocene-early Pliocene climate history of the NE TP ibetan Plateau and to assess the regional climatic differences between the central and western CLP, multiple climatic proxies were analyzed from the Xiaoshuizi red clay sequence. Our results demonstrate the occurrence of minimal weathering and pedogenesis from during 6.7- to 4.8 Ma, which indicates that mplicates that the climate was sustained arid. We speculate that precipitation delivered by the palaeo- East Asian Summer Monsoon (EASM) was limited during this period, and that instead the intensification of the westerlies circulation resulted in arid conditions in the study region. Subsequently, enhanced weathering and pedogenesis occurred during the interval of 4.8-3.6 Ma, which attests to an increaseing in -effective moisture. We Thus, we ascribe the obvious arid-humid climatice transition near 4.8 Ma to the expansion of the palaeo-EASM. expansion. Increasing Arctic temperatures, the vast poleward expansion of the tropical warm

pool into ~~the~~ subtropical regions and the ~~water~~ freshening of ~~in~~ the subtropical Pacific in response to the closure of the Panamanian Seaway may have been responsible for the thermodynamical enhancement of the palaeo-EASM system, which permitted more moisture to be transported ~~carried~~ to the NE TP.~~ibetan Plateau.~~

Keywords: Late Miocene-Pliocene; Xiaoshuizi ~~Peneplain~~Planation surface; Red Clay; Palaeo-EASM; Westerly Circulation

1. Introduction

The Pliocene, including the Zanclean (5.33-3.60 Ma) and Piacenzian (3.60-2.58 Ma) stages, is one of the most intensively studied intervals of the pre-Quaternary on climate change research. The Zanclean climate was generally warm~~ and~~ -wet and often used as an analogue for near-future climate conditions ~~it is analogous to the present day~~ in terms of ~~(i) land-sea distribution, (ii) orbital configuration, (iii)~~ carbon dioxide levels ranging from 280-280-~~380~~ 415 ppm (Tripati et al., 2009; Pagani et al.,2010~~Raymo et al., 1996; Fedorov et al., 2013~~), and ~~(iv)~~ comparable temperatures in the tropic region (Herbert et al., 2010, 2016). ~~In addition, both the Holocene and Zanclean are transitional periods from cold to warm climatic conditions. For these reasons, the early Pliocene climate is often used as an analogue for that of the Holocene and attracts much attention.~~ On the other hand, the Zanclean is ~~unique and some crucial transitions of the~~ markedly different from today and several critical changes in thermohaline and atmospheric circulation towards modern conditions were occurring ~~undergoing~~(Haug et al., ~~1998,~~ 2005; Lawrence et al., 2006;

Chaisson and Ravelo, 2000). For example, the early-Pliocene global mean temperature was approximately 4 ℃ warmer (Brierley and Fedorov, 2010) and the sea levels estimated to have been ~25 m higher than today (Dowsett et al., 2010). Temperatures at ~~the~~ high northern northern latitudes were considerably higher and therefore continental glaciers were almost absent from the Northern Hemisphere (Ballantyne et al., 2010; Dowsett et al., 2010). The zonal and meridional sea surface temperature gradients in the Northern Hemisphere was weak and gradually changed toward a modern much more pronounced spatial temperature contrasts (Fedorov et al., 2013； Brierley et al., 2009, 2010). ~~The warm and wet climate prevailed across the major continents and the warm Arctic is thought to have resulted from an enhanced ggreenhouse effect caused by higher atmospheric moisture content (Abbot and and Tziperman, 2008).~~ The low meridional surface temperature gradient resulted in weaker meridional circulation ~~an "equable" climate~~ during this interval (~~Abbot and Tziperman., 2008;~~ Fedorov et al., 2013; Brierley et al., 2009~~, 2010~~) and ~~. The~~ low east-west sea surface temperature gradient in the tropical Pacific during this interval ~~is also believed to be low, which~~is believed to have ~~is tightly linked with~~ given rise to a permanent El Nino Southern Oscillation (Lawrence et al., 2006). However, ~~debate persists on~~ whether permanent El Nino–like conditions were sustained during the Pliocene is still controversial (Wara et al., 2005; Watanabe et al., 2011; Zhang et al., 2014). Meanwhile, the ~~most significant tectonic movements were the~~ episodic uplift of the TP (Li et al., 2015; Zheng et al., 2000; Fang et al., 2005a, 2005b) and gradual closing of the Panama seaway (Keigwin et al., 1978; O'Dea et al., 2016) were underway. The former substantially influenced the palaeoclimate change (An et al., 2001; Ding et al., 2001; Liu et al., 2014) and the later resulted in reorganization of the global thermohaline circulation (Haug et al., 1998, 2001). (Lunt et al., al., 2008; Haug et al., 1998, 2005). These tectonic movements resulted in major changes in the global thermohaline and atmospheric circulation system which were thought to make crucial preconditions for both appearing of ice sheet in northern hemisphere at ~3Ma (Haug et al., 1998, 2005; Driscoll et al., 1998) and development of modern east-west hydrographic gradient in the equatorial Pacific (Lawrence et al., 2006;Chaisson et al., 2000).Together these observations imply a structural change in global climate from the early early Pliocene to present. We have to ask what the regional climate like under such special climatic and tectonic settings.

East Asia is one of the key regions for studying the aridification of the Asian interior and the Asian monsoon evolution which is tightly linked to the uplift of the TP, the regional climate change and global temperature and ice volume evolution (An et al., 2001; Ding et al., 2001; Li et al., 2008; Clift et al., 2008; Nie et al., 2014; Ao et al., 2016; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014).The ASM and meridional (westerlies) circulation systems, as major components of atmospheric circulation, delivered moisture to Eurasia which might have prepared enough moisture for long-term growth of ice sheet in northern hemisphere between 3 and 2 Ma (Driscoll et al., 1998). Make clear the evolution of the palaeo-ASM and westerlies during early Pliocene is critical to understanding formation mechanism of ice sheet at the Northern high latitudes. Furthermore, the palaeo-ASM might be dynamically linked with the TP uplift, changes in latitudinal and longitudinal heat gradients, global temperature and ice volume during early Pliocene. Warm and wet climate background tends to yield wet climate condition

~~while reductions in the east-west sea surface temperature (SST) gradient in the tropical Pacific results in a weakened summer monsoon (Wang et al., 2000). Several studies have shown that a major atmospheric teleconnection links the ASM with both Arctic volume and the TP uplift (Ding et al., 1990; Li et al., 1991; An et al., 2001; Clift et al., 2008; Sun et al., 2015). Thus, it is crucial to make clear what the climate was like in East Asia under such warm and equable climatic conditions in the Northern Hemisphere.~~

Previous research has revealed that ~~since~~ the ~~late Miocene,~~ red clay was widely deposited since the late Miocene across the CLP, indicating that the ~~onset of interior~~ Asian aridification related to the uplift of the TP ~~occurred~~enhanced (Guo et al., 2001; Song et al., 2007; An et al., 2014; Ao et al., 2016; Li et al., 2017). ~~Element, strata and pollen evidence from the Qaidam and Tarim basin demonstrated that the aridification had intensified since early Pliocene (Fang et al., 2008; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014).~~ In the eastern and central CLP where climate is dominated by East Asian Monsoon, palaeontological evidence, mineral magnetic parameters and geochemical records from the red clay ~~also~~ indicate ~~a~~ dry climatic ~~e~~ conditions during the late Miocene~~;,~~ but ~~however, aridification process was interrupted by a long interval of~~generally wet climatic conditions~~climate~~ during the early Pliocene (Wang et al., 2006; Guo et al., 2001; Wu et al., 2006; Song et al., 2007; Sun et al., 2010; An et al., 2014; Ao et al., 2016). The most controversial climatic~~e~~ change occurred during the interval from ~~of~~ 4.8-4.1 Ma, for which climate reconstructions from different proxies indicate ~~reveal~~ conflicting palaeo-environmental trends. For example, field observations and pollen records indicate an intensified summer monsoon ~~system~~intensity, but low magnetic susceptibility values are more consistent with arid rather than wet climatic conditions (Ding et al., 2001; Ma et al., 2005; Song et al., 2007; Sun et al., 2010). It is ~~'s~~ thought ~~to be substantial gleying~~ that waterlogging and iron reduction resulting ~~ed~~ from high ~~large amount~~ precipitation significantly affected the climatic significance of~~made~~ magnetic susceptibility records during ~~invalid over~~ this period (Ding et al., 2001).~~Obviously, climate changes in westerlies dominated regions and monsoon dominated regions are discrepancy. The inconsistent climate change may be related to different response of westerlies and the palaeo-ASM to global climate changes and the TP uplift during early Pliocene. To clarify the evolution and dynamic of westerlies and the palaeo-ASM, requires accurate paleoclimatic reconstructions in the CLP, especially in the western CLP.~~ In addition to the East Asian Monsoon, the westerlies also had an impact on climate of East Asia. However, patterns of climate change in westerlies dominated regions were different from the eastern and central CLP during the early Pliocene. Geochemical, stratigraphic and pollen evidence from the Qaidam and Tarim basins has demonstrated that aridification had intensified since the early Pliocene (Fang et al., 2008; Sun et al., 2006a, 2017; Chang et al., 2013; Liu et al., 2014). Although the general climatic trends of the main CLP and northern TP during this period were well recorded, palaeoclimatic change in the NE TP which is at the junction of the westerlies and monsoonal influences remains unclear. Therefore, determining the climatic conditions of the NE TP during the early Pliocene not only improves our understanding of the regional climate change, but also provides insights into the responses of the palaeo-EASM and westerlies to TP uplift and changes in the global climate system at this time.

~~Till now, early Pliocene paleoclimatic records from the western CLP red clay are~~

~~lacking. Recently, C~~Continuous red clay sequence was recently discovered ~~has been found~~ on the uplifted ~~Xiaoshuizi (~~XSZ~~)~~ ~~peneplain~~ planation surface in the NE ~~Tibetan Plateau~~TP and has been ~~well~~ dated via high-resolution magnetostratigraphy analysis (Li et al., 2017). The distinctive ~~special~~ geomor~~o~~phological and climatic characteristics of the XSZ ~~iaoshuizi~~ red clay sequence ~~makes~~ differentiates it ~~different~~ from the main CLP red clay, and provides the ~~particular~~ opportunity to reveal the late Miocene-early Pliocene climate history of the~~in~~ NE T~~ibetan Plateau~~ P and to discuss the climatic differences between the central and western CLP ~~red clay~~. In this study, we measured multiple climatic proxies from the ~~have been applied in the Xiaoshuizi~~ late Miocene-Pliocene XSZ red clay ~~sequence~~core and then~~. Then we reconstruct~~ the detailed history of precipitation, chemical weathering and pedogenesis ~~history in the Xiaoshuizi planation surface~~ during ~~the interval of~~ 6.7-3.6 Ma are reconstructed. Finally, the regional climate evolution and its possible mechanisms have been further discussed.

2. Regional background

The XSZ planation surface is ~~locates~~ located in Yuzhong County in the western Chinese Loess Plateau (Fig. 1). The main XSZ planation surface is at an altitude of 2800 m in ~~the~~ Maxian~~shan~~ mountains where it has truncated Precambrian gneiss. The Maxianshan are rejuvenated mountains which protrude into the broad Longzhong Basin, and are in a climatically sensitive zone because of the combined influences of the Asian Monsoon and the northern branch of the mid-latitude westerly circulation system. The planation surface is mantled by over 30 m of loess and over 40 m of red clay. Our previous biomagnetostratigraphic study has demonstrated that the red clay sequence covering ~~ed on~~ the XSZ ~~peneplain~~ planation surface is dated to ~6.9-3.6 Ma (Li et al., 2017). ~~, h~~Here, ~~-~~we use ~~choose~~ the ~~Xiaoshuizi~~ XSZ drill core to reconstruct and discuss the regional climate during the Miocene-Pliocene. The long, continuous well-dated record of the drill core is superior to that of the ~~because of its continuous deposit and whole timescale relative to the~~ Shangyao~~n~~tan core mentioned in Li et al. (2017). Yuzhong County lies within the semi-arid temperate climate zone at the junction of the eastern monsoon area, the arid area of northwest ~~china~~China, and the TP ~~Tibetan Plateau~~ cold region. ~~The mean annual temperature is about 6.7 ℃ and the precipitation amount is 300-800 mm.~~ The mean annual temperature during 1986-2016 was ~7.0 ℃ and the annual precipitation was 260-550 mm. Most (80%) of the precipitation is in summer and autumn. The data were obtained from the National Meteorological Information Center (http://data.cma.cn/) of the Chinese Meteorological Administration (MCA). The spatial distribution of precipitation is uneven, decreasing from south to north in Yuzhong County. Precipitation amount increases with elevation at a rate of 27 mm per 100 m, attaining a maximum of 800 mm at the top of Maxianshan.

3. Material and methods

The XSZ core (35.81154 °N, ~~;~~ 103.8623 °E and 2758.1 m above sea level) is composed of 42 m of pure red clay and ~3 m of red clay with an increasing angular gravel content at the base (Fig. 1b). The red clay is composed of brownish red and yellowish clay layers (Fig. 2). The upper 20 m contains numerous ~~is impregnated with many~~ horizontal carbonate nodule horizons and most of these horizons underline the brownish red layer. There are also ~~; there~~

~~are~~ occasional carbonized plant root channels, elliptical worm burrows and fossil snail shell ~~fossil~~ fragments. Fe-Mn stains are more frequent in the brownish layers than in the yellowish layers, which is also the case for the ~~horizons containing~~ carbonized root channels. The red clay across ~~over~~ the ~~Xiaoshuizi~~ XSZ planation surface is similar to that of typical eolian red clay in the CLP; both are ~~, all of which are~~ characterized by numerous ~~many~~ carbonate nodule-rich horizons (Fig. 2 b).

Samples for ~~Gr~~grain-size, carbonate content and magnetic susceptibility measurements ~~samples~~ were taken at 5-cm intervals, and ~~while~~ samples for geochemical analysis were collected at 25-cm intervals. ~~Each sample age was modeled using linear interpolation to derive absolute ages, constrained by our previous magnetostratigraphic study.~~ The grain-size distribution of samples was measured with a Malvern Mastersizer 2000 with a detection range of 0.02-2000 μm. Magnetic susceptibility ~~(χ)~~ was measured using a Bartington MS2 meter and MS2B dual-frequency sensor at two frequencies (470 Hz and 4700 Hz, designated χ_{lf} and χ_{hf}, respectively). Three measurements were made at each frequency and the final results were averaged. The frequency-dependent magnetic susceptibility (χ_{fd}) was calculated as $\chi_{lf}-\chi_{hf}$. Chemical composition was measured via X-ray fluorescence using a Panalytical Magix PW2403. The sample preparation procedure for XRF analysis was as follows: ~~first, the b~~Bulk samples were ~~as~~ heated to 35℃ for 7 days and then ~~, then each sample was~~ ground to less than 75μm using an agate mortar;~~,~~ ~~and~~ finally, ~~about~~ ~4 g of powdered sample was pressed into a pellet with a borate coating using a semiautomatic oil-hydraulic laboratory press (model YYJ-40). All the measurements were conducted ~~finish~~at ~~ed in~~ the MOE Key Laboratory of Western China's Environmental Systems, Lanzhou University.

Silicate-bound CaO (CaO*) can be estimated, in principle, by the equation: CaO*(mol) = CaO(mol) – CO_2(calcite mol) − 0.5 CO_2(dolomite mol) − 10/3 P_2O_5(apatite mol) (Fedo et al., 1995). It is generally calculated based on the assumption that all the P_2O_5 is associated with apatite and all the inorganic carbon is associated with carbonates. Thus, ~~The~~the ~~molar content of silicate Ca (~~CaO*~~)~~ of the XSZ red clay was calculated using the following equivalent equation:

$$CaO^*(mol) = CaO(mol) - CaCO_3(mol) - \frac{10}{3} * \frac{P_2O_5}{M(P_2O_5)}$$

The carbonate content was measured with a calcimeter using the volumetric method of Avery and Bascomb (1974) in the Key Laboratory of Mineral Resources in Western China (Gansu Province), Lanzhou University.

We use the coefficient of variation (CV) to measure the variability of the records. The higher the CV, the more variable the record. The CV is defined as:

$$CV = 100 * \frac{Standard\ deviation}{Mean}$$

Each sample age was estimated using linear interpolation to derive absolute ages, constrained by our previous magnetostratigraphic study (Fig. 1). The average temporal resolution of the records is 3.8 kyr. Some 80 % of the sequence has a sampling resolution of 4 kyr or less.

4. Results

Profiles of the various proxies are illustrated in Figure 3 and there is an obvious difference in the character of the fluctuations above and below the depth of 16.5 m (~ 4.8

Ma). Above 16.5 m, the carbonate content fluctuates at a lower level but with greater amplitude accompanied by the noted increase in nodule horizons underlaying leached zones in the field, and the magnetic susceptibility also fluctuates at greater amplitude. In addition, the CV of most of the records is greater above the boundary than below (Table 1). This suggests that the climate became more humid and variable after 4.8 Ma. Meanwhile, a noticeable drop in deposition rate around 4.8 Ma occurred (Li et al., 2017). Thus, the red clay sequence was divided into two intervals: *Interval Ⅰ* (6.7-4.8 Ma) and *Interval Ⅱ* (4.8-3.6 Ma). The characteristics of the individual proxy records are described in detail below.

Carbonate content

~~According to the fluctuations in carbonate content, the red clay sequence was divided into two intervals: *Interval Ⅰ* is from 6.7-4.8 Ma, during which~~ During *Interval Ⅰ*, the carbonate content fluctuates from 3.8-39.2% ~~with an average of~~ and has a high average value (17.4%); the carbonate content contrast between leach layers and accumulation layers~~amplitude of fluctuations~~ is generally low ~~small~~ and the carbonate content decreases upwards (Fig. 3). From ~~5.4-4.9~~ 829-16.5 ~~Ma~~m, the ~~carbonate content~~ fluctuations are of greater amplitude than during ~~6.7-5.4 Ma~~42-29 m. ~~*Interval Ⅱ* is from 4.8-3.6 Ma, during which~~ During *Interval Ⅱ*, the carbonate content fluctuat~~es~~ions have a large amplitude (from 1.6-~~-~~39.1%) but a low ~~with an~~ average value ~~of~~ (13.8%). From ~~4.8-3.9~~16.5-4.5 ~~Ma~~ m there are several leaching-accumulation layers, ~~-~~with <7% carbonate content in the leached layers and >20% carbonate content in the accumulation layers.

Element geochemistry

The XSZ red clay consists mainly of SiO_2, Al_2O_3, CaO and Fe_2O_3 with low concentrations (<5%) of MgO, K_2O, Na_2O, Sr, Rb and Ba (Table 1). During *Interval* Ⅰ, K_2O ranges from 1.9-3.3% with an average content of 2.6%. Na_2O ranges from 0.14-1.52% with an average content of 1.2%. Rb ranges from 80-125 ppm with an average content of 103.9 ppm. Sr ranges from 150-252 ppm with an average content of 211.7 ppm. During *Interval* Ⅱ, K_2O ranges from 2-3.7% with an average content of 3%. Na_2O ranges from 0.94-1.54 % with an average content of 1.23%. Rb ranges from 74-134 ppm with an average content of 109.9 ppm. Sr ranges from 141-281 ppm with an average content of 214.6 ppm. ~~The variations in Al_2O_3 and K_2O are synchronous and roughly opposite to that of CaO.~~ The variations in CaO show the same trend as carbonate content. The variations of Rb and K_2O are synchronous and roughly opposite to that of CaO. The changes of Sr show some similarity with magnetic susceptibility before 4.8 Ma but with CaO after 4.8 Ma. ~~When the carbonate content is high, CaO is high, while Al_2O_3 and K_2O are low. The contents of Al_2O_3 and K_2O from 4.8-3.6 Ma are clearly higher than those from 6.7-4.8 Ma. The variations in these element concentrations from 4.8-3.6 Ma are also greater than those from 6.7-4.8 Ma. The changes in Sr are similar to those of CaO, but opposite to those of Ba and Rb.~~Accordingly, table 2 indicates CaO shows positive correlation with $CaCO_3$ and Sr, while negative correlation with other elements. The variations in CaO, K_2O, Sr and Rb content during 4.8-3.6 Ma are greater than those during 6.7-4.8 Ma, which is also indicated by the CV of these elements (Table 1).

Magnetic susceptibility

Magnetic susceptibility also shows pronounced differences between the two intervals (Fig. 3). During *Interval*– Ⅰ, χ_{hf} ranges ~~changes~~ from 9.6-33.3×10^{-8} m^3/kg with an average of

19.4×10^{-8} m^3/kg; ~~,~~ χ_{lf} ranges from 11.4-36.1$\times10^{-8}$ m^3/kg with an average of 20.3$\times10^{-8}$ m^3/kg; and ~~, whilst~~ χ_{fd} ranges ~~fluctuates~~ from 0-2.8$\times10^{-8}$ m^3/kg with an average of 1.0$\times10^{-8}$ m^3/kg. During *Interval*~~–~~ *II*, χ_{hf} ranges from 12.8-53.9$\times10^{-8}$ m^3/kg with an average of 25.4$\times10^{-8}$ m^3/kg; ~~,~~ χ_{lf} ranges from 13.~~5~~6-59.0$\times10^{-8}$ m^3/kg with an average of 26.9$\times10^{-8}$ m^3/kg; ~~,~~ and χ_{fd} ranges from 0-4.7$\times10^{-8}$ m^3/kg with an average of 1.2$\times10^{-8}$ m^3/kg. Clearly, the average values of the three parameters are higher ~~larger~~ during *Interval* ~~-~~ *II* than during *Interval* ~~-~~ *I*. The ~~;~~ ~~the~~ amplitudes ~~and durations~~ of the fluctuations ~~of~~ in the three parameters during *Interval* ~~-~~ *II* are also larger ~~and longer~~ than those during *Interval*~~–~~ *I*. From 16-15 m~~4.8-4.7 Ma~~, 13-11 m ~~4.6-4.25 Ma~~ and ~~from~~ 7-5 m~~4.1-3.9 Ma~~, the values of the three parameters are high~~, and they exhibit peaks from 4.6-4.25 Ma~~.

Grain- size ~~analysis~~

The average clay content (<2 μm~~-~~) is 8.2% during *Interval – I* ~~interval – I~~ and 8.0% during *Interval– II*~~interval II~~. The fluctuations in clay content are minor, except for maxima at about 15m~~5 Ma~~, ~~4.6 Ma~~12m and ~~4.2 Ma~~6m (Fig. 3). The coarse silt component (>~~43~~ 40 μm), mainly carried by the East Asian w~~W~~inter m~~M~~onsoon, exhibits a different trend to that of the clay content, as well as to other proxies described above. From 6.7-4.8 Ma, the variation of the >~~43~~ 40 μm fraction ~~curve~~ is characterized by low values and high-frequency fluctuations, whereas ~~ile~~ after 4.8 Ma it exhibits high values and lower frequency ~~ong-duration~~ fluctuations.

5. Discussion

5.1 Palaeoenvironmental interpretation ~~explanation~~ of the proxies

The carbonate content of aeolian sediments is sensitive to changing ~~varying~~ climatic conditions, and can be readily remobilized and deposited in responses to changes in precipitation and evaporation intensity. Previous studies demonstrated that carbonate in the loess-red clay sequences of~~n~~ the CLP ~~records~~ varies with precipitation (Fang et al., 1999; Sun et al., 2010). The carbonate is mainly derived from a mixture of airborne dusts (Fang et al., 1999). Soil micromorphological evidence from the Lanzhou loess demonstrates that the carbonate grains in loess are little altered, whereas ~~ile~~ those in the palaeosols have undergone a reduction in size as a result of leaching and reprecipitation in the lower Bk horizons as secondary carbonate (Fang et al., 1994, 1999). Furthermore, seasonal alternations between wet and dry conditions are thought to be a key factor in driving carbonate dissolution and reprecipitation (Sun et al., 2010). Thus, changes in carbonate content are generally controlled by the effective precipitation. When effective precipitation is high, carbonate leaching increases, and vice versa. Thus, ~~So~~ the carbonate content is regarded as an effective precipitation proxy for characterizing ~~studying~~ wet-dry oscillations as well as summer monsoon evolution (Fang et al., 1999; Sun et al., 2010).

Chemical weathering intensity is generally evaluated by the ratio of mobile (e.g. ~~i.e.,~~ K, Ca, Sr and Na) to non-mobile elements (e.g.~~,~~ Al and Rb). In general, Sr shows analogous geochemical behavior to Ca and is easily released into solution and mobilized in the course of weathering, whereas~~ile~~ Rb is relatively immobile under moderate weathering conditions due to its strong adsorption to clay minerals (Nesbitt et al., 1980; Liu et al., 1993). Thus, the Rb/Sr ratio potentially reflects chemical weathering intensity. However, ~~the initial Rb/Sr ratio can be affected by the precipitation of secondary carbonate leached from overlying sediments~~

during pedogenesis Sr may substitute for Ca in carbonates, which may limit the environmental significance of the Rb/Sr ratio (Chang et al., 2013; Buggle et al., 2011), which may limit its environmental significance. The correlation between Sr and CaO* (silicate CaO) is significant at the 99% confidence interval, while the correlation between Sr and $CaCO_3$ is not significantin the XSZ section, while the correlation between Sr and $CaCO_3$ is not significant (99% confidence interval). This means that the variation of Sr is determined by weathering intensity. Thus, we speculate that in our samples the Rb/Sr ratio mainly reflects the weathering intensity in our studied samples (Fig. 4 ed and fe). In addition, previous study has proposed that the K_2O/Al_2O_3 ratio can also indicate the weathering intensity. Al_2O_3 is typically chosen to measure the mobility of elements due to its high stability (Taylor et al., 1983), while K_2O (mainly produced by the physical weathering of potash feldspar) is easily leached from primary minerals and then absorbed by secondary clay minerals with ongoing weathering (Yang et al., 2006; Liang et al., 2013). In the arid and semi-arid regions of Asia, K_2O is enriched in palaeosols compared to loess horizons (Yang et al., 2006), meaning that the enrichment of K_2O is positively related with the amount of secondary clay. Thus, to some extent, K_2O/Al_2O_3 reflects the amount of secondary clay and hence weathering intensity. Generally, the K_2O/Na_2O ratio is used to evaluate the secondary clay content in loess and is also a measure of plagioclase weathering, avoiding biases due to uncertainties in separating carbonate Ca from silicate Ca (Liu et al., 1993; Buggle et al., 2011). As the product of plagioclase weathering, Na_2O is easily leached by increasing precipitation. Na_2O is mainly produced by plagioclase weathering and is easily lost during leaching as precipitation increases. By contrast, K_2O (mainly produced by the weathering of potash feldspar) is easily leached from primary minerals and is then absorbed by secondary clay minerals with ongoing weathering (Yang et al., 2006;- Liang et al., 2013). In the arid and semi-arid regions of Asia, K_2O is enriched in palaeosols compared to loess horizons (Yang et al., 2006). As mentioned above, K_2O is easily absorbed by secondary clay particles, meaning that Thus, high K_2O/Na_2O ratios are indicative of intense chemical weathering.

In the red clay-loess sequence of the CLP, magnetic parameters and the clay (<2 μm) content are well correlated and thus are regarded as the proxies of the EASM strength (Liu et al., 2004). AEeolian particles usually have two distinct magnetic components, consisting of detrital and pedogenic material (Liu et al., 2004). χ_{lf} can reflect the combined susceptibility of both components, but changes in χ_{lf} are dominantly affected by changes in the concentration of pedogenic grains (Liu et al., 2004). The Ggrain--size distribution of pedogenic particles confining within the superparamagnetic (SP) to and single-domain (SD) size range grain size has been shown proven to be constant steady (Liu et al., 2004, 2005). Thus, χ_{fd} can be used detect superparamagnetic minerals produced by pedogenesis and therefore the correlation coefficient between χ_{lf} and χ_{fd} is can a measure of the contribution of SP grains (<0.03 μm for magnetite) to the bulk susceptibility (Liu et al., 2004; Xia et al., 2014). As shown in Figure 4aA, χ_{lf} is positively correlated with χ_{fd}, which means that the magnetic susceptibility of the XSZ red clay mainly ostly reflects pedogenic enhancement of the primary aeolian ferromagnetic content through the in--situ formation of fine-grained ferrimagnetic material. This means that the magnetic susceptibility of the red clay on the XSZ planation surface reflects primarily reflects pedogenic intensity. Both the original and pedogenic magnetic signals can be separated using a simple linear regression method (Liu et al., 2004; Xia et al., 2014), which . Wwe use this method to extract the lithogenic original magnetic component (χ_0) and the pedogenic magnetite/maghemite component (χ_{pedo}) components. In this study, pedogenic magnetite/maghemite accounts for χ_{fd} explains 11% of the susceptibility in terms of pedogenic magnetite/maghemite ($\chi_{pedo} = \chi_{fd} / 0.11$).

Pedogenesis results in enhanced secondary clay formation (Sun et al.,and Huang, 2006b); however, not all of the clay particles are derived from in situ pedogenesis, but rather are inherited from aeolian transport and deposition. Clay particles can adhere to coarser silt and sand particles (Sun et al.,and Huang, 2006b). In the western CLP, the coarse silt (>40 μm) content is regarded as a rough proxy for the winter monsoon strength (Wang et al., 2002). Therefore, to eliminate this signal from the primary clay particles, the <2 μm/>40 μm ratio can be used is proposed to evaluate pedogenic intensity. Furthermore, the similarity of the variations of between the <2 μm/>40 μm ratio and χ_{pedo} confirms that both proxies are sensitive to pedogenic intensity in the XSZ red clay (Fig. 6).

5.2 Time- domain and frequency- domain analysis of the carbonate content and χ_{pedo}

Power spectral analyses of carbonate content and χ_{pedo} show different dominant cycles (Fig. 5). In detail, χ_{pedo} is concentrated in the eccentricity (100 kyr), obliquity (41 kyr) and precession (21 kyr) bands and another periodicities (71 kyr and 27 kyr) are also evident. In contrast, the carbonate signal is concentrated in the precession (21 kyr) and obliquity (41 kyr) bands, but it also exhibits even more prominent periodicities at 56 kyr and 30 kyr. Furthermore, the fluctuations in $CaCO_3$, weathering and pedogenesis indices agree well with orbital eccentricity variations during 4.8-3.9 Ma (Fig. 5). Three orbital periodic signals were also detected in the other sites of the CLP from late Miocene to early Pliocene, which means changes of orbital parameters really had impact on climate of the CLP (Han et al., 2011).~~Morlet wavelet transform analysis of both carbonate content and χ_{pedo} show that the orbital signal increases from 4.8 to 4.1 Ma (Fig. 5D).~~

~~As for the non-orbital cycles,~~ King (1996) proposed that non-orbital cycles ~~these~~ may possibly originate from harmonics or interactions of the orbital cycles, while Lu (2004) ascribed them to ~~the~~ unstable dust depositional processes followed by varying degrees of pedogenesis in palaeosol units. In the XSZ section, deposition rate was low and uneven, which potentially resulted in the incomplete preservation of the paleoclimatic signal, especially for short precession cycles. Meanwhile, pedogenic and post-depositional compaction would also weaken the orbital signals and produce spurious cycles.~~Here we speculate that they may be caused by the low deposition rate, which potentially resulted in the incomplete preservation of the paleoclimatic signal, especially for short cycles of precipitation change. Thus, the incomplete nature of the red clay time series may be responsible for the presence of spurious cycles.~~ In addition, the carbonate content at various depths is affected by leaching which means that the record integrates soil polygenetic processes, thus obscuring orbital forcing trends related to precipitation amount. Therefore, we speculate that uneven and low deposition rates combined with compaction and leaching processes may weaken the orbital signals and be responsible for presence of non-orbital cycles in XSZ section.

~~Low deposition rates, compaction and leaching processes would obscure the orbital cycles, and spectral peaks that do not correspond to orbital cycles may reflect these processes.~~

To investigate the post-6.7 Ma evolution of the climate signals in the XSZ section in the frequency domain, we filtered the carbonate content and χ_{pedo} time series at the 100, 41, and 21-kyr periods, using Gaussian band filters centered at frequencies of 0.01, 0.02439, and 0.04762, respectively, and compared them with the equivalent filtered components of the stacked deep-sea benthic foraminiferal oxygen isotope record. The Our results show that the fluctuations of the three filtered components (especially the 41-kyr component) of both two proxies changes rapidly from a very low amplitude during amplitude from 6.7-4.8 Ma to a relatively high a much larger large amplitude during from 4.8-4.13.9 Ma (Fig. 5). The enhanced orbital-scale variability of the two proxies from 4.8-4.13.9 Ma implies an increased seasonality and wet-dry contrasts. This shift is not observed in the Eearth orbital parameters but is observed in the filtered 41-kyr component of the stacked deep-sea benthic foraminiferal oxygen isotope record ($\delta^{18}O$). This may means that the enhancement for wet-dry contrastincreased contrast in wet-dry oscillations at the XSZ site was not driven directly by changes in solar radiation intensity but rather was linked with changes in ice volume or global temperature.

5.3 Late Miocene-Pliocene climate history revealed by the Xiaoshuizi red clay

5.3.1 Multi poroxy evidence for a the dry climate during the interval of 6.7-4.8 Ma

We used the aforementioned Based on the previous mentioned proxies of pedogenesis and chemical weathering to , we reconstruct the late Miocene and early Pliocene climatic history of the Xiaoshuizi peneplainplanation surface., NE Tibetan Plateau. As shown in Figure 6 and Table 3, we observe that there is a significant change in recorded by most of the proxies (carbonate, Rb/Sr, $K_2O/Na_2O$$K_2O/Al_2O_3$ and χ_{pedo}) occurred near 4.8-4.7 Ma, and therefore the climatic record was can be generally divided into two intervals. During interval

I (6.7-4.8 Ma), the relatively high carbonate values with minor fluctuations indicate that the climate was dry, ~~–~~and low Rb/Sr~~, K_2O/Al_2O_3~~ and K_2O/Na_2O ratios also support the occurrence of weak chemical weathering. Notably, ~~Importantly,~~ both the Rb/Sr and K_2O/Na_2O ratios show opposite trends to ~~with~~ carbonate content, meaning that low effective precipitation resulted in weak chemical weathering. ~~intensity.~~ Furthermore, the pedogenic proxies (<2 µm/>40 µm ratio, χ_{pedo} and χ_{lf})~~,~~ ~~which~~ characterised by low values with minor fluctuations, generally support~~s~~ the occurrence of weak pedogenesis under an ~~the~~ arid climate. Thus, ~~during this interval~~ the climate at the XSZ ~~iaoshuizi~~ site during this interval ~~climate~~ was relatively arid, ~~which~~ characterized by weak chemical weathering and pedogen~~es~~ic~~s~~ intensity. However, subtle differences exist between the carbonate and pedogenic indexes~~when these proxies detailed climate changes especially when climate is relative wet~~. It is evident that the carbonate content decreases with increased variation amplitude after 5.5 Ma, which is consistent with the cycles of carbonate nodules within paleososol horizons observed in the field (Li et al., 2017). It is possible ~~may be~~ that increased precipitation since 5.5 Ma ~~which~~ induced eluviation-redeposition of carbonate~~since 5.5 Ma~~. However, the ~~from~~ pedogenic ~~esis~~ indexes indicate that ~~we observe that~~ the generally arid climate was interrupted by two episodes of enhanced pedogenesis, ~~events (occurred~~ at 5.85-5.7 Ma and 5.5-5.35 Ma.~~, respectively).~~ The subtle differences may result from ~~different~~ differences in the sensitivity of magnetic susceptibility and carbonate content to precipitation variability when precipitation is low (Sun et al., 2010). In addition, a coeval mollusk record ~~of mollusks~~ from the western Liupanshan showed that cold-aridiphilous species dominated, ~~ing~~ which also indicates that ~~document the~~ cold and dry climatic ~~e~~ conditions occurred in ~~on~~ the western

CLP during the late Miocene (Fig. 7 g).

Coeval ~~During this interval,~~ pollen, mollusk and magnetic records from the central and eastern CLP also indicate generally dry and cold climatic conditions (Wang et al., 2006; Wu et al., 2006; Nie et al., 2014). However, the principal ~~obvious~~ difference is that at ~~the~~ XSZ ~~iaoshuizi~~ the arid climate was~~is~~ relatively stable, while the climate of the central and eastern CLP was interrupted by several ~~obvious~~ humid stages. For example, ~~instance,~~ two humid stages (at 6.2-5.8 Ma and 5.4-4.9 Ma) are recorded by the magnetic susceptibility of red clay in the ~~hinterland of~~ central and eastern CLP, but are absent in the magnetic susceptibility record from ~~not recorded by the~~ XSZ ~~iaoshuizi magnetic susceptibility~~ (Fig. 7). Notably, ~~It is worth noting that~~ the 41-kyr filtered component of thermo-humidiphilous species from ~~the~~ Dongwan was damped in the late Miocene (Li et al., 2008). Similarly, the amplitude of the orbital periodicities, filtered from the XSZ carbonate content and χ_{pedo} records, was~~are~~ obviously damped during ~~from~~ 6.7-4.8 Ma. However, the three periodicities in the Summer Monsoon ~~Index~~ index from the central CLP show no obvious difference between the late Miocene and Pliocene, but only a slight reduction in variability after 4.2 Ma (Sun et al., 2010). Therefore, we agree that a dry climate prevailed on the CLP during the interval of 6.7-~~5.2~~4.8 Ma. However, the ~~. The~~ only difference was~~is~~ that the climate in the central and eastern CLP ~~hinterland~~ fluctuated more substantially than was the case in the vicinity of the ~~significantly than that of the~~ XSZ ~~iaoshuizi~~ red clay section.

The especially ~~particularly~~ damped response of the ~~western CLP~~ wet-dry climatic oscillations in the western CLP to obliquity forcing may indicate that the palaeo-EASM had a negligible influence in ~~on~~ the western CLP. It is widely known that the summer monsoon intensity decreasessd from southeast to northwest across the CLP. A regional climate model experiment demonstrated that the modern East Asian Summer Monsoon was not fully established in the late Miocene and had only a small impact on the northern China (Tang et al., 2011). A The weak palaeo-EASM intensity from 7.0-4.8 Ma was has been revealed by hematite/goethite and smectite/kaolinite ratios at ODP Site 1148 in from the South China Sea (SCS) (Fig. 7. i and j). Therefore, we infer deduce that the Asian monsoonpalaeo-EASM was weak and had only a minor put a small impact on the climate in the study region. Xiaoshuizi climate. In addition, during the late Miocene, the TP had not yet been substantially was not intensively uplifted and thus it did not completely could not block the influence of the westerlies completely (Li et al., 2015). However, Pprevious studies indicated suggested that the red clay may have been transported by both low-level northerly winds and upper-level westerlies (Sun et al., 2004; Vandenberghe et al., 2004) and thus . This means the impact of the westerly circulation on the study region cannot be ignored. Notably, the variation of the pedogenesis pedogenic proxies roughly parallels to that of the stacked deep-sea benthic foraminiferal oxygen isotope curve (Fig. 6), that and χ_{pedo} shows a significant positive relationship with $\delta^{18}O$ at 80 % confidence interval (Fig. 4 f). It indicates when global temperature was low, pedogenic esis intensity increased. It is unreasonable to conclude that if the precipitation in the study area was dominated by the palaeo-EASM and . Tthus, we speculate that from 6.7- to 4.8 Ma, the precipitation transported by the palaeo--EASM was limited and the westerly circulation probably dominated the regional climate. of our study region.

The simultaneous reduction in amplitude of the 41-kyr filtered components from the western CLP and the deep sea δ^{18}O record from 6.7-4.8 Ma likely indicates that the dry climate was related to changes in global temperature and ice volume. A sustained cooling occurred in both hemispheres during the late Miocene and the cooling culminated between 7 and 5.4 Ma (Herbert et al., 2016). ~~Look around the globe, a cooling climate would be witnessed in late Miocene.~~ δ^{18}O records from DSDP and ODP sites show an increase of ~1.0‰ during the late Miocene which resulted from the increased ice volume and the associated decrease in global temperature (Zachos et al., 2001). In the Northern Hemisphere, transient glaciations appeared when the cooling culminated (Herbert et al., 2016). Records from high latitude regions of the N~~n~~orthern Hemisphere indicate ~~show~~ continuously decreasing temperatures and increasing ice volume during the late Miocene (Jansen and Sjøholm, 1991; Mudie and Helgason, 1983; Haug et al., 2005). During ~~In~~ the Quaternary, a~~the~~ dry climate prevailed during glacial periods when global average temperature (especially in summer) was low. Cool summers ~~would have resulted~~could result in a small land-sea thermal contrast which in turn weakened the palaeo-EASM~~ in the late Miocene~~. Furthermore, the increased ice volume in the Northern Hemisphere resulted in an increased meridional temperature gradient (Herbert et al., 2016), thus strengthening the westerlies and driving them southward. This would have prevented the northwestward penetration of the Asian Summer Monsoon, which is ~~was~~ also proposed as the driving mechanism for a weak EASM in northern China during glacial periods (Sun et al., 2015). Thus, the southward shift of the westerlies had a significant impact on the XSZ region. However, moisture sources for the westerly flow are distant from the CLP (Nie et al., 2014), ~~Global cooling and the growth of polar ice sheets reduced the amount of atmospheric water vapor;~~ and only a ~~, thus~~ relatively small amount of little moisture was carried to the CLP, producing resulting in a dry and stable climate in the XSZ region. In conclusion, global cooling and increasing ice volume in the Northern Hemisphere contributed to the dry climatic conditions in the study region.

5.3.2 Humid climate with pronounced enhanced fluctuations during the interval of 4.8-3.6 Ma

During interval Ⅱ (4.8-3.6 Ma), the available proxy evidence indicates that the previously arid climate of the Xiaoshuizi XSZ area became climate turns into humid. condition from previous arid climate. The carbonate content was low on average but with large fluctuations, indicating that the climate was generally humid with increased dry-wet oscillations, especially during the interval of 4.8-3.9 Ma. Several obvious eluvial-illuvial cycles are evident observed during from 4.8- to 3.9 Ma; . Ththe carbonate content in the eluvial horizons was less than 7%, whereas in illuvial horizons it exceeded 3020% (Fig. 6). Research on migration process of carbonate indicated seasonally wet/dry climate is a key factor in driving carbonate dissolution and reprecipitation, and strong seasonally biased precipitation enhances the leaching process and produces thick leached horizons (Rossinsky and Swart, 1993; Zhao, 1995, 1998). The emergence of high--frequency cycles of carbonate eluviation-redeposition indicates that seasonal precipitation was increased during this interval. Furthermore, the variations of Rb/Sr and K_2O/Na_2O ratios are very similar to those of carbonate content, which suggests that weathering intensity was related to precipitation amount. Generally, high <2 μm / >40 μm ratio, χ_{pedo} and χ_{lf} correspond to large contrasts in carbonate content between eluvial and illuvial horizons; thus, increased precipitation had a significant influence on enhanced pedogenic intensity. From 4.8 to 3.9 Ma, h High precipitation persisted from 4.8-3.9 Ma and ~~the~~ weathering and ~~pedogenesis~~ pedogenic intensity were strong.~~The K_2O/Al_2O_3 ratio also increased rapidly at about 4.8-4.7 Ma and maintained relatively high values after 4.7 Ma. This may indicate that the overall weathering intensity was sufficient to produce secondary clays, resulting in a spike in K_2O concentration.~~ From 4.60-4.25 Ma, pedogenesis and weathering intensity reached a ~~the~~ maximum, as did ~~was~~ precipitation intensity, which is ~~was~~ manifested by the enhanced eluviation and carbonate accumulation. ~~From 3.9 to 3.6~~During 3.9-3.6 Ma, precipitation decreased, and ~~then~~ weathering and pedogenic ~~sis~~ intensity also weakened~~, which may indicate that the Xiaoshuizi climate is generally humid toward arid direction~~. Consistent ~~ing~~ with the records of the XSZ section, ~~records, Dongwan~~ mollusk records from Dongwan also indicate~~d~~ the occurrence of ~~the~~ warm and humid ~~wet~~ conditions in ~~on~~ the western CLP during the early Pliocene (Fig. 7 h).

Palynological and terrestrial mollusk records from the central CLP also indicate relatively humid conditions during the early Pliocene (Wang et al., 2006；Wu et al., 2006). ~~The m~~Magnetic susceptibility records from the central and eastern CLP ~~hinterland~~ are ~~exhibit~~ similar to that from the ~~characteristics to the~~ XSZ section ~~re~~in that both the ~~cords that both the~~ magnitude and the variability ~~of magnetic susceptibility~~ are high during ~~large from~~ 4.8-3.6 Ma. From 4.1-3.9 Ma, the increased ~~enhancement of~~ magnetic susceptibility indicates that humid climatic conditions prevailed across the entire CLP (Fig. 7). Evidently, ~~Obviously,~~ when precipitation amount peaked during ~~from~~ 4.60-~~-~~4.25 Ma in the vicinity of the XSZ section, the magnetic susceptibility ~~χ_{lf}~~ values at Xifeng, Lingtai and Chaona were low.

However, a record of ~~the Lingtai~~ Fe_2O_3 ratio from Lingtai ~~record~~ reveals ~~showed a~~extremely ~~n extraordinary~~ high values, corresponding to the presence of abundant clay coatings, during ~~over the interval of about~~ 4.8~~ Ma -~~-4.1 Ma and this interval was interpreted as experiencing the strongest EASM intensity in the CLP since 7.0 Ma (Ding et al., 2001). In addition, the relative intensity of pedogenic alteration of the grain-size distribution was the strongest during the interval from 4.8-4.2 Ma in the Lingtai section (Sun et al., 2006c). Pollen assemblages at Chaona indicate a substantially ~~considerably~~ warmer and more humid climate from 4.61-4.07 Ma (Ma et al., 2005). These various lines of ~~ese~~ evidence~~s~~ indicate that during 4.60- 4.25 Ma the climate ~~f~~was~~rom 4.6-4.25 Ma is~~ warm and humid ~~wet~~ in the central CLP. Gleying has been implicated in reducing the value of magnetic susceptibility as a record of precipitation during this period (Ding et al., 2001). When soil moisture regularly exceeds the critical value, dissolution of ferrimagnetic minerals occurs and the susceptibility signal is negatively correlated with pedogenesis (Liu et al., 2003). This by itself indicates that precipitation was likely to have been very high during this interval.

In summary, a wet climate prevailed across the CLP in the early Pliocene. At the same time, the hematite/goethite ratio from the SCS also indicates ~~showed~~ enhanced precipitation amount and the ~~S~~smectite/~~Kaolinite~~ kaolinite ratio indicates ~~there showed~~ increased seasonality at ~~about~~ ~4.8 Ma (Fig. 7 i and j), and thus the ~~which indicate the~~ enhancement of the palaeo-EASM (Clift et al., 2006, 2014). Therefore, ~~us,~~ we regard the climatic change evident in XSZ ~~climate change of Xiaoshuizi~~ section as the result of the expansion of the p~~P~~alaeo-EASM ~~expressed in its intensity and reach during this interval~~.

The remarkably increased amplitude of the 41-kyr filtered components from the XSZ section and the deep sea $\delta^{18}O$ record at about 4.8 Ma indicates the expansion of the palaeo-EASM may have been related to changes in global temperature and ice volume. Furthermore, a decrease ~~ing input~~ in the input of ~~of~~ ice-~~-~~rafted debris to the sediments of the ~~into~~ subarctic northwest Pacific was synchronous with the expansion of the palaeo-EASM during the early Pliocene (Fig. 6). In addition, from 4.8-4.7 Ma and 4.6-4.25 Ma, the high values of the three pedogenic indices at the XSZ section indicate that strong pedogenic intensity corresponded with high SSTs in the ~~eastern~~ Eastern ~~equatorial~~ Equatorial Pacific (EEP). This~~ese~~ coherence between the record of the XSZ section and marine records ~~coincides~~ implies ~~y~~ that phases of enhanced precipitation were ~~may be~~ correlative ~~ed~~ with changes in SST and ice volume (or temperature) at northern high latitudes.

5.4 Possible driver of ~~mechanism for the~~ palaeo-EASM expansion during early Pliocene

Ding (2001) proposed that the uplift of the TP to a critical elevation resulted in an enhanced summer monsoon system during 4.8-~~-~~4.1 Ma. ~~The~~ TP uplift was shown to have had profound effects on the EASM in terms of its initiation and ~~, having~~ strength~~ened ASM intensity~~ as well as ~~and~~ changing the ~~ed~~ distribution of the band of high ~~the shape of the~~ precipitation ~~band~~ in East Asia (Li et al., 1991, 2014; An et al., 2001). A ~~more~~ detailed modeling study demonstrated that the uplift of the northern TP mainly resulted in an intensified summer monsoon and increased precipitation in northeast Asia (Zhang et al., 2012). From 8.26-4.96 Ma, massive deltaic conglomerates were widely deposited and the sediment deposition rate increased, indicating the uplift of the Qilian Mountains (Song et al., 2001). At the same time, the Laji Mountains underwent ~~a~~ pronounced uplift by thrusting at ~~about~~ ~8 Ma, which resulted in the current basin-range pattern (Li et al., 1991; Fang et al., 2005a; Zheng et al., 2000). However, geological and palaeontological records indicate that the uplift of the eastern and northern margins of the TP was very minor small from the late Miocene to the middle Pliocene (Li et al., 1991, 2015; Zheng et al., 2000; Fang et al., 2005a, 2005b). Therefore, weSo we speculate that uplift of the TP was uplift may be not the major cause conof the tribution to the expansion of the palaeo-EASM at ~occurred at 4.8 Ma.

As mentioned above,Tthe occurrence of an extremely humid wet climate across the CLP was synchronous with the gradual closure of the Panama Seaway (Keigwin et al., 1978; O'Dea et al., 2016)., which led to a larger reorganization of the global thermohaline circulation pattern. Nie (2014) proposed that the freshening of the Eastern Equatorial and North Pacific surface water, resulting from the closure of the Panama Seaway since 4.8 Ma (Haug et al., 2001), led to sea ice formation in the North Pacific Ocean, which enhanced the high-pressure cell over the Pacific and increased the strength of southerly and southeasterly winds. However, there was a warming trend in the Northern Hemisphere at 4.6 Ma (Haug et al., 2005; Lawrence et al., 2006). The gradual closure of the Panama Seaway resulted in the reorganization of surface currents in the Atlantic Ocean. Notably, In particular, the Gulf Stream was enhanced and began to transport warm surface waters to high northern latitudes, thus strengthening the Atlantic meridional overturning circulation and warming the Arctic (Haug and Tiedemannet al., 1998,; Haug et al., 2005). This in turn resulted in higher global atmospheric water vapor levels which promoted warm moist conditions during the Pliocene (Abbot and Tziperman, 2008; Dowsett et al., 2010). Three independent proxies from an early Pliocene peat deposit in the Canadian High Arctic indicate that Arctic temperatures were 19 ℃ warmer during the early Pliocene than today at present (Ballantyne et al., 2010).~~Therefore, even freshening of the Pacific led to sea ice formation in the North Pacific Ocean. However, this process would be delayed (occurring during 3.2-2.7 Ma) and the extent of the sea ice in the early Pliocene was thus very limited.~~ This warmth is also confirmed by other records from high northern latitude regions: diatom abundances and assemblages, pollen data, magnetic susceptibility and sedimentological evidence from Siberia all indicate that the climate was warm and wet in the early Pliocene (Memb B. D. P., 1997, 1999). ~~In contrast, the~~ The warming of the northern high latitude region led to increases in summer temperature in the mid-latitudes of Eurasia. On the other hand, equatorial SSTs remained stable or cooled slightly (Brierley et al., 2009; Fedorov et al., 2013)~~. This amplified~~ , and thus the land-ocean thermal contrast was intensified. ~~essential for enhancing the palaeo-ASM.~~ Furthermore, external heating derived from a reduced ~~planetary~~ ice albedo at high northern latitudes also enhanced the thermal contrast between the Pacific and Eurasian regions (Dowsett et al., 2010). This large land-ocean thermal contrast was essential for enhancing the palaeo-EASM. On the other hand, the unusually warm Arctic and small meridional heat gradient in the Northern Hemisphere pushed the Intertropical Convergence Zone northward (Chang et al., 2013; Sun et al., 2015), which~~. This~~ weakened the westerly circulation and thus facilitated the northwestward expansion of the palaeo-EASM.

Figure 6 shows that ~~indicated~~ high values of pedogenic indices in ~~at~~ the XSZ section correspond with high SSTs in the EEP. This appears to be contradictory to the case of the ~~It seems to be discrepancy with the~~ modern ENSO ~~cases~~ (when the EEP temperature is high, the precipitation amount in ~~of~~ the western CLP is low). The discrepancy may indicate that the nature of sea-air interactions during the early Pliocene was ~~is~~ different from today. From 4.8-

~~to~~ 4.0 Ma, the ~~thermahaline~~ thermohaline circulation was reorganizing and creating a precondition for the development of the modern equatorial Pacific cold tongue (Chaisson and Ravelo, 2000). Several ~~ome c~~crucial changes linked with the summer monsoon occurred: There was ~~. We noticed~~ a vast expansion of the western Pacific warm pool into subtropical regions ~~occurred~~ in the early Pliocene (Brierley et al., 2009; Fedorov et al., 2013), and ~~.~~ ~~T~~temperatures at the edge of the warm pool showed a warming trend of ~2℃ from the latest Miocene to the early Pliocene (Karas et al., 2011). This enhanced ~~. The~~ thermal state of the WEP warm pool significantly enhanced the summer monsoon and its northward extension. Today, ~~In modern times,~~ when the northern part of the ~~of~~ western pacific warm pool is ~~was~~ warm, ~~the~~ convection over and around the Philippines is ~~was~~ enhanced; and ~~. S~~subsequently, the northern extent of the western Pacific subtropical high shifts ~~ed~~ northwards from the Yangtze River valley to the Yellow River valley and moisture is ~~was~~ introduced across the entire CLP (~~Wang et al., 2000;~~ Huang et al., 2003). Further research is needed to determine if ~~Whether~~ this was ~~it is~~ also the case during the ~~for the~~ early Pliocene. ~~or not needs further researching.~~ However, the warming and freshening ~~seawater~~ of the subtropical Pacific would have promoted increased ~~been more readily~~ evaporation ~~ed~~ which would have provided enhanced moisture for the palaeo-EASM, resulting in ~~leading to~~ increased rainfall across the CLP.

In conclusion, we infer that the ~~Thus, we deduce it may be~~ warming of high northern latitudes, accompanied by the vast poleward expansion of the tropical warm pool into ~~the~~ subtropical regions and the freshening of ~~water in~~ the subtropical Pacific, facilitated the expansion of the palaeo-EASM during the early Pliocene.

6. Conclusions

The ~~C~~continuous late Miocene-Pliocene red clay sequence preserved on the ~~representative~~ planation surface in the NE Tibetan Plateau provides the ~~particular~~ opportunity to elucidate the history of the ~~discuss the~~ Asian monsoon in the western CLP. ~~history.~~ Multi-proxy records from the XSZ section, ~~planation surface in the western CLP,~~ together with other paleoclimatic records from the CLP, reveal two intervals of major climatic change from 6.7- ~~to~~ 3.6 Ma. During the first interval (6.7-4.8 Ma), ~~the XSZ records indicate that~~ both the amount and variability of precipitation over the XSZ section were small; however, they were much greater in ~~the hinterland of~~ the central and eastern CLP. Thus, the palaeo-EASM had little influence on the climate of the western CLP at this time. ~~during this interval.~~ During the second interval (4.8-3.6 Ma), the records from the XSZ section ~~records~~ indicate that both the amount and variability of precipitation were large. ~~From 4.8 and 3.6 Ma, t~~The climate was characterized by abrupt increases in the seasonality of precipitation, which attests to a major northwestward extension and enhancement of the summer monsoon. Obviously, multiple paleoclimatic proxies show that the strongest summer monsoon occurred during ~~the interval of~~ 4.60-4.25 Ma. The expansion of the palaeo-EASM may have been caused by warming of the Arctic region, a ~~the~~ vast poleward expansion of the tropical warm pool into ~~the~~ subtropical regions, and freshening of ~~water in~~ the subtropical Pacific in response to the closure of the Panamanian Seaway during the early Pliocene.

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Figures and tables

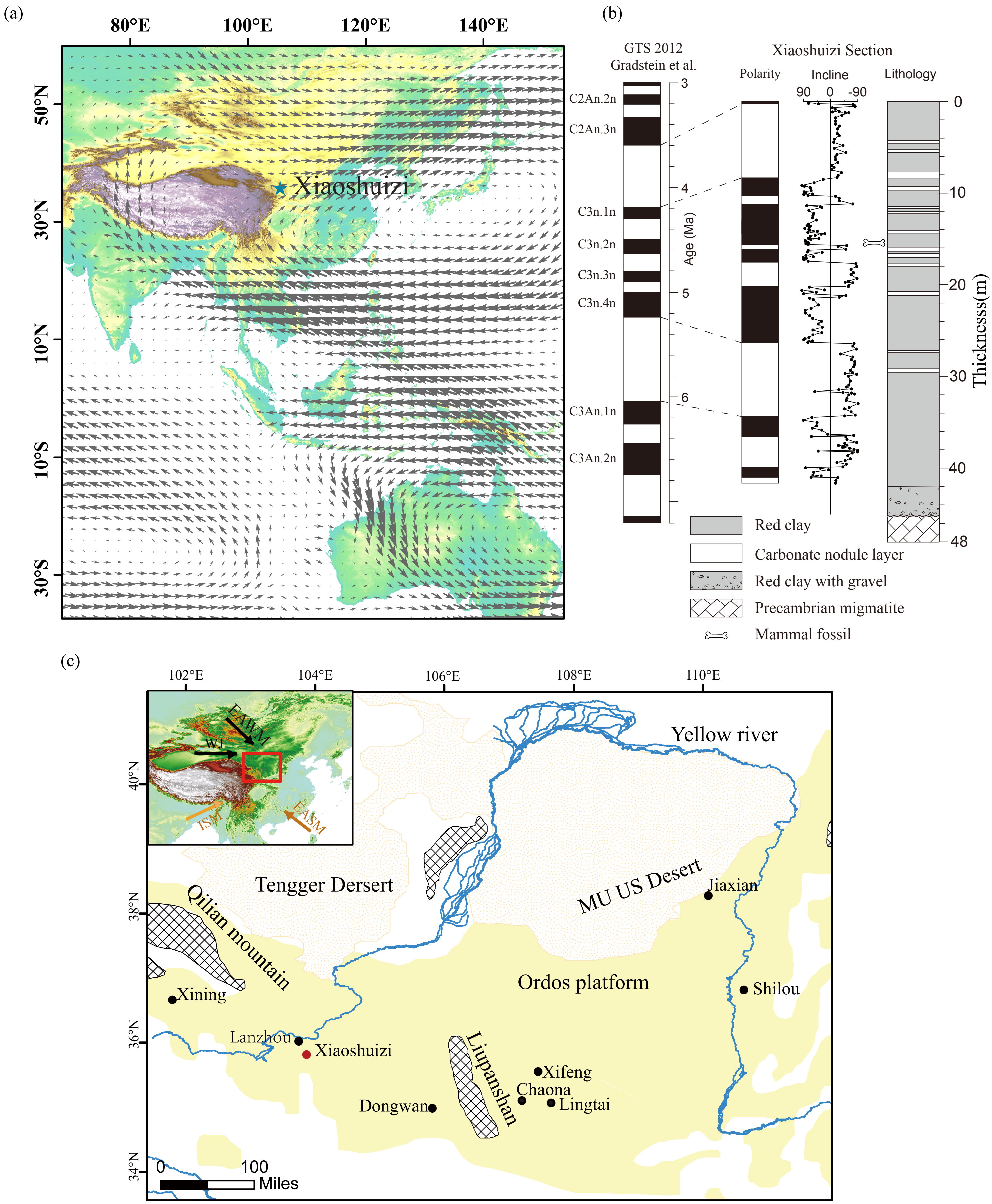
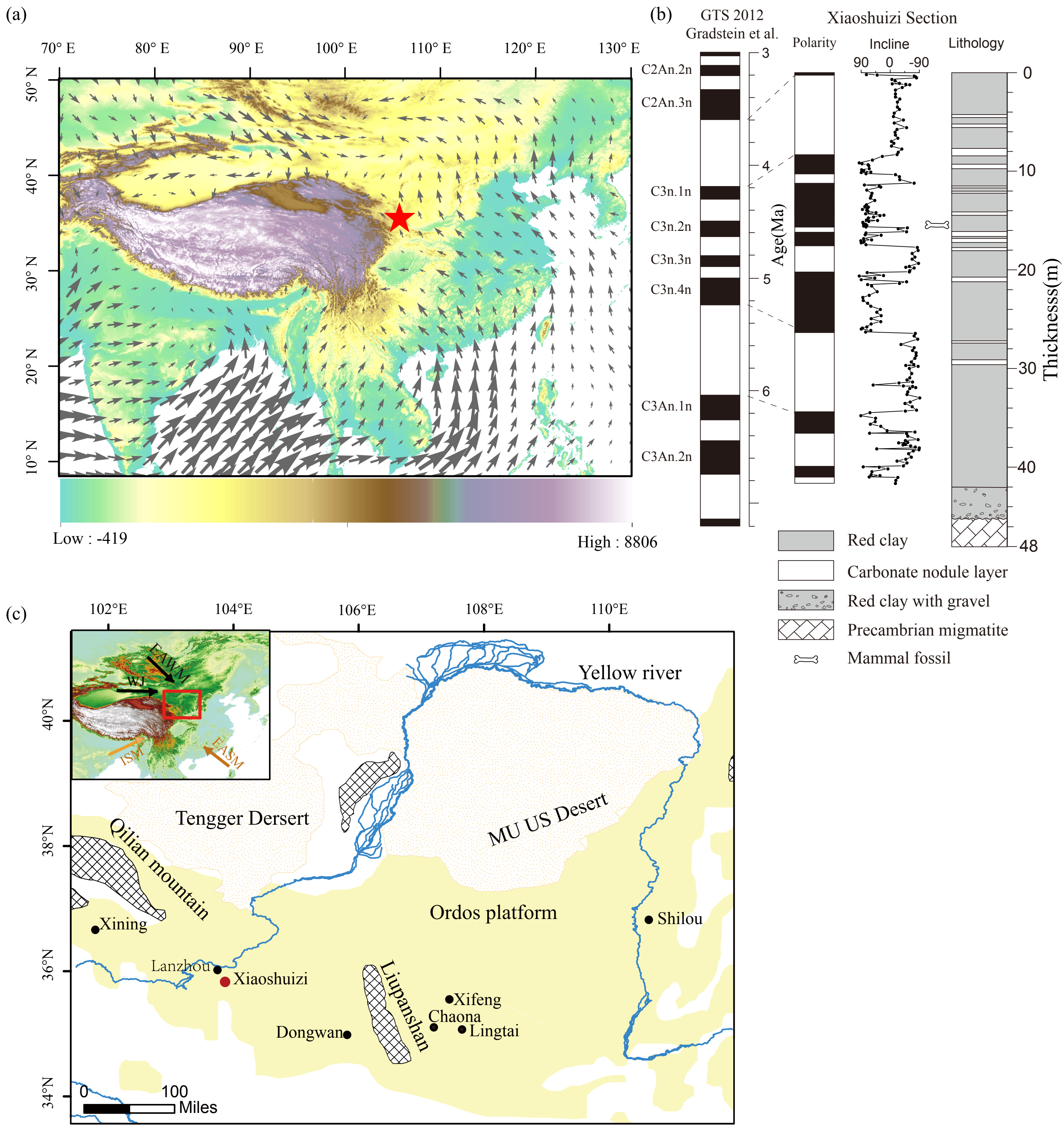


Fig. 1. The location of the study area and atmospheric circulation patterns. (a) 850 mb vector windaveraged from June to August for 1982-2012 based on NOAA Earth System Research Laboratory reanalysis data (Compo et al., 2013). (b) Lithology and magnetostratigraphy of the XSZ drill core (Li et al., 2017). (c) The Chinese Loess Plateau with locations of the studied Xiaoshuizi site and other sections mentioned in the text.



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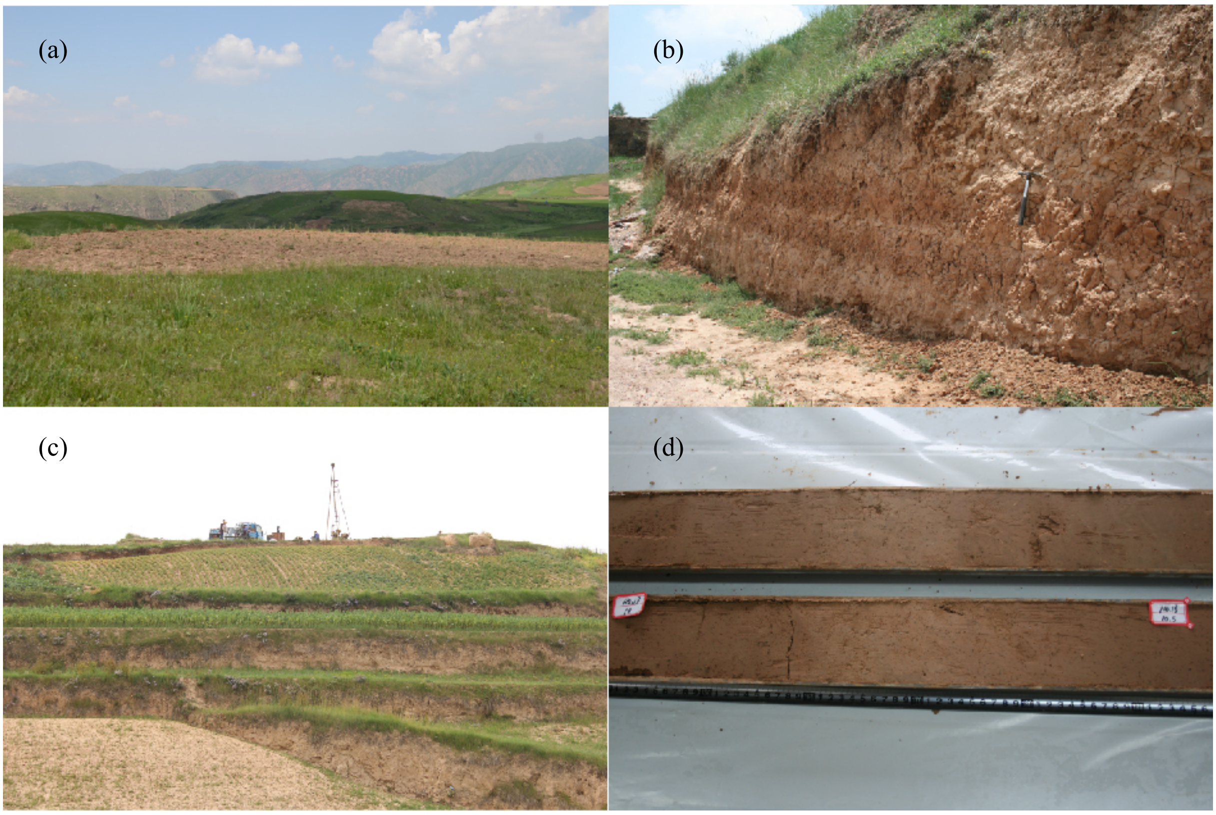
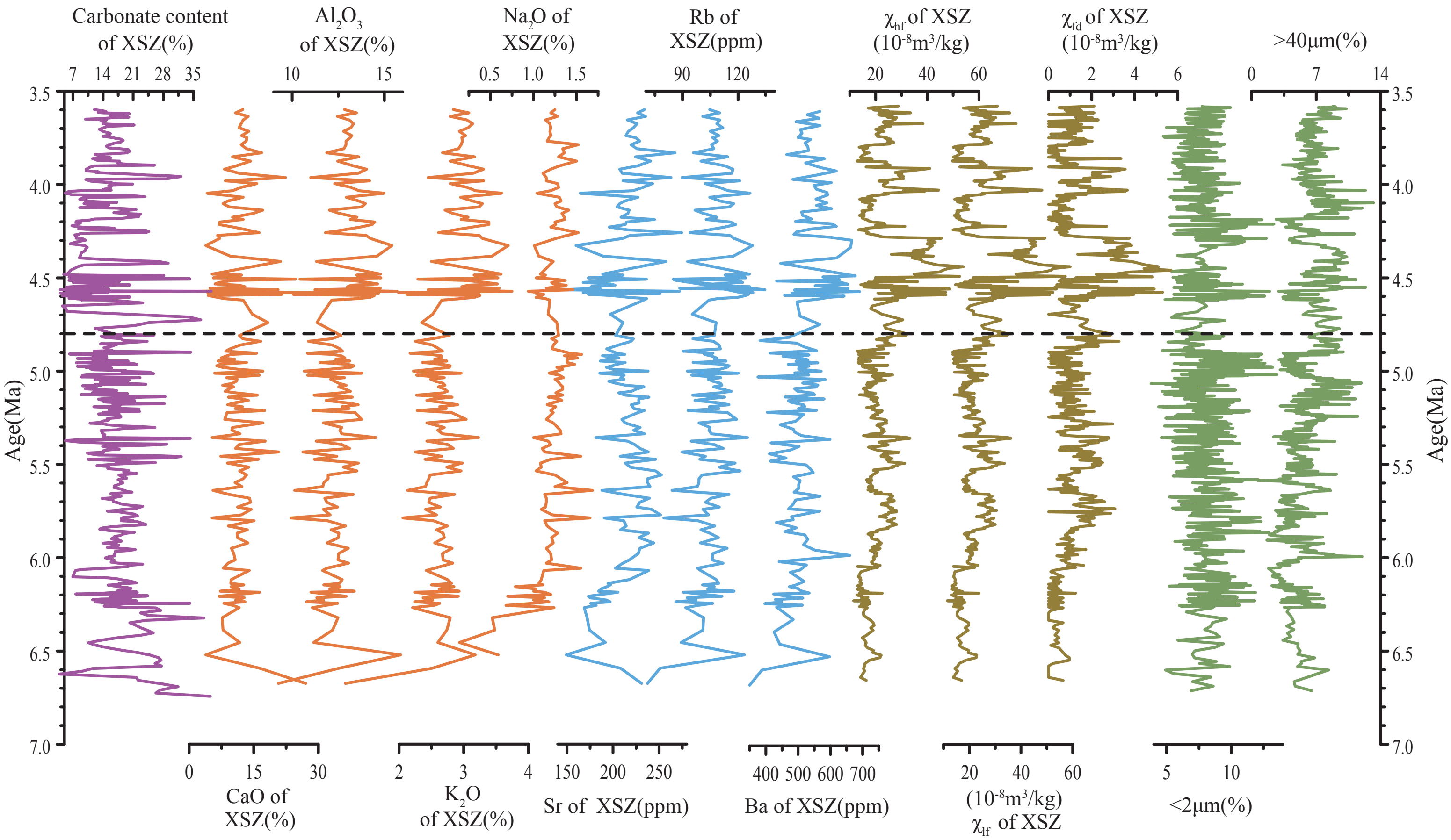
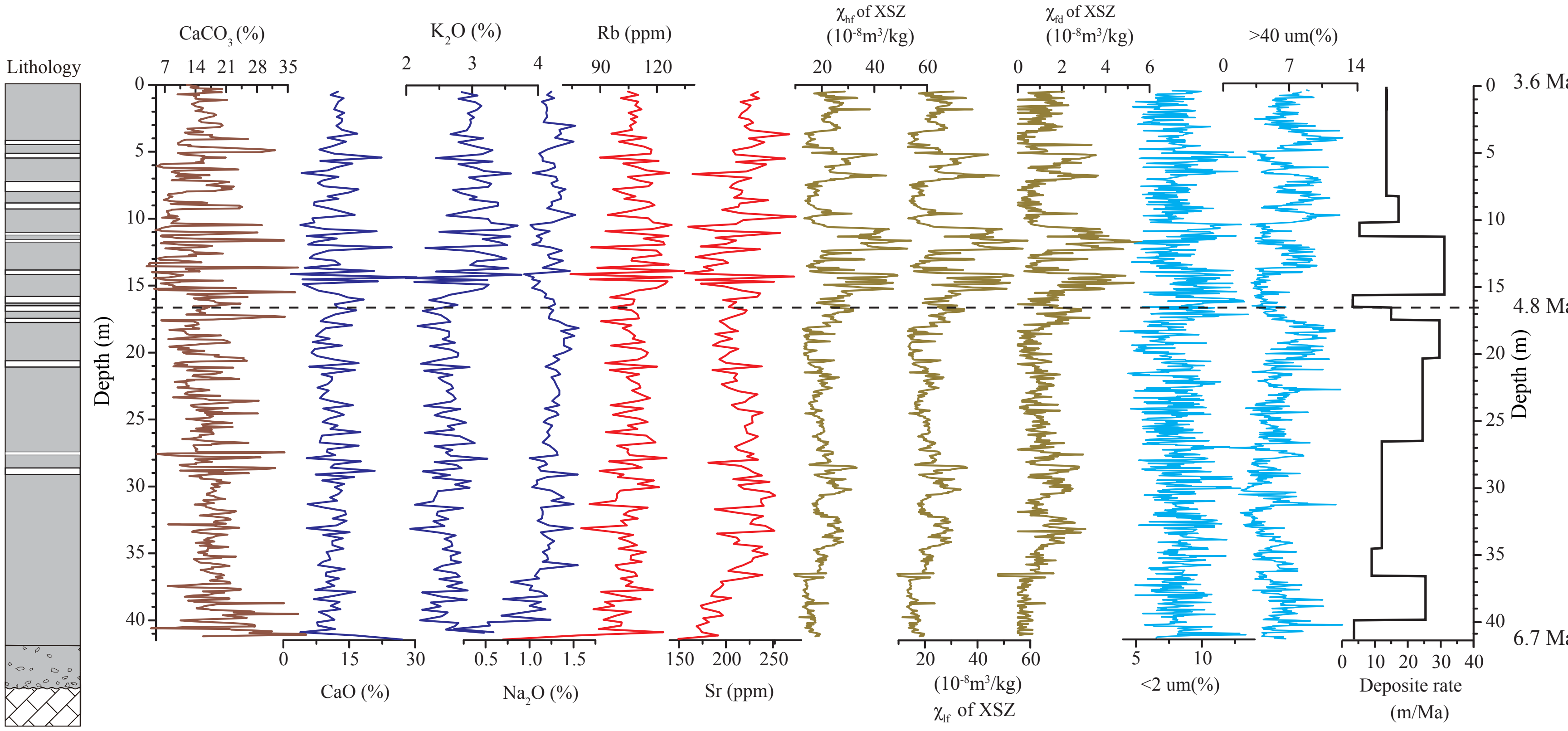


Fig. 2. Photos of the XSZ planation surface and the red clay. (a) XSZ planation surface. (b) Red clay outcrop, XSZ. (c) Position of the XSZ drilling hole. (d) The XSZ drill core.



~~Fig. 3. Variations in carbonate content, major element concentration, minor element concentration, magnetic susceptibility and grain size from the XSZ red clay section, spanning 6.7-3.6 Ma.~~



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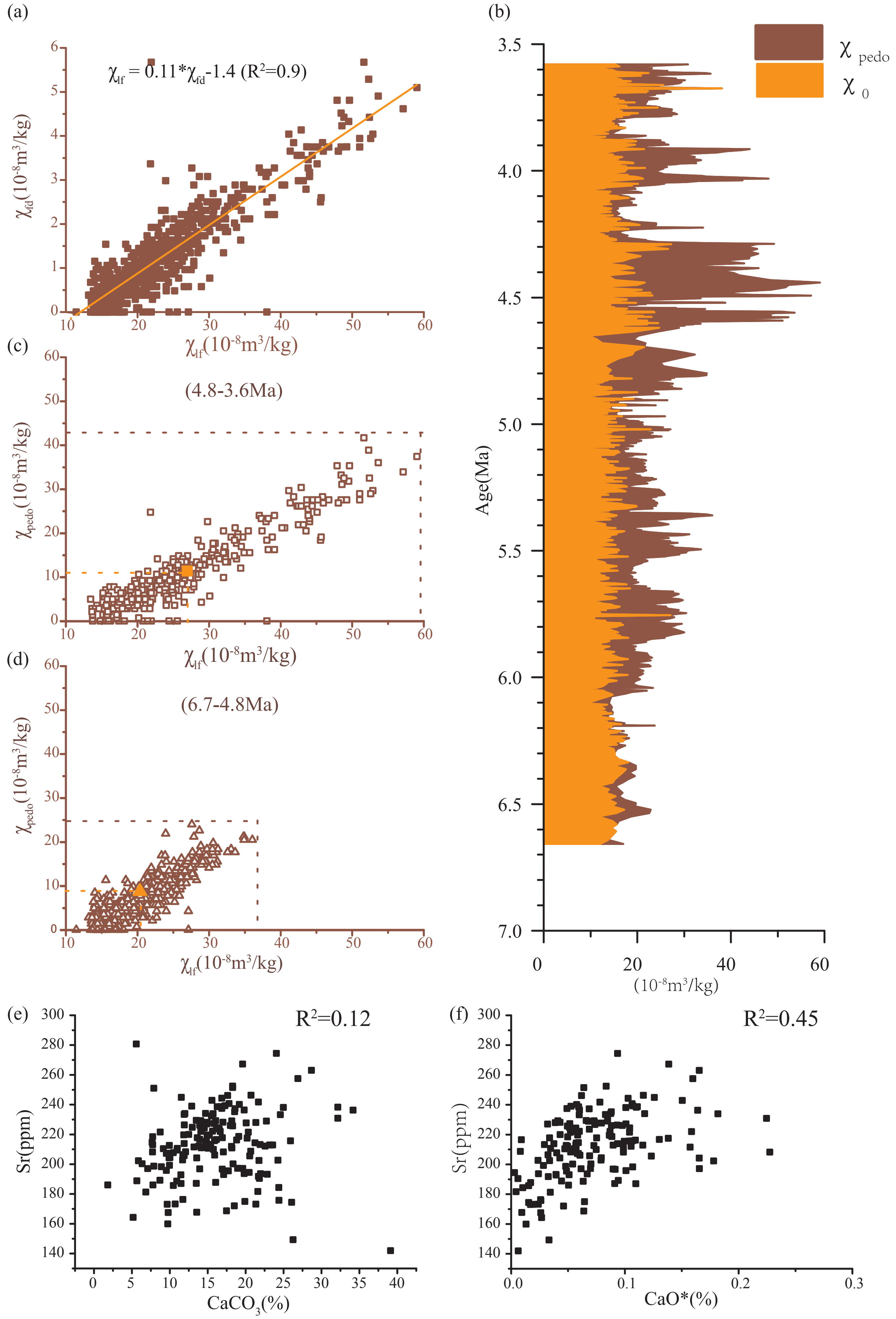
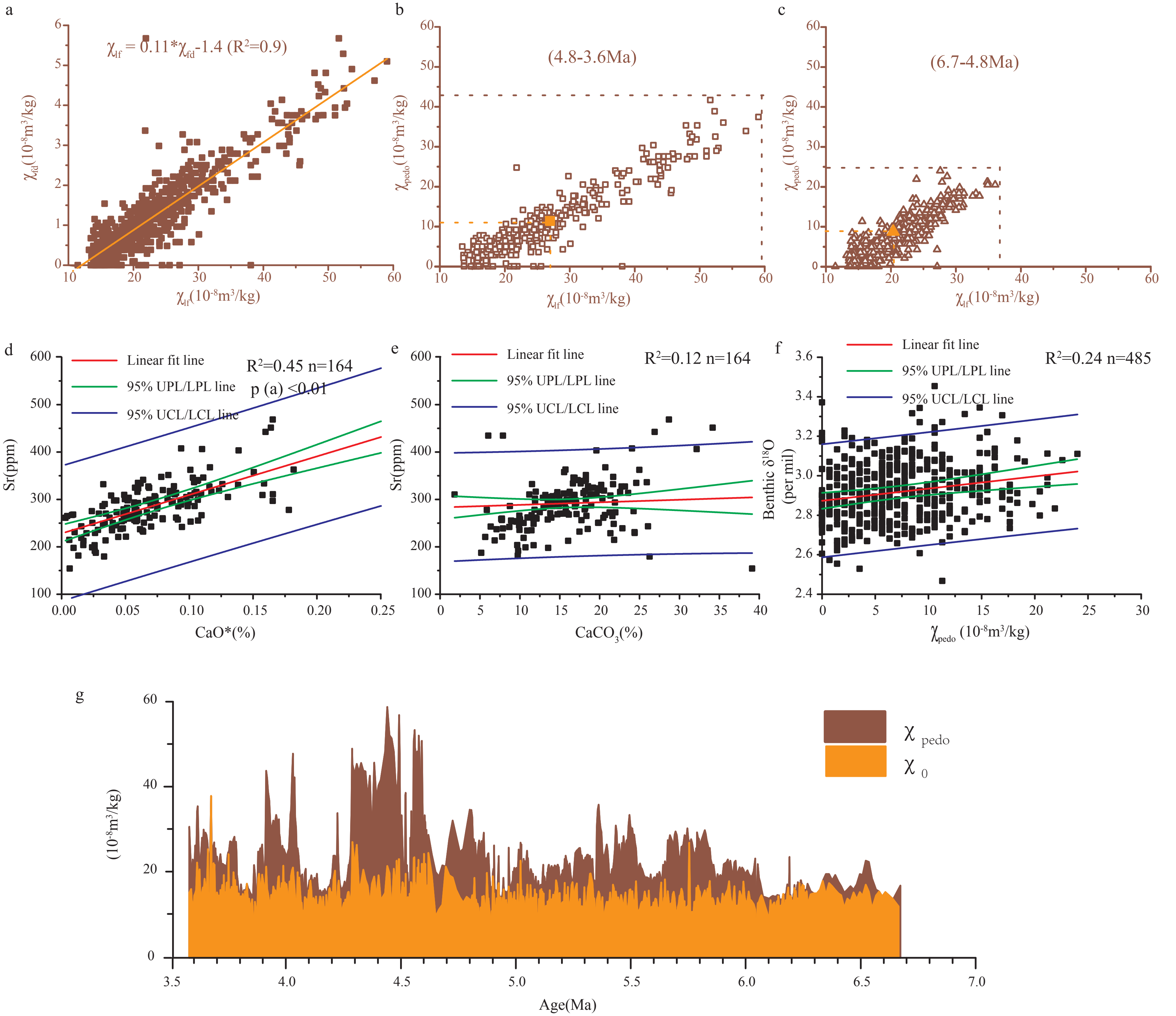


Fig. 4. (a) Scatter plots of χ_{lf} versus χ_{fd}. (b) Separation of χ_{pedo} and χ_0. (c) Scatter plot of χ_{lf} versus χ_{pedo} during 4.8-3.6 Ma. (d) Scatter plot of χ_{lf} versus χ_{pedo} during 6.7-4.8 Ma. (e) Scatterplot of Sr versus $CaCO_3$. (f) Scatter plot of Sr versus CaO*. Solid squares and triangles are the average values during 4.8-3.6 Ma and 6.7-4.8 Ma, respectively. χ_{pedo} is the magnetic susceptibility of pedogenic origin and χ_0 is the magnetic susceptibility of the detrital material.



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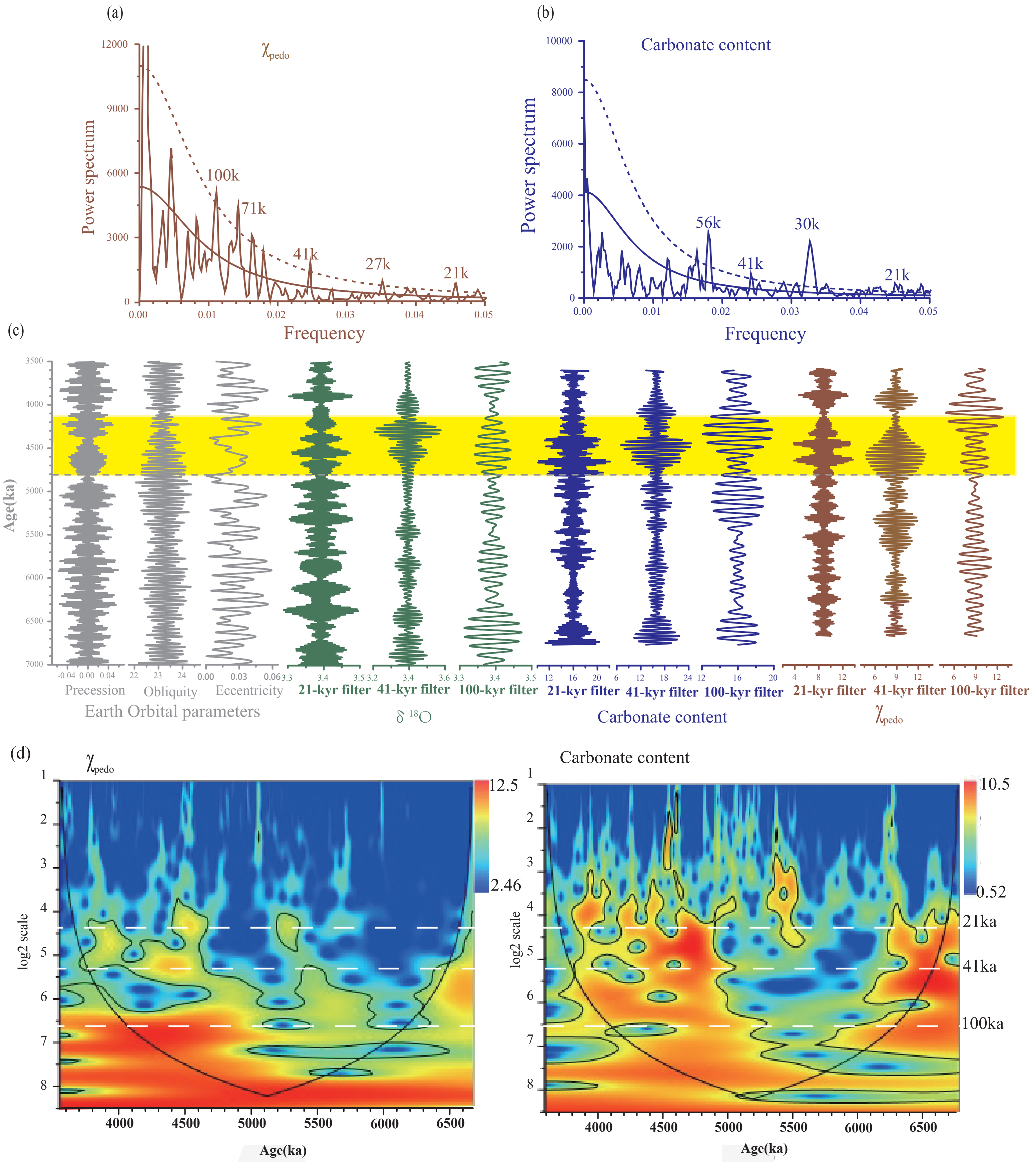
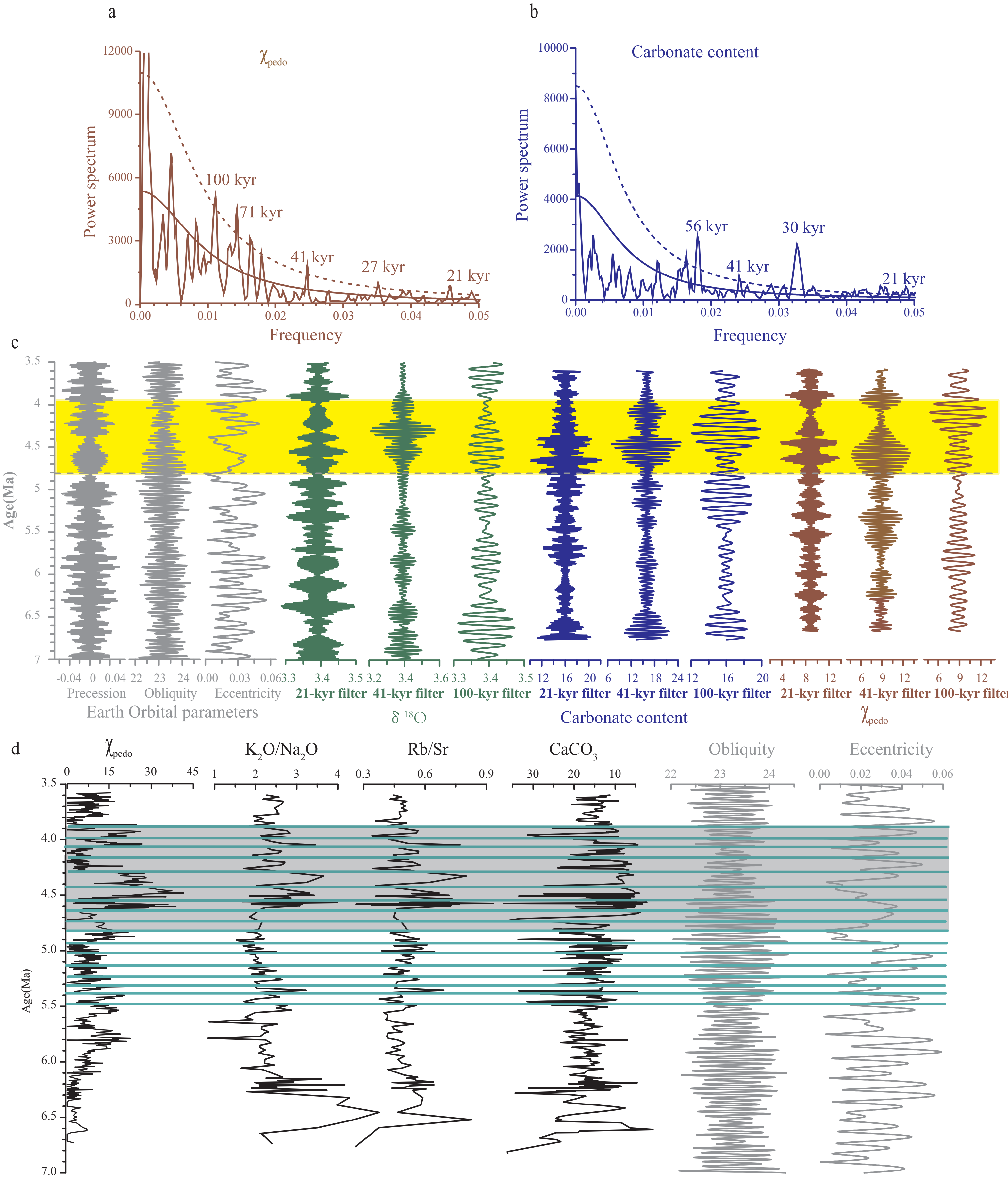


~~Fig. 5. Spectrum analysis of the red clay. (a) χ_{pedo} and (b) carbonate content(blue) on original paleomagnetism chronology. Dashed lines are 90% confidence limit lines. (c) Comparison of orbital parameters (i.e., eccentricity, obliquity and precession,Laskar et al., 2004) with filtered components of the carbonate content, χ_{pedo} and $\delta^{18}O$ records (Zachos et al.,2001) at the 21-kyr, 41-kyr, and 100-kyr bands. Yellow shading denote the largest amplitude of filtered components of carbonate and χ_{pedo} at the three orbital bands. Dashed lines indicate a large shift in the East Asian monsoon circulation occurred around 4.8 Ma. (d) Results of the wavelet transform of χ_{pedo} and carbonate content time series.~~



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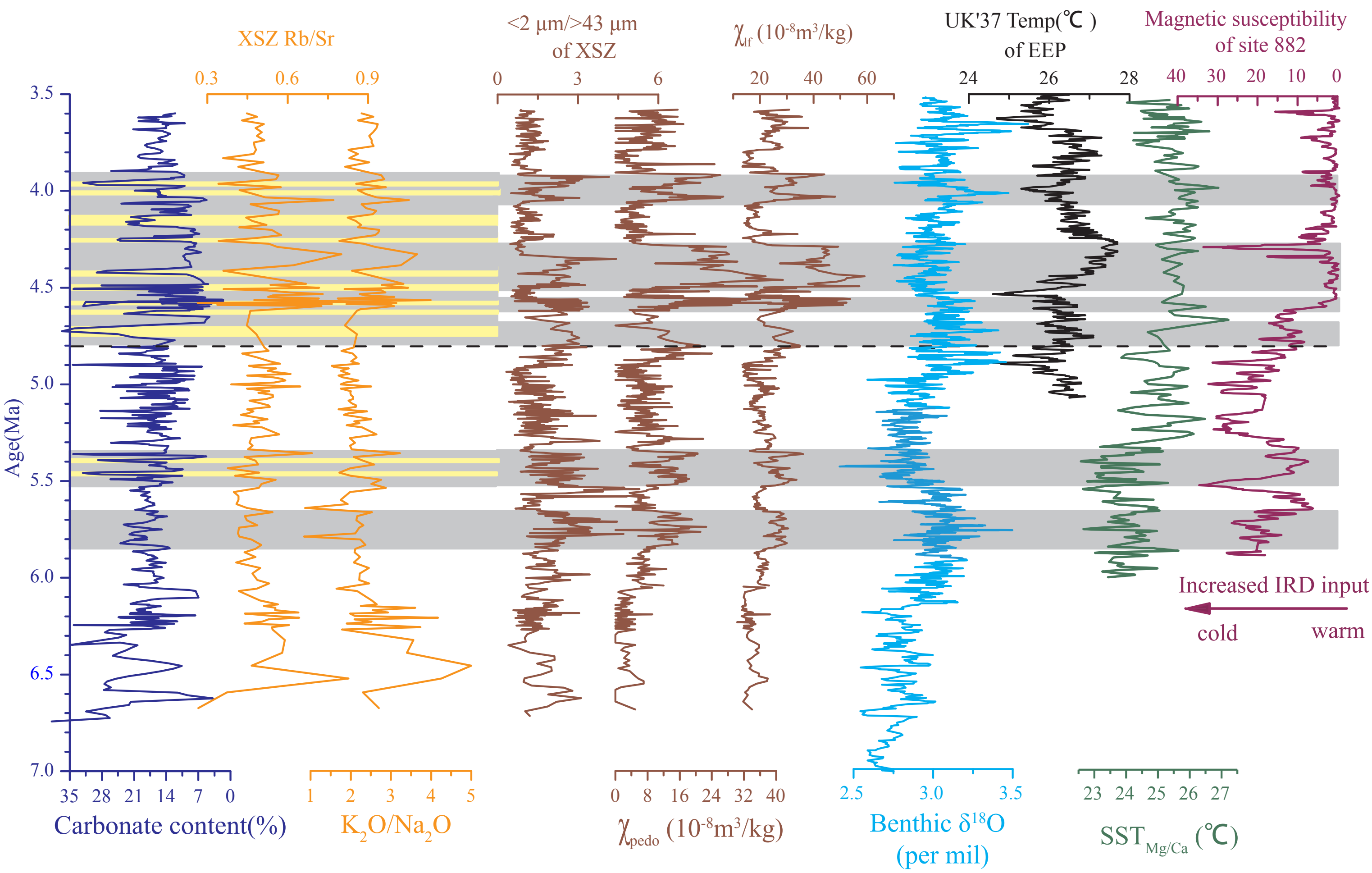

Fig. 6. Temporal evolution of the palaeo-ASM. The dark blue line represents changes in effective precipitation at XSZ, the orange line represents changes in chemical weathering intensity, and the brown lines represent changes in pedogenic intensity. The blue line is the stacked deep-sea benthic foraminiferal oxygen isotope curve compiled from data from DSDP and ODP sites (Zachos et al., 2001). The black line is a reconstruction of sea surface tempeature in the eastern equatorial Pacific (EEP) from ODP Site 846 (Lawrence et al., 2006). Green line is a reconstruction temperature at the edge of warm pool from southwest Pacific Ocean Site 590B (Karas et al., 2011). Purple line is magnetic susceptibility from ODP Site 882 (Haug et al., 2005). Gray shading shows ~~intervals of strong palaeo-ASM~~ relatively wet periods and the light-yellow shading shows intervals of carbonate accumulation.

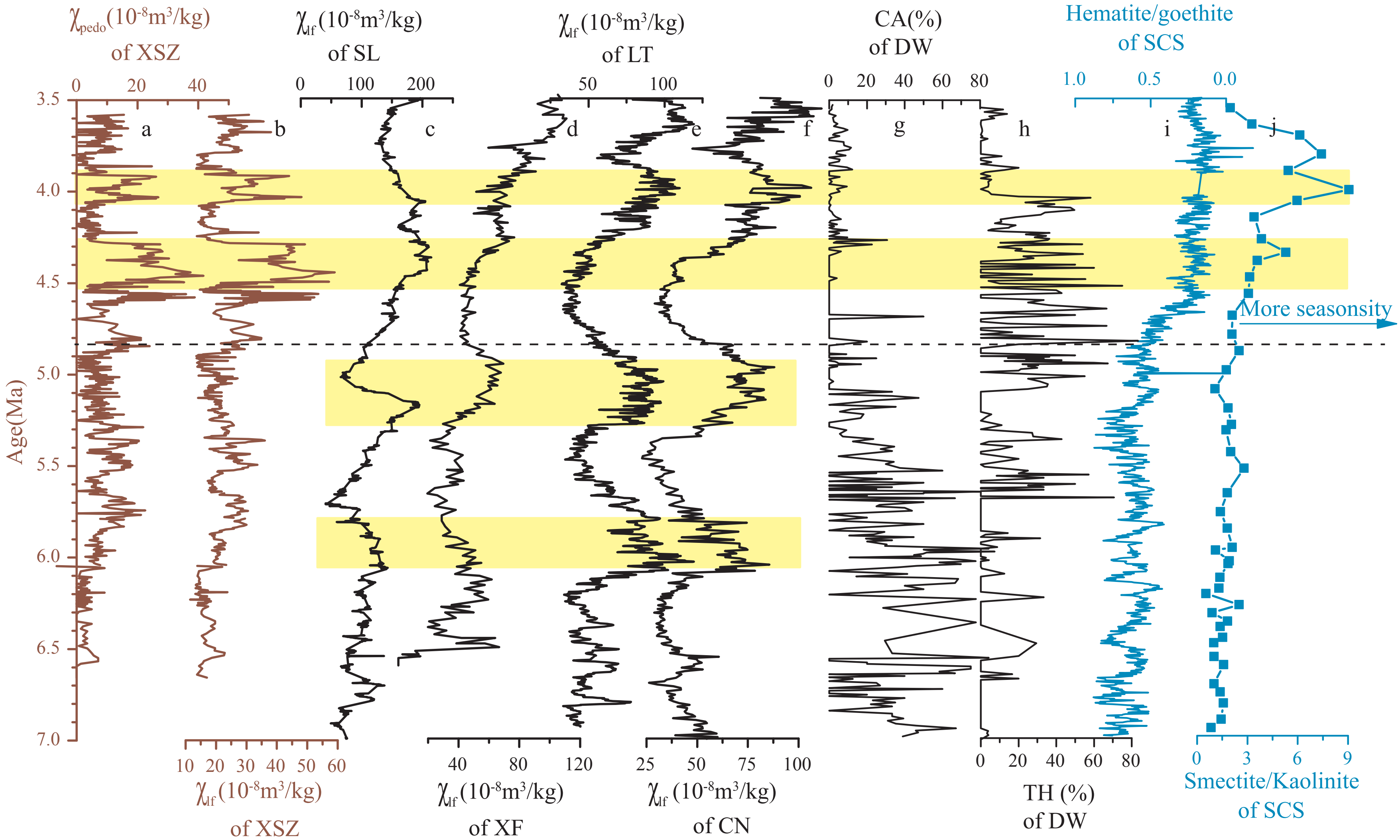

Fig. 7. Comparison of late Miocene-Pliocene paleoclimatic records from Asia. (a-b) χ_{pedo} and χ_{lf} from the XSZ section. (c-f) χ_{lf} record from Shilou (Ao et al., 2016), Xifeng (Guo et al., 2001), Lingtai (Sun et al., 2010) and Chaona (Song et al., 2007). (g-h) Percentages of cold-aridiphilous (CA) mollusk group and thermo-humidiphilous (TH) mollusk group from Donwan(Li et al., 2008) , (i) Hematite/goethite ratio from the South China Sea (Clift, 2006). (j) Smectite/Kaolinite ratio from the South China Sea (Wan et al., 2010; Clift et al., 2014).

Table 1. major element compositions of XSZ red clay.

Content	SiO_2(%)	Al_2O_3(%)	Fe_2O_3(%)	CaO(%)	MgO(%)
Average	49.16	12.61	5.38	11.36	2.76
6.7-4.8Ma	48.85	12.22	5.18	11.20	3.06
4.8-3.6Ma	49.50	13.22	5.69	11.60	2.30
Content	K_2O(%)	Na_2O(%)	Rb(ppm)	Sr(ppm)	Ba(ppm)
Average	2.76	1.2	106.2	212.8	519.0
6.7-4.8Ma	2.59	1.20	103.9	211.7	494.3
4.8-3.6Ma	3.03	1.23	109.9	214.6	558.0

Table. 1. The average value and coefficident of variation of the records during two periods of 6.7-4.8 Ma and 4.8-3.6 Ma.

		SiO_2(%)	Al_2O_3(%)	CaO(%)	Fe_2O_3(%)	K_2O(%)
4.8-3.6 Ma	Average	48.9	13.2	11.6	5.69	3
	CV	14.6	9.58	45.57	9.3	12.3
6.7-4.8 Ma	Average	49.5	12.2	11.2	5.2	2.6
	CV	11.6	9.09	32.18	9.6	10.3
		Na_2O(%)	MgO(%)	Sr(ppm)	Rb(ppm)	Ba(ppm)
4.8-3.6 Ma	Average	1.23	2.3	214.6	109.9	558
	CV	24.4	9	12.5	10.9	11.5
6.7-4.8 Ma	Average	1.2	3.1	211.7	103.9	494
	CV	10.2	61	10.04	10.8	13.2
		$CaCO_3$(%)	χ_{hf}	χ_{lf}	χ_{fd}	
4.8-3.6 Ma	Average	13.8	25.4	26.9	1.2	
	CV	45.6	38.3	36.2	78.2	
6.7-4.8 Ma	Average	17.4	19.4	20.3	1	
	CV	29.3	23.8	21.2	72.8	

Table. 2. The correlation coefficient between elements and CaO, $CaCO_3$ and K_2O

	CaO	$CaCO_3$	K_2O
Fe_2O_3	-0.63	-0.18	-0.29
SiO_2	-0.95	-0.39	0.72
Al_2O_3	-0.77	-0.61	0.95
CaO	1	0.51	-0.67
MgO	-0.04	0.13	-0.11
Na_2O	-0.06	-0.10	-0.38
K2O	-0.67	-0.47	1

Rb	-0.20	-0.36	0.12
Sr	0.24	0.34	-0.29
Ba	-0.25	-0.33	0.63
$CaCO_3$	0.51	1	-0.47

Table. 3. The average value and coefficient of variation of the proxies during two periods of 6.7-4.8 Ma and 4.8-3.6 Ma.

		$CaCO_3$	Rb/Sr	K_2O/Na_2O	χ_{lf}	χ_{pedo}	<2um/>43um
4.8 -3.6	Average	13.8	0.52	2.49	26.9	10.9	1.33
Ma	CV	45.59	23.1	19.4	36.17	78.24	55.7
6.7-4.8	Average	17.4	0.5	2.35	20.3	9.1	1.52
Ma	CV	29.31	14.6	21.3	21.93	72.79	47.55