The emergence of modern zoogeographic regions in Asia examined through climate–dental trait association patterns [Appendix]

Liping Liu[1,2*], Esther Galbrun[3*], Hui Tang[1,4,5], Anu Kaakinen[1], Zhongshi Zhang[6], Zijian Zhang[7] and Indrė Žliobaitė[8,1]

[1]Department of Geosciences and Geography, University of Helsinki, P.O. Box 64, University of Helsinki, FI-00014, Finland.
[2]Department of Palaeobiology, the Swedish Museum of Natural History, P.O. Box 50007, Stockholm, SE-104 05, Sweden.
[3]School of Computing, University of Eastern Finland, Technopolis, Microkatu 1, Kuopio, FI-70210, Finland.
[4]Finnish Meteorological Institute, P.O. Box 503, Helsinki, FI-00101, Finland.
[5]Department of Geosciences, University of Oslo, P.O. Box 1022, Oslo NO-0315, Norway.
[6]Department of Atmospheric Science, School of Environmental Studies, China University of Geoscience, 388 Lumo Road, Wuhan, 430074, China.
[7]Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Science, 19, Beitucheng Western Road, Chaoyang District, Beijing, 100029, China.
[8]Department of Computer Science, University of Helsinki, P.O. Box 64, University of Helsinki, FI-00014, Finland.

*Corresponding author(s). E-mail(s): liping.liu@helsinki.fi; esther.galbrun@uef.fi;

Abstract

The complex and contrasted distribution of terrestrial biota in Asia has been linked to active tectonics and dramatic climatic changes during the Neogene. However, the timings of the emergence of these distributional patterns and the underlying climatic and tectonic mechanisms remain disputed. Here, we apply a computational data analysis technique, called redescription mining, to track these spatiotemporal phenomena by studying the associations between the prevailing herbivore dental traits of mammalian communities and climatic conditions during the Neogene. Our results indicate that the modern latitudinal zoogeographic division emerged after the Middle Miocene climatic transition, and that the modern monsoonal zoogeographic pattern emerged during the late Late Miocene. Furthermore, the presence of a montane forest biodiversity hotspot in the Hengduan Mountains alongside Alpine fauna on the Tibetan Plateau suggests that the modern distribution patterns may have already existed since the Pliocene.

Keywords: Asia, Neogene, zoogeographic region, mammalian communities, dental traits, paleoclimate simulation, redescription mining

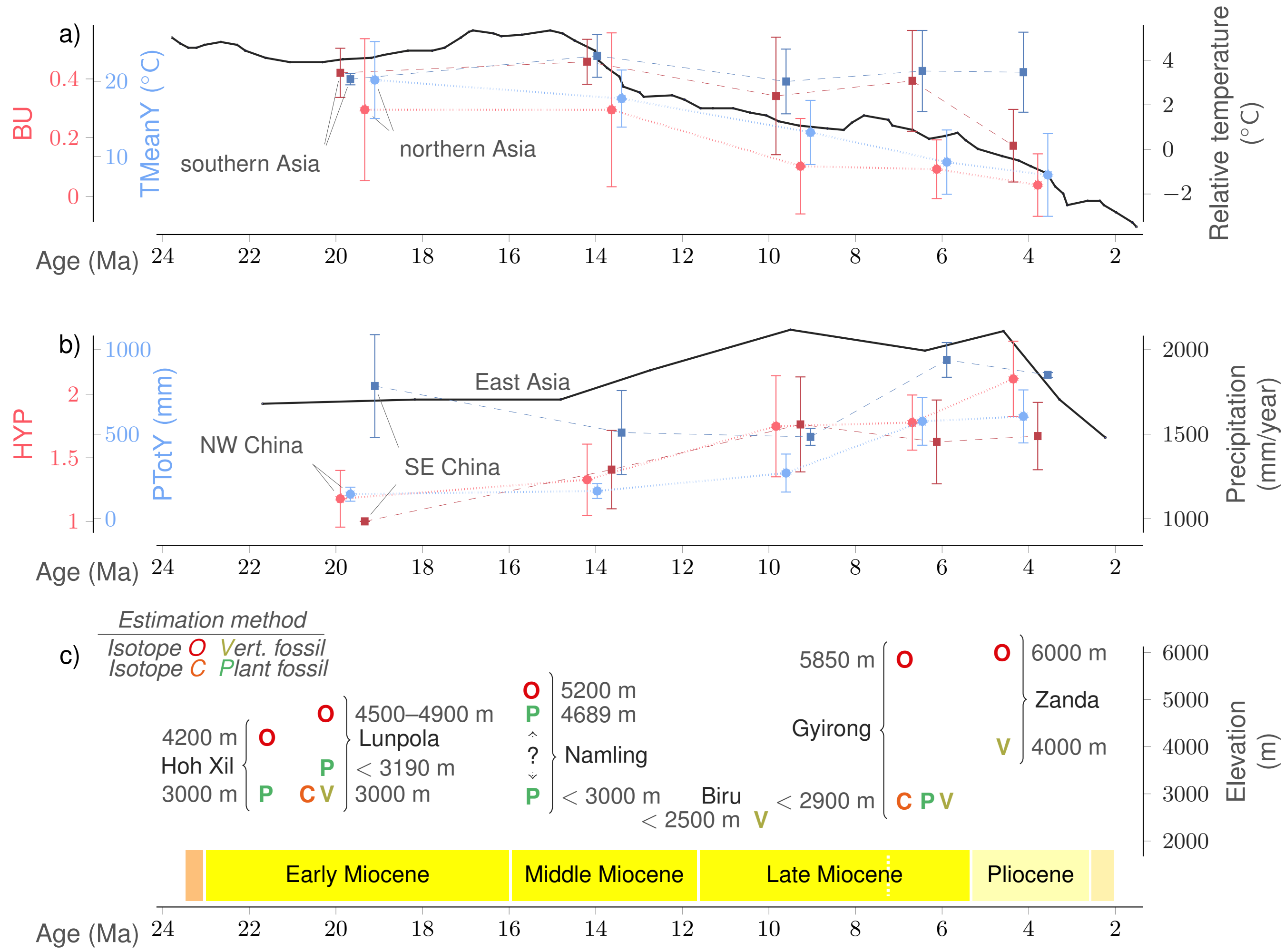

Figure 1 Temperature, precipitation, elevation, bunodonty and hypsodonty trends through the Neogene. a) Global temperature trend (based on [1]) and average bunodonty values in northern and southern Asia. b) Modeled mean annual precipitation for East Asia (based on [2]) and average hypsodonty values in northwestern (NW) and southeastern (SE) China. c) Elevation estimates for the Tibetan Plateau (data resources in Supplementary Information).

References

[1] Zachos, J., Pagani, M., Sloan, L., Thomas, E. & Billups, K. Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* **292** (5517), 686–693 (2001). https://doi.org/10.1126/science.1059412

[2] Farnsworth, A. *et al.* Past east asian monsoon evolution controlled by paleogeography, not CO2. *Science Advances* **5** (10), eaax1697 (2019). https://doi.org/10.1126/sciadv.aax1697

[3] Polissar, P. J., Freeman, K. H., Rowley, D. B., McInerney, F. A. & Currie, B. S. Paleoaltimetry of the tibetan plateau from d/h ratios of lipid biomarkers. *Earth and Planetary Science Letters* **287** (1), 64–76 (2009). https://doi.org/10.1016/j.epsl.2009.07.037

Table 1 Data sources for the elevation estimates for the Tibetan Plateau from Figure 1.

Time interval	Site	Estimation method			
		Isotope O	Isotope C	Plant fossil	Vertebrate fossil
Early Miocene	Lunpola	4500–4900 m [3]	3000 m [4]	$<$ 3190 m [5]	3000 m [6]
	Hoh Xil	4200 m [3]		3000 m [7]	
Middle Miocene	Namling	5200 m [8]		4689 m [9] $<$ 3000 m [10]	
early Late Miocene	Biru				$<$ 2500 m [11]
late Late Miocene	Gyirong	5850 m [12]	$<$ 2900 m [13]	$<$ 2900 m [11]	$<$ 2900 m [13]
Pliocene	Zanda	6000 m [14]			4000 m [15]

Table 2 Coordinates of the corners of the rectangles used to define the study region. The first five formed the dataset considered in our previous study [16] whereas the last four have been added in the present study and constitute the northern extension of our dataset.

Name	south-west	north-east
South East	$10°$N, $90°$ E	$20°$ N, $115°$E
South West	$5°$N, $66°$ E	$28°$ N, $90°$E
North East	$20°$N, $80°$ E	$35°$ N, $125°$E
North West	$28°$N, $67°30'$E	$37°30'$N, $90°$E
North Mid	$35°$N, $80°$ E	$40°$ N, $120°$E
Extension North East	$42°$N, $130°$ E	$50°$ N, $142°$E
Extension North Mid	$42°$N, $125°$ E	$50°$ N, $130°$E
Extension Korea	$30°$N, $125°$ E	$42°$ N, $130°$E
Extension West	$36°$N, $67°30'$E	$50°$ N, $125°$E

Table 3 Geographic conditions defining the groups of localities for computing and comparing dental traits and climate trends in Figure 1.

	x_1	x_2
(A)	$28°$N	
(B)	$18°$N, $106°$E	$36°$N, $70°$E
(C)	$43°$N, $124°$E	$24°$N, $87°$E

condition	group
north of (A)	northern Asia
south of (A)	southern Asia
north-east of (B) and south-east of (C)	northwestern (NW) China
north-east of (B) and north-west of (C)	southeastern (SE) China

[4] Jia, G., Bai, Y., Ma, Y., Sun, J. & Peng, P. Paleoelevation of tibetan lunpola basin in the oligocene–miocene transition estimated from leaf wax lipid dual isotopes. *Global and Planetary Change* **126**, 14–22 (2015). https://doi.org/10.1016/j.gloplacha.2014.12.007

[5] Sun, J. *et al.* Palynological evidence for the latest oligocene–early miocene paleoelevation estimate in the lunpola basin, central tibet. *Palaeogeography, Palaeoclimatology, Palaeoecology* **399**, 21–30 (2014). https://doi.org/10.1016/j.palaeo.2014.02.004

[6] Deng, T. *et al.* A mammalian fossil from the dingqing formation in the lunpola basin, northern tibet, and its relevance to age and paleo-altimetry. *Chinese Science Bulletin* **57** (2), 261–269 (2012). https://doi.org/10.1007/s11434-011-4773-8

[7] Sun, B. *et al.* Early miocene elevation in northern tibet estimated by palaeobotanical evidence. *Scientific Reports* **5** (1), 10379 (2015). https://doi.org/10.1038/srep10379

[8] Currie, B. S., Rowley, D. B. & Tabor, N. J. Middle Miocene paleoaltimetry of southern Tibet: Implications for the role of mantle thickening and delamination in the Himalayan orogen. *Geology* **33** (3), 181–184 (2005). https://doi.org/10.1130/G21170.1

[9] Spicer, R. A. *et al.* Constant elevation of southern tibet over the past 15 million years. *Nature* **421** (6923), 622–624 (2003). https://doi.org/10.1038/nature01356

[10] Zhou, Z., Yang, Q. & Xia, K. Fossils of quercus sect. heterobalanus can help explain the uplift of the himalayas. *Chinese Science Bulletin* **52** (2), 238–247 (2007). https://doi.org/10.1007/s11434-007-0005-7

[11] Deng, T. & Ding, L. Paleoaltimetry reconstructions of the tibetan plateau: progress and contradictions. *National Science Review* **2** (4), 417–437 (2015). https://doi.org/10.1093/nsr/nwv062

[12] Rowley, D. B., Pierrehumbert, R. T. & Currie, B. S. A new approach to stable isotope-based paleoaltimetry: implications for paleoaltimetry and paleohypsometry of the high himalaya since the late miocene. *Earth and Planetary Science Letters* **188** (1), 253–268 (2001). https://doi.org/10.1016/S0012-821X(01)00324-7

[13] Wang, Y., Deng, T. & Biasatti, D. Ancient diets indicate significant uplift of southern tibet after ca. 7 ma. *Geology* **34** (4), 309–312 (2006). https://doi.org/10.1130/G22254.1

[14] Saylor, J. E. *et al.* The late miocene through present paleoelevation history of southwestern tibet. *American Journal of Science* **309** (1), 1–42 (2009). https://doi.org/10.2475/01.2009.01

[15] Deng, T. *et al.* Locomotive implication of a pliocene three-toed horse skeleton from tibet and its paleo-altimetry significance. *Proceedings of the National Academy of Sciences* **109** (19), 7374–7378 (2012). https://doi.org/10.1073/pnas.1201052109

[16] Galbrun, E., Tang, H., Kaakinen, A. & Žliobaitė, I. Redescription mining for analyzing local limiting conditions: A case study on the biogeography of large mammals in china and southern asia. *Ecological Informatics* **63**, 101314 (2021). https://doi.org/10.1016/j.ecoinf.2021.101314