



**HAL**  
open science

## Proto-monsoon rainfall and greening in Central Asia due to extreme early Eocene warmth

Niels Meijer, Alexis Licht, Amber Woutersen, Carina Hoorn, Faez Robin-Champigneul, Alexander Rohrmann, Mattia Tagliavento, Julia Brugger, Fanni Kelemen, Andrew Schauer, et al.

### ► To cite this version:

Niels Meijer, Alexis Licht, Amber Woutersen, Carina Hoorn, Faez Robin-Champigneul, et al.. Proto-monsoon rainfall and greening in Central Asia due to extreme early Eocene warmth. *Nature Geoscience*, 2024, 17 (2), pp.158-164. 10.1038/s41561-023-01371-4 . hal-04426859

**HAL Id: hal-04426859**

**<https://hal.science/hal-04426859v1>**

Submitted on 30 Jan 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

1 **Proto-monsoon rainfall and greening in Central Asia due to extreme early**  
2 **Eocene warmth**

3 Niels Meijer<sup>1</sup>, Alexis Licht<sup>2</sup>, Amber Woutersen<sup>3</sup>, Carina Hoorn<sup>3</sup>, Faez Robin-  
4 Champigneul<sup>4</sup>, Alexander Rohrmann<sup>5</sup>, Mattia Tagliavento<sup>6</sup>, Julia Brugger<sup>1</sup>, Fanni D.  
5 Kelemen<sup>7</sup>, Andrew J. Schauer<sup>8</sup>, Micheal T. Hren<sup>9</sup>, Aijun Sun<sup>10-12</sup>, Jens Fiebig<sup>6</sup>,  
6 Andreas Mulch<sup>1,6</sup>, Guillaume Dupont-Nivet<sup>13,14</sup>

7 1) Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt am  
8 Main, Germany.

9 2) CNRS, IRD, INRAE, CEREGE, Aix Marseille University, Aix-en-Provence, France.

10 3) Department of Ecosystem and Landscape Dynamics (ELD), Institute for Biodiversity  
11 and Ecosystem Dynamics (IBED), University of Amsterdam, Amsterdam, the  
12 Netherlands.

13 4) Maastricht University, Faculty of Science and Engineering, Maastricht Science  
14 Programme, Maastricht, the Netherlands.

15 5) Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

16 6) Goethe University Frankfurt, Institute of Geosciences, Frankfurt am Main, Germany.

17 7) Goethe University Frankfurt, Institute for Atmospheric and Environmental Sciences,  
18 Frankfurt am Main, Germany.

19 8) Department of Earth and Space Sciences, University of Washington, Seattle, WA,  
20 USA.

21 9) Department of Earth Sciences, University of Connecticut, Storrs, CT, USA

22 10) Key Laboratory of Western China's Environmental Systems (Ministry of  
23 Education), College of Earth and Environmental Sciences, Lanzhou University,  
24 Lanzhou, China.

- 25 11) Key Laboratory of Desert and Desertification, Northwest Institute of Eco-  
26 Environment  
27 and Resources, Chinese Academy of Sciences, Lanzhou, China.  
28 12) University of Chinese Academy of Sciences, Beijing, China.  
29 13) Géosciences Rennes-UMR CNRS 6118, Univ Rennes, CNRS, Rennes, France.  
30 14) GFZ German Research Centre for Geosciences, Potsdam, Germany

31

32 **The dry continental interior of Asia has remained arid throughout most of its**  
33 **geological history, yet the future of this unique ecosystem remains unclear.**  
34 **Here, we use palynological and isotopic records to track vegetation and**  
35 **moisture throughout the warm early Eocene (57 to 44 million years ago) as an**  
36 **analogue for extreme atmospheric CO<sub>2</sub> scenarios. We show that rainfall**  
37 **temporarily doubled and replaced the regional steppe by forested ecosystems.**  
38 **By reconstructing the season of pedogenic carbonate growth we constrain the**  
39 **soil hydrologic regime and show that most of this rainfall occurred during the**  
40 **summer season. This humid event is therefore attributed to an inland expansion**  
41 **of monsoonal moisture following the massive greenhouse gas release of the**  
42 **Paleocene-Eocene Thermal Maximum (PETM) as identified by a negative carbon**  
43 **isotope excursion. The resulting abrupt greening of the Central Asian steppe-**  
44 **desert would have enabled mammal dispersal and could have played a role in**  
45 **carbon cycle feedbacks by enhancing soil organic carbon burial and silicate**  
46 **weathering. These extreme Eocene proto-monsoons, albeit different from the**  
47 **topography-driven Asian monsoon today, highlight the potential for abrupt**  
48 **shifts in Central Asian rainfall and ecosystems under future global warming.**

49

50 The vast Asian continental interior is home to a unique and diverse steppe-desert  
51 biome that has existed for millions of years<sup>1</sup>, yet its hydroclimatic future and response  
52 to extreme atmospheric CO<sub>2</sub> concentrations (pCO<sub>2</sub>) remains poorly understood<sup>2</sup>.  
53 Sedimentary archives of past warming events together with climate model simulations  
54 provide valuable insights<sup>3</sup>, especially regarding the Eocene period (56-34 Ma) which  
55 was characterized by short-lived hyperthermal events of abrupt warming<sup>4,5</sup>. The  
56 largest and most pronounced of these is the Paleocene-Eocene Thermal Maximum  
57 (PETM; 56 Ma) lasting several 10 ka, during which pCO<sub>2</sub> reached more than 6× the  
58 pre-industrial atmospheric CO<sub>2</sub> concentration<sup>6-8</sup>. Records of such hyperthermal events  
59 affecting inland Asia are rare and hard to decipher because we commonly lack  
60 unambiguous rainfall proxies with respect to the various regional moisture sources,  
61 thereby limiting our understanding of the hydroclimatic response to climate forcing,  
62 including future projections under higher pCO<sub>2</sub><sup>3</sup>.

63

64 The scarce precipitation reaching inland Asia today mostly originates from monsoons  
65 during summer or the mid-latitude westerlies during winter to spring (Fig. 1 A;  
66 Extended Data Fig. 1)<sup>9,10</sup>. Paleoclimate models and geological records indicate that  
67 growth of the Tibetan-Himalayan orogen and retreat of the Paratethys Sea modulated  
68 monsoons and westerlies since the Eocene (Fig. 1 A)<sup>11-14</sup>. Proto-monsoons existed  
69 already before significant surface uplift of the Tibetan Plateau, but it remains debated  
70 whether these were similar to today<sup>15-17</sup>, less intense<sup>18</sup> or only restricted to the tropical  
71 low latitudes<sup>13,14,19</sup> except during extreme orbital conditions<sup>20,21</sup>. Eocene  
72 paleobotanical data show that summer monsoons transported abundant precipitation  
73 to the East Asian coast<sup>17,22</sup>, while regional soil respiration derived from carbon isotope  
74 ratios ( $\delta^{13}\text{C}$ ) of pedogenic carbonates suggest that monsoons may have reached

75 further inland<sup>10</sup>. Oxygen isotope ratios ( $\delta^{18}\text{O}$ ) on the other hand, suggest that the mid-  
76 latitude westerlies provided winter to springtime precipitation to Central Asia,  
77 especially before the Neogene surface uplift of the Tien Shan and Pamir mountains,  
78 which block most of this moisture today<sup>9,10,23</sup>. However, the isotopic composition of  
79 this westerly precipitation is difficult to distinguish from summer monsoonal moisture  
80 reaching the continental interior<sup>10</sup>.

81

82 Key in distinguishing between these different Asian moisture regimes is therefore to  
83 identify not only the isotopic composition and amount of precipitation, but also the  
84 seasonal timing, which remains difficult to assess from geological records. Here, we  
85 address this issue using a novel approach of combining fossil sporomorphs (pollen  
86 and spores) and soil organic matter as proxy for precipitation<sup>24</sup> together with clumped  
87 isotope ( $\Delta_{47}$ ) temperatures of co-occurring pedogenic carbonates which mostly form  
88 during the dry season<sup>25,26</sup>. By comparing these  $\Delta_{47}$ -derived soil temperatures with  
89 seasonal climate model estimates we distinguish whether soil dewatering occurred  
90 predominantly during a winter-time dry season after a wet summer monsoon, or during  
91 summer drying of westerly-derived soil moisture<sup>27,28</sup>. Today, the monsoons and  
92 westerlies meet along the northeastern margin of the Tibetan Plateau, which includes  
93 the continental Xining Basin (China) and is ideally located to track the evolution of  
94 these moisture sources (Fig. 1). Previous soil temperature reconstructions throughout  
95 the middle Eocene and Oligocene show that the Xining Basin was at low elevation<sup>27</sup>,  
96 while steppe-desert pollen, presence of evaporites and reduced soil respiration  
97 indicate aridity<sup>1,23,29</sup>. Dating of this sedimentary record has now been extended to the  
98 early Eocene based on magnetostratigraphy and radiometric ages<sup>23,30</sup> allowing us to  
99 investigate the Central Asian steppe response to hyperthermal conditions.

100

101 **Increased rainfall during a carbon isotope excursion**

102

103 Early Eocene hyperthermals were driven by the periodic injection of greenhouse gases  
104 into the atmosphere from low- $\delta^{13}\text{C}$  reservoirs. This resulted in negative carbon isotope  
105 excursions (CIE) across the globe that have been detected in various terrestrial  
106 proxies such as plant waxes ( $\delta^{13}\text{C}_{\text{wax}}$  of  $\text{C}_{29}$  to  $\text{C}_{31}$  *n*-alkanes) or bulk soil organic  
107 matter ( $\delta^{13}\text{C}_{\text{SOM}}$ )<sup>6</sup>. In the Xining Basin,  $\delta^{13}\text{C}$  values are relatively high throughout most  
108 of the Eocene, but we identify an abrupt and large CIE of -6‰ in  $\delta^{13}\text{C}_{\text{SOM}}$  and -8‰ in  
109 compound specific  $\delta^{13}\text{C}_{\text{wax}}$  (Fig. 2). This is significantly larger than the CIEs related to  
110 early Eocene hyperthermals which typically attain magnitudes of up to -4‰<sup>4,5</sup>, but very  
111 similar in both shape and magnitude to continental records of the PETM<sup>6,32,33</sup>.

112

113 The Xining CIE is preceded by alluvial mudflat deposits at the basin margin (Ledu  
114 section) and organic-rich gypsum in the basin center (Bingling Shan and Caijia  
115 sections) indicating dry conditions. This is corroborated by the predominance of  
116 steppe-desert shrubs in the palynological record and high  $\delta^{13}\text{C}$  values which today are  
117 only found in extremely dry ecosystems<sup>24,34</sup> (Fig. 2). The negative CIE starts abruptly  
118 in the uppermost gypsum bed and spans ~30 meters into the overlying organic-rich  
119 alluvial mudflat deposits<sup>30</sup>. Steppe-desert pollen decrease during this interval and the  
120 vegetation becomes dominated by temperate forests and ferns indicating a shift to  
121 wetter conditions. Less water stress experienced by C3 vegetation and the  
122 corresponding shift in biome typically results in lower  $\delta^{13}\text{C}$  values<sup>34,35</sup>. If combined with  
123 a dramatic drop of atmospheric carbon isotopic composition ( $\delta^{13}\text{C}_{\text{atm}}$ ), such as seen

124 during hyperthermals<sup>6,35,36</sup>, these ecological changes could produce the large size of  
125 the CIE observed in the Xining Basin.

126

127 Organic matter recorded in soils provides a natural average of the aboveground  
128 biomass and can be used to reconstruct the amount of rainfall when corrected for  
129 changes in  $\delta^{13}\text{C}_{\text{atm}}$  (Fig. 2 and Extended Data Fig. 2)<sup>24</sup>. Even when assuming an  
130 extreme change of  $\delta^{13}\text{C}_{\text{atm}}$  such as observed during the PETM<sup>6,35</sup>, reconstructed mean  
131 annual precipitation (MAP) values suggest at least a doubling of MAP in the Xining  
132 Basin during the CIE (~574 mm/year) compared to the evaporites below (~177  
133 mm/year). Using the  $\delta^{13}\text{C}_{\text{atm}}$  value of lower magnitude Eocene hyperthermals would  
134 result in an even larger increase in MAP (~984 mm/year) and using the early Eocene  
135 baseline value would imply an unrealistic MAP of >4000 mm/year (Supplementary  
136 Data 4). Throughout the remainder of the Eocene Xining record,  $\delta^{13}\text{C}_{\text{SOM}}$  values  
137 remain relatively high<sup>29</sup> indicating aridity which fits the predominant redbeds,  
138 evaporites and steppe-desert shrubs observed in the record<sup>1,23</sup>. The CIE in the Xining  
139 Basin is thus a unique window where both palynological assemblages and  $\delta^{13}\text{C}$  values  
140 show a significant greening of the otherwise arid Asian interior. In the following, we will  
141 use soil carbonates to test whether this greening was driven by increased westerly  
142 moisture or monsoons (Fig. 1).

143

#### 144 **Clumped isotope evidence for summer rainfall**

145 Well-developed pedogenic carbonate nodules are rare in the Xining Basin record but  
146 were identified in three horizons of the Ledu section. In consequence, the carbonate  
147 component of the alluvial mudrocks was assessed as well using Scanning Electron

148 Microscopy (SEM), X-Ray Diffraction (XRD; Fig. 2; Extended Data Fig. 3) and both  
149 optical and cathodoluminescence (CL) microscopy (Extended Data Fig. 4). The strata  
150 between 50 Ma and 45 Ma contain mostly calcian dolomite (6-20%), while the intervals  
151 above and below are dominated by calcite (1-14%). This calcite is mostly dull  
152 luminescent micrite and is interpreted as vadose-grown cement with no evidence of  
153 phreatic overprinting (Extended Data Fig. 4 A and B). These cements precipitate either  
154 from rising shallow groundwater or percolating soil water and are similar to pedogenic  
155 carbonates<sup>37</sup>. In contrast, the calcian dolomite may have formed either by syn-  
156 sedimentary precipitation from saline brines or late diagenetic replacement of calcite  
157 cements<sup>38</sup>. Hence, we focus our isotope investigations solely on the vadose-grown  
158 calcite and micritic pedogenic nodules (Extended Data Fig. 4 C) to avoid diagenetic  
159 overprinting.

160 Clumped isotope thermometry measures the relative abundance of calcite-derived  
161 CO<sub>2</sub> isotopologues of mass 47 compared to the predicted stochastic distribution ( $\Delta_{47}$ ).  
162 Since the bonding between the heavy isotopes (<sup>13</sup>C-<sup>18</sup>O) is temperature-dependent,  
163 this measurement allows reconstructing soil temperatures at the time of carbonate  
164 growth without prior knowledge of the isotopic composition of the soil water<sup>39</sup>. Most  
165 Holocene pedogenic carbonates provide  $\Delta_{47}$  temperatures that are warmer than mean  
166 annual temperatures (MAT) because intense soil dewatering and carbonate formation  
167 is typically biased towards the summer season<sup>25,26</sup>. So far, the only location where soil  
168  $\Delta_{47}$  temperatures have systematically yielded winter temperatures is the monsoonal  
169 tropical domain, where winters are dry and warm enough for the accumulation of  
170 pedogenic carbonates while summers are typically too wet<sup>28</sup>. Colder-than-MAT  $\Delta_{47}$   
171 temperatures can thus be interpreted as a signature for a summer rainy season,



172 especially during Eocene times when winter temperatures were overall warmer,  
173 facilitating carbonate growth in the winter<sup>28</sup>.

174

175 Overall, the pedogenic and vadose-grown carbonates in the Xining strata show a wide  
176 spread of  $\Delta_{47}$  temperatures ranging from  $9 \pm 3$  °C to  $38 \pm 4$  °C (Fig. 2). This range could  
177 be due to high evaporative demand throughout the year, resulting in soil drying shortly  
178 after erratic rainfall events under variable temperature conditions<sup>26</sup>. In contrast, the  $\Delta_{47}$   
179 temperatures during the wetter CIE interval (Fig. 2) are remarkably stable at  $20 \pm 3$  °C  
180 and surprisingly low, especially given the hyperthermal conditions. When compared  
181 with simulated temperatures in the Xining Basin from the various climate models of  
182 the Deep-Time Model Intercomparison Project (DeepMIP)<sup>40</sup> these simulated  
183 temperatures indicate that carbonate growth during the CIE was biased towards the  
184 colder winter months (Fig. 3 A). Especially when considering that the soil temperature  
185 might have been 1-4 °C warmer than the simulated surface air because of ground  
186 heating effects<sup>41</sup>.

187

188 The  $\Delta_{47}$  temperatures during the CIE therefore suggest that soil drying in the Xining  
189 Basin occurred during the winter season, while the increased rainfall recorded in the  
190 palynological assemblage and  $\delta^{13}\text{C}$  values must have occurred mostly during the  
191 summer. This is similar to the modern monsoonal setting in which pedogenic  
192 carbonates near Xining are formed during the fall and after the wet season<sup>42</sup>.  
193 Reconstructed soil water  $\delta^{18}\text{O}$  ( $-6 \pm 1.5$ ‰; Extended Data Fig. 5 and 6) is similar to  
194 coeval records of both summer monsoonal and westerly moisture in the region<sup>10</sup>, but  
195 the cold  $\Delta_{47}$  temperatures in combination with increased MAP indicate an  
196 intensification of summer monsoons deep within the Asian continent shifting the timing

197 of carbonate formation to the winter season. Cold  $\Delta_{47}$  temperatures are not unique to  
198 the CIE and reappear episodically in the Xining Basin ~10 million years later and  
199 persist into the Oligocene (Fig. 3 A), possibly due to the combined effects of global  
200 cooling and an increased role for summer monsoonal moisture<sup>27</sup>. However, the  
201 palynological records show that the region remained extremely dry throughout the late  
202 Eocene to Oligocene<sup>1</sup> and unlike the intensified monsoon seen during the CIE (Fig.  
203 2).

204

### 205 **Proto-monsoon intensification in hyperthermal conditions**

206

207 The simulated temperatures fit well with global proxy compilations<sup>43</sup> and the climate  
208 models show mutual agreement<sup>40</sup> (Fig 3 A), however, differences between models are  
209 large for simulated precipitation<sup>3</sup> (Fig. 3 B). The ‘drier’ models show aridity in the Xining  
210 Basin throughout the year (e.g. COSMOS and IPSL), while the ‘wetter’ models reveal  
211 a summer rainy season (e.g. CESM and HadCM3) not unlike pre-industrial conditions  
212 (Extended Data Fig. 1). Simulated MAP is relatively low and ranges from 25 to 469  
213 mm/year (Fig. 3 B), which fits with the inland evaporative basins in the region<sup>44</sup> and  
214 our proxy estimates for the Paleocene and Eocene background conditions in the  
215 Xining Basin. However, even the ‘wetter’ simulations are lower than our reconstructed  
216 MAP of 574 mm/year for the intensified monsoon during the CIE.

217

218 The distribution of monsoonal domains<sup>45</sup> in the simulations shows that the East Asian  
219 monsoon was less prevalent in the Eocene compared to today (Fig. 4; Extended Data  
220 Fig. 7) and that southern Asia was influenced by the Intertropical Convergence Zone  
221 (ITCZ) as suggested by paleobotanical data<sup>19</sup>. Intriguingly, some of the Eocene

222 simulations also show a monsoonal domain along the East Asian coast (CESM,  
223 COSMOS and GFDL), in particular in the 6x and 9x pCO<sub>2</sub> simulations, which would  
224 have resembled the early Eocene atmosphere<sup>8</sup> (Fig. 4; Extended Data Fig. 7). This  
225 East Asian proto-monsoon agrees well with paleobotanical compilations showing a  
226 humid coast line<sup>17,22</sup>, but none of the DeepMIP models reproduce monsoons extending  
227 far into the continental interior to reach the Xining Basin.

228

229 Other modeling studies have shown that Eocene monsoons can be triggered in  
230 extreme orbital settings with amplified northern hemisphere heating<sup>20,21</sup>. The PETM  
231 and other hyperthermal events correspond to high eccentricity<sup>7</sup> and these unique  
232 conditions combined with extreme greenhouse warming likely conspired to intensify  
233 the proto-monsoons to reach the continental interior of Asia. The shape, large  
234 magnitude and thickness of the Xining CIE, and its occurrence within a long reversed  
235 polarity zone correlated with chron C24r (57.1 Ma to 53.9 Ma) allow us to attribute the  
236 CIE to the PETM (56 Ma), which also fits within the radiometric age constraints (Fig.  
237 2; Extended Data Fig. 8). Alternatively, it could be ETM2 (54 Ma) but this hyperthermal  
238 is considerably smaller in size, shorter and consists of two excursions (H1 and H2)  
239 that have been observed in both marine and terrestrial records<sup>4,5,32</sup> but are absent in  
240 the Xining Basin. Furthermore, negative CIEs with a shape and size similar to the  
241 Xining CIE have been observed in the continental Nanyang and Fushun Basins in  
242 eastern China and are also linked to reduced water stress during the PETM<sup>36</sup>. As the  
243 largest hyperthermal, the PETM is therefore the most likely driver for this unique event  
244 of monsoon intensification and greening in Central Asia.

245

246 Finally, we note that the Eocene proto-monsoons were significantly different from the  
247 modern-day East Asian monsoon, which is mostly driven by interaction between the  
248 subtropical jet stream and the high topography of the Tibetan Plateau<sup>12</sup>. Eocene proto-  
249 monsoons occur even in the DeepMIP simulations with no Tibetan Plateau at all (Fig.  
250 4) and are driven by a distinct low atmospheric pressure anomaly developing during  
251 summer over the vast and flat Asian continent (Extended Data Fig. 9). This suggests  
252 that the proto-monsoons were similar to a large sea breeze driven by land-sea thermal  
253 contrasts<sup>18</sup> and explains their sensitivity to hyperthermal conditions. Global cooling  
254 after the early Eocene reduced regional thermal contrasts, dampening the ability of  
255 proto-monsoons to episodically expand inland and could explain the overall  
256 aridification trend of Central Asia throughout the Eocene and culminating at the  
257 Eocene-Oligocene Transition (EOT; 33.9 Ma)<sup>27,29,46</sup>. Only until the subsequent surface  
258 uplift and northward expansion of the Tibetan Plateau during the Neogene would the  
259 modern-day East Asian monsoon have returned to the Xining Basin and the Asian  
260 interior<sup>11-14</sup>.

261

262 Our study thus reveals a prominent role for Eocene proto-monsoons in occasionally  
263 greening the otherwise dry Asian interior under hyperthermal conditions. The PETM,  
264 but also other hyperthermals such as the Middle Eocene Climatic Optimum (MECO)  
265 are associated with major mammal dispersals in and out of Asia<sup>47,48</sup> and future work  
266 should consider the role of proto-monsoons in shifting biomes<sup>49</sup> and opening dispersal  
267 corridors within continental Asia. Replacing the steppe-desert by forested ecosystems  
268 could have also played a major role in buffering the massive carbon release during  
269 hyperthermals by enhancing soil organic carbon burial and silicate weathering<sup>50</sup>.  
270 Finally, our work provides paleoclimate evidence highlighting the abrupt and non-linear

271 response of Asian monsoons to extreme greenhouse warmth. Although the Eocene  
272 Asian paleogeography and hydroclimate were markedly different from today, the  
273 mechanisms leading to abrupt greening of the Asian interior should be further tested  
274 and simulated because of their significance for predicting future rainfall patterns.

275

## 276 **Acknowledgments**

277 This study was funded by an ERC consolidator grant (MAGIC 649081 to GDN) and  
278 through the VeWA consortium by the LOEWE programme of the Hessen Ministry of  
279 Higher Education, Research and the Arts, Germany. We thank Rainer Petschick for  
280 help with the XRD analyses as well as Jeremy McCormack and Amelia Davies for  
281 suggestions on the formation of dolomite. We acknowledge Roy Erkens and the  
282 following students from Maastricht University for their help in exploring the  
283 palynological samples: Henry del Marmol, Lucas Sauerschnig, Kaatje de Jong, Amaia  
284 Villagrasa, Lael Licht, Henry de Schrevel, and Benedetto Diana. We also acknowledge  
285 Hanna van den Hill (University of Amsterdam) and Julia Gravendeyk (University of  
286 Bonn) for extensive sporomorph documentation. We thank Hanno Meyer for kindly  
287 providing organic stable isotope analyses and Armelle Ballian, Sven Hofmann and  
288 Simon Anderson for assistance with stable and clumped isotope analyses. We also  
289 thank Christina Günter and Uwe Altenberger for their help with the SEM and CL. We  
290 are grateful to Natasha Barbolini, Xiang-Jun Liu, Xiaohui Wu, Zhipeng Wu, Meimei  
291 Xiao and Yang Zhang for their support with collecting the samples. We also  
292 acknowledge the efforts of the DeepMIP community and are thankful for the available  
293 climate model simulation data.

294

295 **Author contributions**

296 N.M., A.L. and G.D.-N. designed the study. N.M., A.L., A.W., A.R., A.S. and G.D.-N.  
297 conducted the field work and collected the samples. N.M. performed the XRD and  
298 petrographic analyses. A.W., F.R.-C. and C.H. prepared and analysed the  
299 palynological samples. A.R. and M.T.H. performed the *n*-alkane analyses. N.M., A.L.,  
300 A.J.S. and A.M. conducted the stable isotope analyses. N.M., M.T. and J.F. performed  
301 the clumped isotope analyses. J.B. and F.D.K. analysed and plotted the climate model  
302 simulation data. N.M. wrote the manuscript with major input from A.L., G.D.-N. and  
303 A.M. All co-authors contributed to interpreting the data and writing the manuscript.

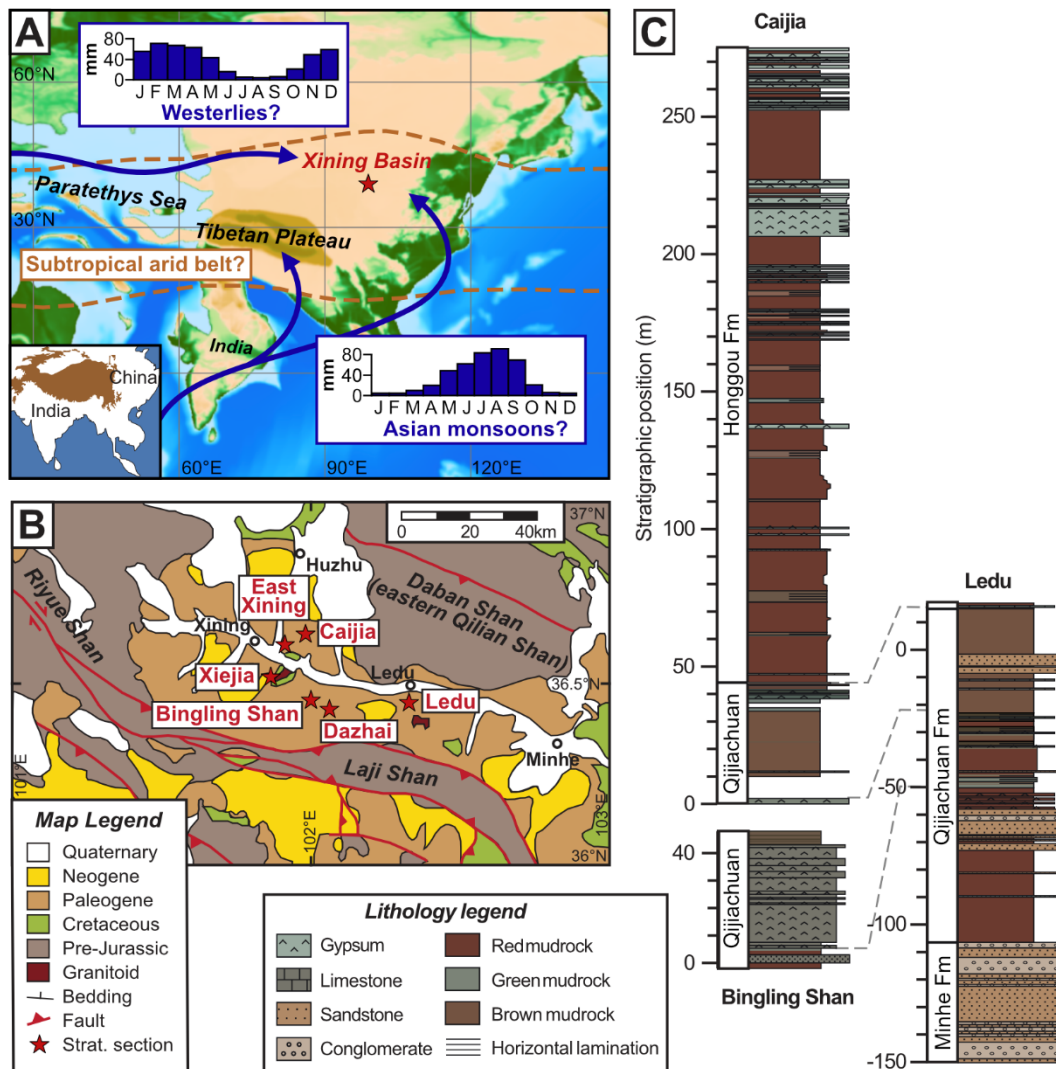
304

305 **Competing Interests Statement**

306 The authors declare no competing interests.

307

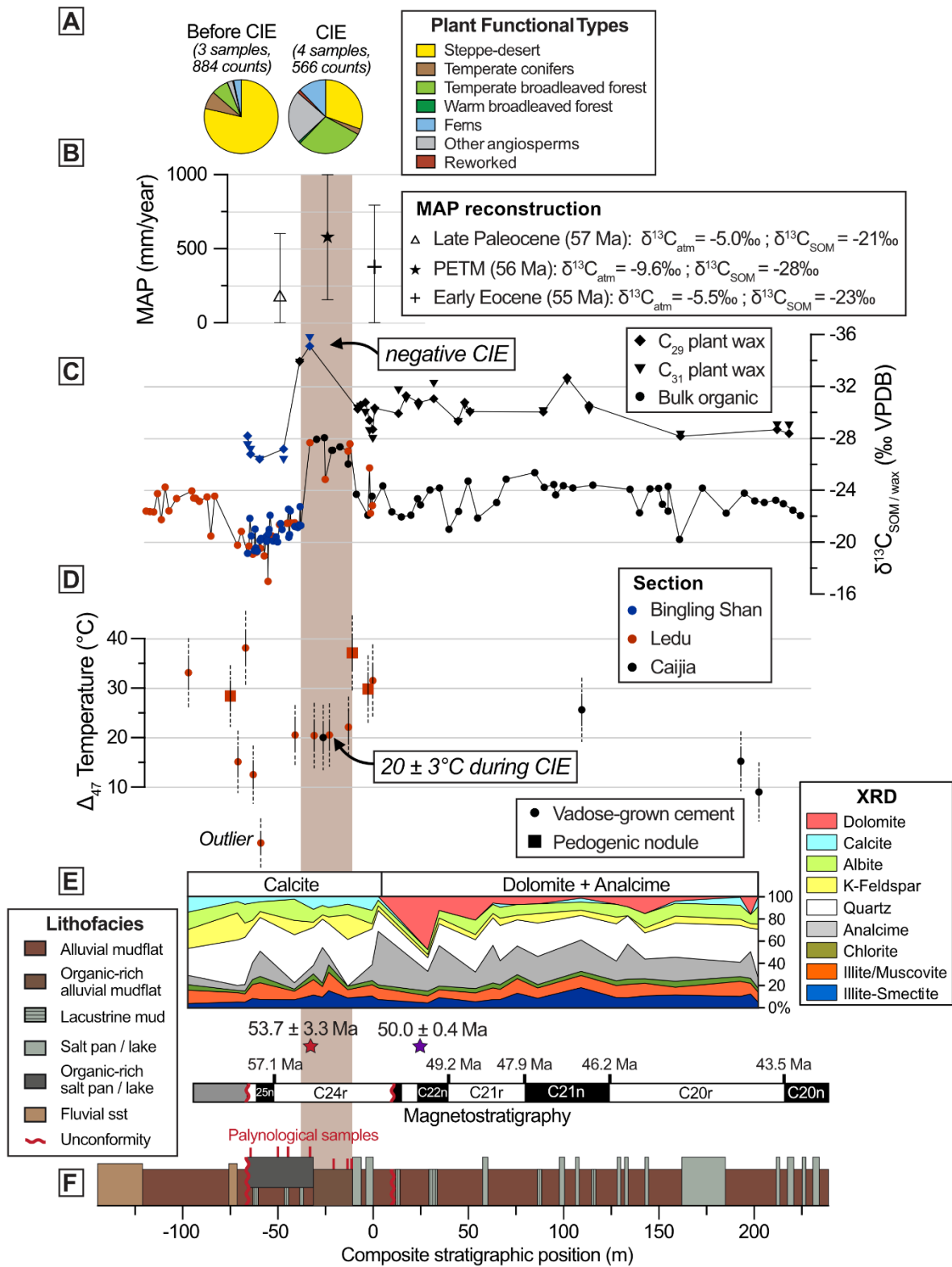
308 **Figures**



309

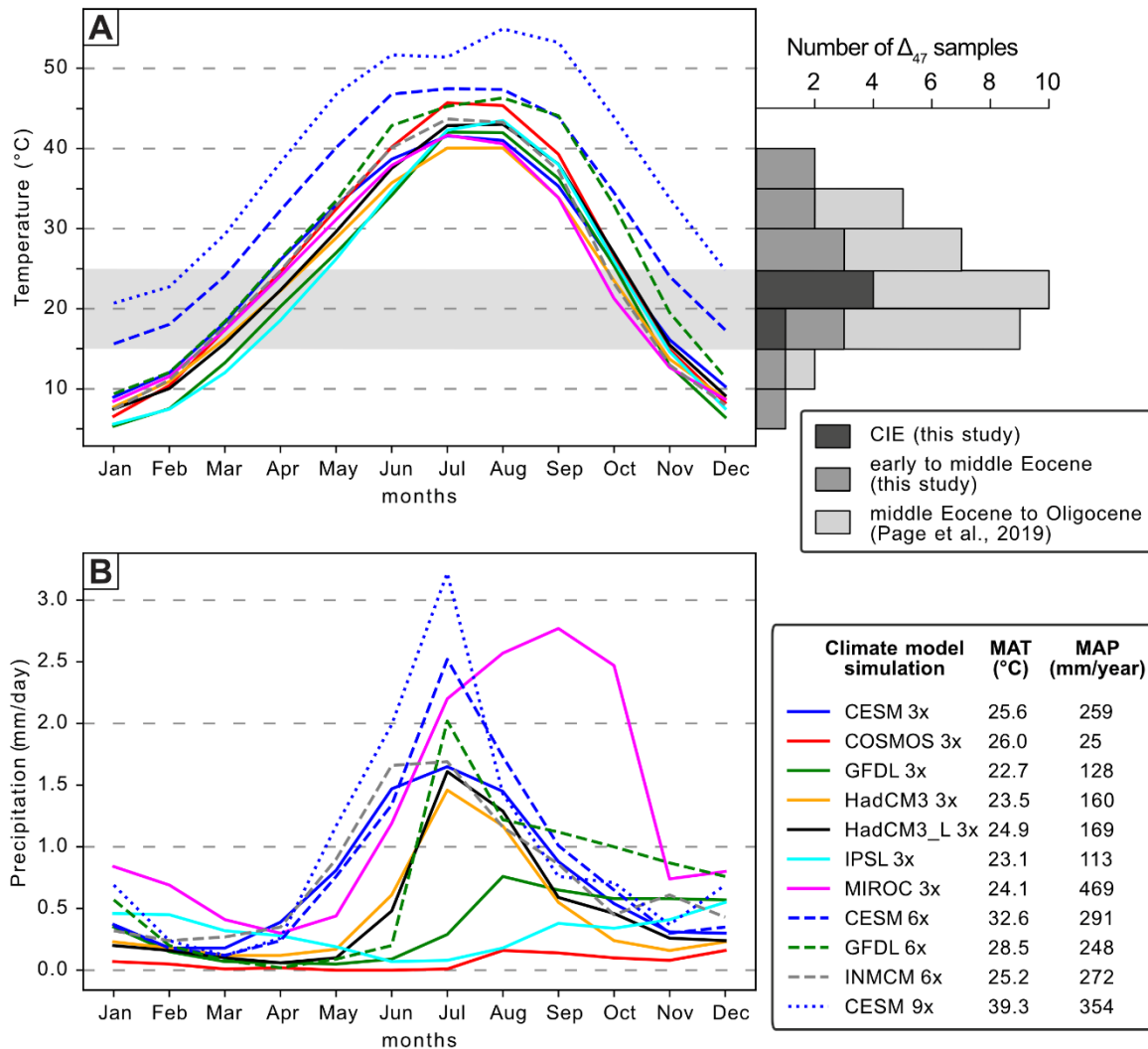
310 *Fig. 1. Geological setting showing hypothesized Eocene hydroclimates in Asia*  
 311 *including a subtropical arid belt, westerly or monsoonal domain. A) Paleogeographic*  
 312 *map of Asia at 50 Ma (million years ago)<sup>31</sup> showing the location of the Xining Basin.*  
 313 *Blue arrows show potential moisture sources. Histograms reflect the seasonal*  
 314 *distribution of this rainfall based on modern-day observations in monsoonal Xining and*  
 315 *westerly-dominated Tashkent ([https://www.ncei.noaa.gov/products/wmo-climate-](https://www.ncei.noaa.gov/products/wmo-climate-normals)*  
 316 *[normals](https://www.ncei.noaa.gov/products/wmo-climate-normals)).* *Climate model simulations indicate a similar seasonal distribution of rainfall*  
 317 *in these domains during the Eocene<sup>9,20</sup>. Inset shows present-day geographical*  
 318 *location. B) Geological map of the Xining Basin (modified from ref<sup>30</sup>) showing the*

319 locations of the studied sections and palynological sampling. C) Lithostratigraphy of  
 320 the Caijia, Bingling Shan and Ledu key sections<sup>23,30</sup>.





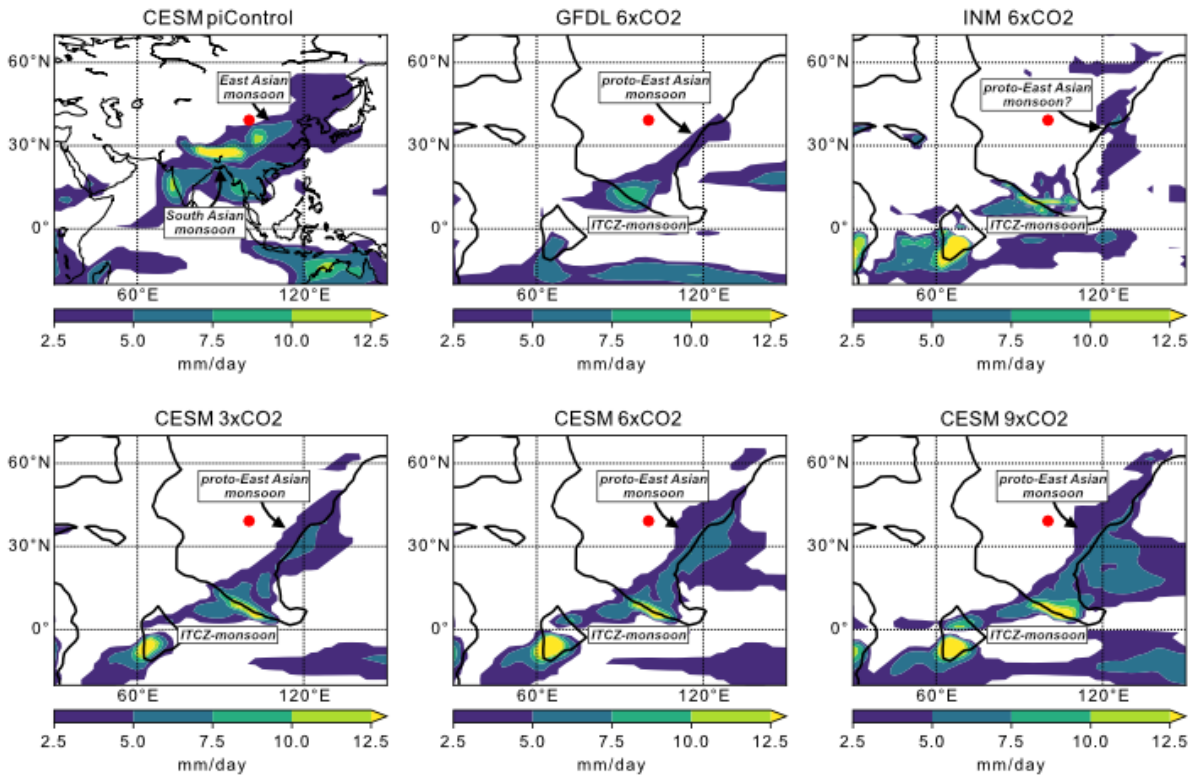
322 *Fig. 2. Paleo-environmental reconstruction showing temperate forests replacing*  
323 *steppe shrubs during a negative carbon isotope excursion (CIE). The CIE is indicated*  
324 *by the brown shaded vertical bar. Data include: A) palynological data classified in Plant*  
325 *Functional Types, B) reconstructed Mean Annual Precipitation (MAP) using late*  
326 *Paleocene, PETM and early Eocene  $\delta^{13}\text{C}_{\text{atm}}$  and  $\delta^{13}\text{C}_{\text{SOM}}$  values (root mean square*  
327 *error of  $\pm 422$  mm/year of the MAP proxy is shown)<sup>24</sup>, C)  $\delta^{13}\text{C}$  values of both soil*  
328 *organic matter and n-alkanes, D)  $\Delta_{47}$  temperatures of vadose-grown carbonates (with*  
329 *solid and dashed lines indicating 68% and 95% confidence intervals respectively*  
330 *based on at least 13 replicates), one sample produced an unrealistically low*  
331 *temperature of  $-1.3^\circ\text{C}$  and is considered an outlier, E) X-Ray Diffraction (XRD) derived*  
332 *mineral content, F) age constraints<sup>23,30</sup> based on radiometric ages (stars) and*  
333 *magnetic polarities (black ticks), lithostratigraphy showing stratigraphic positions of*  
334 *palynological samples with red marks.*



335

336 *Fig. 3. Proxy comparison with simulated surface air temperature (A) and precipitation*  
 337 *(B) in the Eocene Xining Basin. Averaged values were derived from a box of 1.875°*  
 338 *latitude by 2.5° longitude centred at the paleolocation of the Xining Basin (102.5°N,*  
 339 *39.5°E). Simulations are derived from the DeepMIP climate model ensemble (colors*  
 340 *indicate each model) under an early Eocene paleogeography with no Tibetan Plateau*  
 341 *and a Paratethys Sea lowstand, preindustrial orbital configuration and 3x, 6x or 9x*  
 342 *preindustrial pCO<sub>2</sub> when available (solid, dashed and dotted lines respectively)<sup>40</sup>. The*  
 343 *histogram in A) shows the number of measured  $\Delta_{47}$  temperatures in 5°C bins. CIE*  
 344 *temperatures of ~20°C are best explained by soil dewatering and carbonate formation*

345 during the colder winter months. Simulated precipitation in B) varies from dry  
 346 throughout the year to summer wet similar to the present-day monsoons.



347  
 348 *Fig. 4. Distribution of monsoonal domains in climate model simulations. Upper panel*  
 349 *shows a pre-industrial control simulation (CESM) and two early Eocene simulations*  
 350 *with 6x pCO<sub>2</sub> (GFDL and INM). Lower panel shows different pCO<sub>2</sub> scenarios (3x, 6x*  
 351 *and 9x) of the CESM model. Additional simulations are shown in Extended Data Fig.*  
 352 *7. Summer (MJJAS) minus winter precipitation (NDJFM) is used as a metric and*  
 353 *regions where this difference is >2.5 mm/day are considered monsoonal<sup>45</sup>. Red dot*  
 354 *indicates the location of the Xining Basin. All Eocene simulations show an ITCZ*  
 355 *(Intertropical Convergence Zone) monsoon near the equator. CESM and GFDL show*  
 356 *a proto-monsoonal domain along the East Asian coast, but none of the models*  
 357 *simulate monsoons extending far into the Asian interior.*  
 358

359 **References**

- 360 1. Barbolini, N., Woutersen, A., Dupont-Nivet, G., Silvestro, D., Tardif, D., Meijer,  
361 N., Chang, C., H.-X. Zhang, A. Licht, Rydin, C., Koutsondendris, A., Han, F.,  
362 Rohrmann, A., Liu, X.-J., Zhang, Y., Donnadieu, Y., Fluteau, F., Ladant, J.-B.,  
363 Le Hir, G., Hoorn, C. (2020). Cenozoic evolution of the steppe-desert biome in  
364 Central Asia. *Science Advances*, 6(41), eabb8227.  
365 <https://doi.org/10.1126/sciadv.abb8227>
- 366 2. Li, C., Fu, B., Wang, S., Stringer, L. C., Wang, Y., Li, Z., Liu, Y. & Zhou, W.  
367 (2021). Drivers and impacts of changes in China's drylands. *Nature Reviews*  
368 *Earth & Environment*, 2(12), 858-873. [https://doi.org/10.1038/s43017-021-](https://doi.org/10.1038/s43017-021-00226-z)  
369 [00226-z](https://doi.org/10.1038/s43017-021-00226-z)
- 370 3. Cramwinckel, M. J., Burls, N. J., Fahad, A. A., Knapp, S., West, C. K., Reichgelt,  
371 T., Greenwood, D. R., Chan, W.-L., Donnadieu, Y., Hutchinson, D. K., de Boer,  
372 A. M., Ladant, J.-B., Morozova, P. A., Niezgodzki, I., Knorr, G., Steinig, S.,  
373 Zhang, Z., Zhu, J., Feng, R., Lunt, D. J., Abe-Ouchi, A. & Inglis, G. N. (2023).  
374 Global and zonal-mean hydrological response to early Eocene warmth.  
375 *Paleoceanography and Paleoclimatology*, e2022PA004542.  
376 <https://doi.org/10.1029/2022PA004542>
- 377 4. Westerhold, T., Marwan, N., Drury, A. J., Liebrand, D., Agnini, C., Anagnostou,  
378 E., Barnet, J. S. K., Bohaty, S. M., De Vleeschouwer, D., Florindo, F.,  
379 Frederichs, T., Hodell, D. A., Holbourn, A. E., Kroon, D., Lauretano, V., Littler,  
380 K., Lourens, L. J., Lyle, M., Pälike, H., Röhl, U., Tian, J., Wilkens, R. H., Wilson,  
381 P. A., Zachos, J. C. (2020). An astronomically dated record of Earth's climate  
382 and its predictability over the last 66 million years. *Science*, 369(6509), 1383–  
383 1387. <https://doi.org/10.1126/science.aba6853>

- 384 5. Abels, H. A., Lauretano, V., Van Yperen, A. E., Hopman, T., Zachos, J. C.,  
385 Lourens, L. J., Gingerich, P. D. & Bowen, G. J. (2016). Environmental impact  
386 and magnitude of paleosol carbonate carbon isotope excursions marking five  
387 early Eocene hyperthermals in the Bighorn Basin, Wyoming. *Climate of the*  
388 *Past*, 12(5), 1151-1163. <https://doi.org/10.5194/cp-12-1151-2016>, 2016
- 389 6. McInerney, F. A., & Wing, S. L. (2011). The Paleocene-Eocene Thermal  
390 Maximum: A perturbation of carbon cycle, climate, and biosphere with  
391 implications for the future. *Annual Review of Earth and Planetary Sciences*, 39,  
392 489-516. <https://doi.org/10.1146/annurev-earth-040610-133431>
- 393 7. Zeebe, R. E., & Lourens, L. J. (2019). Solar System chaos and the Paleocene–  
394 Eocene boundary age constrained by geology and astronomy. *Science*,  
395 365(6456), 926-929. <https://doi.org/10.1126/science.aax0612>
- 396 8. Rae, J. W., Zhang, Y. G., Liu, X., Foster, G. L., Stoll, H. M., & Whiteford, R. D.  
397 (2021). Atmospheric CO<sub>2</sub> over the past 66 million years from marine archives.  
398 *Annual Review of Earth and Planetary Sciences*, 49, 609-641.  
399 <https://doi.org/10.1146/annurev-earth-082420-063026>
- 400 9. Bougeois, L., Dupont-Nivet, G., de Raféllis, M., Tindall, J. C., Proust, J. N.,  
401 Reichart, G. J., de Nooijer, L. J., Guo, Z. & Ormukov, C. (2018). Asian  
402 monsoons and aridification response to Paleogene sea retreat and Neogene  
403 westerly shielding indicated by seasonality in Paratethys oysters. *Earth and*  
404 *Planetary Science Letters*, 485, 99-110.  
405 <https://doi.org/10.1016/j.epsl.2017.12.036>
- 406 10. Caves Rügenstein, J. K., & Chamberlain, C. P. (2018). The evolution of  
407 hydroclimate in Asia over the Cenozoic: A stable-isotope perspective. *Earth-*

- 408 Science Reviews, 185, 1129-1156.  
409 <https://doi.org/10.1016/j.earscirev.2018.09.003>
- 410 11. An, Z., Kutzbach, J. E., Prell, W. L., & Porter, S. C. (2001). Evolution of Asian  
411 monsoons and phased uplift of the Himalaya–Tibetan plateau since Late  
412 Miocene times. *Nature*, 411(6833), 62. <https://doi.org/10.1038/35075035>
- 413 12. Molnar, P., Boos, W.R., Battisti, D.S. (2010). Orographic controls on climate  
414 and paleoclimate of Asia: thermal and mechanical roles for the Tibetan Plateau.  
415 *Annu. Rev. Earth Planet. Sci.*38. [https://doi.org/10.1146/annurev-earth-](https://doi.org/10.1146/annurev-earth-040809-152456)  
416 [040809-152456](https://doi.org/10.1146/annurev-earth-040809-152456).
- 417 13. Sun, X., & Wang, P. (2005). How old is the Asian monsoon system?—  
418 Palaeobotanical records from China. *Palaeogeography, Palaeoclimatology,*  
419 *Palaeoecology*, 222(3-4), 181-222.  
420 <https://doi.org/10.1016/j.palaeo.2005.03.005>
- 421 14. Wu, F., Fang, X., Yang, Y., Dupont-Nivet, G., Nie, J., Fluteau, F., Zhang, T. &  
422 Han, W. (2022). Reorganization of Asian climate in relation to Tibetan Plateau  
423 uplift. *Nature Reviews Earth & Environment*, 3(10), 684-700.  
424 <https://doi.org/10.1038/s43017-022-00331-7>(Wu et al. 2022)
- 425 15. Huber, M., & Goldner, A. (2012). Eocene monsoons. *Journal of Asian Earth*  
426 *Sciences*, 44, 3-23. <https://doi.org/10.1016/j.jseaes.2011.09.014>
- 427 16. Licht, A., Van Cappelle, M., Abels, H.A., Ladant, J.B., Trabucho-Alexandre, J.,  
428 France-Lanord, C., Donnadieu, Y., Vandenberghe, J., Rigaudier, T., Lécuyer,  
429 C., Terry Jr., D., Adriaens, R., Boura, A., Guo, Z., Aung Naing, Soe, Quade, J.,  
430 Dupont-Nivet, G., Jaeger, J.-J., (2014). Asian monsoons in a late Eocene  
431 greenhouse world. *Nature* 513 (7519), 501–506.  
432 <https://doi.org/10.1038/nature13704>

- 433 17. Quan, C., Liu, Z., Utescher, T., Jin, J., Shu, J., Li, Y., Liu, Y.S.C. (2014).  
434 Revisiting the Paleogene climate pattern of East Asia: a synthetic review. *Earth-*  
435 *Sci. Rev.* 139, 213–230. <https://doi.org/10.1016/j.earscirev.2014.09.005>.
- 436 18. Farnsworth, A., Lunt, D. J., Robinson, S. A., Valdes, P. J., Roberts, W. H., Clift,  
437 P. D., et al. (2019). Past East Asian monsoon evolution controlled by  
438 paleogeography, not CO<sub>2</sub>. *Science Advances*, 5(10), eaax1697.  
439 <https://doi.org/10.1126/sciadv.aax1697>
- 440 19. Spicer, R. A., Yang, J., Herman, A. B., Kodrul, T., Maslova, N., Spicer, T. E.,  
441 Aleksandrova, G. & Jin, J. (2016). Asian Eocene monsoons as revealed by leaf  
442 architectural signatures. *Earth and Planetary Science Letters*, 449, 61-68.  
443 <https://doi.org/10.1016/j.epsl.2016.05.036>
- 444 20. Zhang, Z., Flatøy, F., Wang, H., Bethke, I., Bentsen, M., & Guo, Z. (2012). Early  
445 Eocene Asian climate dominated by desert and steppe with limited monsoons.  
446 *Journal of Asian Earth Sciences*, 44, 24-35.  
447 <https://doi.org/10.1016/j.jseaes.2011.05.013>
- 448 21. Tardif, D., Toumoulin, A., Fluteau, F., Donnadieu, Y., Le Hir, G., Barbolini, N.,  
449 Licht, A., Ladant, J.-B., Sepulchre, P., Viovy, N., Hoorn, C. & Dupont-Nivet, G.  
450 (2021). Orbital variations as a major driver of climate and biome distribution  
451 during the greenhouse to icehouse transition. *Science Advances*, 7(43),  
452 eabh2819. <https://doi.org/10.1126/sciadv.abh2819>
- 453 22. Li, Q., Utescher, T., Liu, Y. C., Ferguson, D., Jia, H., & Quan, C. (2022).  
454 Monsoonal climate of East Asia in Eocene times inferred from an analysis of  
455 plant functional types. *Palaeogeography, Palaeoclimatology, Palaeoecology*,  
456 601, 111138. <https://doi.org/10.1016/j.palaeo.2022.111138>.

- 457 23. Meijer, N., Dupont-Nivet, G., Abels, H. A., Kaya, M. Y., Licht, A., Xiao, M.,  
458 Zhang, Y., Roperch, P., Poujol, M., Lai, Z., & Guo, Z. (2019). Central Asian  
459 moisture modulated by proto-Paratethys Sea incursions since the early  
460 Eocene. *Earth and Planetary Science Letters*, 510, 73–84.  
461 <https://doi.org/10.1016/j.epsl.2018.12.031>
- 462 24. Stein, R. A., Sheldon, N. D., & Smith, S. Y. (2021). Soil carbon isotope values  
463 and paleoprecipitation reconstruction. *Paleoceanography and  
464 Paleoclimatology*, 36(4), e2020PA004158.  
465 <https://doi.org/10.1029/2020PA004158>
- 466 25. Breecker, D. O., Sharp, Z. D., & McFadden, L. D. (2009). Seasonal bias in the  
467 formation and stable isotopic composition of pedogenic carbonate in modern  
468 soils from central New Mexico, USA. *The Geological Society of America  
469 Bulletin*, 121(3–4), 630–640. <https://doi.org/10.1130/b26413.1>
- 470 26. Kelson, J. R., Huntington, K. W., Breecker, D. O., Burgener, L. K., Gallagher,  
471 T. M., Hoke, G. D., & Petersen, S. V. (2020). A proxy for all seasons? A  
472 synthesis of clumped isotope data from Holocene soil carbonates. *Quaternary  
473 Science Reviews*, 234, 106259.  
474 <https://doi.org/10.1016/j.quascirev.2020.106259>
- 475 27. Page, M., Licht, A., Dupont-Nivet, G., Meijer, N., Barbolini, N., Hoorn, C., et al.  
476 (2019). Synchronous cooling and decline in monsoonal rainfall in northeastern  
477 Tibet during the fall into the Oligocene icehouse. *Geology*, 47(3), 203–206.  
478 <https://doi.org/10.1130/g45480.1>
- 479 28. Licht, A., Kelson, J., Bergel, S., Schauer, A., Petersen, S. V., Capirala, A.,  
480 Huntington, K. W., Dupont-Nivet, G., Win, Z. & Aung, D. W. (2022). Dynamics  
481 of pedogenic carbonate growth in the tropical domain of Myanmar.



- 482 Geochemistry, Geophysics, Geosystems, 23(7), e2021GC009929.  
483 <https://doi.org/10.1029/2021GC009929>
- 484 29. Licht, A., Dupont-Nivet, G., Meijer, N., Rugenstein, J. C., Schauer, A., Fiebig,  
485 J., et al. (2020). Decline of soil respiration in northeastern Tibet through the  
486 transition into the Oligocene icehouse. *Palaeogeography, Palaeoclimatology,*  
487 *Palaeoecology*, 560, 110016. <https://doi.org/10.1016/j.palaeo.2020.110016>
- 488 30. Meijer, N., Dupont-Nivet, G., Licht, A., Roperch, P., Rohrmann, A., Sun, A., Lu,  
489 S., Woutersen, A., & Nowaczyk, N. (2023). Early Eocene magnetostratigraphy  
490 and tectonic evolution of the Xining Basin, NE Tibet. *Basin Research*.  
491 <https://doi.org/10.1111/bre.12720>
- 492 31. Aminov, J., Dupont-Nivet, G., Ruiz, D., & Gailleton, B. (2023). Paleogeographic  
493 reconstructions using QGIS: Introducing Terra Antiqua plugin and its  
494 application to 30 and 50 Ma maps. *Earth-Science Reviews*, 104401.  
495 <https://doi.org/10.1016/j.earscirev.2023.104401>
- 496 32. Chen, Z., Ding, Z., Tang, Z., Wang, X., & Yang, S. (2014). Early Eocene carbon  
497 isotope excursions: Evidence from the terrestrial coal seam in the Fushun  
498 Basin, Northeast China. *Geophysical Research Letters*, 41(10), 3559-3564.  
499 <https://doi.org/10.1002/2014GL059808>
- 500 33. Chen, Z., Wang, X., Hu, J., Yang, S., Zhu, M., Dong, X., Tang, Z., Peng, P. &  
501 Ding, Z. (2014). Structure of the carbon isotope excursion in a high-resolution  
502 lacustrine Paleocene–Eocene Thermal Maximum record from central China.  
503 *Earth and Planetary Science Letters*, 408, 331-340.  
504 <https://doi.org/10.1016/j.epsl.2014.10.027>
- 505 34. Kohn, M. J. (2010). Carbon isotope compositions of terrestrial C3 plants as  
506 indicators of (paleo) ecology and (paleo) climate. *Proceedings of the National*

- 507 Academy of Sciences, 107(46), 19691-19695.  
508 <https://doi.org/10.1073/pnas.100493310>
- 509 35. Diefendorf, A. F., Mueller, K. E., Wing, S. L., Koch, P. L., & Freeman, K. H.  
510 (2010). Global patterns in leaf  $^{13}\text{C}$  discrimination and implications for studies  
511 of past and future climate. *Proceedings of the National Academy of Sciences*,  
512 107(13), 5738-5743. <https://doi.org/10.1073/pnas.0910513107>
- 513 36. Chen, Z., Dong, X., Wang, X., Tang, Z., Yang, S., Zhu, M., & Ding, Z. (2020).  
514 Spatial change of precipitation in response to the Paleocene-Eocene thermal  
515 Maximum warming in China. *Global and Planetary Change*, 194, 103313.  
516 <https://doi.org/10.1016/j.gloplacha.2020.103313>
- 517 37. Beckner, J. R., & Mozley, P. S. (1998). Origin and spatial distribution of early  
518 vadose and phreatic calcite cements in the Zia Formation, Albuquerque Basin,  
519 New Mexico, USA. *Carbonate Cementation in Sandstones: Distribution  
520 Patterns and Geochemical Evolution*, 27-51.  
521 <https://doi.org/10.1002/9781444304893.ch2>
- 522 38. Warren, J. (2000). Dolomite: occurrence, evolution and economically important  
523 associations. *Earth-Science Reviews*, 52(1-3), 1-81.  
524 [https://doi.org/10.1016/S0012-8252\(00\)00022-2](https://doi.org/10.1016/S0012-8252(00)00022-2)
- 525 39. Eiler, J. M. (2007). "Clumped-isotope" geochemistry—The study of naturally-  
526 occurring, multiply-substituted isotopologues. *Earth and planetary science  
527 letters*, 262(3-4), 309-327. <https://doi.org/10.1016/j.epsl.2007.08.020>
- 528 40. Lunt, D. J., Bragg, F., Chan, W. L., Hutchinson, D. K., Ladant, J. B., Morozova,  
529 P., Niezgodzki, I., Steinig, S., Zhang, Z., Zhu, J., Abe-Ouchi, A., Anagnostou,  
530 E., de Boer, A. M., Coxall, H. K., Donnadieu, Y., Foster, G., Inglis, G. N., Knorr,  
531 G., Langebroek, P. M., Lear, C. H., Lohmann, G., Poulsen, C. J., Sepulchre, P.,

- 532 Tierney, J. E., Valdes, P. J., Volodin, E. M., Dunkley Jones, T., Hollis, C. J.,  
533 Huber, M. & Otto-Bliesner, B. L. (2021). DeepMIP: Model intercomparison of  
534 early Eocene climatic optimum (EECO) large-scale climate features and  
535 comparison with proxy data. *Climate of the Past*, 17(1), 203-227.  
536 <https://doi.org/10.5194/cp-17-203-2021>
- 537 41. Molnar, P. (2022). Differences between soil and air temperatures: Implications  
538 for geological reconstructions of past climate. *Geosphere*, 18(2), 800-824.  
539 <https://doi.org/10.1130/GES02448.1>
- 540 42. Hough, B. G., Garzione, C. N., Wang, Z., Lease, R. O., Burbank, D. W., & Yuan,  
541 D. (2011). Stable isotope evidence for topographic growth and basin  
542 segmentation: Implications for the evolution of the NE Tibetan Plateau. *Bulletin*,  
543 123(1-2), 168-185. <https://doi.org/10.1130/B30090.1>
- 544 43. Inglis, G. N., Bragg, F., Burls, N. J., Cramwinckel, M. J., Evans, D., Foster, G.  
545 L., Huber, M., Lunt, D. J., Siler, N., Steinig, S., Tierney, J. E., Wilkinson, R.,  
546 Anagnostou, E., de Boer, A. M., Dunkley Jones, T., Edgar, K. M., Hollis, C. J.,  
547 Hutchinson, D. K. & Pancost, R. D. (2020). Global mean surface temperature  
548 and climate sensitivity of the early Eocene Climatic Optimum (EECO),  
549 Paleocene–Eocene Thermal Maximum (PETM), and latest Paleocene. *Climate*  
550 *of the Past*, 16(5), 1953-1968. <https://doi.org/10.5194/cp-16-1953-2020>
- 551 44. Gu, C., & Renaut, R. W. (1994). The effect of Tibetan uplift on the formation  
552 and preservation of Tertiary lacustrine source-rocks in eastern China. *Journal*  
553 *of Paleolimnology*, 11, 31-40. <https://doi.org/10.1007/BF00683269>
- 554 45. Wang, B., Kim, H. J., Kikuchi, K., & Kitoh, A. (2011). Diagnostic metrics for  
555 evaluation of annual and diurnal cycles. *Climate dynamics*, 37, 941-955.  
556 <https://doi.org/10.1007/s00382-010-0877-0>

- 557 46. Dupont-Nivet, G., Krijgsman, W., Langereis, C. G., Abels, H. A., Dai, S., & Fang,  
558 X. (2007). Tibetan plateau aridification linked to global cooling at the Eocene–  
559 Oligocene transition. *Nature*, 445(7128), 635-638.  
560 <https://doi.org/10.1038/nature05516>
- 561 47. Bowen, G. J., Clyde, W. C., Koch, P. L., Ting, S., Alroy, J., Tsubamoto, T.,  
562 Wang, Y. & Wang, Y. (2002). Mammalian dispersal at the Paleocene/Eocene  
563 boundary. *Science*, 295(5562), 2062-2065.  
564 <https://doi.org/10.1126/science.1068700>
- 565 48. Chaimanee, Y., Chavasseau, O., Beard, K. C., Kyaw, A. A., Soe, A. N., Sein,  
566 C., Lazzari, V., Marivaux, L., Marandat, B., Swe, M., Rugbumrung, M., Lwin, T.,  
567 Valentin, X., Thein, Z. M. M. & Jaeger, J. J. (2012). Late Middle Eocene primate  
568 from Myanmar and the initial anthropoid colonization of Africa. *Proceedings of*  
569 *the National Academy of Sciences*, 109(26), 10293-10297.  
570 <https://doi.org/10.1073/pnas.1200644109>
- 571 49. Robin-Champigneul, F., Gravendyck, J., Huasheng, H., Woutersen, A.,  
572 Pocknall, D., Meijer, N., Dupont-Nivet, G., Erkens, R. H. J., Hoorn, C. (2023)  
573 Northward expansion of the southern-temperate podocarp forest during the  
574 early Eocene: Palynological evidence from the NE Tibetan Plateau (China).  
575 *Review of Paleobotany and Palynology*, 104914.  
576 <https://doi.org/10.1016/j.revpalbo.2023.104914>
- 577 50. Fang, X., Galy, A., Yang, Y., Zhang, W., Ye, C., & Song, C. (2019). Paleogene  
578 global cooling–induced temperature feedback on chemical weathering, as  
579 recorded in the northern Tibetan Plateau. *Geology*, 47(10), 992-996.  
580 <https://doi.org/10.1130/G46422.1>

581

582 **Methods**

583

584 *Sampling*

585

586 Rock samples were collected after digging trenches of at least ~0.5 meter deep in the  
587 Bingling Shan (BS), Caijia (CJ) and Ledu (LD) sections covering the early to middle  
588 Eocene<sup>23,30</sup>. In addition, three horizons with pedogenic carbonate nodules were  
589 identified and sampled at the Ledu section. Samples for plant wax analyses were  
590 collected using gloves and wrapped in aluminum foil to prevent contamination.  
591 Palynological samples were collected from the Bingling Shan and Caijia sections as  
592 well as the East Xining (EX), Xiejia (XJ) and Dazhai (DZ) sections<sup>23,30</sup>.

593

594 *Composite section and age model*

595

596 The individual sections were combined into one composite section using litho- and  
597 magnetostratigraphic correlations<sup>30</sup>. First, we assembled the core of the composite  
598 section by stitching the Honggou Fm of the Caijia section (CJ) and the Qijiachuan Fm  
599 of the Ledu section (LD) together at the liver-brown to red mudrock transition observed  
600 in both locations (transition from Qijiachuan to Honggou Fm; blue dashed line Fig. 2  
601 in ref<sup>30</sup>). We assume this to be a chronostratigraphic marker and define it as the 0  
602 meter-level in the composite log. The stratigraphic positions of these sections can be  
603 converted to the composite stratigraphic position as follows:

604

605 Comp m level = CJ [44.5m to 280m] - 44.5

606 Comp m level = LD [entire section] - 15

607

608 Next, we project the Qijiachuan Fm of the Caijia (CJ) and Bingling Shan (BS) sections  
609 on the composite section making sure that the lithostratigraphic boundaries between  
610 the evaporites of the middle Qijiachuan Fm and the liver-colored mudrocks of the  
611 upper Qijiachuan Fm correlate. This is necessary because the thicknesses of the  
612 formations vary between the sections and the transition between these formations is  
613 assumed to represent a chronostratigraphic marker. The stratigraphic positions of  
614 these sections can be converted to the composite stratigraphic position as follows:

615

616 Caijia:

$$\begin{aligned} 617 \text{ Comp m level} &= (\text{CJ}[2\text{m to } 44.5\text{m}] - 44.5) * (1 - 5.9 / 42.5) \\ 618 &= \text{CJ}[0 \text{ to } 2\text{m}] - 38.6 \end{aligned}$$

619 Bingling Shan:

$$\begin{aligned} 620 \text{ Comp m level} &= ((\text{BS}[5.2\text{m to } 43\text{m}] - 79.6) + ((\text{BS}[5.2\text{m to } 43\text{m}] - 43) / -37.8) * 8.05) \\ 621 &= \text{BS}[43\text{m and higher}] - 79.6 \end{aligned}$$

622

623 Based on our observation of the large negative CIE, we propose to revise the age  
624 model of ref<sup>30</sup>. The previous age model is reliable down to chron C22n and constrained  
625 by the radiometric age of a tuff<sup>23</sup>. However, chron C23n below is very short and does  
626 not fit the pattern of the geomagnetic polarity timescale<sup>30</sup>. Hence, we infer an  
627 unconformity at the base of C23n which also corresponds to the lithological shift from  
628 calcareous to dolomitic mudrocks (Fig. 2). The negative CIE occurs within a long  
629 reversed polarity zone on top of a short normal zone. This polarity pattern fits well with  
630 C25n and C24r and is within the radiometric age constraints of 53.7±3.3 Ma recorded  
631 in a carbonate bed just below the CIE (Fig. 2)<sup>30</sup>. The PETM and ETM2 occur in C24r

632 and could correlate with the CIE in the Xining Basin as discussed in the main text.  
633 Throughout the manuscript we use the geomagnetic polarity timescale of ref<sup>4</sup> for  
634 correlating our paleo-environmental data with the Cenozoic Global Reference benthic  
635 foraminifera carbon and oxygen Isotope Dataset (CENOGRID).

636

### 637 *XRD*

638

639 X-ray diffractometry (XRD) analyses were performed on 27 mudrock samples and 5  
640 carbonate beds throughout the stratigraphy to assess the mineralogy and the  
641 carbonate type. Powdered rock samples were measured using a PANALYTICAL  
642 X'Pert Bragg-Brentano diffractometer using a copper beam powered by 30 mA and 40  
643 KV generator current. The characteristic diffraction maxima of the mineral phases  
644 were determined using the MacDiff software ([http://mill2.chem.ucl.ac.uk/ccp/web-](http://mill2.chem.ucl.ac.uk/ccp/web-mirrors/krumm/html/software/macdiff.html)  
645 [mirrors/krumm/html/software/macdiff.html](http://mill2.chem.ucl.ac.uk/ccp/web-mirrors/krumm/html/software/macdiff.html)). Intensities were converted to 1°  
646 divergence characteristics and weighted by reference intensity ratios (RIR) to  
647 semiquantitatively calculate the relative abundance of each mineral phase. The  
648 identified mineral phases are (Extended Data Fig. 3): mixed-layer illite-smectite (main  
649 diffraction maxima position: 10.4 Å, RIR value: 0.52), illite/muscovite (10.0 Å, 0.43),  
650 chlorite (14.0 Å, 1.00), analcime (3.43 Å, 1.41), quartz (4.26 Å and 3.34 Å, 3.03) K-  
651 feldspar (3.25 Å, 0.60), albite (3.20 Å, 0.64), calcite (3.04 Å, 2.20) and calcian dolomite  
652 (2.91 Å, 2.51). The mol% of MgCO<sub>3</sub> in the calcian dolomite was estimated using the  
653 relative position of the 104 peak (d in Å) compared to calcite (3.035 Å) and  
654 stoichiometric dolomite (2.885 Å):

$$655 \quad \text{Mol\% MgCO}_3 = \frac{3.035 - d}{3.035 - 2.885} \times 50\%$$

656

657 *Compound-specific lipid biomarkers and stable isotopes*

658 Plant waxes were extracted from 25 mudrock and gypsiferous mudrock samples at  
659 the Organic Surface Geochemistry Lab (OSGLab) at the German Research Centre for  
660 Geosciences (GFZ) in Potsdam. Samples were crushed and then powdered using a  
661 shatterbox with an agate grinding chamber. Soluble organic matter was extracted  
662 using a Dionex accelerated solvent extractor (ASE 350) with a  
663 dichloromethane/methanol mixture of 9:1 at 100°C and 1500 psi. Total extracts of  
664 three 18-minute cycles were captured in 250 ml bottles, later concentrated to 4 ml in  
665 a Turbovap, and then separated on silica gel using a solid phase extraction (SPE) as  
666 described in ref<sup>51</sup>. The C<sub>27</sub>, C<sub>28</sub>, C<sub>29</sub>, C<sub>30</sub>, C<sub>31</sub>, C<sub>32</sub>, and C<sub>33</sub> *n*-alkanes were identified  
667 and quantified using a gas chromatograph with a coupled flame ionization and mass-  
668 selective detector (GC-FID/MSD Agilent 7890A GC, 5975C MSD) flushed with helium  
669 carrier gas. Temperatures in the GC oven were programmed to increase at a rate of  
670 12°C/min starting from 70°C to 320°C at which temperatures were held constant for  
671 21 min. The PTV injector had a split ratio of 5:1 at an initial temperature of 70°C. The  
672 *n*-alkane FID-peak areas were compared with a previously added 5 $\alpha$ -androstane  
673 standard from which *n*-alkane concentrations were calculated. The *n*-alkane  
674 concentrations are reported as  $\mu\text{g}/\text{gram}$  dry sediment. In addition the average chain-  
675 length (ACL) and the carbon preference index (CPI) were calculated.

676

677 For all samples compound specific stable isotope values were measured using a GC-  
678 Isolink coupled to a Thermo Scientific MAT 253 isotope ratio mass spectrometer  
679 (IRMS) at the Stable Isotope and Organic Molecular Biogeochemistry Laboratory at  
680 the University of Connecticut. The *n*-alkane fractions were dried and concentrated to  
681 200  $\mu\text{g}/\mu\text{l}$  per compound in hexane for  $\delta^2\text{H}_{\text{wax}}$  measurements. Each sample was



682 measured in at least duplicate and in most samples triplicate analysis. The injector of  
683 the GC was operated in splitless mode at 300°C and the oven was held at 70°C for 2  
684 minutes. The oven was heated at 15°C/min until 150°C, then heated with 5°C/min to  
685 320°C. The final temperature was held for 10 minutes. The column effluent was  
686 transferred into an isotope ratio mass spectrometer after conversion to H<sub>2</sub> in a high-  
687 temperature oven at 1420°C. Stable isotopes are reported in delta notation in permil  
688 (‰). The standard deviation for each sample was better than 3‰ and the  $\delta^2\text{H}_{\text{wax}}$  are  
689 reported in Vienna Standard Mean Ocean Water scale (VSMOW).  $\delta^{13}\text{C}_{\text{wax}}$  values were  
690 measured using the same fractions used for  $\delta^2\text{H}_{\text{wax}}$ . The *n*-alkane fractions were  
691 concentrated to 60 µg/µl in hexane for  $\delta^{13}\text{C}_{\text{wax}}$  measurements. The same instrumental  
692 setup (GC-IRMS) and temperature programming was used as for the  $\delta^2\text{H}_{\text{wax}}$   
693 measurements, only the oxidation oven was run at a lower temperature of 960°C.  
694 Duplicates were measured for each sample and a CO<sub>2</sub> gas with known isotopic  
695 composition was used as reference gas and  $\delta^{13}\text{C}_{\text{wax}}$  values are reported in Vienna  
696 Pee Dee Belemnite scale (VPDB). The analytical precision of each sample had a  
697 typical standard deviation of 0.5‰. Isotopic compositions were standardized using a  
698 suite of *n*-alkanes in a standard mixture.

699

#### 700 *Stable and clumped isotopes*

701

702 Bulk organic stable isotopes were measured on 113 mudrock and gypsiferous  
703 mudrock samples. These samples were decarbonated twice with 6N HCl and washed  
704 with 18 M-Ohm water several times for acid removal; carbon content and organic  
705 matter  $\delta^{13}\text{C}$  values were then measured. Samples from the Ledu section were  
706 measured using a Costech ECS 4010 Elemental Analyzer coupled to a Thermo

707 Scientific MAT 253 gas source IRMS at the University of Washington. Samples from  
708 the Caijia section were measured using a Flash Elemental Analyzer 1112 connected  
709 to a Thermo Scientific MAT 253 IRMS at the Goethe University-Senckenberg BiK-F  
710 Stable Isotope Facility in Frankfurt. Samples from the Bingling Shan section were  
711 measured using a Flash Elemental Analyzer 2000 coupled to a Thermo Scientific  
712 Delta-V IRMS at the Alfred-Wegener Institute Isotope Laboratory (AWI) in Potsdam.  
713 Measured  $\delta^{13}\text{C}$  values (all relative to VPDB) were corrected using in-house reference  
714 materials and long-term repeatability was below 0.2‰. International reference  
715 materials USGS 24 and IAEA-CH-7 were analyzed along with the samples to check  
716 for accuracy.

717

718 Carbonate stable isotopes were measured on 51 calcite-bearing mudrocks and 3  
719 pedogenic carbonate nodules. The calcite-bearing mudrocks were reacted with 105  
720 % orthophosphoric acid and carbonate  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values were then measured.  
721 Samples from the Ledu section were measured using a Thermo Scientific Kiel III  
722 Carbonate Device coupled to a Thermo Scientific Delta Plus IRMS at University of  
723 Washington. Samples from the Caijia section were measured with a Thermo Scientific  
724 GasBench II interfaced with a Thermo Scientific MAT 253 IRMS at the Goethe  
725 University-Senckenberg BiK-F Stable Isotope Facility. Measured carbon and oxygen  
726 isotopic compositions were corrected using in-house reference materials as well as  
727 NBS18 and NBS19 carbonate reference materials. Long-term repeatability was below  
728 0.03‰ for  $\delta^{13}\text{C}$  and below 0.06‰ for  $\delta^{18}\text{O}$ . All  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values are expressed  
729 relative to VPDB.

730

731 Clumped isotopes were analyzed on 16 of these calcite-bearing mudrocks and on the  
732 3 pedogenic nodules at the Goethe University-Senckenberg BiK-F Stable Isotope  
733 Facility, using a Thermo Scientific Kiel IV Carbonate Device paired with a Thermo  
734 Scientific MAT 253 Plus IRMS. The Kiel IV was modified from its original configuration  
735 with the addition of two water traps and a different heating-cooling system on the  
736 purification trap. Depending on the carbonate content, 110 to 2500  $\mu\text{g}$  of sample was  
737 reacted with 105% orthophosphoric acid at 70°C for 5 minutes starting from the last  
738 acid drop. In each sequence, half of the analyses were reserved for measurement of  
739 the ETH carbonate standards<sup>52</sup>, with ETH 1 and 2 measured in equal numbers as ETH  
740 3, and with ETH 4 less frequently. Data were corrected for negative background using  
741 intensities measured on the 47.5 Faraday cup during acquisition, scaled by a factor  
742 that minimizes the slope between ETH 1 and 2. Baseline corrected data were  
743 projected into the Intercarb Carbon-Dioxide Equilibrium Scale (I-CDES)<sup>52</sup> using the  
744 “independent” approach in the python package D47crunch<sup>53</sup>. The resulting  $\Delta_{47}$  values  
745 were converted into temperature using the calibration of ref<sup>54</sup>. Each sample was  
746 measured in 13 to 18 replicates and the errors are reported as both 68% and 95%  
747 confidence intervals (1SE and 2SE respectively). Long-term repeatability of both  
748 samples and ETH standards was 0.035‰.

749

750 The  $\delta^{18}\text{O}$  values of the soil water ( $\delta^{18}\text{O}_{\text{water}}$ ) are reconstructed using the  $\Delta_{47}$ -derived  
751 temperatures and the equation of ref<sup>55</sup>. These values are compared with modern-day  
752  $\delta^{18}\text{O}_{\text{water}}$  values of the summer monsoon and wintertime westerlies<sup>56</sup> (Extended Data  
753 Fig. 5).

754

755 *Palynology*

756

757 The palynological samples were prepared by Palynological Laboratory Services  
758 (Anglesey, UK) using standard palynological techniques (HCL, HF, sieving at 10 $\mu$ m),  
759 the University of Amsterdam (Amsterdam, the Netherlands; HCL, sieving at 212 $\mu$ m,  
760 20% pyrophosphate, acetolysis, bromoform treatment), and at the Sediment  
761 Laboratory of the Vrije Universiteit (Amsterdam, the Netherlands; following methods  
762 of ref<sup>57</sup> and described in ref<sup>58</sup>). Plant Functional Types (PFTs) were assigned using  
763 the Nearest Living Relatives (NLR) approach applied by ref<sup>59</sup>.

764

765 *MAP reconstruction*

766

767 We use an empirical relationship which can be used to reconstruct Mean Annual  
768 Precipitation (MAP) using the  $\delta^{13}\text{C}_{\text{SOM}}$  values of top soils (O- and A-horizons)<sup>24</sup>. The  
769 organic matter in deeper horizons might be affected by decomposition resulting in  
770 fractionation to higher  $\delta^{13}\text{C}_{\text{SOM}}$  values<sup>60</sup>, which would lead to an underestimation of the  
771 MAP. The alluvial mudflat deposits of the Xining Basin show clear evidence of  
772 pedogenesis such as vertic slickensides, mudcracks, mottling, blocky peds, and clay  
773 coatings in thin sections, but no obvious horizonation due to overprinting of stacked  
774 paleosols. It is therefore impossible to preselect only O- and A-horizons. Nevertheless  
775 we argue that the bulk  $\delta^{13}\text{C}_{\text{SOM}}$  values and the CIE are not strongly affected by  
776 degradation because we observe no clear relationship between  $\delta^{13}\text{C}_{\text{SOM}}$  and total  
777 organic content (Extended Data Fig. 2) and the  $\delta^{13}\text{C}_{\text{SOM}}$  values of alluvial mudflats are  
778 indistinguishable from laterally equivalent gypsum beds which have a high quality of  
779 organic preservation<sup>59</sup>. In addition, an even larger CIE is observed in the *n*-alkanes

780 ( $\delta^{13}\text{C}_{\text{wax}}$ ) which are less affected by degradation<sup>61</sup>. If this difference in CIE is caused  
781 by the decomposition of bulk organic matter, the actual CIE and precipitation changes  
782 could be even larger and our MAP reconstructions should be considered as a minimum  
783 estimate.

784

785 Before using the paleoprecipitation proxy, we correct the  $\delta^{13}\text{C}_{\text{SOM}}$  values to account  
786 for the different  $\text{CO}_2$   $\delta^{13}\text{C}$  values ( $\delta^{13}\text{C}_{\text{atm}}$ ) of the Paleocene/Eocene atmosphere  
787 compared to the pre-industrial value of -6.5‰ that is implicit in the empirical relation<sup>24</sup>.  
788 We apply a -1.5‰ correction to the  $\delta^{13}\text{C}_{\text{SOM}}$  values to correct for the baseline  
789 Paleocene ( $\delta^{13}\text{C}_{\text{atm}} = -5.0\text{‰}$ )<sup>62</sup>, a +3.1‰ correction for the PETM assuming a lowering  
790 of 4.6‰ ( $\delta^{13}\text{C}_{\text{atm}} = -9.6\text{‰}$ ) through the injection of  $^{13}\text{C}$ -depleted carbon<sup>35,62</sup> and a -  
791 1.0‰ correction for the early Eocene baseline ( $\delta^{13}\text{C}_{\text{atm}} = -5.5\text{‰}$ )<sup>62</sup>. Other early Eocene  
792 hyperthermals corresponded to smaller isotope excursions than the PETM and we use  
793 a lowering of 3.0‰ ( $\delta^{13}\text{C}_{\text{atm}} = -8.5\text{‰}$ ) to illustrate the effect on the MAP reconstruction.  
794 The MAP is then calculated using the following equation<sup>24</sup>:

795

$$796 \text{ MAP (mm/year)} = \exp( (\delta^{13}\text{C}_{\text{SOM}} + 11.94) / -2.04)$$

797

### 798 *Carbonate characterization*

799 We have characterized the carbonates of the Xining strata following the methods of  
800 ref<sup>27</sup>. Thin sections were prepared for six representative mudrock samples and three  
801 carbonate nodules. These were examined using cathodoluminescence (CL) and  
802 plane- and cross-polarized microscopy to examine the origin and possible diagenesis  
803 of the carbonates. The samples were examined at the University of Potsdam using an  
804 Olympus BXFM-F polarizing microscope equipped with a lumic hot-cathode electron

805 source and an Olympus XC10 digital color camera. In addition, seven powdered  
806 samples were mounted on a stub and carbon coated. These were further examined at  
807 the University of Potsdam using a JEOL JSM-6510 Scanning Electron Microscope  
808 (SEM) coupled to an Oxford Instruments INCAx-act Energy Dispersive X-ray  
809 Spectrometer (EDS) to assess their mineralogy.

810 The calcite is a dull luminescent micrite and is observed throughout the clayey matrix  
811 (Extended Data Fig. 4 A, B). Some brighter specks of microspar are observed as well  
812 but no detrital carbonate grains nor blocky sparite in cracks, veins or vugs which would  
813 have been typical for phreatic cements<sup>37,63</sup>. These observations are very similar to  
814 ref<sup>27</sup> and we follow their interpretation of an early diagenetic cement forming in the  
815 vadose zone from either shallow groundwater or percolating soil water<sup>37,63</sup>. The  
816  $\delta^{18}\text{O}_{\text{carb}}$  values are consistent with coeval pedogenic carbonates in the region<sup>10</sup> and  
817 the  $\delta^{13}\text{C}_{\text{carb}}$  are very low ( $\sim -9\text{‰}$  in Caijia and  $\sim -11\text{‰}$  in Ledu) as is expected during the  
818 negative CIE (Extended Data Fig. 5). The stable isotope values do show some positive  
819 linear relation (Extended Data Fig. 6) indicating the effects of evaporation<sup>64</sup>. This  
820 suggests that the carbonates formed relatively close to the surface of the paleosol.  
821 The calcite occurs in a specific stratigraphic interval in multiple locations of the basin  
822 (Fig. 2), which suggests a primary origin rather than precipitation/precipitation during  
823 modern-day weathering which would have affected all mudrocks. In addition, Eocene  
824 climatic events such as the EOT have been recorded in these calcite cements with no  
825 indication for overprinting<sup>27</sup>.

826 In addition to the calcareous mudrocks, three horizons with pedogenic nodules were  
827 observed in the Ledu section. Most of these nodules are entirely composed of micrite  
828 and floating detrital grains (Extended Data Fig. 4 C), but some contain vugs filled with

829 sparite indicating a phreatic overprint. These were carefully avoided when powdering  
830 the samples for isotopic analyses. The nodules occurring in the coarse sandstone (at  
831 53.3 Ma) show features of a mixed origin. The floating grains show an isopachous rim  
832 of microspar / sparite while the rest of the matrix is filled with micrite (Extended Data  
833 Fig. S4 D). This indicates an initial vadose origin for the micrite which is overprinted  
834 by phreatic cements filling circum-granular cracks<sup>37</sup>.

835 Dolomite occurs as rhombic crystals within the mudrock matrix (Extended Data Fig. 4  
836 E and F), but also as massive cm-scale beds interbedding lacustrine mudrocks  
837 (Extended Data Fig. 4 G) and as cm-scale burrows (Extended Data Fig. 4 H). The  
838 SEM-EDS analysis revealed that the dolomites are non-ferroan but calcian dolomite  
839 with an XRD peak at  $\sim 2.91 \text{ \AA}$  (Extended Data Fig. 3) and  $\text{MgCO}_3$  contents ranging  
840 from 44 to 46%. No dolomite has been reported from the mountain ranges surrounding  
841 the Xining Basin<sup>65</sup> and a detrital origin is therefore unlikely. Instead, the dolomite could  
842 have formed either by diagenetic replacement of calcite or syn-sedimentary / early-  
843 diagenetic precipitation from saline brines on a mudflat<sup>38,66-68</sup>. We note that the  
844 dolomite co-occurs in a specific stratigraphic interval with analcime, which typically  
845 forms in saline brines<sup>69</sup>, and with increased concentrations of hematite<sup>70</sup> indicative of  
846 dry conditions<sup>71</sup>. This suggests a paleo-environmental control on the formation of  
847 calcian dolomite, but we cannot rule out the role of diagenetic replacement.

848

#### 849 *DeepMIP climate model simulations*

850

851 We use the DeepMIP climate model ensemble<sup>40</sup> to compare our proxy  
852 reconstructions with simulated early Eocene precipitation and temperature

853 estimates. The paleolocation of the Xining Basin was reconstructed using the  
854 hotspot reference frame ref<sup>72</sup> at 55 Ma  
855 (<https://www.odsn.de/odsn/services/paleomap/paleomap.html>). This resulted in a  
856 paleolocation (102.5°N, 39.5°E) which fits well in relation to paleotopographic  
857 features such as the Hangay Dome and Qinling belt that are observed on the  
858 paleogeographic map used in the DeepMIP simulations<sup>73</sup>.

859

#### 860 **Data availability**

861 Palynology counts, TOC and bulk organic  $\delta^{13}\text{C}$ , *n*-alkane  $\delta^{13}\text{C}$  and  $\delta^2\text{H}$ , XRD bulk  
862 mineralogy and carbonate  $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$  and  $\Delta_{47}$  are available at  
863 <https://doi.org/10.1594/PANGAEA.962894>. The DeepMIP preindustrial and Eocene  
864 climate model simulations are available by following the instructions at  
865 <https://www.deepmip.org/data-eocene/>. The weather station data from Xining and  
866 Tashkent is available at <https://www.ncei.noaa.gov/products/wmo-climate-normals>.

867

#### 868 **Methods references**

869 51. Rohrmann, A., Sachse, D., Mulch, A., Pingel, H., Tofelde, S., Alonso, R. N., &  
870 Strecker, M. R. (2016). Miocene orographic uplift forces rapid hydrological  
871 change in the southern central Andes. *Scientific reports*, 6(1), 35678.  
872 <https://doi.org/10.1038/srep35678>

873 52. Bernasconi, S., Daëron, M., Bergmann, K., Bonifacie, M., Meckler, A. N., Affek,  
874 H., et al. (2021). InterCarb: A community effort to improve inter-laboratory  
875 standardization of the carbonate clumped isotope thermometer using  
876 carbonate standards.



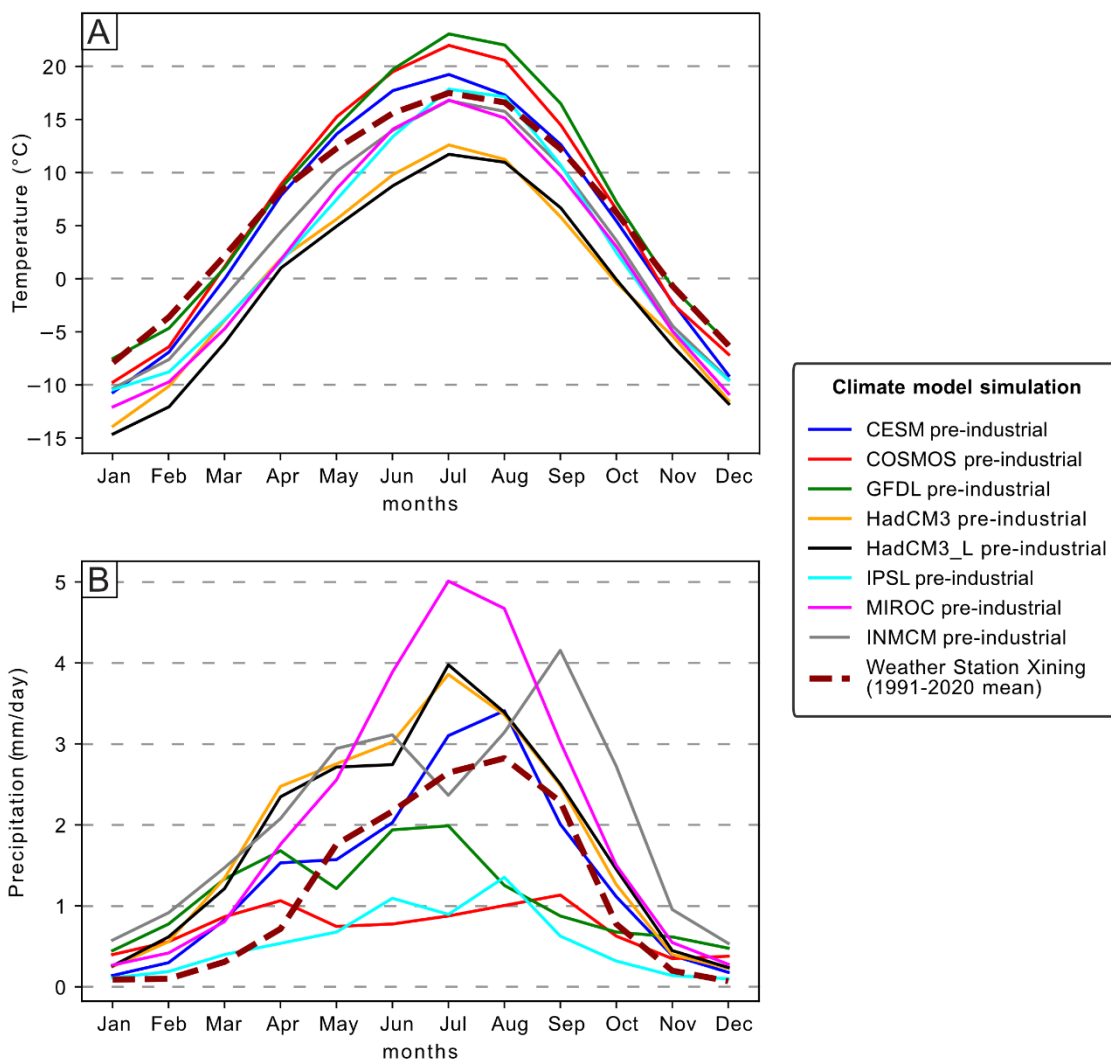
- 877 53. Daëron, M. (2021). Full propagation of analytical uncertainties in  $\Delta 47$   
878 measurements. *Geochemistry, Geophysics, Geosystems*, 22(5),  
879 e2020GC009592. <https://doi.org/10.1029/2020GC009592>
- 880 54. Anderson, N. T., Kelson, J. R., Kele, S., Daëron, M., Bonifacie, M., Horita, J.,  
881 et al. (2021). A unified clumped isotope thermometer calibration (0.5–1100°C)  
882 using carbonate-based standardization. *Geophysical Research Letters*, 48(7),  
883 e2020GL092069. <https://doi.org/10.1029/2020gl092069>
- 884 55. Kim, S. T., & O'Neil, J. R. (1997). Equilibrium and nonequilibrium oxygen  
885 isotope effects in synthetic carbonates. *Geochimica et cosmochimica acta*,  
886 61(16), 3461-3475. [https://doi.org/10.1016/S0016-7037\(97\)00169-5](https://doi.org/10.1016/S0016-7037(97)00169-5)
- 887 56. Araguás-Araguás, L., Froehlich, K., & Rozanski, K. (1998). Stable isotope  
888 composition of precipitation over Southeast Asia. *Journal of Geophysical*  
889 *Research*, 103(D22), 28721–28742. <https://doi.org/10.1029/98jd02582>
- 890 57. Horowitz, A. (1992). *Palynology of arid lands*. Elsevier Science, 568 p.
- 891 58. Dupont-Nivet, G., Hoorn, C., & Konert, M. (2008). Tibetan uplift prior to the  
892 Eocene-Oligocene climate transition: Evidence from pollen analysis of the  
893 Xining Basin. *Geology*, 36(12), 987–990. <https://doi.org/10.1130/G25063A.1>
- 894 59. Hoorn, C., Straathof, J., Abels, H. A., Xu, Y., Utescher, T., & Dupont-Nivet, G.  
895 (2012). A late Eocene palynological record of climate change and Tibetan  
896 plateau uplift (Xining Basin, China). *Palaeogeography, Palaeoclimatology,*  
897 *Palaeoecology*, 344, 16–38. <https://doi.org/10.1016/j.palaeo.2012.05.011>
- 898 60. Wynn, J. G. (2007). Carbon isotope fractionation during decomposition of  
899 organic matter in soils and paleosols: implications for paleoecological  
900 interpretations of paleosols. *Palaeogeography, Palaeoclimatology,*

- 901 Palaeoecology, 251(3-4), 437-448.  
902 <https://doi.org/10.1016/j.palaeo.2007.04.009>
- 903 61. Diefendorf, A. F., & Freimuth, E. J. (2017). Extracting the most from terrestrial  
904 plant-derived n-alkyl lipids and their carbon isotopes from the sedimentary  
905 record: A review. *Organic Geochemistry*, 103, 1-21.  
906 <https://doi.org/10.1016/j.orggeochem.2016.10.016>
- 907 62. Tipple, B. J., Meyers, S. R., & Pagani, M. (2010). Carbon isotope ratio of  
908 Cenozoic CO<sub>2</sub>: A comparative evaluation of available geochemical proxies.  
909 *Paleoceanography*, 25(3). <https://doi.org/10.1029/2009PA001851>
- 910 63. Mack, G. H., Cole, D. R., & Treviño, L. (2000). The distribution and  
911 discrimination of shallow, authigenic carbonate in the Pliocene–Pleistocene  
912 Palomas Basin, southern Rio Grande rift. *Geological Society of America  
913 Bulletin*, 112(5), 643-656. [https://doi.org/10.1130/0016-  
914 7606\(2000\)112<643:TDADOS>2.0.CO;2](https://doi.org/10.1130/0016-7606(2000)112<643:TDADOS>2.0.CO;2)
- 915 64. Quade, J., Rech, J. A., Latorre, C., Betancourt, J. L., Gleeson, E., & Kalin, M.  
916 T. (2007). Soils at the hyperarid margin: the isotopic composition of soil  
917 carbonate from the Atacama Desert, Northern Chile. *Geochimica et  
918 Cosmochimica Acta*, 71(15), 3772-3795.  
919 <https://doi.org/10.1016/j.gca.2007.02.016>
- 920 65. Bureau of Geological and Mineral Resources of Qinghai Province (BGMQRQP).  
921 (1965). Regional geological survey reports of Ledu sheet (1:200000), Qinghai  
922 Province, P.R. China (in Chinese).
- 923 66. Last, W. M. (1990). Lacustrine dolomite—an overview of modern, Holocene,  
924 and Pleistocene occurrences. *Earth-Science Reviews*, 27(3), 221-263.  
925 [https://doi.org/10.1016/0012-8252\(90\)90004-F](https://doi.org/10.1016/0012-8252(90)90004-F)

- 926 67. Peterson, M. N. A., Bien, G. S., & Berner, R. A. (1963). Radiocarbon studies of  
927 recent dolomite from Deep Spring Lake, California. *Journal of Geophysical*  
928 *Research*, 68(24), 6493-6505. <https://doi.org/10.1029/JZ068i024p06493>
- 929 68. Wolfbauer, C. A., & Surdam, R. C. (1974). Origin of nonmarine dolomite in  
930 Eocene Lake Gosiute, Green River Basin, Wyoming. *Geological Society of*  
931 *America Bulletin*, 85(11), 1733-1740. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1974)85<1733:OONDIE>2.0.CO;2)  
932 [7606\(1974\)85<1733:OONDIE>2.0.CO;2](https://doi.org/10.1130/0016-7606(1974)85<1733:OONDIE>2.0.CO;2)
- 933 69. Remy, R. R., & Ferrell, R. E. (1989). Distribution and origin of analcime in  
934 marginal lacustrine mudstones of the Green River Formation, south-central  
935 Uinta Basin, Utah. *Clays and Clay minerals*, 37, 419-432.  
936 <https://doi.org/10.1346/CCMN.1989.0370505>
- 937 70. Fang, X., Zan, J., Appel, E., Lu, Y., Song, C., Dai, S., & Tuo, S. (2015). An  
938 Eocene–Miocene continuous rock magnetic record from the sediments in the  
939 Xining Basin, NW China: Indication for Cenozoic persistent drying driven by  
940 global cooling and Tibetan Plateau uplift. *Geophysical Journal International*,  
941 201(1), 78–89. <https://doi.org/10.1093/gji/ggv002>
- 942 71. Lepre, C. J., & Olsen, P. E. (2021). Hematite reconstruction of Late Triassic  
943 hydroclimate over the Colorado Plateau. *Proceedings of the National Academy*  
944 *of Sciences*, 118(7), e2004343118. <https://doi.org/10.1073/pnas.2004343118>
- 945 72. Müller, R. D., Royer, J. Y., & Lawver, L. A. (1993). Revised plate motions  
946 relative to the hotspots from combined Atlantic and Indian Ocean hotspot  
947 tracks. *Geology*, 21(3), 275-278. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1993)021<0275:RPMRTT>2.3.CO;2)  
948 [7613\(1993\)021<0275:RPMRTT>2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021<0275:RPMRTT>2.3.CO;2)
- 949 73. Herold, N., Buzan, J., Seton, M., Goldner, A., Green, J. A. M., Müller, R. D.,  
950 Markwick, P. & Huber, M. (2014). A suite of early Eocene (~ 55 Ma) climate

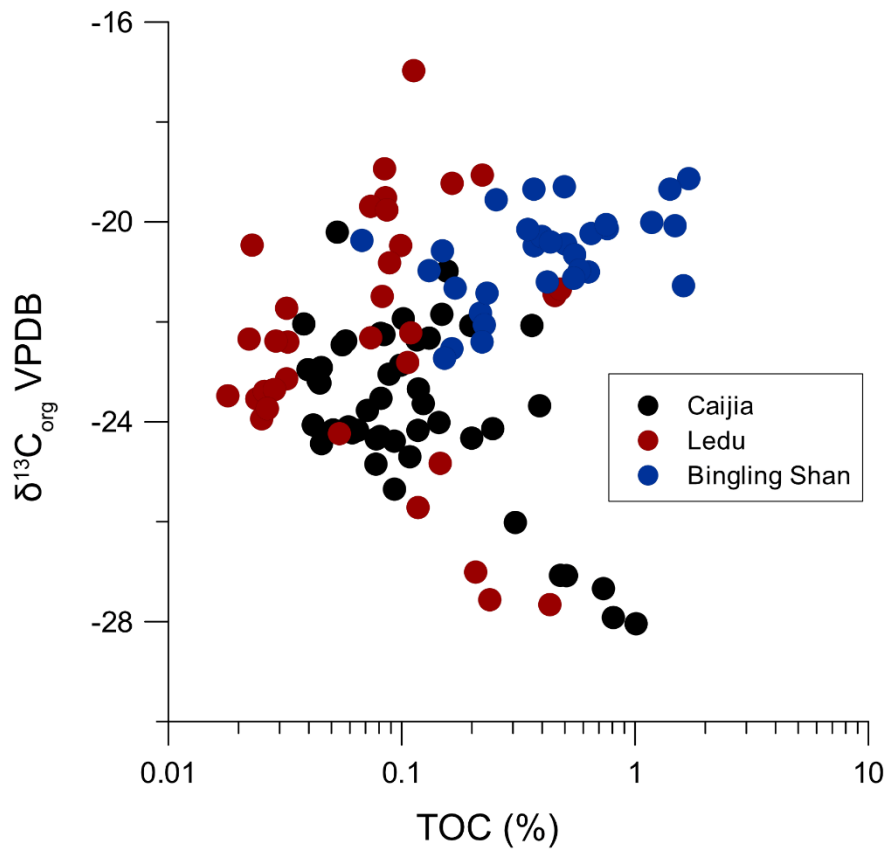
951 model boundary conditions. *Geoscientific Model Development*, 7(5), 2077-  
 952 2090. <https://doi.org/10.5194/gmd-7-2077-2014>  
 953 74.Laskar, J., Fienga, A., Gastineau, M., & Manche, H. (2011). La2010: a new  
 954 orbital solution for the long-term motion of the Earth. *Astronomy & Astrophysics*,  
 955 532, A89. <https://doi.org/10.1051/0004-6361/201116836>

956  
 957 **Extended Data**



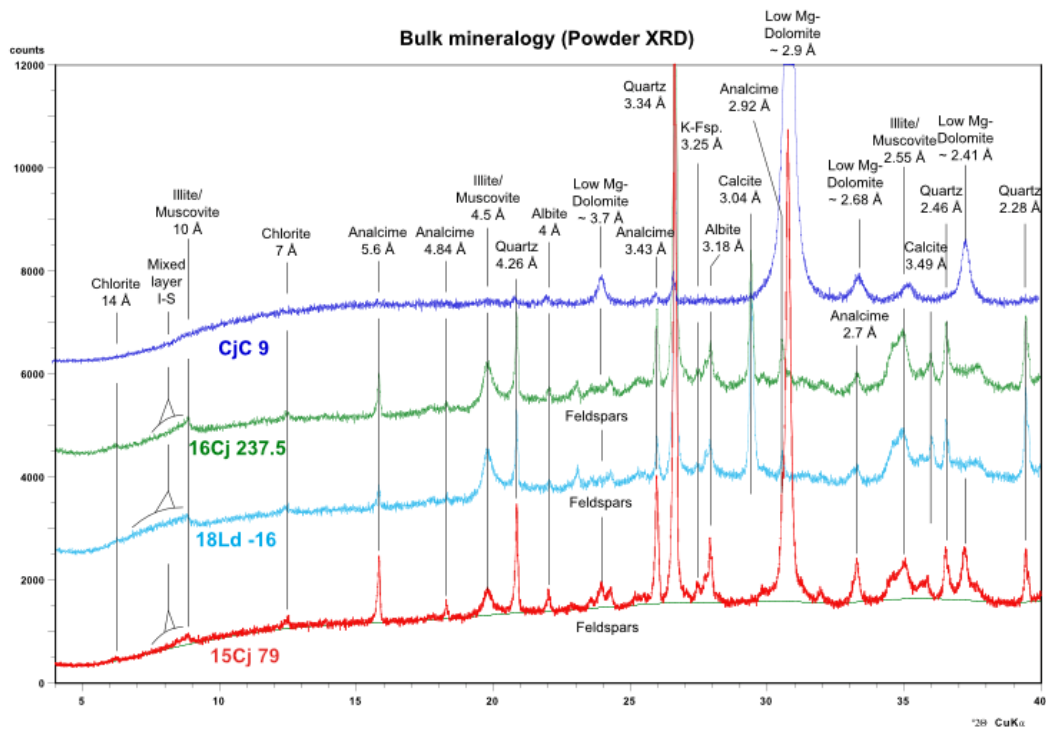
958  
 959 *Extended Data Fig. 1. Pre-industrial control simulations and weather station data from*  
 960 *the Xining Basin. Weather station precipitation data*  
 961 *(<https://www.ncei.noaa.gov/products/wmo-climate-normals>) and pre-industrial control*

962 simulations of A) temperature and B) precipitation in the Xining Basin using the  
963 DeepMIP climate model ensemble.



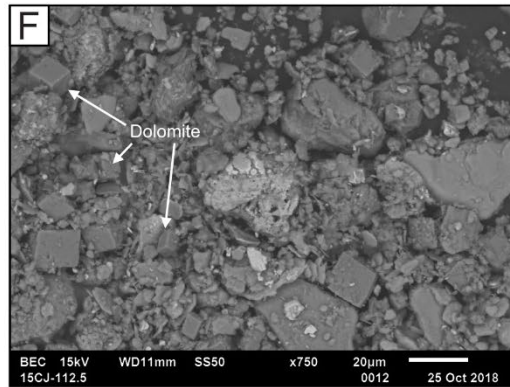
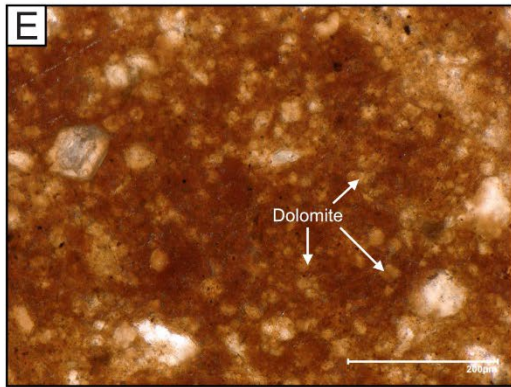
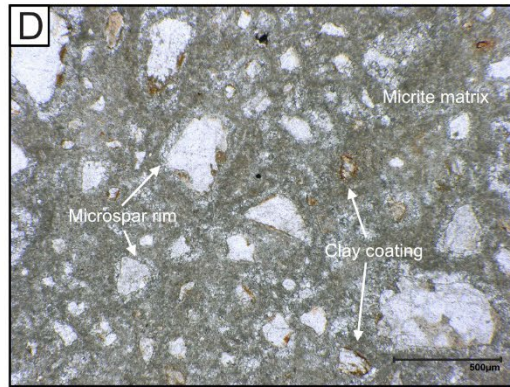
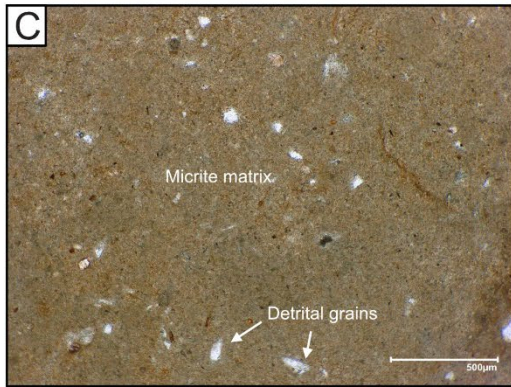
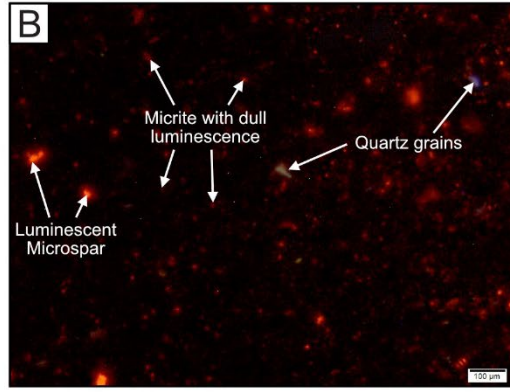
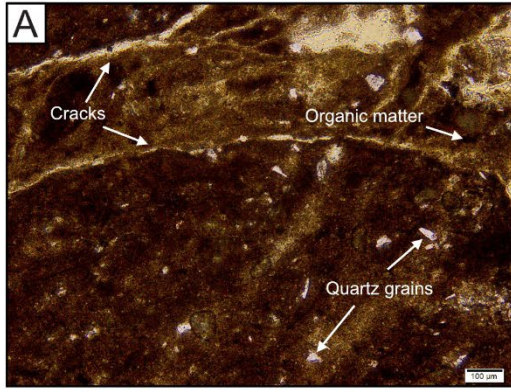
964

965 *Extended Data Fig. 2. Soil organic matter  $\delta^{13}\text{C}$  versus Total Organic Content (TOC).*



966

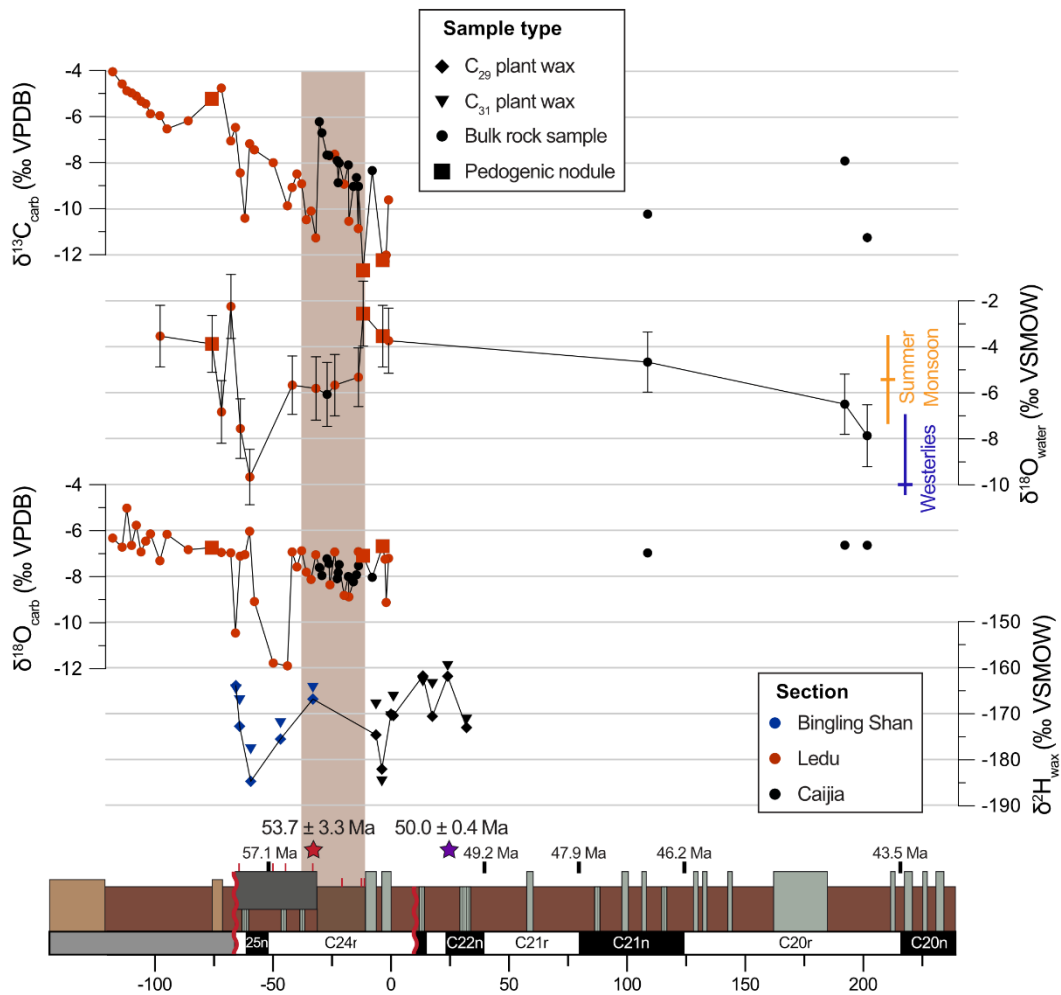
967 *Extended Data Fig. 3. XRD diffractograms showing the dominant peaks and bulk*  
 968 *mineralogy of selected samples including: a dolomite bed (CjC9, as shown on*  
 969 *Extended Data Fig. 4G; composite position: -37.1 m), a calcareous mudrock*  
 970 *(16Cj237.5; composite position: 193 m), a calcareous mudrock from the CIE interval*  
 971 *(18Ld-16; composite position: -31m) and a dolomitic mudrock (15Cj79; composite*  
 972 *position: 54 m). The samples 16Cj237.5 and 18Ld-16 were used for stable and*  
 973 *clumped isotope analyses.*



974

975 *Extended Data Fig. 4. Microscope and field photographs. A) and B) Cross-polarized*  
 976 *and cathodoluminescence image of a mudrock sample with vadose-grown calcite*  
 977 *cement (18LD-15; Ledu section; -15 meter-level) showing silt-sized matrix with*

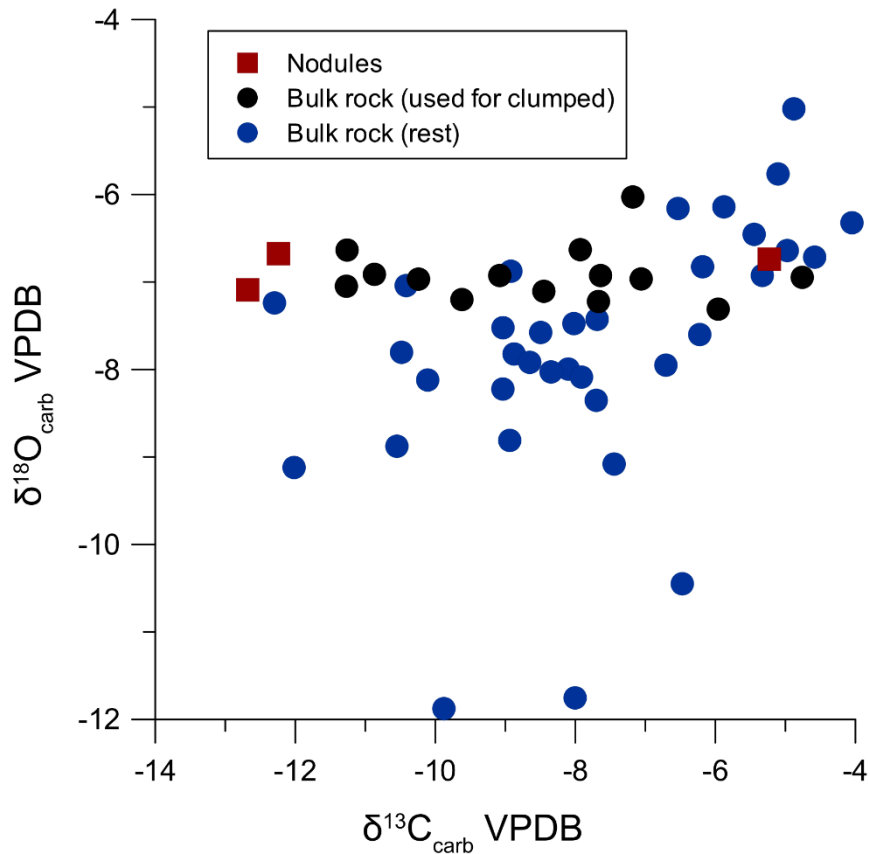
978 dispersed organic matter, dull luminescent micrite and some luminescent microsparite  
 979 and sparite. Plane-polarized images of pedogenic nodules showing: C) Micrite matrix  
 980 with floating detrital grains in 18LD+4nodB (Ledu section; 12.3 meter-level). D)  
 981 Floating detrital grains with isopachous microsparite to sparite rim and micritic matrix  
 982 in 18LDconglonod (Ledu section; -60 meter-level). Massive red dolomitic mudrock  
 983 samples showing rhombohedral dolomite crystals in E) plane-polarized light (15CJ-  
 984 111\_75; Caijia section 131.25 meter-level) and F) SEM (15CJ-112\_5; Caijia section;  
 985 132 meter-level). G) Greenish lacustrine mudrocks interbedded with massive dolomite  
 986 beds (Caijia section; 75 meter-level), hammer for scale. H) Dolomite-filled burrow  
 987 (Caijia section; 93 meter-level).



988

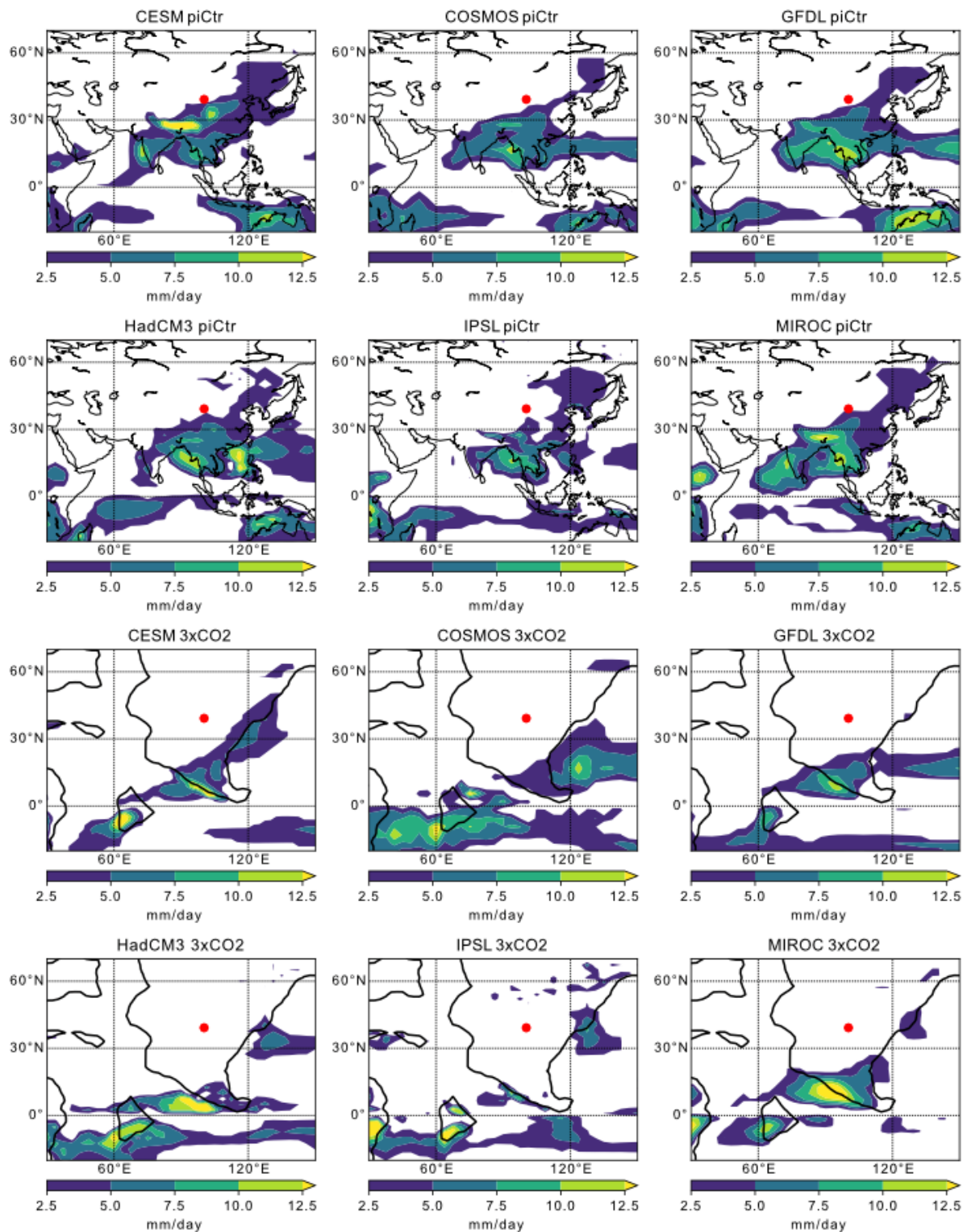


989 *Extended Data Fig. 5. Carbonate and plant wax stable isotopes. Stable isotope record*  
990 *( $\delta^{18}\text{O}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{carb}}$ ) of the vadose-grown and pedogenic carbonates and  $\delta^2\text{H}_{\text{wax}}$*   
991 *values of plant waxes.  $\delta^{18}\text{O}$  values of the soil water ( $\delta^{18}\text{O}_{\text{water}}$ ) are reconstructed using*  
992 *the  $\Delta_{47}$ -derived temperatures. Modern-day  $\delta^{18}\text{O}_{\text{water}}$  values of the summer monsoon*  
993 *and wintertime westerlies are shown<sup>57</sup>.*



994

995 *Extended Data Fig. 6. Carbonate stable isotope biplot. Stable isotope biplot of the*  
996 *studied calcites.*



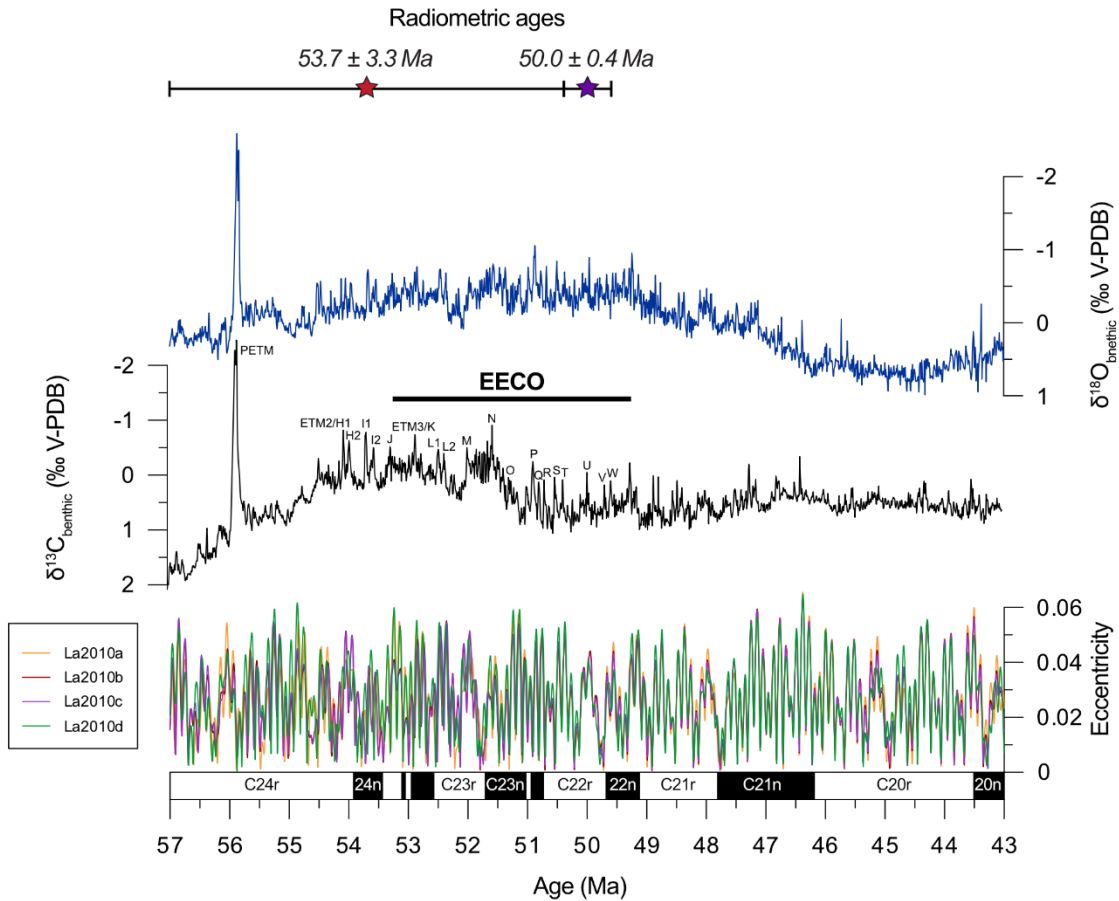
997

998 *Extended Data Fig. 7. Monsoonal domains in DeepMIP climate model simulations.*

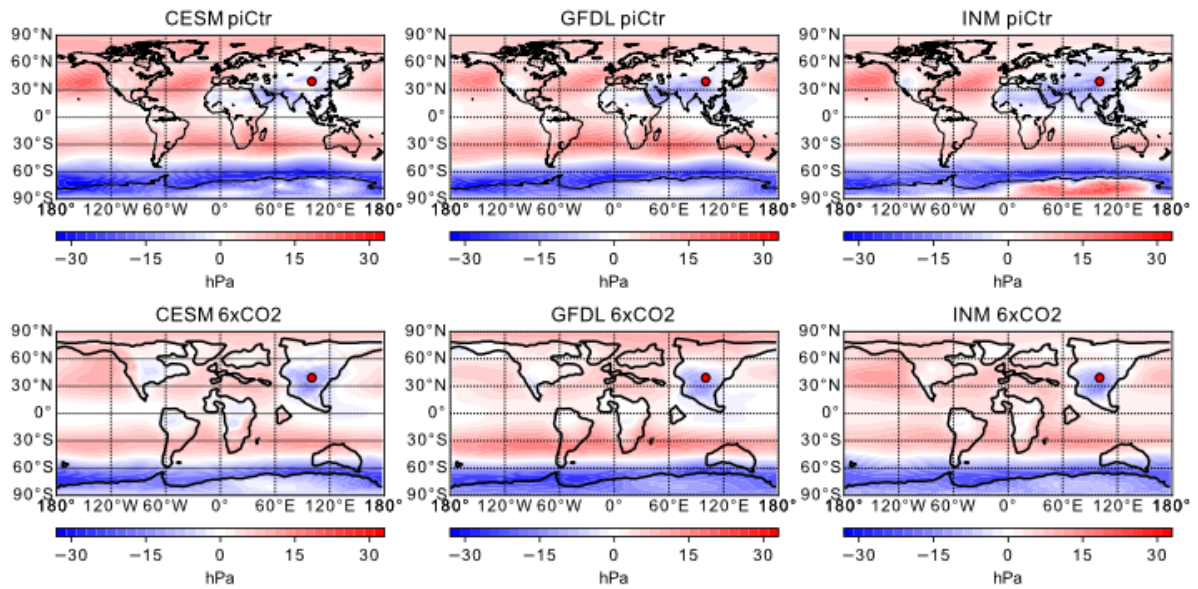
999 *Distribution of monsoonal domains in the pre-industrial control and 3x pCO<sub>2</sub> Eocene*

1000 *DeepMIP simulations. Summer (MJJAS) minus winter precipitation (NDJFM) is used*

1001 as a metric and regions where this difference is  $> 2.5$  mm/day are considered  
 1002 monsoonal<sup>44</sup>. Red dot indicates the location of the Xining Basin.



1003  
 1004 *Extended Data Fig. 8. Timing of Xining CIE compared with CENOGRID and*  
 1005 *astronomical solutions. CENOGRID showing the evolution of benthic foraminifera*  
 1006 *stable isotope values<sup>4</sup>. The  $\delta^{18}\text{O}$  values show peak warmth of the EECO and the  $\delta^{13}\text{C}$*   
 1007 *values show several hyperthermal events characterized by negative CIE's. The*  
 1008 *astronomical solutions<sup>76</sup> show the evolution of the eccentricity of Earth's orbit. The*  
 1009 *radiometric ages bracketing the CIE in the Xining Basin are indicated.*



1010

1011 *Extended Data Fig. 9. Summer sea-level atmospheric pressure anomalies in DeepMIP*  
 1012 *climate model simulations. Sea-level atmospheric pressure anomalies during summer*  
 1013 *(JJA) in the 6x pCO<sub>2</sub> Eocene and the pre-industrial control simulations of the DeepMIP*  
 1014 *ensemble. Red dot indicates the location of the Xining Basin.*

1015