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Preface

Mesozoic and Cenozoic palaeogeography, palaeoclimate and palaeoecology in the eastern Tethys

1. Introduction

It is now more than 100 years since Suess advanced the concept of the Tethys Ocean in 1893. Since the 1960s when the theory of plate tectonics became established, the Tethys region has attracted the attention of many geologists because it has experienced a complex evolution involving numerous continental fragments drifting in several discrete stages from the Gondwanan margin in the Southern Hemisphere northward to amalgamate with Eurasia in the Northern Hemisphere (Chang and Cheng, 1973; Şengör, 1979; Tapponnier et al., 1981; Audley-Charles, 1983; Allègre et al., 1984; Chang et al., 1986; Chatterjee et al., 2013). The subsequent orogenies associated with consecutive microplate collisions caused great changes to the regional topography and environments, which researchers now realize had global impacts on climate, biotic evolution, and biogeography (e.g., Molnar and Tapponnier, 1975; Audley-Charles, 1987; Raymo and Ruddiman, 1992; Molnar et al., 1993; Ramstein et al., 1997; An et al., 2001).

The vast literature on the evolution of the Tethys Ocean highlights several critical scientific issues that require further investigation. These include especially: (1) what was the extent of the Tethys and its surrounding landmasses at the time that Pangea began to break up?; (2) when and how did the Cimmeride terranes rift from Gondwana and collide with proto-Eurasia?; (3) what was the motion history of the Indian plate during its northward journey, and when and where did it collide with Eurasia?; (4) when did the Neo-Tethys come into being and subsequently close up?; (5) what was the driving force behind continental fragmentation that gave rise to the Neo-Tethys?; (6) what processes were involved in the uplift of the Qinghai-Xizang Plateau, and what was the chronology of uplift events?; (7) what were the impacts of these events on Earth's climate and biotas? (Fig. 1). The answers to each question are complex and involve a multitude of geological phenomena. In particular, a detailed understanding of the palaeogeography and palaeoenvironmental characteristics of the Tethyan region at each stage of its geological history is crucial for understanding the evolution of its biota and biogeography.

The eastern part of the Tethys, which encompasses a wide area now ranging from China and central Asia in the north, through Indochina in the east, to Australia, New Zealand and Antarctica in the south, witnessed the step-wise breakup of Gondwana during the Mesozoic and early Cenozoic (Fig. 2; Şengör, 1979; Tapponnier et al., 1981; Audley-Charles, 1983; Allègre et al., 1984; Chang et al., 1986; Li and Powell, 2001; Veevers, 2004; Chatterjee et al., 2013; Metcalfe, 2013). The separation of Australia from Antarctica, and New Zealand from Australia represented the final stages of Gondwanan breakup at the eastern end of the Tethys. The collision of India with southern Eurasia caused the Himalayan orogeny, which has severely distorted the geological record of Tethys-fringing landmasses and the biotas that occupied these areas. Reconstructing the evolutionary history of the region has become a complex challenge that must overcome multiple phases of deformation, subduction, and stratal erosion. The harsh climate and extreme elevation in the plateau region have further hindered fieldwork to resolve the history of the eastern Tethys.

The papers contained in this special issue include the latest research results in magmatic petrology, geochemistry, palaeontology and sedimentology from the eastern Tethys (Fig. 2). A multitude of issues relating to the evolution of the Tethys are covered, such as the timing of initiation of the Neo-Tethys, the properties of the Bangong-Nujiang Tethys, the rifting process of the Indian plate, palaeoenvironmental events during Tethyan evolution, the impact on terrestrial ecosystems of closure of the Tethys, and the effects of uplift of the Qinghai-Xizang Plateau. These advances provide insights into and will stimulate further research on the evolution of the eastern Tethys.

2. Contents of this SI: topics and progress

2.1. Breakup of Pangea

When did Pangaea split into Laurasia and Gondwana or, equivalently, when was the Hispanic Corridor established? Various studies have inferred ages ranging from the middle Late Triassic (Norian) to the late Early Jurassic (Pliensbachian). On the basis of the temporal and spatial distribution of some pan-tropical cosmopolitan Jurassic epi-byssate pectinid and epi-cemented ostreid bivalves, Sha (this volume) concludes that the Hispanic Corridor was formed, or the northern Atlantic opened, in the earliest Jurassic (Hettangian) or even as early as the latest Triassic (end of the Rhaetian).

2.2. Rifting of India from Gondwana

When and how the Indian Plate rifted from Gondwana and drifted northward is key to reconstructing the evolutionary history of the Neo-Tethys. The separation of the Indian Plate from Australia–Antarctica and its drift northward occurred concurrently with the subduction of the Neo-Tethys before the Indian-Eurasian collision. Although previous studies have indicated the initiation of this separation in the Late Jurassic or Early Cretaceous (Li and Powell, 2001; Veevers, 2004; Metcalfe, 2013), little direct evidence has been forthcoming from the Qinghai-Xizang Plateau to indicate concomitant subduction. Zeng et al. (this volume) report newly discovered rift-related dolerites from southern Tibet that provide magmatic clues to the breakup of India from eastern Gondwana. These magmatic rocks of earliest Cretaceous age (~142 Ma) denote relatively high melting temperatures indicative of partial melts of a rising asthenospheric mantle that was triggered by

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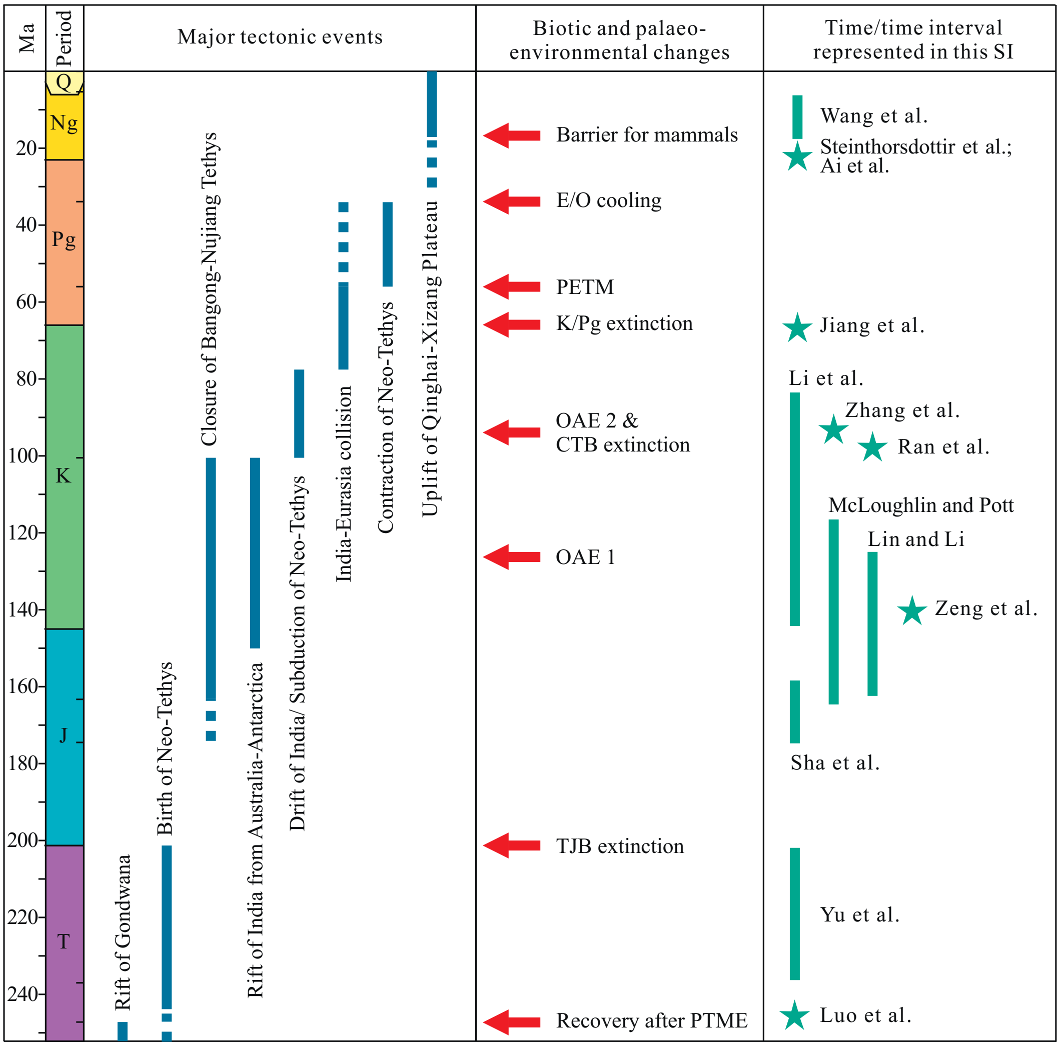

Fig. 1. A summary of key events in the evolution of Tethys as studied by previous researchers and authors in this issue. Selected changes in biotas and palaeoenvironments during the period are also illustrated (data according to Ogg et al., 2016). The time (green star) or time interval (green bar) represented by each contribution to this SI is plotted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rifting. This magmatic evidence may mark the earliest phase of the breakup between India and Australia-Antarctica in the northeastern sector of the rift zone. However, this process was probably slow, as a palynofloristic analysis (Li et al., this volume) shows that these two regions were not sufficiently separated at that time to hinder exchanges of land floras. Palynofloras from southern Xizang are strongly similar to those of Australia and Antarctica until the Albian. By the Albian, India was completely separated from Australia—at which time distinct palynofloristic differences become apparent between the two continents.

2.3. Initiation of Neo-Tethys subduction

Li et al. (this volume) propose a reconstruction of the drift history of the Indian plate during the Cretaceous by employing comparative analyses of the palynofloras between southern Xizang, Australia and Africa. Their conclusion suggests that the northward drift of the Indian plate, or subduction of the Neo-Tethys, began in the Cenomanian. It is notable that this conclusion is supported by petrogeochemical data of Ran et al. (this volume), who discovered subduction-related volcanic rocks with an age of 97.1–90.1 Ma from the southern margin of the Lhasa Block, providing direct evidence for the northward subduction of the Neo-Tethys along the southern margin of the Lhasa Terrane in the early Late Cretaceous. Therefore, the new, independent results from palaeontology and volcanic petrology support the hypothesis that the Neo-Tethys began to subduct during the Cenomanian.

2.4. Impacts of tectonic events on palaeoenvironments and biotas

Tectonic events, such as continental drift and collision, resulted in palaeogeographic changes in the Tethyan region that influenced ocean circulation as well as regional palaeoenvironments and biotas. Investigations of these biological and environmental changes through time can provide insights into relationships between lithospheric tectonic evolution and the biotas occupying separate terranes, and, thus, provide a historical basis for assessing the impact of today's global change.

Previous studies have revealed some major events in the Mesozoic–Cenozoic biological and environmental evolution of the Qinghai-Xizang Plateau. For example, Wan et al. (2003) recorded a major extinction of foraminifera and calcareous nannoplankton near the end of the Cenomanian in southern Xizang (Tibet). Zhang et al. (this volume) examine this event from the perspective of the oceanic nitrogen cycle. They found that the marine faunal turnover coincided with the perturbation of the N cycle, suggesting that the expansion of anoxic watermasses may have played an important role in the extinction of marine organisms in the eastern Tethys. Their conclusions

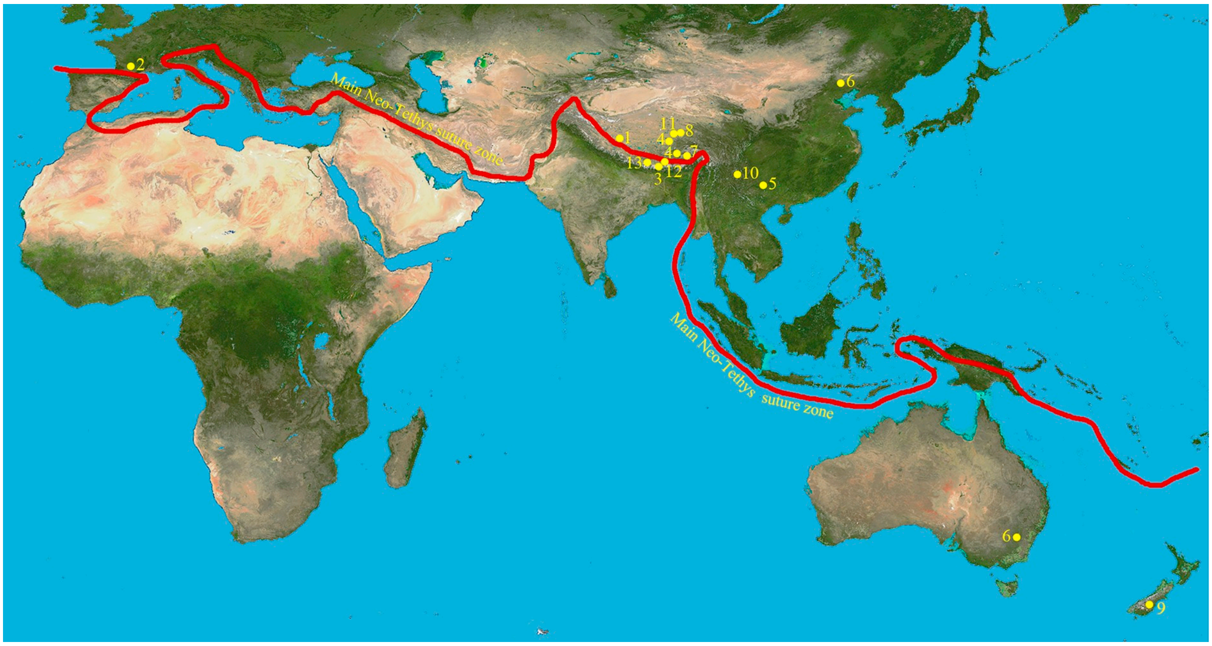

Fig. 2. Map of the Tethyan region showing the locations of the contributed studies to this SI. Red line represents the main Neo-Tethys suture zone. 1. Ai et al.; 2. Jiang et al.; 3. Li et al.; 4. Lin and Li; 5. Luo et al.; 6. McLoughlin and Pott; 7. Ran et al.; 8. Sha; 9. Steinthorsdottir et al.; 10. Wang et al.; 11. Yu et al.; 12. Zeng et al.; 13. Zhang et al. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

support a link between the physical evolution of the Tethys and its biotas.

Luo et al. (this volume) study the recovery process of trace fossils after the Permian-Triassic Mass Extinction (PTME) in the lower Middle Triassic Luoping Biota of Yunnan Province, South China. Their research demonstrates that bottom-water conditions were probably the main factor controlling the recovery of the trace-maker organisms in an offshore setting. If this is the case, it has implications for understanding the mechanism of how the breakup of the northern margin of Gondwana to form the Neo-Tethys impacted the recovery of marine invertebrates.

Jiang et al. (this volume) study calcareous nannoplankton across the K/Pg boundary, providing another example of how palaeoceanography influenced marine biotas. Their analysis shows that nannoplankton from different environments underwent similar but subtly varied responses to the K/Pg ecological crisis. Differences in palaeogeographic setting are cited as the reason for the different rates of extinction and the subsequent environmental restoration and biological recovery. Owing to their smaller water volume, shelf environments have a poorer capacity to buffer the lethal effects of impact-induced flash warming, 'nuclear-winter' cooling, and acidification compared to the deep ocean.

The tectonic evolution of the Tethyan region resulted in palaeogeographic changes that created favorable conditions for the accumulation of organic matter. One example is the organic-rich Upper Triassic Bagong Formation in northern Qiangtang, whose deposition was linked to spreading of the Bangong-Nujiang Neo-Tethys Ocean. Yu et al. (this issue) investigate the mechanism of organic matter accumulation by analyzing total organic carbon (TOC) content together with mineralogic compositions, carbon isotopes, palynology, and major and trace element concentrations of these rocks. They infer that rapid sedimentation rates and high primary productivity under a warm and humid climate were the main factors favoring organic matter enrichment.

The tectonic evolution of the Tethys region also affected terrestrial ecosystems. In a comparative phytogeographic analysis of Cretaceous palynofloras of southern Xizang, Li et al. (this volume) show that the fossil record of terrestrial plants in marine settings can be used as a tool to reconstruct palaeo-plate motions. The same principle is applied to Upper Jurassic to Lower Cretaceous pollen-spore floras of the Lhasa Block by Lin and Li (this volume). These floras are notably similar to those on the Qiangtang Block as the two regions had merged to form the new southern margin of Eurasia prior to the Late Jurassic. Coeval pollen-spore assemblages from southern Xizang, e.g., those from Gamba documented by Li et al. (this issue) and Gyangze (Li et al., 2013), are distinct from palynomorph suites on the Lhasa and Qiangtang blocks owing to their isolation by the Neo-Tethys. Of course, the effects of marine isolation on plant evolution may vary at different taxonomic levels. McLoughlin and Pott (this volume) present an investigation of plant disseminule dispersal strategies among four Middle Jurassic to Lower Cretaceous Lagerstätten in China and Australia. Their results show that similar patterns of germinule modifications evolved among different plant groups on both sides of the Neotethys during the Middle Jurassic to Early Cretaceous. Their case study reveals parallel evolution in dispersal strategies among mid- to high-latitude land plants in both hemispheres in response to similar palaeoclimatic conditions.

Although some major palaeoenvironmental changes in the Tethys Ocean were related to tectonic events, other changes can be linked to global climatic or orbital drivers. Steinthorsdottir et al. (this volume) measure the $p\mathrm{CO}_2$ of the Oligocene–Miocene transition (OMT) using the stomatal proxy method on fossil Lauraceae leaves from New Zealand. Their work reveals a much higher value of $p\mathrm{CO}_2$ at the OMT than during the early Miocene. This result implies that $p\mathrm{CO}_2$ played an important role in climate dynamics during the OMT, which was potentially responsible for the abrupt termination of glaciation at higher latitudes.

2.5. *Palaeoecological implications of closure of the Neo-Tethys*

The closure of the eastern part of the Neo-Tethys Ocean profoundly changed climates and environments in East Asia, i.e., through the elevation of high plateaus, inland desertification, and establishment of the modern monsoon system (Raymo and Ruddiman, 1992; Kutzbach et al., 1993; Molnar et al., 1993; Ramstein et al., 1997; An et al., 2001). However, diverse views persist on many aspects of these issues. For example, there is a heated debate about the timing and process of Lhasa Block uplift. Spicer et al. (2003) considered a near-present elevation for this block at ca. 15 Ma (early middle Miocene) using CLAMP analysis. Some stable isotope research has suggested an earlier (pre-Miocene) uplift to the same elevation (e.g., Rowley and Currie, 2006; DeCelles et al., 2007). Contrary to those views, other studies have proposed a much lower elevation for this block during the Oligocene (Deng et al., 2012; Sun et al., 2014; Li, 2015; Ding et al., 2017; Wu et al., 2017). Ai et al. (this volume) report a well-dated (23.3 Ma; latest Oligocene) plant megafossil assemblage from the Kailas Formation of the Kailas Basin in the western part of the southern Lhasa Block that represents a temperate and humid deciduous broad-leafed forest at low to moderate altitudes (< 2500 m a.s.l.) based on the dominance of poplar, birch, and legumes. This low elevation is in sharp contrast to the high altitude of the basin today, and it was not sufficiently high to obstruct the South Asian monsoon from passing northward over the plateau.

The principle that fossil faunas can be used to indicate topographic elevation depends on the barrier imposed by the plateau to the migration of animals. Comparison of proboscidean fossils between Southeast Asia, northern China, and the Indian Subcontinent leads Wang et al. (this volume) to conclude that an uplifted Qinghai-Xizang Plateau was a barrier to proboscidean migrations between northern China and Siwalik/Southeast Asia in the middle Miocene. The late Miocene aridification of Asia drove these animals to migrate from North China to Yunnan as their final refuge.

3. Conclusions and perspectives

This special issue reports the latest discoveries of scientists from various disciplines on the evolution of the eastern Tethys region. Their studies encompass the geological evolution of the Neo-Tethys from the origins of deep-sea barriers established by Gondwanan rifting to the final contraction of the Tethys and emergence of high plateaus in southern Asia. The independence, yet consistency, of these results from different research areas, including igneous petrology, geochemistry, palaeontology, and biogeography supports the robustness of these findings. For example, palaeontological records reflecting northward motion of the Indian plate during the Cenomanian is consistent with the age of rift-related volcanic eruptions in the southern Qinghai-Xizang Plateau. This consistency not only provides more robust models for Tethyan evolution, but also gives us more confidence in the relationships between biotic evolution, tectonics and sedimentary data. In this issue, several examples show the feasibility of using palaeontology to explore tectonic problems. The conclusions of these studies can be mutually validated, as well as complemented with data from previous studies, to provide new perspectives or methodologies for studying problems such as plate movement (Fig. 1). The new advances in this special issue provide not only a better understanding of some basic but unresolved questions concerning the evolution of the eastern Tethys, but also contribute to our understanding of such fundamental problems as modeling plate tectonics, continental collision, the uplift of plateaus and impact of these events on regional or global palaeonvironments and biotas. A multitude of unsolved but critical geological problems remain in understanding the evolution of the eastern Tethys. We see the current set of studies as a springboard to further research in this region of complex tectonics and biotas.

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