

Dear Editor,

We have carefully revised and edited the manuscript entitled “Liu, J., Li, J. J., Song, C. H., Yu, H., Peng, T. J., Hui, Z. C., and Ye, X. Y.: Sporopollen evidence for Late Miocene stepwise aridification on the Northeastern Tibetan Plateau, *Climate of the Past Discussions*, 11, 5243-5268, 2015.”, based on the valuable comments and suggestions from Dr. L. Dupont and the anonymous reviewer. Below please find the detailed responses. In addition, other minor modifications are also listed.

Best Regards,

Jijun Li

Responds to Reviewer #1 (Dr. L. Dupont)

We thank you for your helpful comments. All the suggested modifications will be carefully revised. The point to point responses to the comments are listed as followed.

1. The timing of the aridification is discussed in the context of the Miocene cooling as recorded in benthic foraminifera and in the context of the uplift of the Himalaya. The discussion about the foraminifer record is not very clear and I have some questions put on the annotated manuscript (page 5255). The discussion is illustrated with Figure 4 and, although I have some issues with its caption (see specific remarks), the message seems to be clear: the aridification of central Asia between 7 and 8 Ma falls during a period of major Tibetan Plateau uplift but not during the strong Miocene global cooling trends. This is at odds with the conclusion ‘that global cooling may have been a potential driving force for aridification of the Asian interior, and that TP uplift probably enhanced this process’. Therefore, I suggest clarifying the discussion and altering the conclusion as to present the uplift as the main driver of aridification during the late Miocene to which global cooling might have helped.

Response: Your suggestions are reasonable. Although the global cooling should somehow lead to net aridification on the planet, cooling and aridification trends do not seem to run parallel (van Dam, 2006). However, integrated studies showed that the global cooling during the late Cenozoic had significant influences on driving the Asian monsoon and inland arid climate (e.g. Lu et al. 2010; Lu and Guo, 2014; Tang and Ding, 2013). In particular, it might have played a more important role since the late Miocene (Lu and Guo, 2014). It is clear that the global cooling has strengthened the Siberia High, which dominates winter monsoon circulation and aridity in eastern Asia (Lu and Guo, 2014). This would result in enhanced and more frequent cold surges in the mid-latitudes of Northern Hemisphere. Meanwhile, the global cooling caused the weakening of hydrological cycle, expanding of ice sheets, lowering of sea

level and increasing of continental surface. For east Asia, cooling weakens monsoon circulation, and consequently drying conditions expand following retreat of the monsoonal rain belt, while in the west, cooling reduces water vapor pressure and therefore reduces the moisture mass transported into the continental interior (Tang and Ding, 2013). Nevertheless, the most significant late Neogene global cooling event occurred at ~14Ma (Mudelsee et al., 2014; Zachos et al., 2001), followed by a longer-term, but minor cooling 4-to-10-Ma trend (named by Mudelsee et al., 2014); hence, only minor cooling events occurred at ~10.1Ma and ~7.4Ma. However, seasonal sea ice was present in the Arctic Basin during the late Miocene (6-10Ma) when Greenland glacial ice began to grow (Moran et al., 2006). Therefore, we think that the global cooling might force the Asian climate change during the late Miocene, no matter whether the Tibetan Plateau (TP) uplift. The general trend towards a dry climate in interior Asian might be correlated with long-term global cooling. Meanwhile, the uplift of the TP played an essential role in forming the monsoon and arid climate by blocking moisture transported from the ocean to the interior Asia, enhancing the heating difference between the ocean and land, and affecting the atmospheric circulation that controlled precipitation in east Asia (An et al., 2001; Boos and Kuang, 2010, 2013; Dettman et al., 2001, 2003; Kutzbach et al., 1993; Li, 1999; Liu and Yin, 2011; Wu et al., 2012). Although numerous geological evidences suggest that the TP experienced rapid uplift during ~8-10Ma (Enkelmann et al., 2006; Fang et al., 2003, 2005; Lease et al., 2007; Li et al., 2014; Molnar, 2005; Molnar et al., 2010; Wang et al., 2006; Zheng et al., 2006, 2010), there is still much disagreement on the timing and amplitude of the uplift. The northern and northeastern TP significantly uplifted in the late Miocene and the Pliocene-Pleistocene, but the main uplift occurred as late as the Pleistocene (Li et al., 1979; Li, 1999). Base on model researches, Liu and Yin (2011) indicate that, once the plateau reached certain elevation, arid climate may continue to irreversibly exist in north and northwest China. However, the integration research shows that the Pliocene era might be wetter than the late Miocene in China (Guo et al, 2008). Meanwhile, the Chinese major deserts' formation time might be the Quaternary (Dong et al., 2013). We recognize that the

aridification of the Asian interior may have been enhanced by the TP uplift during the late Miocene, but the significantly impact on Asia climate should be the uplift during the Pliocene and Quaternary.

In summary, with reference to your suggestions, the conclusion will be “The general long-term drying trend was a response to the global cooling, while the stepwise aridification in study area was mainly caused by the regional tectonic uplift.”

2. In the discussion, the magnetic susceptibility record of the section is mentioned (and shown in Figure 4). However, there is no reference indicating that the susceptibility data have not been properly published, yet. If that is the case, please describe the measurement and the results in the appropriate sections.

Response: We cite the magnetic susceptibility from Zhang (2013). This reference will be added in the revise manuscript.

Zhang, J.: Late Miocene climatic changes recorded by colors in the Yaodian section of the Tianshui Basin and its influencing factors, Science Paper Online, 201301-272, 1-10, 2013.

SPECIFIC REMARKS

RESULTS. Please add the depth (in meters) to the description of the zones in the results section. Do not give percentages with a precision that is not warranted. Round all percentage values to the nearest integer. The sentence “This diagram principally demonstrates that tree pollen decline stepwise as herbaceous pollen increases” is bad for several reasons. Not the POLLEN decline but the PERCENTAGES decline. The more important objection concerns the meaninglessness of the remark. Because the values are expressed in percentages of the total, the values of the one always will decline if those of the other increase. The Euphorbiaceae is a large plant family with many representatives, some of them ubiquitous. I cannot believe that no

Euphorbiaceae are growing in the area.

Response: Thanks for your advice. We will modify these in the revised manuscript.

DISCUSSION. I do not understand the argument about global cooling leading to a gradual aridity increase (page 5255, line 15-16) in contrast to a stepwise one. Please clarify.

Response: Global cooling is an ongoing process during our studied interval, and affects the environment through a series of feedback process. Presumably, under the assumption of linear forcing, when the global cooling occurs gradually and consistently, such as LTEC-I, LTEC-II and 4-to-10-Ma (named by Mudelsee et al., 2014), the corresponding climate change will be gradual and consistent; if the cooling is episodic, such as Eocene-Oligocene Transition, Oligocene-Miocene Boundary and Middle Miocene Climate Transition (Mudelsee et al., 2014; Zachos et al., 2001), then the corresponding climate change will be intermittent and abrupt. The reality, however, is not such simple because of the non-linear character of the climate system. Here we consider the global cooling as the tectonic scale. We simply think that global cooling would reduce evaporation and evapotranspiration from the ocean and land surfaces, and subsequently decrease the moisture holding capacity of atmosphere and cause long-term decreasing trends in precipitation during our studied interval.

FIGURE CAPTIONS. Please add an explanation of ‘GPTS’ in the caption of Figure 2. The reference Li et al. (2007) is not listed in the reference list. Please delete the names of the mammals in the caption of Figure 4 as these details are beyond the scope of the paper. Add an explanation for panel (g).

Response: Thank you for your careful reading of our manuscript. We will correct these in the revised manuscript.

LANGUAGE. Sporopollen is a casual term that might better be substituted by ‘pollen and spores’ or ‘palynomorphs’ in writing. In the title I suggest to use ‘palynological’. As the paper does not disclose any spore data, you also could just write ‘pollen’. The use of the word ‘spectrum’ might induce associations with spectral analysis and for that reason, I advise not to use it. Please refrain from the use of vis-à-vis. Often ‘low abundance’ is preferable to ‘low content’. The use of the word ‘content’ in the meaning of ‘percentages’ might be confusing. I learned that in English (I am not a native speaker) ‘this’ is used sparingly and in many cases can be replaced by ‘the’. The Chinese Loess Plateau is only mentioned three times and, therefore, it does not have to be abbreviated.

Response: Thanks for your advice. We will carefully correct these mistakes.

Response to Reviewer #2:

We thank the anonymous referee for her or his helpful comments. All the suggested modifications will be carefully revised in our manuscript. The detailed responses to the reviewer's comments are listed as followed.

Discussion:

1) The effect of uplift on climate is regionally differing (e.g. Liu and Yin (2002) and also many of the other studies go into more detail with that). Kutzbach, Prell et al. (1993) also mention the regional response to a uniform Tibetan uplift and monsoon intensification (wetter to the south and east of Tibetan plateau, dryer to the north and west).

Response: Different model setups and boundary conditions could affect the simulation results. Firstly, Kutzbach et al. (1993) conducted simulation experiments using scenarios of “full-mountain” and “no-mountain”. However, the TP uplift had been intermittent or episodic. To make the numerical simulations closer to the geological history, phased uplift of the TP in subsequent experiments were designed to examine its impact on the climates in Asia (e.g. An et al., 2001; Kitoh, 2004; Liu and Yin, 2002). Even then, the phased uplift conforms closer to the geological records of the plateau uplift, but this type of experimental design is still not perfect, because the plateau uplift has obvious sub-regional differences, and which would then produce different effects on the climatic environment of various regions in the surroundings (e.g. Boos and Kuang, 2010, 2013; Chen et al., 2014; Tang et al., 2011, 2013; Wu et al., 2012). However, although the different sub-systems of Asian monsoon have various responses to the TP uplift in different models, the climate effects are same (the south and east TP become wetter, while the north and west TP become drier) when the TP exceed a critical height.

2) Additionally there is the hypothesis (and modelling studies exist) that show the

importance of the drying of the Paratethys during the late Miocene for Asian monsoon development. This point should also be mentioned (Ramstein, Fluteau et al. 1997; Guo, Sun et al. 2008). Guo, Sun et al. (2008) mention also the effect of a spreading of the South China Sea.

Response: The model simulation results suggest that the westward retreat of the Paratethys from central Asian and the spreading of the South China Sea have significant impact on Asian climate (Guo et al., 2008; Ramstein et al., 1997; Zhang et al., 2007). The former not only has a significant impact on the major climate reorganization in Asia during the late Oligocene/early Miocene (Guo et al., 2008; Ramstein et al., 1997; Zhang et al., 2007), but also have a profound climate impact on Europe and north Africa during the late Miocene (Micheels et al., 2007, 2011; Zhang et al., 2014). The latter may help to enhance the south-north contrast of humidity in China (Guo et al., 2008). However, A large number of geological evidences suggest that the vast majority/even all Paratethys regression from the Tarim Basin (northwest China) occurred in Oligocene ago (e.g. Bershaw et al., 2012; Bosboom et al., 2014), and that the spreading of the South China Sea might bring more precipitation in Asian. Therefore, we think that the retreat of the Paratethys and the spreading of the South China Sea during the late Miocene should have a limited effect on the formation and development of the Asian inland arid climate.

3) It would be advantageous to confront also the different modelling studies and proxy records as far as possible (e.g. general intensification of monsoon, but regional effects on precipitation vary largely among the studies). For example, the study of Tang, Micheels et al. (2011) indicates that with uplift only the EASM strengthens, whereas the EAWM weakens, which is at odds with proxy records of the publications you mention here)

Response: We totally agree that both the proxy records and the model simulations are indispensable to fully understand the effect mechanism of TP on regional climate and the regional climatic response to TP uplift. Actually, although both of proxy records

and modelling studies can reconstruct the history of climate changes, each approach has its advantages and weaknesses (Liu and Yin, 2011); even sometimes the results of them are inconsistent with each other. Boundary conditions should be based on the geological/proxy results and are the weak points of models (Micheels et al., 2011). For instance, the uplift of TP was not synchronized across the plateau during the late Miocene, and is still discussed controversially; hence, the paleoelevation history of TP is not fully clear (Lu and Guo, 2014; Molnar, 2005) and this will be cause more uncertainties in the model boundary conditions. Furthermore, the model resolves the regional scale and can represent the larger-scale rainfall trend, whereas proxy data are local conditions (Micheels et al., 2011). In addition, the model is designed as an average state over the entire period (Micheels et al., 2007), while the climate was not constant during the time interval. Due to this integration, it is not trivial to compare model results with proxy data (Micheels et al., 2007). For example, with regard to European proxy data, Micheels et al. (2007) observed that the Tortonian run tends to correspond rather more to the late Tortonian than to earlier parts of the time interval. Moreover, the geological/proxy records also have their inherent problems, such as the uncertainty of the physical/chemical/biological mechanism in some geological/proxy records. Meanwhile, the proxy records are usually use relative wet or dry climate to indirectly reflect the monsoon strength. And monsoon intensity indicated by proxy records is generally relative to the previous or subsequent time period of the strength of the monsoon, while the models are relative to the present. For us, Zone-2 and Zone-3 in our palynology record reflect temperate open forest and open forest-steppe environment, respectively, and consist with Tang et al.'s (2011) TORT-model setup (open forest in the northern TP and the Loess Plateau). In addition, the study of Tang et al. (2011) indicates that their regional Tortonian model run shows a stronger East Asian winter monsoon and a weaker summer monsoon compared to today. The proxy records of our cited publications also indicate a weaker summer monsoon during the late Miocene and a relatively strong winter monsoon toward the end of the Miocene. It is consistent with Tang's results. Meanwhile, the northern and northeastern TP significantly uplifted in the late Miocene and the Pliocene-Pleistocene, and the main

uplift occurred as late as the Pleistocene (Li et al., 1979; Li, 1999). Although the TP experienced rapid uplift during the late Miocene, its paleoelevation might be just reach Tang et al.'s (2011) TORT-model setup (northern TP: 30% (of present-day height); central and southeastern TP: 80%; southern TP: 100%; Tian Shan, Gobi Altai and Zagros: 70%; other orography: 70-90%).

4) Last but not least with the discussion of model experiments the large differences between the different studies should be mentioned (resolution, uplift scenarios, types of models –coupled or atmosphere only, RCM or GCM, differences in other boundary conditions that might influence the model response-e.g. Tortonian boundary conditions and forcing data in Tang, Micheels et al. (2011) etc.).

Response: In our manuscript, we mainly used palynological record to discuss the late Miocene vegetation evolution in the northeastern TP. Given the research focus and the limited length, we did not perform detailed comparison of models and only cited the results of model simulations, but we will supplement the comparison between different models with different model setups and boundary conditions mentioned by reviewer.

The scenarios of whole-plateau uplift (e.g. Kutzbach et al., 1993), phased uplift (e.g. An et al., 2001; Kitoh, 2004; Liu and Yin, 2002) and sub-regional uplift (e.g. Boos and Kuang, 2010, 2013; Chen et al., 2014; Tang et al., 2011, 2013; Wu et al., 2012) are usually designed for discovering the cause-effect relations between the plateau uplift and paleoclimate change. With increasing complexity, the numerical simulations' boundary conditions are closer to the geological history of the TP. In addition, the low spatial resolutions in most models prevent accurate portray of the real topographic features, which may have exerted substantial impact on the development of the Asian monsoon in the late Miocene (Tang et al., 2011). Furthermore, different model setups and boundary conditions also influence the explanation of the effect mechanism of the plateau uplift on regional climate. For example, the thermal forcing of the TP drives the Asian monsoon system (e.g. Chen et

al., 2014; Kutzbach et al., 1993); the insulation effect of the narrow orography of the Himalayas and adjacent mountain alone may trigger the Indian monsoon circulation, while the TP may be very important for East Asian climate (Boos and Kuang, 2010, 2013); Wu et al., (2012) results that the heating of the TP is still necessary to maintain the Asia monsoon circulation; some modeling research also considered the regional difference and asynchronous growth of the plateau, and reached the same conclusion that the regional tectonic could affect the monsoon circulation (Chen et al., 2014; Tang et al., 2011, 2013). Although the climate response mechanism of the plateau uplift still has not consensus, the climate effects are seemingly uniform (wetter to the south and east of TP, drier to the north and west of TP).

5) You might find the following publications also useful: (Kitoh 2004; Wu, Liu et al. 2009; Boos and Kuang 2010; Kitoh, Motoi et al. 2010; Zhang and Liu 2010; Wu, Liu et al. 2012; Wu, Liu et al. 2012; Boos and Kuang 2013; Chen, Liu et al. 2014)

Response: Thanks for your advice and important references will be added in manuscript.

6) Please also add some more detail on your discussion of the impact of global cooling on Asian climate evolution.

Response: Ok, more detailed discussion will be added in revised manuscript. Considering the decreased atmospheric moisture content with decreasing air temperature, it is to be expected that the global cooling should somehow lead to net aridification on the whole planet, but cooling and aridification trends do not seem to run parallel (van Dam, 2006). The spatial complexity of the systems of atmospheric and oceanic circulation ensures that general cooling may result in precipitation decrease in some regions and increase in others (van Dam, 2006). However, integrated studies indicate that the global cooling during the late Cenozoic had significant influences on driving the Asian monsoon and inland arid climate (e.g. Lu et al. 2010; Lu and Guo, 2014; Tang and Ding, 2013). In particular, the global cooling

might have played a more important role since the late Miocene (Lu and Guo, 2014). It is clear that the global cooling has strengthened the Siberia High, which dominates winter monsoon circulation and aridity in East Asia (Lu and Guo, 2014). This would result in more frequent cold surges in the mid-latitudes of Northern Hemisphere. Meanwhile, the global cooling caused the weakening of hydrological cycle, expanding of ice sheets, lowering of sea level and increasing of continental surface. For East Asia, cooling weakens monsoon circulation, and consequently drying conditions expand following retreat of the monsoonal rain belt, while in the west, cooling reduces water vapor pressure and therefore reduces the moisture mass transported into the continental interior (Tang and Ding, 2013).

Minor comments

Abstract:

P5244, L12: "...more humid climate developed." better: ... rather humid climate existed." as it is not know from the data whether the climate was wetter or dryer before 11.4 Ma.

Response: Thanks for your suggestion. We will revise that.

P5244, L16: "... Asian aridification ... " Maybe better write "Central Asian aridification" or aridification in the study area, as there is no proof for a general aridification trend all over Asia, this is to my knowledge e.g. the case for Central Asia, whereas in some regions even more humid conditions developed during that time period.

Response: Thanks for your suggestion. We will revise that.

Introduction:

P5245, L 1+2: is modern Asian Social development relevant for the study? If not, please eliminate that sentence.

Response: Thanks for your suggestion. We will eliminate that sentence.

P5245, L 28+29: "... of northern China through and the evolution of the Asian Monsoon." this sentence is weird.

Response: It will be modified to "Its particular geological and geographical characteristics make it sensitive to document the aridification history of northern China and the evolution of Asian Monsoon accurately."

P5246, 1st paragraph: please indicate a reason why you assume the Longzhong Basin to be the most promising for distinguishing TP uplift and any assoc. env. change.

Response: Geographically, the basin is located in the northeasternmost margin of the Tibetan Plateau, the transition zone of the main TP and Chinese Loess Plateau. The basin infill will record the uplift history of the plateau (Li et al., 2014). Climatically, the basin is located in the transition zone of the monsoon region and the non-monsoon region, sensitively response to climate change (Li et al., 2014). Moreover, this northeasternmost corner of the collision highlands also provides the best model of a small, still actively growing and rising, TP (Tapponnier et al., 2001). Meanwhile, Molnar (2005) indicate that, in a search for the ideal field area, the northeast margin of the plateau might allow precise timing of both tectonic and local climatic events using the same material.

Discussion:

P5255, L6: "...during toward..." -double wording?

Response: Thanks for your suggestion. We will modify that.

Figure captions:

Figure 4: the labelling is mixed up:

what is g) in the figure is not included in the caption, whereas g) in the caption should

be h) and h) should be i).

Response: Thanks for your careful work. (g) Carbon isotope ratios of leaf wax C₃₁ *n*-alkane extracted from ODP Site 722 (Huang et al., 2007).

Other Modifications:

Besides the modifications are mentioned by the reviewers, we also made the other changes. All modifications can be found on the marked manuscript.

1. In marked manuscript page 2, line 3, “understanding” is replaced with “illustrating”.
2. In marked manuscript page 2, line 6 and 7, “understand better the relations between” is replaced with “better understand the relationships among”.
3. In marked manuscript page 2, line 12, “two-stage” is replaced with “general trend towards dry climate superposed by”.
4. In marked manuscript page 2, line 19, “this persistent aridification” is replaced with “the aridification trend”.
5. In marked manuscript page 3, line 19 and 20, “, polar ice-sheet volumes” is deleted.
6. In marked manuscript page 4, line 11, “region” is deleted after “the Longzhong Basin”.
7. In marked manuscript page 4, line 21, “margins” is replaced with “margin”.
8. In marked manuscript page 4, line 22 and 23, the sentence “We also discuss the possible relation between tectonic activity and climate change” is deleted.
9. In marked manuscript page 5, line 2, a comma is deleted after “mammalian”.
10. In marked manuscript page 5, line 19, “the” is added before “Quaternary”.
11. In marked manuscript page 5, line 25, “mud stone” is replaced with “mudstone”.
12. In marked manuscript page 6, line 9, “yellow” is replaced with “yellowish”.
13. In marked manuscript page 7, it has been more modifications.
14. In marked manuscript page 11, line 18, “reflected” is replaced with “reflects”.

15. In marked manuscript page 12, line 11, “the enhanced oxidation characteristic of” is deleted.
16. In marked manuscript page 12, line 12, the reference (Zhang, 2013) is added.
17. In marked manuscript page 12, line 13, “predominates” is replaced with “predominated”.
18. In marked manuscript page 12, line 21 and 22, the reference “Wang et al., 2012” is replaced with “Y. L. Wang et al., 2012”.
19. In marked manuscript page 13, line 5 and 6, “currently-available data from” is deleted; “data” is added after “fossils”; “suggested” is replaced with “suggests”.
20. In marked manuscript page 13, line 25 and 26, “and hydrogen isotopic ratios” is replaced with “isotopic ratio”.
21. The last two paragraphs within the discussion section 5.2 have been more modifications.
22. In marked manuscript page 18, line 14, “investigated” is replaced with “investigate”.
23. In marked manuscript page 18, line 15, “indicated” is replaced with “indicate”.
24. In marked manuscript page 18, line 26 and 27, the sentence “This study highlights these possible interactions between global cooling and tectonic uplift” is deleted.
25. The sentence “We thank Q. Y. Cui and Y. Z. Ma for their early pollen work, and L. Dupont and an anonymous reviewer for their valuable comments and suggestions” is inserted in section *Acknowledgements*.
26. Some references are added or deleted to section **References**.
27. In marked manuscript page 32, line 2, “sporopollen” is replaced with “pollen”.
28. Cited reference papers in the manuscript sorted by the first letter.

References cited in the Response:

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1 | **Palynological~~Sporopollen~~ evidence for Late Miocene**
2 **stepwise aridification on the Northeastern Tibetan**
3 **Plateau**

4
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11

1 Abstract

2 Holding a climatically and geologically key position both regionally and globally, the
3 northeastern Tibetan Plateau provides a natural laboratory for ~~understanding~~
4 illustrating the interactions between tectonic activity and the evolution of the Asian
5 interior aridification. Determining when and how the Late Miocene climate evolved
6 on the northeastern Tibetan Plateau may help us better understand ~~better—the~~
7 relationships ~~between—among~~ tectonic uplift, global cooling and ecosystem evolution.
8 Previous paleoenvironmental research has focused on the western Longzhong Basin.
9 Late Miocene aridification data derived from ~~spore~~ pollen now requires corroborative
10 evidence from the eastern Longzhong Basin. Here, we present a Late Miocene
11 ~~spore~~ pollen record from the Tianshui Basin in the eastern Longzhong Basin. Our
12 results show a ~~two-stage~~ general trend towards dry climate superposed by stepwise
13 aridification: a temperate forest with a ~~more—rather~~ humid climate developed in the
14 basin between 11.4 and 10.1Ma, followed by a temperate open forest environment
15 with a less humid climate between 10.1 and 7.4Ma; and an open temperate
16 forest-steppe environment with a relatively arid climate occupied the basin during 7.4
17 to 6.4Ma. The vegetation succession demonstrates that the aridification of the Asian
18 interior ~~Asian—aridification~~ occurred after ~7–8Ma, which is confirmed by other
19 evidence from Asia. Furthermore, ~~this—persistent~~ the aridification trend on the
20 northeastern Tibetan Plateau parallels the global cooling of the Late Miocene; the
21 stepwise vegetation succession is consistent with the major uplift of the northeastern
22 Tibetan Plateau during this time. These integrated environmental proxies indicate that
23 the general trend towards a dry climate in interior Asian might be correlated with the
24 long-term global cooling ~~global cooling may have been a potential driving force for~~
25 ~~Asian interior aridification,~~ while the Late Miocene aridification in our study area was
26 probably caused by the Tibetan Plateau uplift. ~~most likely enhanced by stepwise uplift~~
27 ~~of the Tibetan Plateau.~~

29 1 Introduction

1 As the latter stage of the global Cenozoic cooling, the Neogene was a critical period
2 for northern hemispheric aridification, especially the marked aridification of the Asian
3 interior. ~~As the world's largest arid region in a temperate zone, it not only provides~~
4 ~~dust material for the Chinese Loess Plateau (CLP), but also influences modern Asian~~
5 ~~social development.~~ Establishing when, and how, this process of aridification began
6 and evolved is therefore vital for elucidating the interactions ~~between~~ among tectonic
7 uplift, global cooling and ecosystem evolution. Although there is compelling evidence
8 for the aridification of the Asian interior, there is no consensus ~~vis-à-vis~~ concerning its
9 evolution and driving mechanisms. For instance, previous researchers have suggested
10 that the aridification of the Asian interior began in the Late Miocene, based
11 particularly on biological and isotopic evidence ([Andersson and Werdelin, 2005](#);
12 [Cerling et al., 1997](#); [Dettman et al., 2001](#); Eronen et al., 2012; [Quade et al., 1989](#);
13 ~~Andersson and Werdelin, 2005~~; Wang and Deng, 2005; Zhang et al., 2012; ~~Quade et~~
14 ~~al., 1989~~; ~~Dettman et al., 2001~~; ~~Cerling et al., 1997~~). However, others have argued
15 that the process of Asian interior aridification may have begun in the Early Miocene
16 (22Ma) or even earlier (in the Late Oligocene), as inferred from the Miocene or
17 Oligocene eolian deposition (Guo et al., 2002, 2008; Qiang et al., 2011; Sun et al.,
18 2010). The particular driving mechanisms of such aridification also remain enigmatic.
19 Up until now, the tectonic uplift of the Tibetan Plateau (TP), global cooling, ~~polar~~
20 ~~ice sheet volumes~~ and land-sea distributions ~~etc.~~ have been suggested as the major
21 drivers ([An et al., 2001](#); [Gupta et al., 2004](#); Kutzbach et al., 1993; ~~An et al., 2001~~; Liu
22 and Yin, 2002; [Miao et al., 2012](#); Molnar et al., 2010; ~~Gupta et al., 2004~~; ~~Miao et al.,~~
23 ~~2012~~). However, there is little consensus about which one is the most important
24 driver. ~~the question of which one of these has principally controlled Asian climatic~~
25 ~~evolution is far from agreed.~~ We focused on ~~an ideal~~ the region —of the northeastern
26 TP— to explore the nature of the interactions between tectonics and ~~the~~ climate.

27 The geographically-extensive Longzhong Basin, consisting of a series of sub-basins,
28 is located in the northeastern TP. These sub-basins present a continuous record of
29 mammalian fossil-rich Cenozoic sediments, recording the effect of TP uplift on

1 regional climates ([Fang et al., 2003, 2005](#); GRGST, 1984; ~~Fang et al., 2003, 2005~~; Li
2 et al., 2006, 2014). On the other hand, it lies in the so-called monsoonal triangle ~~zone~~,
3 a transition zone from a warm-humid Asian monsoonal climate, to a dry-cold inland
4 climate, ~~and~~ to the alpine climate of the TP (Li et al., 1988, 2014) (Fig. 1a). [Its
5 particular geological and geographical characteristics make it sensitive to document
6 the aridification history of northern China and the evolution of Asian Monsoon
7 accurately.](#) ~~Its particular geological and geographical characteristics make it sensitive
8 to the accurate recording of the aridification of northern China through and the
9 evolution of the Asian Monsoon.~~ As an ~~ideal~~ field laboratory for studying
10 tectonic-climate interactions (Molnar et al., 2010; Tapponnier et al., 2001), the
11 Longzhong Basin ~~region~~ might be the most promising for distinguishing TP uplift and
12 ~~any~~-associated environmental change.

13 As a reliable paleoenvironmental proxy, ~~spore~~pollen has been used to reconstruct past
14 climates because of its abundance and excellent preservation within sediments.
15 Previous research has demonstrated that the Tianshui Basin, as a sub-basin of the
16 Longzhong Basin, exhibits a typical Late Miocene lacustrine-fluvial sedimentary
17 succession containing abundant ~~pollen~~pollen ([Li et al., 2006](#))s. Here we reconstruct a
18 high-resolution palynological record from the well-dated Yaodian Section, located in
19 the southern part of the Tianshui Basin. Our results not only provide new evidence for
20 the evolution of vegetation in the Late Miocene and climate change on the
21 northeastern margins of ~~the~~TP, but also shed new light on the aridification of the
22 Asian interior ~~through time. We also discuss the possible relation between tectonic
23 activity and climate change.~~

24 **2 Geological and geographical settings**

25 The rhomboid-shaped Longzhong Basin, which is one of the largest intermountain
26 and fault-controlled sedimentary basins on the northeastern TP, is geographically
27 delineated by the left-lateral strike-slip Haiyuan Fault to the north, the Liupan Shan
28 Fault to the east and northeast, the Laji Shan Fault to the southwest, and the Western
29 Qinling Fault to the south (Fig. 1b). The Tianshui Basin, one of its sub-basins, is

1 located in the southeastern part of the Longzhong Basin (Fig. 1b). It has witnessed the
2 continuous deposition of mammalian, fossil-rich Cenozoic sediments from the
3 surrounding mountains; these sediments record the interactions between mountain
4 uplift, erosion and climate change ([Alonso-Zarza et al., 2009](#); Li et al., 2006; [Liu et al.,](#)
5 [2015](#); ~~Alonso-Zarza et al., 2009~~; Peng et al., 2012, [2015](#)). At present, the East Asian
6 Monsoon influences this region, engendering a semi-humid, warm temperate,
7 continental monsoon climate, characterized by relatively hot, humid summers and
8 cold, dry winters. The mean annual temperature and mean annual precipitation of this
9 area are ~~~10.4~~[11](#) °C and ~~504mm~~[492mm](#), respectively, with rainfall concentrated
10 mainly in ~~the~~ summer and autumn (Fig. 1c). The modern natural vegetation in this
11 region is warm-temperature forest-grassland. Warm grasslands are distributed in the
12 valleys, and consist mainly of *Arundinella hirta*, *Spodiopogon sibiricus* and *Themeda*
13 *triandran*. Shrubs such as *Zizyphus jujube*, *Sophora viciifolia* and *Ostryopsis*
14 *dauidiana* are found on the hillsides. Trees, including *Quercus liaotungensis*, *Pinus*
15 *tabulaeformis*, *P. armandi* and *Platycladus orientalis*, grow in the mountains (Huang,
16 1997).

17 The selected Yaodian Section (105°55' E, 34°38' N) is located in the southern part of
18 the Tianshui Basin (Fig. 1d). The Neogene sequence in ~~this~~[the](#) section is capped by
19 [the](#) Quaternary loess and lies unconformably on top of the Paleogene Guyuan Group.
20 It has been divided into the Ganquan Formation (Fm), the Yaodian Fm and the
21 Yangjizhai Fm, in sequence upwards (Li et al., 2006). In this study, our research
22 mainly focuses on the Late Miocene Yaodian Fm and Yangjizhai Fm. Based on a
23 determination of lithology and sedimentology, the Yaodian Fm can be divided into
24 three principal strata. The lower stratum consists of massive fine gravel sandstone,
25 sandstone and brown silty mud~~stone~~, occasionally with thin brown mudstone or
26 interbedded paleosols, which can be considered fluvial channel deposits (Fig. 2e).
27 Abundant teeth of *Hipparion weihoense*, *Cervavitus novorossiae*, *Ictitherium* sp. and
28 their bone fragments were excavated from this stratum. The middle stratum of the
29 Yaodian Fm consists of the interbedding of siltstone or fine sandstone with mudstone

1 | intercalated with paleosols, overlying the fluvial channel deposits. ~~This~~The
2 | assemblage's characteristics are typical of floodplain deposition (Fig. 2d). The upper
3 | stratum of the Yaodian Fm is characterized by rhythmic cycles composed of grey or
4 | brown mudstone or sandy marlite and intraclastic marl intercalated with brown
5 | siltstone and mudstone, and contains fossil algae and gastropods; this section is
6 | representative of shallow lake deposition (Fig. 2a and c). ~~This~~The upper stratum is
7 | common throughout the basin, and is analogous to the "Zebra Bed" stratum found in
8 | the Linxia Basin in the western Longzhong Basin (Li et al., 1995). The Yangjizhai Fm
9 | is principally composed of reddish brown mudstone or silty mudstone and yellowish
10 | brown calcrete or calcareous mudstone, with scattered sandstone or grey mudstone
11 | and marlite. These sediments were deposited under strong evaporative conditions in
12 | distal floodplain to palustrine environments (Fig. 2b). Previous paleomagnetic
13 | investigations have indicated that the Yaodian Fm ranges from 11.67 to 7.43Ma in
14 | age, and that the Yangjizhai Fm dates from 7.43 to 6.40Ma, both these ranges being
15 | consistent with the formations' biostratigraphic ages (Li et al., 2006).

16 | **3 Materials and methods**

17 | Most of the samples came from lacustrine mud deposits and fine grain size
18 | intercalations found in floodplain and fluvial channel deposits. Because the lower
19 | 10m of the Yaodian Fm consists of coarse gravel sandstone, and it was difficult to
20 | find fine-grained sediments therein, this part of the formation was not sampled. A
21 | total of 200 samples were processed for ~~sporopollen~~palynological analysis. For each
22 | sample, >100g of sediment was washed in 20% HCl, soaked in 39% HF and then
23 | treated with 10% HCl solution to enable fluoride dissolution. The chemical processing
24 | was followed by physical enrichment procedures ~~such as using~~ ZnCl₂ separation, ~~and~~
25 | ultrasound sieving ~~with over~~ a 10µm filter, ~~and storage~~. Samples were stored in
26 | glycerin. ~~Sporopollen grains~~Pollen and spores were identified by ~~comparing samples~~
27 | ~~with published modern and fossil sporopollen plates (after~~ Wang, ~~(1995;)~~ and Song,
28 | (1999), as well as modern ~~sporopollen reference~~ slides ~~preserved in~~from the collection
29 | of the Laboratory of Sporopollen Analysis of the Geography Department of Lanzhou

1 University.

2 **4 Results**

3 Only 126 of the 200 samples contained enough palynomorphs to provide reliable data;
4 the remaining 74 possessed fewer than 300 identifiable grains and have not been
5 included in the analysis. Most of these latter samples had been preserved under
6 oxidizing conditions, or had ~~abundant~~ high carbonate content. Approximately 80
7 different palynomorphs were identified ~~into~~ at family or genus level. Percentages
8 were expressed on the total number of recognized taxa. Tree pollen consists mainly of
9 *Pinus*, *Cupressaceae* and *Ulmus*, along with *Quercus* and *Betula*. Additionally, a
10 number of subtropical plants pollen, such as *Liquidambar*, *Pterocarya* and *Carya*
11 (which are no longer found in this area today), appear often in low abundance.
12 Herbaceous pollen is mainly from *Artemisia*, *Chenopodioideae*, *Poaceae* and
13 *Asteraceae*. Pollen from extremely drought-tolerant plants, such as *Ephedra* and
14 *Nitraria*, only appear sporadically in single samples. In addition, the section also
15 contains fern spores and *Pediastrum* colonies. A selection of the more important taxa
16 is given in Fig. 3. ~~In order to synthesize the information and highlight palynological~~
17 ~~trends, the major taxa, and their percentage contents vis-à-vis recognized taxa, were~~
18 ~~used to construct a sporopollen diagram (Fig. 3).~~

19 ~~This diagram principally demonstrates that tree pollen declines stepwise as~~
20 ~~herbaceous pollen increases. Tree pollen consists mainly of *Pinus*, *Cupressaceae* and~~
21 ~~*Ulmus*, along with *Quercus* and *Betula*. Additionally, a number of subtropical plants~~
22 ~~such as *Liquidambar*, *Pterocarya*, *Carya* and *Euphorbiaceae* (which is no longer~~
23 ~~found in this area today), appear often, but their contents are lower. Herbaceous~~
24 ~~pollen is mainly from *Artemisia*, *Chenopodioideae*, *Poaceae* and *Asteraceae*. Pollen~~
25 ~~from extremely drought-tolerant plants, such as *Ephedra* and *Nitraria*, only appear~~
26 ~~sporadically in individual samples. In addition, this section also contains some ferns~~
27 ~~and *Pediastrum*. ~~Stratigraphically constrained~~~~The Stratigraphically-constrained
28 cluster analysis (CONISS) yields three distinct zones ~~in the section~~, described from
29 the bottom up as follows:

4.1 Zone 1 (195.5–158.5m, 11.4–10.1Ma)

Samples from this zone exhibit high percentages of tree pollen (~~averaging 75.13%~~) and relatively less herbaceous pollen (~~averaging 23.42%~~). Coniferous taxa are mainly *Pinus* (~~18.57~~19%) and Cupressaceae (~~17.62~~18%), with smaller amounts of *Picea* and *Cedrus*. *Ulmus* (~~19.71~~20%) is the most common broadleaf tree pollen, accompanied by pollen of *Betula* (~~2.73~~3%), *Quercus* (~~2.17~~2%) and *Salix* (~~2.10~~2%). Other arboreal taxa are *Juglans* and *Castanea*, with <2% each. Herbaceous taxa mainly include *Artemisia* (~~7.41~~7%), Chenopodioideae (~~5.51~~6%) and Poaceae (~~2.44~~2%), along with small amounts of Asteraceae, Ranunculaceae and Rosaceae, with amounts <2% each. Aquatic plants, algae and some subtropical taxa are also ~~present~~ represented in this zone, ~~though with low contents~~ with low abundance.

4.2 Zone 2 (158.5–63.5m, 10.1–7.4Ma)

In ~~samples from~~ this zone, total tree pollen ~~content~~ percentage decreases, averaging ~~53.98~~54%, ~~while the percentage of herbaceous pollen (averaging 42.93%) increases~~. Coniferous taxa are principally represented by *Pinus* (~~13.95~~14%), Cupressaceae (~~7.48~~7%), *Picea* (~~2.16~~2%) and *Cedrus* (~~1.49~~1%). Among broadleaf trees, the dominant taxa are *Ulmus* (~~averaging 8.04~~8%), *Quercus* (~~2.35~~2%), *Betula* (~~2.28~~2%), *Salix* (~~1.89~~2%) and *Juglans* (~~1.42~~1%). Herbaceous taxa are dominated by *Artemisia* (~~13.68~~14%) and Chenopodioideae (~~8.83~~9%), along with Poaceae (~~4.89~~5%), Asteraceae (~~3.15~~3%) and Ranunculaceae (~~2.94~~3%). Aquatic vegetation ~~appears successively and~~ reaches the highest value found in the entire profile. ~~There are also some s~~Subtropical taxa ~~with low contents~~, such as *Liquidambar*, *Pterocarya*, *Carya* and Rutaceae, are represented with low abundance. ~~This~~ The zone is divided into two subzones, Zone 2-1 (158.5–106.5m, 10.1–8.6Ma) and Zone 2-2 (106.5–63.5m, 8.6–7.4Ma). Herbaceous pollen percentages are slightly higher in Zone 2-2 than in Zone 2-1.

4.3 Zone 3 (63.5–30m, 7.4–6.4 Ma)

The samples from this zone record a ~~sudden~~ further decrease in tree pollen (~~with~~

1 ~~content averaging 39.20%), mirrored by an increase in herbaceous pollen (averaging~~
2 ~~60.08%)~~ to an average value of 39%. Coniferous taxa are characterized by *Pinus*
3 (~~7.24~~7%) and Cupressaceae (~~5.26~~5%). *Ulmus* (~~5.28~~5%) dominates the broadleaf tree
4 ~~category~~pollen, with *Quercus* and *Betula* accounting for ~~2.33~~ and ~~2.32~~2%,
5 respectively. Herbaceous taxa are composed of *Artemisia* (~~19.42~~19%),
6 Chenopodioideae (~~11.23~~11%) and Poaceae (~~8.59~~9%), together with Asteraceae
7 (~~4.53~~5%), Ranunculaceae (~~3.23~~3%), Brassicaceae (~~3.18~~3%) and Polygonaceae
8 (~~1.86~~2%). Aquatic plants and thermophilic species almost disappear.

9 **5 Discussion**

10 **5.1 Vegetation and climate reconstruction**

11 ~~When discussing the relation between the palynological spectrum and sedimentary~~
12 ~~facies in the Yaodian Section, it becomes apparent that these~~The sedimentary facies
13 ~~have experienced~~of the Yaodian Section indicate four successive depositional stages:
14 fluvial channel; floodplain; shallow lake; and distal floodplain to palustrine.
15 ~~Transitional~~Transitional ages can be dated to 10.4, 9.23 and 7.43Ma, respectively (Li
16 et al., 2006) (Fig. 2). Our palynological ~~spectrum-record~~ shows stepwise changes at
17 10.1 and 7.4Ma, lagging slightly behind those evinced by the sedimentary facies.
18 Another distinctive feature of the palynological ~~spectrum-record~~ is that the green
19 lacustrine deposits of fine grain size exhibit dense palynomorph concentrations, with
20 higher tree pollen percentages. In contrast, the reddish floodplain deposits with coarse
21 grain sizes possess sparse palynomorph concentrations, with higher herbaceous pollen
22 percentages (Fig. 3). However, in the same ~~spore~~pollen zones, we find that the
23 palynomorph concentration clearly changes between different sedimentary facies, but
24 that ~~any variation in overall~~ percentage ~~content is~~fluctuations are minor. ~~Interestingly,~~
25 ~~between~~ different ~~spore~~pollen zones, the palynomorph percentages ~~changes~~ greatly
26 ~~vis-à-vis~~strongly within the same sedimentary facies. We can therefore conclude that
27 ~~these~~ changes in the palynological ~~spectrum-record~~ are caused by changes in regional
28 vegetation, rather than ~~differing~~ different preservation conditions. The paleoecological
29 information inferred from the percentage change of ~~spore~~pollen record can thus be

1 considered reliable.

2 According to modern surface pollen studies, *Pinus* is often overrepresented in pollen
3 records because of its abundant pollen production and the ease with which this pollen
4 is transported over long distances by ~~the~~ wind. As a general rule, it can be assumed
5 that there is/was no proximate pine forest if less than 25 to 30% of *Pinus* pollen
6 occurs in samples (Li and Yao, 1990). Higher percentages of Cupressaceae and
7 Taxodiaceae coexistent with temperate tree, shrub and herbaceous pollen may reflect
8 a warmer, wetter and more humid climate (Song, 1978). Nowadays, *Ulmus* is
9 commonly distributed in the sub-humid temperate and warm temperate mountain
10 foothills of northern China, but percentages of its pollen collected from ~~ELP-the~~
11 [Chinese Loess Plateau](#) surface soils never exceed 1%, even under broadleaved forests
12 containing elm (Liu et al., 1999). In general, when their ~~content~~ [abundance](#) exceeds
13 3–5% of ~~total-the~~ arboreal pollen ~~content~~ [total](#), birch and oak can be considered to
14 be/have been present in woodland (Liu et al., 1999). *Salix* produces very little pollen,
15 and most of this pollen falls near the tree itself (Li et al., 2000). Modern *Artemisia* and
16 Chenopodioideae are extensively distributed throughout the arid and semi-arid
17 regions of China. Chenopodioideae are more drought-resistant than *Artemisia*. [Higher](#)
18 [percentages of](#) *Artemisia* ~~being the dominant vegetation type~~ [pollen](#) may reflect a
19 semi-arid grassland environment, while [higher percentages of](#) Chenopodioideae
20 [pollen](#) may reflect an arid desert environment. Surface pollen analysis shows that
21 *Artemisia* and Chenopodioideae are greatly overrepresented in [the](#) pollen rain. Only
22 when Chenopodioideae and *Artemisia* pollen ~~content~~ [abundance](#) exceeds 30% of the
23 total should their presence be considered as primarily local (Herzschuh et al., 2003;
24 Ma et al., 2008). Poaceae pollen [abundance](#) ~~content~~ is sparse, usually only 3–6%, even
25 when it represents the dominant modern species (Tong et al., 1995).

26 Our record therefore indicates that, during the period when the Yaodian Fm was being
27 deposited, the study area was ~~dominated~~ [covered](#) by temperate forests and a warm and
28 humid climate. Mixed deciduous forests, characterized by the dominance of *Pinus*,
29 Cupressaceae, *Ulmus* and *Quercus*, were distributed within the basin and the low

1 altitude hills surrounding it. Mid- and high-altitude ~~vegetation, such as~~ forests with
2 *Abies*, *Picea* and *Cedrus*; existed in the surrounding uplands. The river banks or lake
3 margins were colonized by *Salix*, *Alnus*, *Fraxinus* and Taxodiaceae. Cyperaceae,
4 *Typha* and *Myriophyllum* grew along the lake shores or in shallow water areas.
5 Ranunculaceae, Poaceae, Chenopodioideae and *Artemisia*, principally occupied the
6 forest understory, or were distributed in forest clearings. However, as indicated by our
7 record, the environment was not static. During 11.4–10.1Ma, temperate forest ~~and a~~
8 more grew in the basin indicating a rather humid climate ~~developed in the basin~~. The
9 growth of fluvial channel deposits and the presentation of a large number of
10 mammalian fossils (Li et al., 2006) also support the theory that much denser
11 vegetation capable of supporting large mammals such as rhinoceroses developed
12 during this interval. Moreover, we know that the northern Tianshui Basin was
13 dominated by temperate and warm-temperate deciduous broadleaf forest (Hui et al.,
14 2011). Our result is also consistent with research into the climatic evolution of the
15 Qaidam Basin, which found that the presence of $\delta^{18}\text{O}$ values characteristic of large
16 mammals indicated a warmer, wetter, and perhaps lower-altitude Qaidam Basin
17 (Zhang et al., 2012). The early Late Miocene mammal fauna discovered in the
18 Qaidam Basin also reflects ~~ed~~ a wooded environment, in which many streams with
19 aquatic plants such as *Trapa* and *Typha* developed (Wang et al., 2007). From 10.1–
20 7.4Ma, the study area was dominated by a warm-temperate open forest environment
21 and ~~an a less humid~~ arid climate, relative to the previous interval. Sedimentary facies
22 become characteristic of shallow lake deposits (Li et al., 2006). Mammal fauna
23 identified in the eastern Qaidam Basin also indicates s that a mixed habitat of open and
24 wooded environments, with abundant freshwater streams, was predominant at that
25 time (Wang et al., 2007). ~~During this interval, In particular after~~ ~~~8.6Ma~~, herbaceous
26 plants also increased their presence in the Tianshui Basin after ~8.6Ma, as confirmed
27 by mammalian fossil records. In the northern Tianshui Basin at ~9.5Ma, there is
28 evidence of a sizeable rhinoceros population, which would have required a relatively
29 moist woodland environment to sustain itself. However, the typical *Hipparion* fauna
30 ~~that presents~~ at ~8.0Ma probably represents a relatively temperate climate with ~~a~~ more

1 | mixed vegetative ~~landscape~~on, i.e. an open forest environment rather than a vast, open
2 | landscape. Large mammals would still have been able to survive in such an
3 | environment (Zhang et al., 2013).

4 | An open temperate forest-steppe environment ~~clearly~~ developed in the study region,
5 | indicating significant aridification after ~7.4Ma. Grassland, composed principally of
6 | Poaceae, *Artemisia* and Chenopodioideae, developed in most of the basin, while
7 | shrinking areas of open forest, dominated by Cupressaceae, *Ulmus* and *Quercus*,
8 | existed in the surrounding mountains. *Salix* continued to grow in relatively humid
9 | environments such as riverbanks. Distal floodplain to palustrine deposits now
10 | characterized d the study area (Li et al., 2006). A sudden increase in magnetic
11 | susceptibility after ~7.4Ma may indicate ~~the enhanced oxidation characteristic of~~ an
12 | arid environment ([Zhang, 2013](#)) (Fig. 4b). In the northern part of the Tianshui Basin,
13 | drought-tolerant *Artemisia* ~~predominates~~ predominated after 7.4Ma, further
14 | confirming the presence of a drier climate (Hui et al., 2011) (Fig. 4c).

15 | ~~Further~~Additionally, the growing presence of grazer mammalian species at the end of
16 | the Miocene in the Tianshui Basin suggests that the local environment was principally
17 | occupied by grassland, with some woodland, and even some desert s~~ification~~ (L. P.
18 | Liu et al., 2011) (Fig. 4d). Furthermore, the gradual increase in eolian sediments after
19 | 7.4Ma in the Linxia Basin would indicate a period of intense desertification in central
20 | China (Fan et al., 2006) (Fig. 4e). Biomarker evidence from the Linxia Basin also
21 | indicates a distinct change in the climate toward arid-cold conditions at ~8Ma ([Y. L.](#)
22 | Wang et al., 2012). The isotopic compositions of herbivorous fossil teeth and
23 | paleosols from the Linxia Basin (Wang and Deng, 2005) and southwestern China
24 | (Biasatti et al., 2012) also indicate a shift to a drier, or seasonally drier, local climate.

25 | In the Qaidam Basin, *Hipparion teilhardi* fossils are characterized by slenderer distal
26 | limbs, and dated to the end of the Miocene, implying ing an adaptation by this animal to
27 | the open steppe environment (Deng and Wang, 2004). Marine sediments also indicate
28 | that the climate changed at this time. For example, local seawater $\delta^{18}\text{O}$
29 | reconstructions from ODP Site 1146 in the northern South China Sea suggest that the

1 | climate of ~~East-east~~ and ~~South-south~~ Asia shifted toward more arid conditions after
2 | ~7.5Ma (Steinke et al., 2010) (Fig. 4f).

3 | **5.2 More arid conditions at the end of the Miocene and ~~their~~ possible** 4 | **causes**

5 | Based on the ~~currently-available data from~~ Late Neogene Chinese mammalian fossils
6 | ~~data~~, Zhang (2006) suggested ~~ed~~ that mammal communities in northern China were
7 | rather stable and uniform from ~13Ma to the end of the Miocene (~7–8Ma), and that
8 | differentiation between the humid fauna communities prevalent in eastern China and
9 | the dry fauna communities identified in western China occurred after the end of the
10 | Miocene. The diversity in Bovidae fossils also increases significantly toward the end
11 | of the Miocene, with some genera ~~even~~-appearing in southwestern China (Chen and
12 | Zhang, 2009), indicating an expansion ~~in-of~~ grasslands and ~~an-aridification-of-the~~
13 | ~~climate~~. Using macro- and microfloral quantitative recovery techniques to reconstruct
14 | the climate in northern China at the time, Y.-S. C. Liu et al. (2011) proposed that the
15 | west–east temperature and precipitation gradient pattern did not develop in northern
16 | China until the end of the Miocene. This corroborates the quantitative results gained
17 | from using mammalian fossils as a proxy for paleoprecipitation (Liu et al., 2009). A
18 | semi-quantitative reconstruction of Chinese Neogene vegetation also ~~indicates~~
19 | ~~indicated~~ that the aridification of western, central and northern China occurred during
20 | the Miocene–Pliocene transition (Jacques et al., 2013). Indeed, in order to adapt to the
21 | arid climate ~~in-of~~ northern China during the end of the Miocene, some plants and
22 | arthropods also evolved more arid-tolerant species, such as *Frutescentes* (Fabaceae)
23 | (Zhang and Fritsch, 2010), *Ephedra* (Ephedraceae) (Qin et al., 2013) and *Mesobuthus*
24 | (Buthidae) (Shi et al., 2013). This marked aridification has been well documented in
25 | other parts of Asia. For example, dramatic changes in the carbon ~~and-hydrogen~~
26 | isotopic ratios of leaf waxes at ODP Site 722 indicate an increasing aridity at the end
27 | of the Miocene in continental source regions, including Pakistan, Iran, Afghanistan,
28 | and the Arabian Peninsula (Huang et al., 2007) (Fig. 4g). The isotopic compositions
29 | of herbivorous fossil teeth and paleosol carbonates also suggest that the climate

1 became drier over the Indian Subcontinent, China, and Central Asia ~~during~~ toward the
2 end of the Miocene ([Badgley et al., 2008](#); [Barry et al., 2002](#); [Biasatti et al., 2012](#);
3 [Cerling et al., 1997](#); Quade et al., 1989; ~~[Cerling et al., 1997](#)~~; Wang and Deng, 2005;
4 ~~[Biasatti et al., 2012](#)~~; ~~[Barry et al., 2002](#)~~; ~~[Badgley et al., 2008](#)~~; Zhang et al., 2009). The
5 evidential synchronicity of these climatic events in Asia strongly suggests that a
6 ~~process of the~~ aridification of the Asian interior began ~~toward~~ at the end of the
7 Miocene (~7–8Ma). The onset of such a marked aridification is further corroborated
8 by the presence of red clay across much of the ~~CLP~~ Chinese Loess Plateau (An et al.,
9 2001).

10 Precipitation in arid northwestern China is primarily caused by the Asian Summer
11 Monsoon, whereas the Asian Winter Monsoon promotes a cold and dry climate.
12 Besides the monsoon source, the westerlies also bring precipitation into China.
13 During the Neogene, Eurasia has experienced global cooling, land-sea redistribution
14 and regional tectonic uplift, and these three factors are considered as the major drivers
15 for the formation and evolution of the Asian monsoon and inland arid climate.

16 During the Late Neogene, the most significant global cooling event occurred at
17 ~14Ma (Mudelsee et al., 2014; Zachos et al., 2001), followed by a longer-term, but
18 minor cooling 4-to-10-Ma trend (named by Mudelsee et al., 2014) (Fig. 4h). Although
19 the global cooling should somehow lead to net aridification on the planet, cooling and
20 aridification trends do not seem to run parallel (van Dam, 2006). The spatial
21 complexity of the atmospheric and oceanic circulation systems ensures that general
22 cooling may result in precipitation decrease in some regions and increase in others
23 (van Dam, 2006). However, integrated studies showed that the global cooling during
24 the Neogene had significant influences on driving the Asian monsoon and inland arid
25 climate (e.g. Lu et al. 2010; Lu and Guo, 2014; Tang and Ding, 2013), especially
26 since the Late Miocene (Lu and Guo, 2014). The possible mechanism lies in three
27 aspects. Firstly, it is clear that the global cooling has strengthened the Siberia High,
28 which dominates winter monsoon circulation and aridity in eastern Asia (Lu and Guo,
29 2014). This would result in enhanced and more frequent cold surges in the

1 mid-latitudes of Northern Hemisphere. Secondly, the global cooling caused the
2 weakening of hydrological cycle, expanding of ice sheets, lowering of sea level and
3 increasing of continental surface. For eastern Asia, cooling weakens monsoon
4 circulation, and consequently drying conditions expand following retreat of the
5 monsoonal rain belt, while in the western, cooling reduces water vapor pressure and
6 therefore reduces the moisture mass transported into the continental interior (Tang and
7 Ding, 2013). Thirdly, seasonal sea ice was present in the Arctic Basin during the Late
8 Miocene (6-10Ma) when Greenland glacial ice began to grow (Moran et al., 2006),
9 despite minor cooling trend occurred during this interval (Mudelsee et al., 2014).
10 Therefore, we speculate that the global minor cooling during the Late Miocene could
11 force the Asian climate change through a series of feedback process, and that the
12 general trend towards a dry climate in interior Asian might be correlated with the
13 long-term global cooling. However, we also note that the aridification in our study
14 region occurred stepwise. Therefore, other factors, such as land-sea redistribution and
15 continental tectonic configuration, also exert a strong effect on the Asian precipitation
16 regimes. It should be note that, although the global cooling may not be the only cause
17 of the interior Asia aridification, there is no doubt regarding its effects on the general
18 trend towards a dry climate in interior Asian.

19 Besides the above focusing on the climate effect of the global cooling, model
20 simulation researches have been paid special attention to the climatic effects of the
21 land-sea redistribution and tectonic activity. For example, the model simulation
22 results suggest that the westward retreat of the Paratethys from central Asian has
23 contributed significantly to Asian climates (e.g. Guo et al., 2008; Ramstein et al.,
24 1997; Zhang et al., 2007). However, a large number of geological evidences suggest
25 that the vast majority/even all Paratethys regression from the Tarim Basin (northwest
26 China) occurred at the Oligocene ago (e.g. Bershaw et al., 2012; Bosboom et al.,
27 2014). Meanwhile, numerical simulation also indicates that the spreading of the South
28 China Sea may enhance the south-north contrast of humidity in China (Guo et al.,
29 2008), and brings more precipitation into Asian. Nevertheless, many studies indicate

1 [that the western and northern China became drier during the Neogene \(e.g. Guo et al.,](#)
2 [2008; Tang and Ding, 2013; Sun and Wang, 2005\).](#) Therefore, although the land-sea
3 [redistribution has significant impact on the major climate reorganization in Asia](#)
4 [during the Late Oligocene/Early Miocene \(Guo et al., 2008; Zhang et al., 2007\), it](#)
5 [should have a limited effect on the formation and development of the Asian inland](#)
6 [arid climate during the Late Miocene.](#)

7 [Tectonic uplift of the TP is a major event in the recent geological history of the earth,](#)
8 [which produced profound impacts on the Asian and global climates. The scenarios of](#)
9 [whole-plateau uplift \(e.g. Kutzbach et al., 1993\), phased uplift \(e.g. An et al., 2001;](#)
10 [Kitoh, 2004; Liu and Yin, 2002\) and sub-regional uplift \(e.g. Boos and Kuang, 2010,](#)
11 [2013; Chen et al., 2014; Tang et al., 2011, 2013; Wu et al., 2012\), with increasing](#)
12 [complexity, are usually designed for discovering the cause-effect relations between](#)
13 [the plateau uplift and paleoclimate change. The different models conclude that the](#)
14 [uplift of the TP played an essential role in affecting the atmospheric circulation and](#)
15 [forming the monsoon and arid climate when the whole/sub-regional plateau exceed a](#)
16 [critical height \(An et al., 2001; Boos and Kuang, 2010, 2013; Chen et al., 2014;](#)
17 [Kutzbach et al., 1993; Liu and Yin, 2002; Tang et al., 2011, 2013; Wu et al., 2012\).](#)
18 [However, because of the different model setups and boundary conditions, the effect](#)
19 [mechanism of the TP on regional climate and the regional climatic response to the TP](#)
20 [uplift still exist many uncertainties \(Liu and Yin, 2011\). The geological/proxy](#)
21 [research can provide the constraints for the model boundary conditions, whereas](#)
22 [numerical simulation can test the geological/proxy result. Therefore, it is useful to](#)
23 [compare the geological/proxy results and the numerical simulations \(Micheels et al.,](#)
24 [2007, 2011\). Many geological studies have suggested that the TP experienced rapid](#)
25 [uplift during the interval ~8–10Ma \(e.g. Enkelmann et al., 2006; Fang et al., 2003,](#)
26 [2005; Lease et al., 2007; Li et al., 2014; Molnar et al., 2010; Wang et al., 2006; X. X.](#)
27 [Wang et al., 2012; Zheng et al., 2006, 2010\) \(Fig. 4i\), despite the timing and degree of](#)
28 [the uplift are still debated. The Late Miocene uplift would have achieved an altitude](#)
29 [sufficient to block the penetration of moisture from the source region into western](#)

1 [China \(Dettman et al., 2001, 2003\)](#). There are also increasing proxy evidences that the
2 [Asian Summer Monsoon weakened after ~10Ma \(e.g. Clift et al., 2008; Wan et al.,](#)
3 [2010\)](#), while the Asian Winter Monsoon strengthened, particularly toward the end of
4 [the Miocene \(e.g. An et al., 2001; Clift et al., 2008; Jacques et al., 2013; Jia et al.,](#)
5 [2003; Sun and Wang, 2005\)](#), implicating the intensified Asian inland aridification.
6 [Combination of the currently-available geological/proxy records, the numerical](#)
7 [simulation results and our results, it can be concluded that the Late Miocene](#)
8 [aridification in our study area might be caused by the TP uplift.](#)

9 ~~In our study, the vegetation succession appears to be consistent with the general~~
10 ~~direction of global cooling, indicating that global cooling may have been a potential~~
11 ~~driving force for the aridification of the Asian interior (Fig. 4h). Because atmospheric~~
12 ~~moisture content decreases as air temperature cools, one would expect global cooling~~
13 ~~to lead to a gradual net global aridification (van Dam, 2006). However, drought~~
14 ~~occurs in a stepwise fashion. Although the most significant Late Cenozoic global~~
15 ~~cooling event occurred at ~14Ma (Zachos et al., 2001), only minor cooling events at~~
16 ~~~10.1Ma and ~7.4Ma have been documented (Fig. 4h). The Late Miocene climate~~
17 ~~was much warmer and/or wetter than today in many regions (Pound et al., 2012).~~
18 ~~Evidently, factors other than global cooling also exert a strong effect on precipitation~~
19 ~~regimes, particularly paleotopography and continental tectonic configuration, which~~
20 ~~themselves affect monsoonal patterns.~~

21 ~~The uplift of the TP is a potentially significant trigger of Asian aridification. First,~~
22 ~~although no consensus exists vis-à-vis the timing and degree of any uplift, many~~
23 ~~studies have suggested that the interval ~8–10Ma not only experienced rapid uplift of~~
24 ~~the TP (Molnar et al., 2010; Fang et al., 2003, 2005; Li et al., 2014; Enkelmann et al.,~~
25 ~~2006; Zheng et al., 2006, 2010; Wang et al., 2012, 2006; Lease et al., 2007) (Fig. 4i),~~
26 ~~but that this uplift achieved an altitude sufficient to block the penetration of moisture~~
27 ~~from the Indian Ocean into western China (Dettman et al., 2001, 2003). Second, the~~
28 ~~main source of water vapor for arid northwestern China has been the Asian Summer~~
29 ~~Monsoon; the Asian Winter Monsoon promotes a cold and dry climate. Atmospheric~~

1 ~~and coupled atmosphere-ocean models show that such massive, continent-spanning~~
2 ~~orogen uplift may have generated, or intensified, Asian monsoonal circulation~~
3 ~~(Kutzbach et al., 1993; An et al., 2001). Moreover, the effect of TP uplift on~~
4 ~~enhancement of the Asian Winter Monsoon was more significant than on the Asian~~
5 ~~Summer Monsoon (Liu and Yin, 2002). There is increasing evidence that the Asian~~
6 ~~Summer Monsoon gradually weakened after ~10Ma (Wan et al., 2010; Clift et al.,~~
7 ~~2008), while the Asian Winter Monsoon gradually strengthened, particularly toward~~
8 ~~the end of the Miocene (An et al., 2001; Jacques et al., 2013; Clift et al., 2008; Sun~~
9 ~~and Wang, 2005; Jia et al., 2003). Therefore, global cooling, most likely enhanced by~~
10 ~~TP uplift, may be a potential driving force for the aridification of the Asian interior.~~

11 **6 Conclusion**

12 The Late Cenozoic basins, ~~in the northeastern~~ located at the northeast TP, document
13 ~~both the tectonic uplift process and its associated~~ the environmental changes
14 associated with tectonic uplift. We investigated a Late Miocene ~~spore~~ pollen record
15 from the Tianshui Basin ~~in the northeastern TP~~. Our results indicated that a temperate
16 forest, with a ~~more~~ rather humid climate regime (11.4–10.1Ma), gave way to a
17 temperate open forest environment with a less humid climate (10.1–7.4Ma); this was
18 in turn replaced by an open temperate forest-steppe landscape, accompanied by a
19 relatively arid climate (7.4–6.4Ma). ~~This~~ The vegetation succession demonstrates that
20 the aridification of the Asian interior occurred after ~7–8Ma, as corroborated by other
21 studies of Asia. Our findings support the idea that the general trend towards a dry
22 climate in interior Asian might be correlated with the long-term global cooling, while
23 the Late Miocene aridification in our study area was probably caused by the TP
24 uplift. ~~global cooling may have been a potential driving force for aridification of the~~
25 ~~Asian interior, and that TP uplift probably enhanced this process.~~

26 ~~This study highlights these possible interactions between global cooling and tectonic~~
27 ~~uplift.~~

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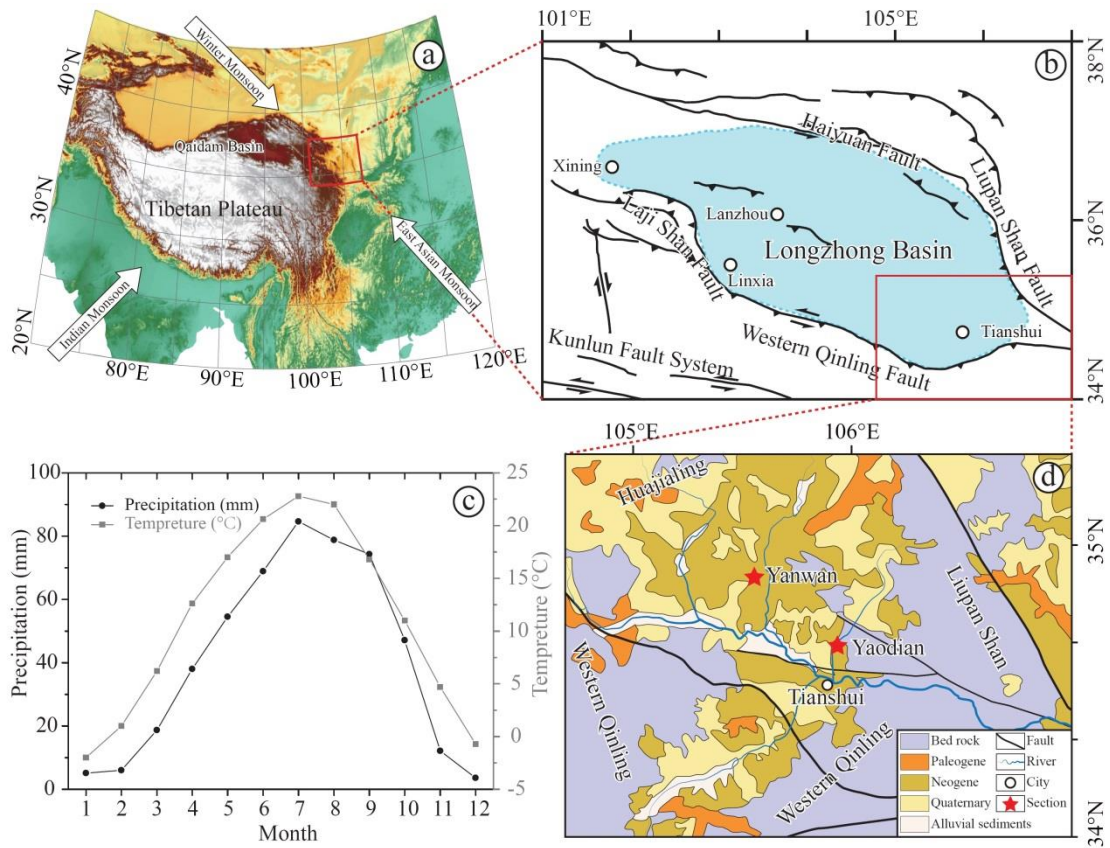
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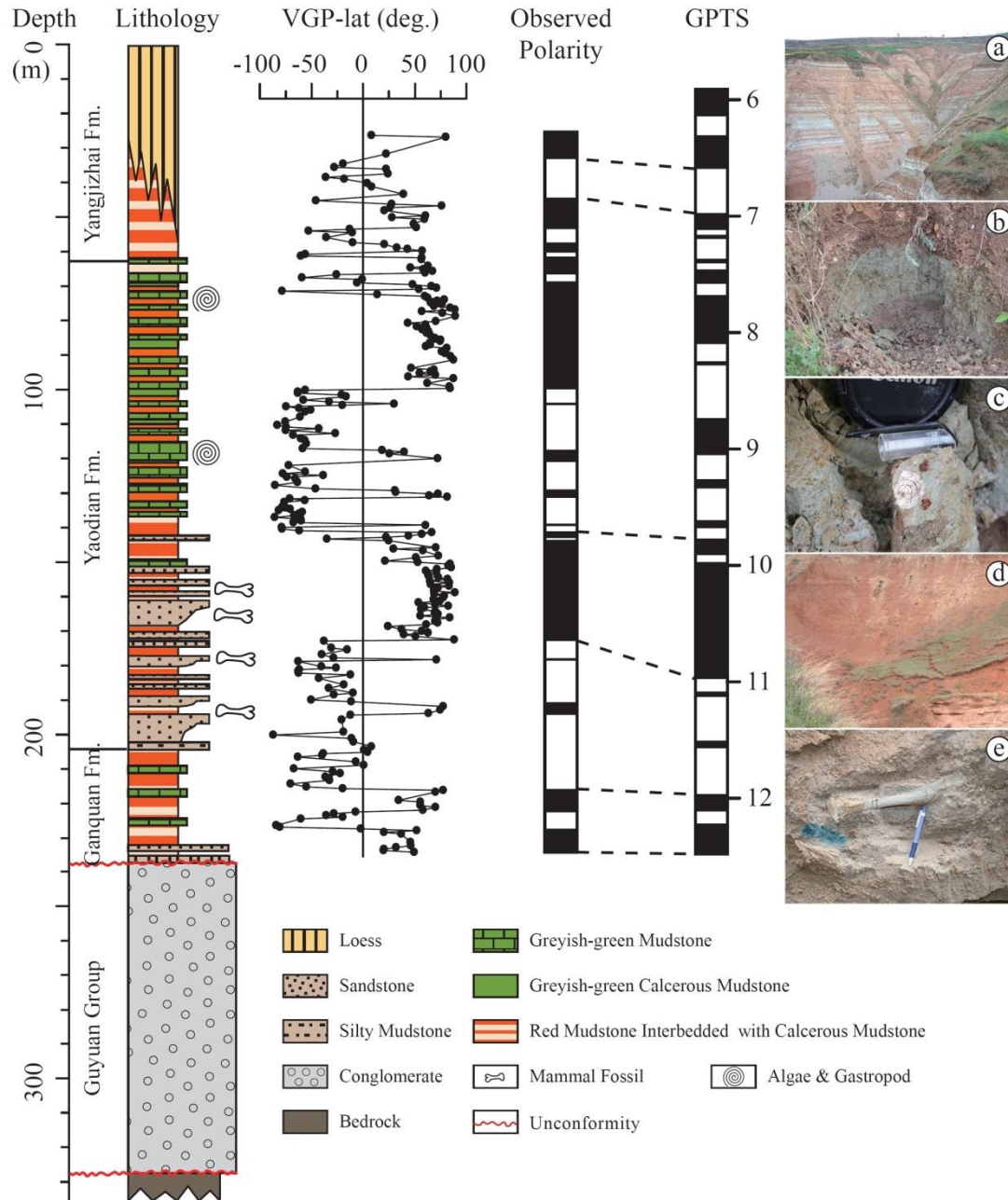
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2 Figure 1. Geographic setting of Yaodian Section. (a) The location of the Longzhong
 3 Basin. (b) The major tectonic faults of the Longzhong Basin. (c) Mean monthly
 4 temperature and mean monthly precipitation between in the Tianshui area, 1971-2000.
 5 (d) Geological map of the Tianshui Basin.

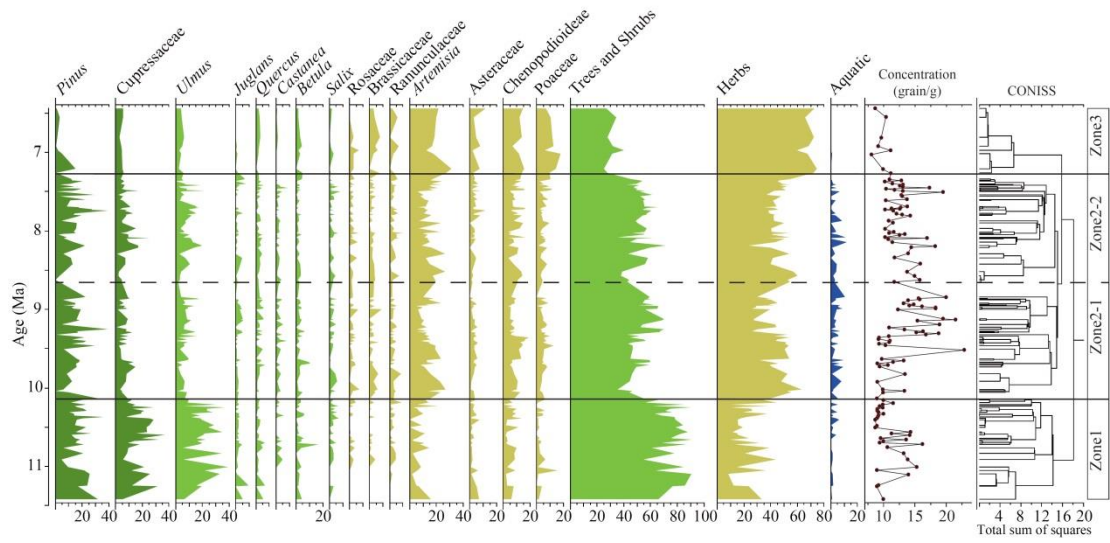
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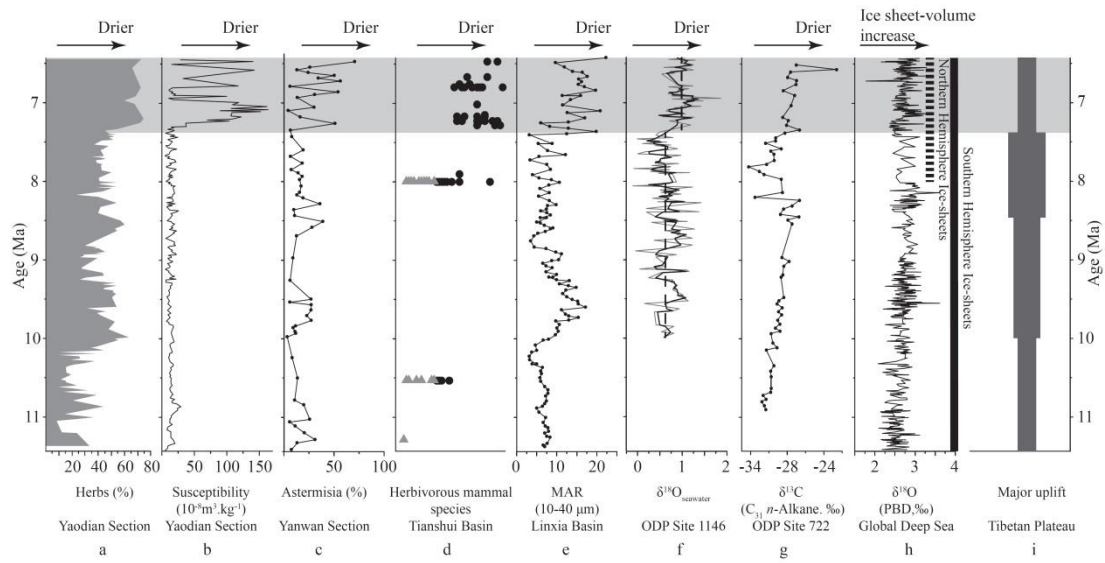
2 Figure 2. Lithology and magnetic stratigraphy of the Yaodian Section (according to Li
 3 et al., 2006, 2007). (a) The entire Yaodian Fm. (b) Yangjizhai Fm distal floodplain to
 4 palustrine deposits. (c) Yaodian Fm upper stratum lacustrine deposits, containing
 5 gastropod fossil fragments. (d) Yaodian Fm middle stratum floodplain deposits, with
 6 paleosols. (e) Yaodian Fm lower stratum fluvial channel deposits, containing
 7 fossilized animal bones. [GPTS, standard geomagnetic polarity timescale in million](#)
 8 [years \(Ma\).](#)

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Figure 3. Histogram showing speropollen percentages for the most significant angiosperms and gymnosperms.



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Figure 4. Proxy records of aridification for East Asia during the Late Miocene. (a) Herbaceous pollen ~~contents (%)~~ percentage for the Yaodian Section (this study); ~~);~~). (b) The magnetic susceptibility of the Yaodian Section ~~magnetic susceptibility~~ ~~(this study~~ ~~Zhang, 2013)~~ ~~);~~). (c) Drought-tolerant *Artemisia* pollen ~~content (%)~~ percentage ~~for~~ in the Yanwan Section, northern Tianshui Basin (Hui et al., 2011); ~~);~~). (d) Herbivorous mammal species in the Tianshui Basin (Guo et al., 2002; L. P. Liu et al., 2011; Li et al., 2006; Zhang et al., 2013; ~~Liu et al., 2011~~). Black circles represent species which adapted to relatively arid environments, and grey triangles represent species which adapted to relatively humid environments. ~~including *Sinoericetus zdanskyi*, *Kowalskia sp.*, *Hansdebminjia pusillus*, *Lophoericetus grabau*, *Mesosiphneus praetingi*, *M. sp.*, *Paralaetaga anderssoni*, *Parasoriculus sp.*, *Prosiphneus eriksoni*, *P. licenti*, *P. tianzuensis*, *Prospermophilus orientalis*, *Pseudomeriones abbreviatus*, *P. complicidens*, *Sciuridae*, *Sicista sp.*, *Alilepus annectens*, *Allorattus sp.*, *Apodemus sp.*, *Chardina n. sp.*, *C. sinensis*, *C. truncatus*, *Chardinomys nihowanicus*, *C. sp.*, *C. yusheensis*, *Pliosiphneus lyratus*, *Cricetinus mesolophidus*, *Mimomys teilhardi*, *Paenepetenyia zhudingi*, *Sinotamias sp.*, *Ochotona gracilis*, *O. lagreli*, *O. lingtaica*, *O. minor*, *O. plicodenta*, *O. sp.*, *Ochotonoma sp.*, *O. primitiva*, *Trischizolagus mirificus*, *Hipparion chiai*, *H. dermatorhinum*, *H. fossatum*, *H. plocodus*, *H. sp.*, *H. weihoense*, and *Gazella sp.*; grey triangles represent species which adapt to relatively humid environment, including ~~*Chleuastochoerus stehlini*, *Cervavitus novorossiae*, *Cervidae*~~~~

1 ~~gen. et sp. Indet., *Palaeotragus microdon*, *P. sp.*, *Samotherium sinense*, *S. sp.*,~~
2 ~~Rhinocerotidae indet., *Acerorhinus fuguebsis*, *Chilotherium habereri*, *C. sp.*, *C.*~~
3 ~~*wimani* and *Protanancus tobieni*.~~ (e) Eolian sediment mass accumulation rates ~~for in~~
4 the Linxia Basin, northeastern TP (Fan et al., 2006); ~~).~~ (f) South China Sea $\delta^{18}\text{O}_{\text{seawater}}$
5 estimates from ODP Site 1146 (Steinke et al., 2010); ~~).~~ (g) Carbon isotope ratios of
6 leaf wax C_{31} *n*-alkane extract from ODP Site 722 (Huang et al., 2007). (gh) Compiled
7 global deep-sea $\delta^{18}\text{O}$ values (Zachos et al., 2001, the data available online
8 <http://www.es.ucsc.edu/~jzachos/Publications.html>. A new compilation has been
9 published by Mudelsee et al. (2014), which is congruent with the Zachos' curve for
10 the Miocene part); ~~).~~ (hi) Schematic model showing the major periods of TP uplift
11 (Enkelmann et al., 2006; Fang et al., 2003, 2005; Lease et al., 2007; Li et al., 2014;
12 Molnar et al., 2010; Wang et al., 2006; X. X. Wang et al., 2012; Zheng et al., 2006,
13 2010~~Molnar et al., 2010; Fang et al., 2003, 2005; Li et al., 2014; Enkelmann et al.,~~
14 ~~2006; Zheng et al., 2006, 2010; Wang et al., 2012; Wang et al., 2006; Lease et al.,~~
15 ~~2007).~~