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## **Introduction to Asian geodynamics, climate and biodiversity**

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HAL Authorization

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3 Introduction to Asian geodynamics, climate and biodiversity  
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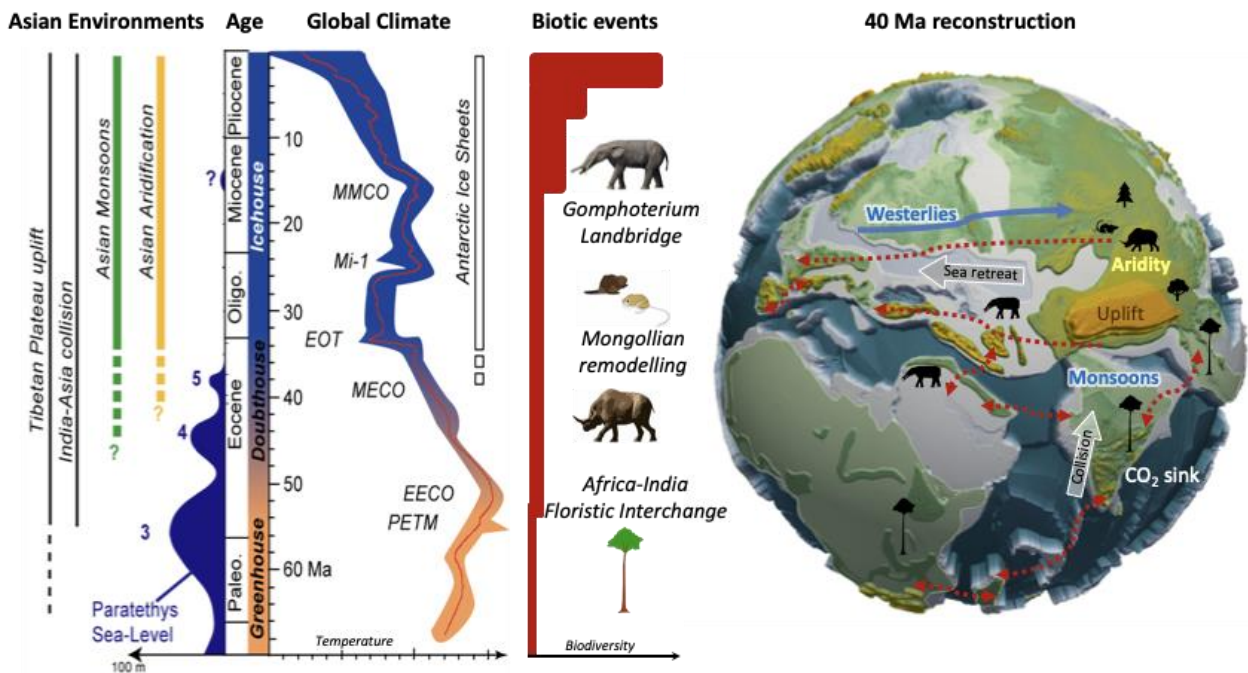
19 **Abstract**

20 **This book addresses the interplay between geodynamics, climate, and biodiversity, focusing on**  
21 **the India-Asia collision, the key abiotic parameter shaping the region's topography, climate,**  
22 **and ecosystems. Asia, with its unparalleled geological activity and rich biodiversity, is ideal for**  
23 **studying interactive processes of Earth System Science. Collision shaped the Himalayan and**  
24 **Tibetan Plateau regions, significantly influencing atmospheric circulation, precipitation**  
25 **patterns, and biotic evolution. Key questions revolve around the timing and mechanisms of**  
26 **these processes, which remain topics of debate. Fossil records highlight evolutionary patterns,**  
27 **such as plant and animal dispersals during tectonic shifts like the “Africa-India Floristic**  
28 **Interchange.” Climatic phenomena, including monsoons and glaciations, further influenced**  
29 **biodiversity by shaping habitats and driving speciation. High-altitude regions, like the**  
30 **Hengduan Mountains, became biodiversity cradles due to habitat heterogeneity and ecological**  
31 **niches. Advances in tools like palaeoaltimetry proxies, molecular phylogenetics, climate and**  
32 **landscape modelling clarify the complex interactions between tectonics, climate, and**  
33 **biodiversity. Asia’s geological history offers vital insights into past climate-biodiversity**  
34 **dynamics, aiding predictions of current ecosystem responses to climate change. This region’s**  
35 **unparalleled geological activity and biodiversity make it a focal point for Earth System Science,**  
36 **highlighting the need for interdisciplinary research to address global biodiversity and**  
37 **environmental challenges.**  
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## Links between geodynamics, climate and the biosphere

How have geodynamics and climate driven Earth surface and biotic processes in Asia? This book examines this long-standing question through an array of studies exploring the India-Asia collision region and timeframe which together offer an ideal laboratory to test methods and constrain models that link topography to geodynamic processes, drainage patterns, biodiversity and climate. Today, this region combines some of the most biologically diverse and tectonically active areas on Earth, including several biodiversity hotspots (including the Caucasus, the mountains of Central Asia to Southwest Asia and the Indo-Burma to Sundaland and Wallacea regions, Myers et al., 2000; Mittermeier et al., 2004; Mutke and Barthlott, 2005; de Bruyn et al., 2014). The area straddles the highest mountains and plateaus on Earth including widely different ecological environments, spanning from the arid subarctic steppes of Central Asia to the humid tropical rainforests of Southeast Asia. In this region Wallace's (1878) Palaeartic and Oriental zoogeographic regions and Good's (1947) Boreal and Palaeotropical floristic kingdoms meet. This extraordinary diversity results from a complex interaction of geodynamic, climatic and Earth surface processes throughout the spatiotemporal framework of the continental collision that started at the onset of the Cenozoic (Figure 1). Understanding the interplay between geodynamic forces, climate dynamics, and biotic evolution in Asia during this eventful timeframe presents a formidable challenge to researchers. The collision between the Indian and Eurasian tectonic plates stands as one of the most significant geological events in Earth's history, constantly reshaping the landscape, climate, and biodiversity of the entire region. The collision is thought to have impacted atmospheric circulation, precipitation, drainage patterns and detrital recycling, geochemical cycles and therefore climate and life on regional and global scales (e.g., Jagoutz et al., 2016). This collision has thus captivated scientists for decades, unravelling a complex tapestry of interactive processes from plate tectonics to climate dynamics and raising numerous outstanding interdisciplinary questions that continue to challenge our understanding: What was the geodynamic configuration of the India-Asia collision and how does it relate to tectonic deformation (van Hinsbergen et al., 2019; Ding et al., 2022) and biotic dispersals between India, Asia and Africa (Bansal et al., 2022)? What is the timing and distribution of topographic growth that led to the formation of the plateau, did it involve interactions between deep to surface processes (Molnar et al., 2015; Yuan et al., 2022) and orchestrate biotic evolution (Favre et al., 2015)? When and how did the collision and linked landscape evolution contribute to regional climate change (monsoons and desertification) and thus affect ecosystems as well as biogeochemical cycles (Sarr et al., 2022; Wu et al., 2022; Tardif et al., 2023; Clift et al., 2024)? How did landscapes, evolving from rugged relief to flat plateau and from sea to desert, act as biotic corridors, cradles, museums and contribute to shaping dispersals and biodiversity hotspots when combined with climatic shifts and variations (Muellner-Riehl et al., 2019; Deng et al., 2019; Barbolini et al., 2020; Tardif et al., 2021)?



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81 **Fig. 1.** Asian abiotic constraints on biodiversity evolution throughout the Cenozoic era (since 66 Million years ago - Ma)  
 82 illustrated by the paleogeographic reconstruction at 40 Ma (Poblete et al., 2020; Westerweel et al., this volume)  
 83 showing the India-Asia plate collision and related topographic growth leading to the formation of the Tibetan Plateau. These  
 84 geodynamic processes are linked to the fluctuations and long-term retreat of the epicontinental sea (“the Paratethys”), the  
 85 deflection of the westerly jet, the intensification of Asian Monsoons and the aridification and the continental interior.  
 86 Climate patterns have been also driven by global climate cooling generally cooling since 55 Ma punctuated by shorter  
 87 term events (Tardif et al., 2023) such as the PETM (Paleocene-Eocene Thermal Maximum), EECO (Early Eocene Climate  
 88 Optimum), MECO (Mid Eocene Climate Optimum, EOT (Eocene-Oligocene Transition), MMCO (Mid Miocene Climate  
 89 Optimum). Biotic events shows biodiversity in Highland Asia with increasing topography, relief and climate variability  
 90 (Mosbrugger et al., 2018; Spicer et al., this volume) and major Asian dispersal events (Barbolini et al., 2020;  
 91 Chattopadhyay et a., this volume; Morley et al., this volume).

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93

94 Answering these questions requires constraining in time and space the environmental  
 95 evolution of the India-Asia collision region; however, this remains a major challenge despite decades  
 96 of intense investigation and development of dedicated methods and databases. Tackling this challenge  
 97 first requires constraining the most fundamental boundary conditions by reconstructing the region’s  
 98 palaeogeographic and climatic evolutions (Fig. 1). This includes the convergence and accretion  
 99 history of the colliding tectonic plates and the closely associated regional topographic evolution  
 100 expressing the interplay between deep and surface processes, but also the extent of the vast  
 101 epicontinental sea that spread across Eurasia influenced by the geodynamic forces and global eustatic  
 102 sea levels related to global climate (Fig. 1). The precise timing and sequence of events associated  
 103 with the collision remain incompletely understood. Geological evidence indicates multiple phases of  
 104 topographic uplift, tectonic deformation, and erosion throughout the development of multiple  
 105 mountain ranges, but the chronology of these events and their relationships to global and regional  
 106 climate change as well as biological evolution remain topics of debate. End-member geodynamic  
 107 models of the India-Asia plate collision have been developed with contrasting timing and  
 108 configurations of island arcs and micro-terrane accretions between the Indian and Eurasian plates  
 109 (Westerweel et al., this volume). Opposing views are proposed in the timing and formation of the  
 110 Himalayan-Tibetan orogeny linked to the collision initiating in the Eocene and leading to the  
 111 formation of the Tibetan Plateau and based on regional geologic data constraining crustal deformation  
 112 and palaeo-topography (Spicer et al., this volume). Different collision and uplift models are being  
 used as boundary conditions for climate simulations to interpret proxy records of regional

113 atmospheric and oceanic circulations, in particular the development of monsoons in Asian coastal  
114 regions and the aridification of continental interiors related to topographic uplift and the retreat of the  
115 vast epicontinental sea that covered most of Eurasia (Clift, this volume; Spicer et al., this volume;  
116 Tardif et al., 2023; Fig. 1). Superimposed on these regional climate drivers is the contribution of  
117 global climate forcing at various timescales ranging from long-term Cenozoic cooling to shorter  
118 hyperthermal events, whose astronomical to glacial cycles and transitions modulated seasons and sea  
119 levels (Fig. 1). The resulting complex climatic evolution combined with geodynamic processes to  
120 control surface denudation, erosion and weathering to generate Asia’s dramatic landscapes featuring  
121 the Earth’s highest uplift rates, relief and largest river drainages and sediment loads. Asia thus  
122 constitutes an ideal setting where various numerical simulations of simplified surface processes have  
123 been tested against proxy records to propose contrasting models of landscape evolution (Yuan et al.,  
124 2022, Chang et al., this volume). Understanding the origin and evolution of Asia’s current  
125 biodiversity throughout the Cenozoic India-Asia collision framework is currently a major  
126 interdisciplinary challenge requiring constraints on the geodynamic, climate and landscape evolution  
127 (e.g. Morley, this volume). The advent of molecular phylogenetic tools, high resolution remote  
128 sensing information systems and biotic-based environmental proxies has led to an explosion of new  
129 data and models with the recognition that mountain landscapes—accounting for over 85% of modern  
130 terrestrial mammals, birds and amphibians in only 25% of global land area—are vital for building  
131 biodiversity (*i.e.*, Antonelli et al., 2018; Hoorn et al., 2018; Rahbek et al., 2019). Understanding the  
132 rich Asian biodiversity requires exploring biotic interchange between and across the continents of  
133 India, Africa and Eurasia during their accretion (e.g., Klaus et al., 2016; Morley, this volume), and  
134 documenting the biotic response to the development of the planet’s largest orogenic system (Favre et  
135 al., 2015; Mosbrugger et al., 2018; Ding et al., 2020). Promising frontier approaches are currently  
136 under development that help to reconcile Asian species richness and biodiversity data with numerical  
137 landscape evolution models (e.g. Chang et al., this volume; Allen et al., this volume).

138 With ongoing human alteration of the Earth’s ecosystems and rapid global warming there is  
139 an urgent need to understand the response of biodiversity and environments to climate change, how  
140 they were created, subsequently evolved and, perhaps, most importantly, how they can be maintained  
141 (IPCC, 2023). Modern observations only offer a limited perspective for study, so that lessons learned  
142 from Earth’s past are essential for understanding how climate change has affected environments and  
143 the distribution and migration of species. In fact, examining how past landscape and climatic changes  
144 influenced the environment and biological diversity is the only way to assess numerical models  
145 forecasting our future. In particular, deep time records documenting major tipping points are essential  
146 to develop reliable simulations. Asia’s topographically complex and tectonically active systems,  
147 which evolved through India-Asia collision and major climatic transitions and formed variegated  
148 biodiversity hotspots, thus provide unique information for future adaptation to climate change. As  
149 such, a focus on Asia makes this research collection globally relevant for researchers interested in a  
150 broad multidisciplinary approach working to address the most fascinating challenges and current  
151 debates across the Earth, Environmental and Life Sciences. The book offers a broad view on the  
152 framework of the regional’s palaeogeographic and climatic evolution with a background focus on  
153 biotic processes presented in the order of the following topics: “Asian geodynamics and  
154 palaeogeography”, “the fossil record”, “Evolving Asian environments” and “Life-Earth interactions”.  
155 These topics are introduced below.

## 156 **Asian Geodynamics and Palaeogeography**

157  
158

159 Accurately reconstructing the palaeogeographic evolution of terranes involved in the India-Asia  
160 convergence, accretion and collision remains essential not only for understanding geodynamic and  
161 orogenic models but has considerable implications for development of the biosphere and  
162 biogeochemical cycles over deep-time ( $>10^6$  yrs). The tectonic accretion of Asian terranes and  
163 associated plate kinematics, as well as the associated orogenic uplift history, remains strongly  
164 debated. In particular, the onset, growth of, and creation of topography and relief across these major  
165 physiographic features, such as the Himalaya, the Hengduan mountains or the Tibetan Plateau, are  
166 highly controversial and rely on widely different plate kinematic models for India-Asia collision.  
167 Understanding how topography has evolved is critical to constraining how this may have interfered  
168 with regional to global atmospheric and environmental phenomena, including monsoons, the jet  
169 stream, long-term desertification, and the CO<sub>2</sub> cycle. Growth of topographic barriers is also a key  
170 component driving isolation of populations and allopatric speciation.

171 **Westerweel et al.** propose a reconstruction of the India-Asia collision based on new  
172 evidence arising from the Burma Terrane. They use palaeomagnetic data from Paleocene to late  
173 middle Eocene rocks to constrain the passage of this block towards Eurasia. This continental fragment  
174 remained in equatorial latitudes and far from Eurasia during the Paleocene and Eocene and thus was  
175 not yet part of Sundaland at that time, contrary to the suggestions made in previous models. Instead,  
176 the Burma Terrane formed part of a Trans-Tethyan subduction system during the Late Cretaceous  
177 and early Paleocene and drifted north with India to collide with Eurasia ~50 Ma. Preservation of  
178 fauna in Cretaceous Burmese amber corroborates palaeomagnetic evidence, together emphasizing  
179 that the Burma Terrane was part of an isolated Trans-Tethyan Arc prior to collision with Eurasia.

180 **Spicer et al.** proposes a comprehensive review on the development of the Tibetan Plateau  
181 region with a critical assessment of methodologies for palaeoaltimetric reconstructions. Based on a  
182 number of strands of new evidence from proxies and numerical simulations, they first examine the  
183 evolving palaeogeography of India-Asia collision region and test whether it involved either an early  
184 high area that preceded the collision, or whether there was a central lowland. This study concludes  
185 that there was an east-west oriented Central Tibetan Valley that served as an important evolutionary  
186 cradle and biogeographic corridor through most of the Paleogene period (66-24 Ma). Specifically,  
187 this valley acted as an incubator for thermophilic taxa and created a physical conduit for the dispersal  
188 of species originating from this region into other parts of Asia. The review extends to various regions  
189 where, similarly, the Qiangtang and Gangdese uplands funnelled more cold-adapted taxa. The rise of  
190 eastern Tibet was particularly important in intensifying rainfall and erosion, which increased the  
191 topographic relief to positively impact biodiversity by creating a range of ecological niches. Such  
192 high-relief landscapes continued to develop into the Miocene and, when these were combined with  
193 repeated climatic oscillations, they likely acted as a ‘stimulator’ for speciation. This study concluded  
194 that a modern monsoon, similar to that active today, developed gradually by the Miocene after the  
195 formation of a more coherent plateau.

## 196 197 **The Fossil Record**

198  
199 The rich fossil record of Asia informs us on the dynamic history of land masses and climate but  
200 importantly also provides a window in which to explore past evolutionary origins, extinctions, and  
201 biotic interchanges that cannot be studied under modern conditions. Two articles in this collection,  
202 **Morley** and **Chattopadhyay et al.**, include contributions on the biogeography of Asia grounded on  
203 terrestrial and marine palaeontological evidence. They address the following questions: (i) what can  
204 the fossil record tell us about the biotic consequences of the tectonic collisions between the African,

205 Indian and Eurasian continents, and how these were related to biotic exchange and the assembly of  
206 biodiversity?; (ii) how does palaeontology inform the evolution of endemic organisms that  
207 characterize Asian biodiversity hotspots?; and (iii) can palaeoenvironmental inferences from the  
208 fossil record be reconciled with independent palaeoclimate reconstructions?

209 **Morley** examines the development and differentiation of Palaeotropical rainforests that occur in  
210 Africa, South and Southeast Asia and Oceania from the Late Cretaceous to the Plio-Pleistocene.  
211 Based on 80 Myr-old *Dipterocarpus* pollen from East Africa the origin of Paleotropical closed-  
212 canopy evergreen rainforest is placed in Africa. The expansion of Palaeotropical rainforests from  
213 Africa all the way to Oceania can be understood as a sequence of interplate plant dispersals facilitated  
214 by plate alignment in equatorial ever-wet climates. Key events were the dispersal of rainforest taxa  
215 from Africa to India with the “Africa-India Floristic Interchange” during the Late Cretaceous-  
216 Paleocene, the “Out of India” dispersal to Southeast Asia during the Eocene starting 48 Ma and the  
217 “Sahul-Sunda-Floristic Exchange” between Southeast Asia and Oceania during the Miocene-  
218 Pliocene. While temperate tree taxa and northern conifers were still present in Southeast Asia during  
219 the Oligocene, indicative of seasonal monsoon climates, the modern humid rainforests of the Sunda  
220 region became established only in the Miocene. To account for this shift in vegetation and climate  
221 Morley challenges existing plate-tectonic models by proposing a clockwise southward rotation of  
222 Borneo in which the island reached its equatorial position with a prevailing everwet climate during  
223 the Miocene. The megadiverse Southeast Asian rainforests with their dominance of the  
224 Dipterocarpaceae are therefore much younger than often assumed, implying rapid diversification.

225  
226 **Chattopadhyay et al.** examine the biotic impact of the Early Miocene ‘*Gomphotherium*  
227 Landbridge’ that formed across the east-west oriented Tethys Ocean to create a proto-Mediterranean  
228 and an Indo-Pacific Ocean. While emergence of this isthmus land-bridge permitted interchange of  
229 terrestrial mammalian fauna, closure of the seaway isolated eastern and western marine fauna. This  
230 compilation, which addresses a variety of marine benthos from the Tethys seaway, demonstrates that  
231 the proportion of marine genera shared between the east and the western parts of Tethys decreased  
232 after the Early Miocene, whereas the proportion of families unique to each sector increased only  
233 during and after the Early Miocene closure. High biodiversity in the Early Miocene is consistent with  
234 a pre-closure shallow seaway that enhanced speciation via increased connectivity. Prior to closure,  
235 evidence suggests formation of discrete Oligo-Miocene biodiversity hotspots but there is only limited  
236 evidence for intermediate hotspots after that time in the provinces. Taxonomic groups demonstrate  
237 variable responses through time and magnitude that likely reflect a combined response related to  
238 preservation bias and the innate yet differential responses of fauna to palaeogeographic change.

## 239 240 **Evolving Asian Environments**

241  
242 Independently reconstructing the evolution of Asian climatic, environmental and ecological  
243 systems remains essential for understanding which mechanisms control their development and,  
244 ultimately, how these systems interact to influence the geo- and biospheres. Major efforts are  
245 currently focused on building accurate proxy records and climate model experiments. Together,  
246 integrated data and models enable interpretations from the geological past to inform future  
247 predictions. However, the onset and intensity of major atmospheric, environmental, and ecological  
248 components (e.g., monsoons, desertification, loess, evolution of C<sub>3</sub> to C<sub>4</sub> carbon fixation pathways in

249 plants) remain controversial such that their driving mechanisms (regional palaeogeography vs. CO<sub>2</sub>)  
250 remain intensely debated in these contributions.

251 **Clift** presents a synthesis of spectral colour data from scientific ocean drilling cores spanning  
252 across the Indian to Pacific oceans to explore development of the coupled Asian and Australian  
253 monsoon systems. Specific wavelengths of light are related to specific iron oxide minerals, with  
254 haematite indicative of drier, more seasonal conditions and goethite related to cooler, wetter  
255 conditions. Strong intensities represent higher relative concentrations. In South Asia, the monsoon  
256 strengthened in the Early Miocene and peaked by 20-17 Ma. This is observed to occur later in  
257 southern China, with a peak at 15-10 Ma. After the middle Miocene, weakening occurs in both areas  
258 with drying particularly noteworthy in the Arabian Sea (western Himalaya) after 8 Ma. By around 5  
259 Ma, sediments in Southeast Asia, as well as in eastern Australia indicate drying of the adjacent  
260 continent, with aeolian dust from the Sea of Japan implying stronger aridity in Central Asia initiating  
261 after 5 Ma. As a result of greater influence from the Indonesian Throughflow, northwest Australia  
262 shows a different trend to the east that highlights that the Australian monsoon became decoupled  
263 from the Asian monsoon throughout the Neogene. When monsoonal records are compared to floristic  
264 datasets, drying correlates and appears to favour development of an herbaceous and conifer-rich flora  
265 in Southeast Asia but not in southern China, while drying in the western Himalaya is coincident with  
266 the spread of more drought-tolerant plant taxa with specialised C<sub>4</sub> photorespiration pathways over  
267 less specialised but more versalite plants with C<sub>3</sub> pathways.

268 **Ghosh et al.** examine the role that depositional environments played in controlling the evolving  
269 vegetation as recorded by the Siwalik Group across the Himalayan foreland basin during the late  
270 Neogene. This study looks at variations in sediment grain size and depositional facies alongside new  
271 and synthesized *n*-alkane stable isotope carbon data from preserved organic matter and soil carbonate  
272 from the Siwalik Group ranging from Pakistan to Nepal. While Neogene climate overall promoted  
273 C<sub>4</sub> plant growth across the foreland basin, positive shifts in <sup>13</sup>C/<sup>12</sup>C ratios in floodplain sediments of  
274 the Siwalik Group document how the evolution of the floodplain architecture-controlled hydrology  
275 to further favour growth of C<sub>4</sub> plants. Conversely, eastern foreland basin channel-fill dominated  
276 deposits favoured C<sub>3</sub> plants over C<sub>4</sub> grasses. This study tracks the long-term development of the late  
277 Neogene foreland basin and its vegetation, whilst demonstrating how apparently contrasting climate-  
278 vegetation records can be explained by the local geomorphology and lithology of the  
279 palaeolandscape.

280

## 281 **Life-Earth Interactions**

282

283 Alexander von Humboldt developed a deep appreciation of the linkages among the biosphere,  
284 climate, and geosphere, where his approach and success continues to inspire reintegration of modern  
285 biological and geoscience observations under a more holistic approach to better decipher the  
286 interactions and feedback between Life and Earth (**Wulf, 2015**). This closing section hosts integrative  
287 studies that focus on deciphering such relationships among abiotic phenomena (e.g., surface  
288 processes, climate variability, soil development, hydrology) and the biosphere in terms of species  
289 richness and evolution.

290 **Chang et al.** use a quantitative approach to examine how biodiversity hotspots emerge in  
291 mountain regions. The Hengduan Mountains in southwest China are collectively one such biodiverse  
292 hotspot where the interplay of active tectonics, high relief, and dynamic climate generated  
293 exceptionally rich montane biodiversity. This study examines three abiotic mechanisms important in  
294 producing rich montane biodiversity: development of more numerous and heterogeneous niche

295 environments through relief and landscape complexity (habitat creation), geophysical vicariance  
296 through fragmentation (habitat disruption), and transient (re)connection of habitat through climate  
297 variability (habitat oscillation). Utilising a species distribution model, this work explores how these  
298 mechanisms explain species richness and phylogenetic endemism in seed plants across the region.  
299 They isolate the components caused by tectono-geomorphic processes and conclude that areas with  
300 very high species richness can be attributed to the combination of habitat heterogeneity and tectonic-  
301 geomorphic processes. In contrast, glaciation and rapid climate change diminished species diversity  
302 and led to extinction and depopulation in the northern regions of the Hengduan Mountains.

303 [Allen et al.](#) further examined timing of floral diversification in the region between the Tibetan  
304 Plateau, the Himalayas and the Hengduan Mountains and attempt to test whether the topographical  
305 development of the region could explain evolutionary trends in Sino-Himalayan angiosperm species  
306 since the Cretaceous. In this study they use Bayesian birth-death skyline inference methods (i.e.,  
307 [Meredith et al., 2011](#); [Stadler et al., 2012](#)) to analyse angiosperm phylodynamics from a database of  
308 extant angiosperms. This approach indicates high rates of evolution during the Paleocene, Late  
309 Miocene and Pliocene but ‘negative rates’ during the Pleistocene caused by higher extinction rates.  
310 After considering whether past global temperatures may have controlled diversity trends, the study  
311 concludes that these were unlikely to have been a driving force for speciation in this region. Instead,  
312 topographic change linked to the India-Eurasia collision, expansion of grassland in the Miocene, and  
313 the onset of glaciation are critical factors for promoting diversification over time.

314

## 315 **Conclusions and perspectives**

316

317 From this broad overview, it first appears that reconstructing palaeogeography incorporating  
318 evidence for the configuration of tectonic plates, land-sea gateways and the evolving topography over  
319 geologic timescales remains absolutely essential for examining evolutionary co-development of the  
320 biosphere alongside the geosphere and atmosphere. This foundational work is especially true with  
321 regard to mountainous Asia. [Westerweel et al. \(this volume\)](#) and [Spicer et al. \(this volume\)](#), highlight  
322 the tremendous achievements both in setting these abiotic constraints and in identifying the vast  
323 knowledge gaps to be filled by future research. Contrasting interpretations concerning the evolution  
324 of the India-Asia collision and the related growth of regional topography remain open for discussion  
325 because of the still inconclusive geologic data available today. More data but also new methods are  
326 clearly needed. Plate configurations can increasingly be used to validate or invalidate dispersal  
327 models, therefore, care must be taken to improve their accuracy and clarify their inherent  
328 uncertainties. For example, there has been a longstanding debate concerning plant and mammal  
329 dispersals between Africa, India and Asia before these continents were firmly connected ([Bansal et al., 2022](#);  
330 [Morley, this volume](#)). Recent plate tectonic models advocate for the presence of a Trans-  
331 Tethyan arc. This arc may have created land bridges or functioned as island chain ‘stepping stones’  
332 and thus created opportunities for floristic and fauna. interchange between these continents as early  
333 as the Late Cretaceous. However, it should remain clear, from evidence presented by the Life science  
334 community, that the Trans-Tethyan arc tectonic model remains one of several hypotheses to be tested  
335 ([Westerweel et al., this volume](#)). It should be considered as a working hypothesis rather than a firm  
336 plate tectonic configuration upon which to anchor biogeographic models. The work presented in this  
337 book thus emphasizes the crucial need to develop collaborative research involving geodynamic and  
338 biotic expertise.

339 The presented work further illustrates how orogenic reconstructions are now carried out with  
340 new methodologies combining proxies and climate modelling that together can better constrain

341 palaeo-elevations (Ibarra et al., 2023; Spicer et al., this volume). Biotic proxies from pollen, plant  
342 fossils or biomarkers (Spicer et al., this volume; Morley, this volume; Gosh et al., this volume)  
343 preserved in well-dated sedimentary records from basins in and around Asian orogenic systems  
344 provide critical constraints over geological times, on geodynamic plate motion, mountain building  
345 and surface processes. Moreover, evolutionary phylogenies have been increasingly used to support  
346 competing plate configurations for India-Asia and/or Arabia-Asia collisions that drove terrestrial and  
347 marine biotic interchanges (Morley, this volume; Chattopadhyay et al., this volume). So far,  
348 uncertainties in phylogenetic data, especially in ages, have been a limiting factor; yet recent  
349 improvements in geochronological and molecular clock techniques, the development of large, open-  
350 access biotic databases (e.g., <https://paleobiodb.org/#/>; <https://nowdatabase.org/>;  
351 <https://www.neotomadb.org/>) and the possibility of combining data from various taxa, which may  
352 provide converging evidence for biogeographic pathways, are all likely to play an increasing role in  
353 future geodynamic and orogenic models that account for the biological record over deep time. The  
354 collection of studies shows, across this exemplar orogen, that accurate assessment of the orogenic  
355 evolution and the development of topography can be achieved through collaborative interdisciplinary  
356 research that may be widely applicable to other regions, thus paving the way for innovative fields of  
357 inquiry. Exemplar applications (Chang et al., this volume; Allen et al., this volume) show how  
358 orogenic reconstructions at higher spatiotemporal resolutions will be increasingly needed to test  
359 models that explore how biotic evolution is affected by increased habitat heterogeneity, and how the  
360 creation of physiographic barriers during orogenesis promotes geographic isolation, vicariance and  
361 allopatric speciation.

362 Climate is the other major abiotic constraint affecting palaeoenvironments and ecosystem  
363 dynamics. Contributions in this book (Clift, this volume; Ghosh et al., this volume) show how  
364 precisely dated multi-proxy records from marine and terrestrial basins can be used as powerful tools  
365 for identifying and disentangling potential drivers of environmental and ecosystem change at different  
366 timescales. This approach is essential in Asia where short- and long-term trends of global climate  
367 (seasonal and astronomical cycles, hyperthermals or million year global cooling trends) are combined  
368 with strong regional changes related to evolving palaeogeography and surface processes. Plate  
369 convergence, orogeny and sea level fluctuations strongly affected moisture sources for major  
370 atmospheric phenomena (i.e., the summer and winter monsoons), which in turn shaped biome  
371 distributions and affected dispersal routes across continents and along orogenic gradients (Fortelius  
372 et al., 2014; Tardif et al., 2023; Spicer et al., this volume). Based on the long term trends in Asia's  
373 climatic evolution, contrasting models of biotic dispersal and interchange through biogeographic  
374 corridors spanning several ecozones have been proposed (Morley, this volume; Chattopadhyay et al.,  
375 this volume). Slow palaeoclimatic variations imposed on given palaeogeographic settings are used to  
376 explain long-term adaptation patterns and continental-scale dispersals, while short-term variations  
377 (e.g., glacial-interglacial climate oscillations) superimposed on relief that concentrates vegetation  
378 belts spatially may explain increased speciation (i.e., species pumps and 'flickering connectivity',  
379 e.g., Mülner-Riel et al., 2019; Flantua et al., 2019; Spicer et al., this volume; Chang et al., this volume;  
380 Allen et al., this volume). Tracking palaeoclimate variations is essential to understand how they have  
381 shaped landscape evolution, shifting drainage patterns and compartmentalized ecosystems (e.g., the  
382 role of drainage configuration and morphology on the Himalayan C<sub>3</sub>-C<sub>4</sub> plant shift, Ghosh et al., this  
383 volume). In turn, Asian biotic activity certainly played a major role in driving surface processes and  
384 weathering with shorter to longer term effects on the regional landscape (Ielpi et al. 2022), as well as  
385 global biogeochemistry of our planet over geological timescales (Boyce et al., 2023; Salles et al.,

386 2023). However, large uncertainties, concerning both the climatic and evolutionary framework, and  
387 the specific processes of abiotic forcing, leave us unable to resolve between potential drivers that led  
388 to current biotic patterns. Despite major efforts to gather new palaeoclimate records with increasingly  
389 accurate proxies that can be successfully coupled to hindcast models, a climatic evolutionary  
390 framework remains far from a consensus. Filling this knowledge gap remains critical for numerical  
391 models that address current biodiversity crises beyond climate tipping points which require validation  
392 by deep time records with analogue conditions and CO<sub>2</sub> levels (e.g., Ehlers et al., 2022).  
393 Strengthening this research direction is essential if we are to infer impacts to biodiversity resilience  
394 due to ongoing increases in monsoonal intensity and extreme events and the melting of glaciers and  
395 permafrost in Asia.

396 A particularly promising area of research in Asia features the combination of numerical  
397 simulations of landscape with climate and biotic models, whose nexus allows statistical comparison  
398 between competing processes and large databases of proxies from different fields (Hagen, 2022;  
399 Allen et al., this volume; Chang et al., this volume). By comparing knowledge from geology and  
400 palaeobiology, the mechanistic links between geological and biological processes can be identified  
401 (e.g., Xing and Ree, 2017). Integration of increasingly large datasets with advanced statistical  
402 methods that will only benefit in the future from machine learning tools that expedite data mining  
403 and pattern recognition (e.g., Sonne et al., 2022). In principle, numerical modelling enables empirical  
404 testing of potential mechanistic links between topographic complexity, associated climate changes,  
405 and high biodiversity, such as proposed in the Tibetan–Himalayan–Hengduan region (e.g., Xing and  
406 Ree, 2020; Allen et al., this volume; Chang et al., this volume; Spicer et al., this volume). Encouraging  
407 results are being obtained from population-based, spatially explicit mechanistic eco-evolutionary  
408 models (Hagen, 2022; Acevedo-Trejos et al., 2023). Yet these biotic models still require accurate  
409 constraints from landscape and climate simulation outputs, which themselves are constrained by  
410 climate and landscape proxy data at a given spatial and temporal resolutions (Boschman &  
411 Condamine, 2022). Furthermore, validating these biotic models requires equally high-resolution  
412 phylogenetic and paleontological databases that appear to be the common limiting factor in many  
413 studies. This shortcoming highlights an urgent need to gather more such data in Asia.

414 This overview only briefly summarises the most recent collaborative developments which  
415 permit a glimpse of what is yet to come in the exploration of deep time relationships between the  
416 geosphere, atmosphere and biosphere in Asia. Given the concentration in this region of the strongest  
417 expression of geologic processes on the planet (the fastest mountain building involving the largest  
418 mountains and rivers, the most intense monsoons with the highest weathering, erosion and sediment  
419 fluxes) combined with the largest concentration of biodiversity hotspots and speciation rates on the  
420 globe, Asia will always be a prime target for understanding interactive Earth System Sciences  
421 processes from deep time to the future. With the recognition that the spatiotemporal dynamics of  
422 biodiversity are only marginally constrained by physical environmental changes compared to  
423 interactive biotic driving mechanisms (e.g., Fortelius et al., 2014), future understanding of biological  
424 evolution will require further cross-disciplinary approaches that synthesise geology and  
425 palaeobiology in a collaborative biogeographic framework.

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