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新生代亚洲季风的演化过程

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The evolutionary process of Cenozoic Asian monsoon

Abstract: [Objective] The formation of monsoon climates is attributed to the seasonal reversal of wind direction and precipitation caused by the difference in thermal capacity between land and ocean. Asia is recognized as the most prominent region globally, with monsoon climates, that affect the largest population. The heavy rainfall accompanying monsoons can result in various secondary disasters, substantially jeopardizing human safety and productivity in the region. Consequently, comprehending the formation process of the Asian monsoon holds paramount importance. [Methods] This study aim to employ geological concepts to establish a connection between the past and present, providing an overview of the components of Asian monsoons, identifying the primary factors influencing their formation and evolution, and summarizing research progress on the South Asian and East Asian monsoons based on sediment records from key Asian locations. [Results] The findings indicate that during the Cenozoic, the collision between the Indian Plate and the southern margin of the Asian continent altered the distribution of land and sea in Asia. Consequently, the Tibetan Plateau experienced initial uplift, contributing to the emergence of monsoon climates in South Asia and East Asia. However, at this stage, the East Asian region was still primarily influenced by the planetary wind system, and the East Asian monsoon was in its early stages, predominantly restricted to the southern margin of the South China Plate in a localized manner. In contrast, the South Asian Monsoon covered a relatively extensive area. This discrepancy may be attributed to the delayed opening of marginal seas in the East Asian region compared to the relatively earlier occurrence of land and sea distribution in South Asia. However, as the Tibetan Plateau continued to uplift and approach its current altitude during the middle to late Cenozoic, the Asian monsoon entered a strengthening phase, notably impacting regional geological evolution processes. Since the middle to late Cenozoic, the development of the North and South Polar ice caps and the upliftment of

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the Tibetan Plateau have controlled the Asian monsoon, leading it to undergo multiple stable periods of development. [Conclusion] The development and evolution of the East Asian and South Asian monsoons are mainly driven by the distribution of sea and land in the Asia, the upliftment of the Tibetan Plateau and the global climate change during the Cenozoic. [Significance] These findings provide valuable insights into the scientific and rational utilization of the Asian monsoon for conducting systematic Earth science research in Asia.

Keywords: Asian Monsoon; East Asian Monsoon; Tibetan Plateau; South Asian Monsoon; Cenozoic

摘要: 陆地和海洋热容量差异会引起风向和降水发生季节性反转形成季风气候。亚洲是世界上季风气候最典型的区域, 同时也有最多的受季风气候影响的人口。季风带来的强降水容易诱发多种次生灾害, 严重影响着区域内人类社会生产、居住的安全, 因而认识亚洲季风的形成过程至关重要。利用将古论今的地学思想, 文章旨在阐述亚洲季风的组成, 列举影响亚洲季风形成、演化的主要因素, 总结亚洲关键地点的沉积记录显示的南亚季风和东亚季风的演化期次。结果表明, 在古近纪, 印度板块与亚洲大陆南缘发生碰撞, 改变了亚洲的海陆分布, 导致青藏高原发生初始隆升, 南亚和东亚均出现季风性气候。但此时的东亚地区依然主要受行星风系的控制, 东亚季风处于孕育阶段, 仅呈条带状局部分布在华南板块的南缘, 而南亚季风的覆盖面积相对广泛。这可能主要是因为东亚地区的边缘海打开时间明显要晚于南亚地区海陆分布出现的时间。但随着青藏高原在中新世整体隆升并接近现今的海拔高度, 亚洲季风全面进入增强阶段, 强烈影响区域内的地质演化过程。自中新世中期以来, 由于受控于青藏高原隆升、南北极冰盖的发育, 亚洲季风经历了多期次的稳定发展阶段。研究成果为科学合理利用季风开展亚洲系统地球科学研究提供了参考。

关键词: 亚洲季风; 东亚季风; 南亚季风; 青藏高原; 新生代

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0 引言

亚洲大陆的面积超过 $4400 \times 10^4 \text{ km}^2$, 是世界上面积最大的大洲, 同时濒临面积最大的大洋——太平洋, 是全球季风气候最显著的地区 (Clift and Plumb, 2008; An, 2014)。得益于季风气候带来的丰沛降水, 东亚、南亚和东南亚的农业得到高度发展, 亚洲成为世界上人口密度最大的区域。目前亚洲地区生活在季风区的人口总数超过 30 亿。这些人口主要以农业生产为主, 经常遭受由季风气候引发的洪涝、台风、干旱和寒潮等恶劣天气的影响 (刘东生等, 1998; 安芷生等, 2015)。此外, 亚洲季风的强降水容易诱发山洪、泥石流、滑坡和崩塌等次生灾害, 严重影响着区域内人类社会生产、居住的安全 (Yancheva et al., 2007; Turner and Annamalai, 2012; 郝青振等, 2016; Spicer et al., 2024)。因而认识亚洲季风的形成过程、发展规律至关重要。但目前关于南亚、东亚季风气候形成的时间, 仍然存在相互矛盾的证据。例如, 巴基斯坦北部植被从森林到草地的变化发生在中新世晚期 (8 Ma), 被认为是南亚季风形成的重要证据 (Quade et al., 1989)。而最近来自

阿拉伯海西部的季风环流带资料表明, 季风最早出现于中新世中期 (12 Ma; Gupta et al., 2015)。此外, 印度西北部的湖相沉积表明始新世早期 (55~52 Ma) 已经存在季风型气候 (Shukla et al., 2014)。在东亚地区, 中国黄土高原的黄土-古土壤序列表明冬季季风和夏季季风交替出现, 东亚季风被认为始于第四纪早期 (2.5 Ma; 刘东生等, 1998); 有研究者根据黄土下的风成红黏土沉积 (An et al., 2001), 将该时代推回至中新世晚期 (8 Ma)。随着中国新生代植被环境变化对比以及亚洲古环境格局的全面重建 (Guo et al., 2002; Qiang et al., 2011; Lu et al., 2023a; Lin et al., 2024a), 东亚季风的形成时间被认为是在渐新世晚期至中新世早期 (25~22 Ma)。但也有研究结果表明东亚季风性气候在始新世已经开始 (Dupont-Nivet et al., 2007; Fang et al., 2021; Su et al., 2022; Zheng et al., 2022)。有学者认为南亚季风的演化过程和青藏高原的隆升密切相关 (Shukla et al., 2014), 但最近的研究则表明南亚季风的演化过程与多种因素有关, 其中海陆分布和地貌因素最为重要 (Tardif et al., 2023)。在东亚季风演化研究中, 对于古近纪东亚地区中纬度地区出现的干湿交替变

化是否可以用于指示季风气候也存在较大争议(Guo et al., 2008; Su et al., 2022)。由于上述研究主要集中在某一地点,很难从宏观尺度上理解亚洲季风的起源和发育过程。亚洲的南亚和东亚季风从何时开始出现?具体的演化过程如何?这些问题至今没有清晰的答案。

因此,文章旨在阐述亚洲季风的内涵(组成部分),列举影响亚洲季风的形成、演化的主要因素,总结亚洲季风两个主要子系统南亚季风和东亚季风的研究进展,阐述亚洲关键地点的沉积记录显示的季风演化期次,力求从时空对比的角度呈现清晰的亚洲季风气候的发育过程,为科学合理利用其开展亚洲系统地球科学研究、预测亚洲季风的变化趋势提供参考。

1 亚洲季风的概念

季风的由来已久,最早阿拉伯人用“季风”这个词来表示印度洋,特别是阿拉伯海沿海地区地面风向的季节反转,但后来这一范围扩大到印度半岛、东南亚和东亚(林祥和钱维宏, 2012)。季风有两个主要特征:一是风向存在明显的季节反转;二是干、湿季或雨季迅速交替。大多数西方学者认为,早期的亚洲季风是热带的印度季风或南亚

季风,东亚夏季风只是印度季风向北和向东的延伸或扩展(丁一汇等, 2013)。1980年以后,亚洲夏季风应划分为南亚和东亚两个子系统的观念逐渐在国际上被接受(Ding and Chan, 2005)。

根据地理位置划分,亚洲存在两个季风子系统,即南亚季风与东亚季风,对应着亚洲季风中的热带季风系统和亚热带-温带季风系统(安芷生等, 2015; Fang et al., 2021)。由于太阳辐射的年循环,热带辐合带产生季节性移动,造成越赤道的气压梯度出现,导致热带季风形成;亚热带-温带季风的出现与亚热带高压的季节性移动和海陆分布密切相关。南亚季风主要影响印度半岛、中南半岛以及中国西南地区,其中以印度半岛最为典型(图1)。东亚季风的影响范围大致包括中国东部、朝鲜半岛、日本群岛等地区。中国位于南亚季风和东亚季风的交汇地带,因此同时受到这两个季风子系统的影响。

南亚和东亚季风系统既相互独立,又密切联系(Wang et al., 2003a; 陈际龙和黄荣辉, 2006),其形成过程为:北半球夏季亚洲地区盛行夏季风,澳大利亚北部盛行冬季风;澳大利亚高压北侧东南气流在索马里附近穿越赤道受地转偏向力影响转向成西南气流,与来自红海和波斯湾的气流在阿拉伯海汇合成强大的西南季风,经印度半岛、孟加拉湾、中南半岛流向东亚,给途径区域带去丰沛的降水(图2a)。

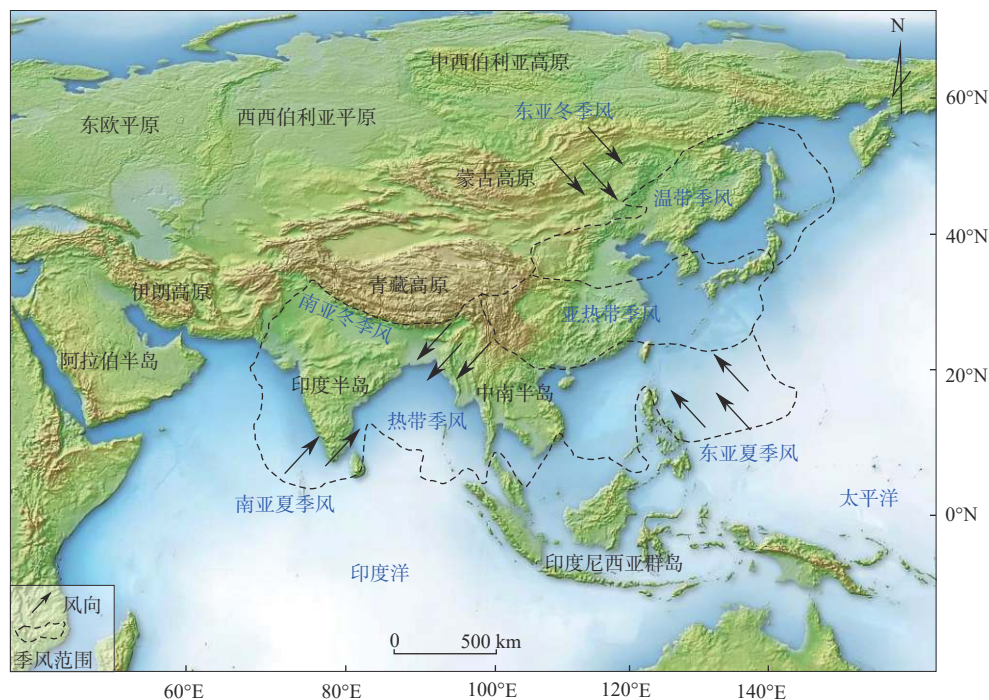
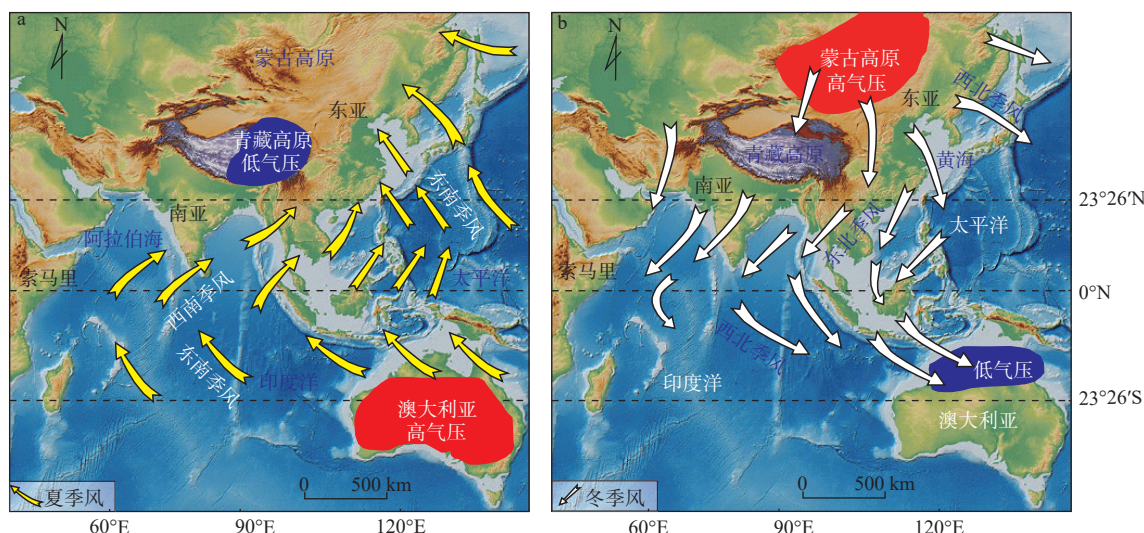


图1 亚洲季风组成分布图(据林旭等, 2023 修改)

Fig. 1 Composition distribution map of Asian monsoon (modified after Lin et al., 2023)

南半球夏季澳大利亚北部盛行夏季风, 亚洲地区盛行冬季风。由蒙古、西伯利亚等地寒潮爆发带来的强西北风自中国东北经黄海, 于北纬 25° 附近转向南下与热带西太平洋的偏东气流汇合经南海分为两支: 一支以东北气流南下在海洋地区越过赤道, 转向为南半球的热带西北夏季风, 并在南纬 15° 附

近与南半球的东南气流汇合组成南半球热带辐合带; 另一支以偏东气流西进经孟加拉湾, 与印度半岛和阿拉伯地区局地环流形成的东北气流合并, 在东非沿岸越赤道转向南下, 最终汇入南半球副高带北侧的偏东气流中(图 2b)。



a—亚洲夏季风形成过程图; b—亚洲冬季风形成过程图

图 2 亚洲季风形成图

Fig. 2 The formation map of Asian monsoon

(a) Map showing the formation process of the Asian summer monsoon; (b) Map showing the formation process of the Asian winter monsoon

2 新生代亚洲季风形成的主要因素

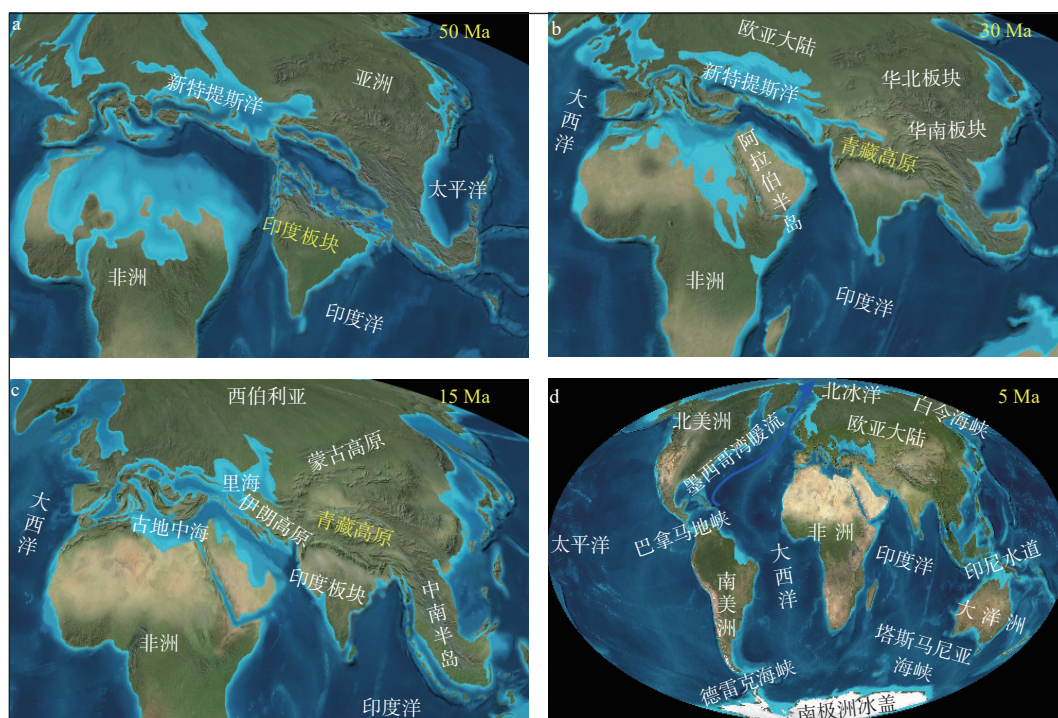
新生代亚洲季风的形成和发展除与全球海陆分布变化、青藏高原生长密切相关外, 还受全球冰量、海平面和大气 CO_2 浓度等气候因素的影响(Guo et al., 2008; Lu and Guo, 2014; Liu et al., 2019)。

2.1 新生代全球海陆格局演化

板块运动造成海道的开启或闭合将影响洋流的循环, 改变海洋/大气环流、热量和水汽的传输, 从而导致气候格局发生变化, 促进新生代气候变化(Raymo and Ruddiman, 1992; Wang, 2004)。在新生代早期, 印度板块与欧亚大陆碰撞的远程效应引起青藏高原北部塔里木盆地周缘古生代和中生代构造带再次活化(图 3a)。随着构造活动的持续进行和全球海平面下降, 塔里木盆地在始新世和渐新世之交(34 Ma)最终结束海洋沉积环境(林旭等, 2019a; Wang et al., 2020; 图 3b)。阿拉伯板块、非洲板块与欧亚板块会聚、碰撞, 进一步加速了新特提斯洋向

西退却(McQuarrie et al., 2003)。在中新世中期时(17~13 Ma), 海水从伊朗高原北部退出(Sun et al., 2021; 图 3c), 并在中新世晚期—上新世(7~5 Ma)残退形成古地中海(Hsü et al., 1973), 从而彻底改变了中亚地区的海陆分布格局, 增加了亚洲大陆的裸露面积, 增强了亚洲大陆与周缘大洋的海陆热力学差异(图 3d)。

此外, 塔斯马尼亚海峡、德雷克海峡和白令海峡的开启(图 3d), 巴拿马海峡和印尼水道的闭合等改变了全球性大洋环流模式, 进而通过水汽传输变化影响全球气候(Livermore et al., 2007; Straume et al., 2020; Bahr et al., 2023)。在 34 Ma 前后, 南极绕极环流的形成与塔斯马尼亚和德雷克海峡的开启密切相关(Lawver and Gahagan, 2003), 导致南半球低纬向南极输送的热量降低了 15%~20%, 由此造成南极大陆的热隔绝, 促使南极冰盖的大面积形成, 全球气候系统由温暖期转为寒冷期(裴军令等, 2021)。白令海峡在约 5 Ma 开启后, 北太平洋的海水通过海峡进入北冰洋, 加强了北太平洋—北冰洋—北大西



a—始新世; b—渐新世; c—中新世; d—上新世

图3 新生代亚洲海陆分布图

Fig. 3 Cenozoic marine and land distribution map in Asia

(a) Eocene; (b) Oligocene; (c) Miocene; (d) Pliocene

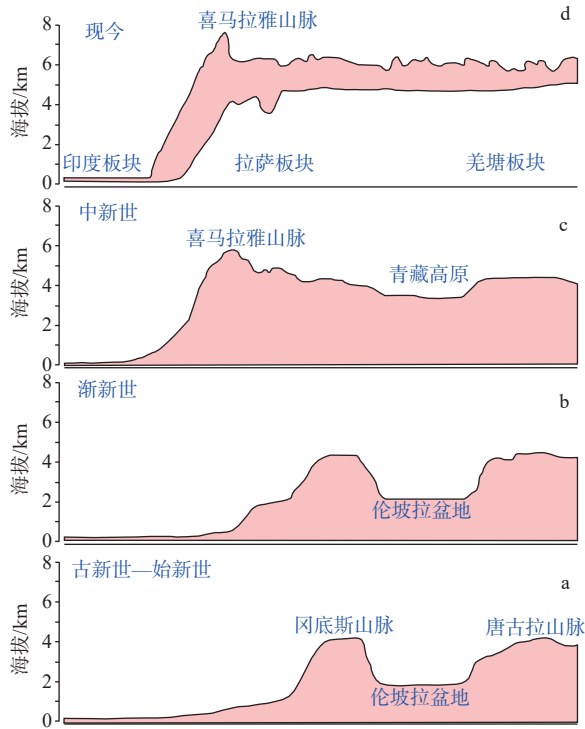
洋之间的海水交换 (Gladenkov et al., 2002)。北太平洋海水相较于北大西洋海水盐度低, 北太平洋海水流入北冰洋后, 有效地降低了北冰洋海水的盐度, 提高了海水冰点 (Knies et al., 2014); 当北太平洋海水进入北大西洋后, 造成大西洋径向环流减弱, 从根本上改变了大西洋径向环流的稳定性, 导致变冷事件的发生, 促进了北极冰盖的形成 (Naafs et al., 2010)。巴拿马海峡在上新世晚期之前曾是太平洋和大西洋的关键连通水道, 其在 3 Ma 的关闭切断了赤道太平洋和大西洋海水的交换, 造成了洋流的重大改组, 促使太平洋和大西洋现代环流模式的形成 (Keigwin, 1978; Bahr et al., 2023)。巴拿马海道关闭后使大西洋一侧的墨西哥湾暖流增强 (O'Dea et al., 2016), 为沿途的北大西洋带来了充足的水汽, 在西风的影响下导致西伯利亚河流径流量增加, 造成北冰洋淡水输入增多, 促进北冰洋形成海冰和气候变冷 (Alekseev and Drouchits, 2004; Ma et al., 2021)。印尼海峡是连接太平洋和印度洋的重要海道之一, 目前仍处于未完全关闭的状态。澳大利亚板块于 10 Ma 开始向北俯冲, 使印尼海道逐渐关闭, 改变了西太平洋和东印度洋之间的洋流体系 (Hall et al.,

2009)。在上新世时期, 作为西太平洋暖池和东印度洋暖池的连接纽带, 印尼海道的贯穿水体由高温高盐的南赤道水团转变为低温低盐的北赤道水团 (Karas et al., 2017)。印尼海道的关闭不仅造成印度洋变冷以及非洲干旱化 (Cane et al., 2001), 还降低了对北半球高纬地区的热输送, 导致西太平洋暖池逐渐强化 (Gallagher and Molnar, 2009), 造成北半球低纬地区和极地之间的温差变大, 驱动亚洲季风的增强 (Srinivasan and Sinha, 1998)。

2.2 新生代青藏高原隆升

新生代早期印度板块与亚洲大陆碰撞, 导致青藏高原开始隆升, 其持续的会聚作用伴随着高原向北和向东生长及中部和南部地区大幅抬升的复杂过程, 最终形成了地势高耸的青藏高原 (Liu-Zeng et al., 2008; Wang et al., 2014; Lin et al., 2021; Lu et al., 2023a)。这是新生代时期全球最为重要的地质事件之一, 对亚洲乃至全球的气候都有着深远影响 (Li et al., 2014; Miao et al., 2022; Wu et al., 2022)。Rowley and Currie (2006) 通过对青藏高原中部伦坡拉盆地的牛堡组、丁青组的湖泊与古土壤钙结核碳酸盐氧同位素组成的研究, 利用瑞利分馏模型的氧同位素高

度效应,提出高原中部在始新世晚期(35 Ma)已达到与现今类似高度(4600~4800 m)。但来自伦坡拉盆地的后续研究发现,无论是古脊椎动物古生态重建(Deng et al., 2019),还是孢粉化石组合古高度重建均认为其渐新世晚期—中新世早期的高度不超过 3000 m(Sun et al., 2014)。近期,Spicer et al.(2020)汇总数值模拟、同位素分析以及古生物证据重建了青藏高原古海拔,研究结果认为青藏高原的高度在新近纪逐渐建立。最新的地质学和古生物学证据表明,在新生代早期,青藏高原中部存在着一条东西走向的低谷(Su et al., 2019, 2020; 图 4a、4b),其南面和北面分别是冈底斯山脉和中央分水岭山脉(Ding et al., 2022),由于南亚季风带来的暖湿气团越过冈底斯山脉,于是在低谷中孕育热带、亚热带性质的动植物区系。在 40~30 Ma,以伦坡拉盆地为代表的中央低谷已经发生了强烈抬升(Ding et al., 2022)。中央低谷经历南北向的挤压变形而不断变窄,在新近纪被进一步挤压填充,逐渐达到现在的高度(Ding et al., 2022; Xiong et al., 2022; 图 4c、4d)。



a—古新世—始新世; b—渐新世; c—中新世; d—现今

图 4 新生代青藏高原演化过程图(据 Su et al., 2019 修改)

Fig. 4 Cenozoic evolutionary process diagram of the Tibetan Plateau (modified after Su et al., 2019)

(a) Paleocene-Eocene; (b) Oligocene; (c) Miocene; (d) Present day

从构造变形、岩浆作用、沉积盆地特征及剥蚀演化过程来看,青藏高原中新世以来整体快速隆升的阶段出现在: 26~20 Ma、16~14 Ma、10~7 Ma、4.5~2.6 Ma、1.6~1.0 Ma、0.7 Ma 和 0.15 Ma。在 26~20 Ma, 印度板块向欧亚大陆俯冲的岩石圈地幔发生拆沉作用, 不仅导致喜马拉雅及冈底斯山体的强烈隆升(Ding et al., 2017; Lu et al., 2018), 还使整个高原向东、向北生长(林旭等, 2017; Wang et al., 2017; Lin et al., 2019), 并伴随着强烈的岩浆侵入和火山喷溢作用(Chung et al., 1998)。在 16~7 Ma, 青藏高原向东及东北继续生长, 其分布范围和海拔已基本接近现在(Yan et al., 2006; Zheng et al., 2006; Tian et al., 2015; Liu-Zeng et al., 2018)。自上新世(4.5~2.6 Ma)以来, 青藏高原北部和东部的边缘地带继续生长和隆升, 除塔里木盆地、柴达木盆地等几个大型盆地外, 大部分地区处在隆起剥蚀区(Li et al., 2014)。

2.3 新生代全球气候变化

全球有孔虫氧同位素记录大致将新生代气候演化分为 3 个阶段(Zachos et al., 2001; 图 5a)。

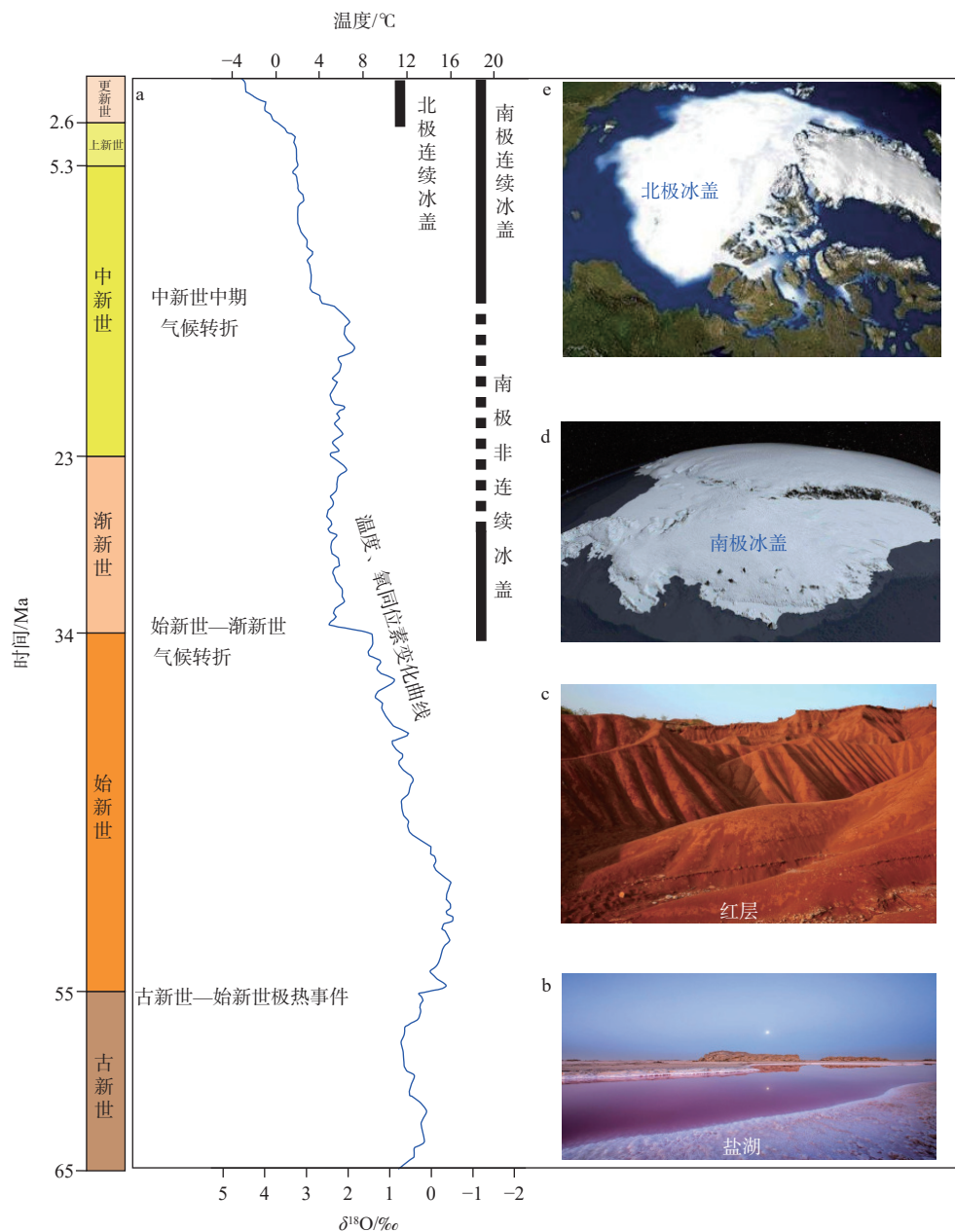
(1) 古新世—始新世两极无冰期

在始新世早期之前, 地球表层的气温比现在高出近 10 °C, 全球植被以常绿和落叶森林为主。在始新世与古新世之交(55 Ma)发生了全球性气候变暖事件, 深海碳氧同位素组成均急剧负偏(降幅约 1.0‰), 导致中国出现大面积盐湖沉积(Sun and Wang, 2005; 图 5b)。约 53~50 Ma 是新生代最为温暖的一段时期, 气温比现在高约 12 °C, 被称为始新世早期气候适宜期, 此时厚层红色地层在中国华南和华北广泛分布(Guo et al., 2008; 图 5c)。进入始新世晚期之后, 深海有孔虫 $\delta^{18}\text{O}$ 值开始增加, 全球温度显著降低, 南极开始发育非永久性冰盖(Ehrmann and Mackensen, 1992)。

(2) 渐新世—中新世中期南极冰盖增长期

在 34 Ma 左右, 深海有孔虫 $\delta^{18}\text{O}$ 突然增加了近 1‰, 指示全球气候急剧变冷, 而南极的冰筏碎屑沉积、黏土矿物组成及化石记录, 则更为直接地表明此时南极大陆永久冰盖的增长(Wilson et al., 2013; 图 5d)。从始新世晚期(34 Ma)到中新世中期(14 Ma), 深海有孔虫 $\delta^{18}\text{O}$ 总体稳中有降, 其中在 17~15 Ma 时全球温度比现今高出近 8 °C, 为中新世中期气候适宜期。

(3) 中新世晚期—第四纪两极冰盖扩张期



a—新生代全球深海氧同位素曲线(据 Zachos et al., 2001 修改); b—古新世干旱气候下形成的盐湖; c—始新世干燥气候形成的红层; d—中新世连续性南极冰盖出现; e—上新世晚期—更新世连续性北极冰盖出现

图 5 新生代气候变化特征

Fig. 5 Characteristics of Cenozoic climate change

(a) Cenozoic global deep-sea oxygen isotope curve (modified after Zachos et al., 2001); (b) Salt lakes formed in the arid climate of the Paleocene; (c) The red layer formed in the dry climate of the Eocene; (d) The emergence of a continuous Antarctic ice sheet during the Miocene; (e) The late Pliocene-Pleistocene continuous Arctic ice sheet appeared

中新世中期之后,深海有孔虫 $\delta^{18}\text{O}$ 呈急剧增加趋势,代表了南极冰盖的增长和全球降温。到大约 3 Ma,由于北极冰盖开始显著扩张(Duk-Rodkin et al., 2004; Clotten et al., 2019; 图 5e),地球进入两极有冰的时期。新生代全球气候从两极无冰到单极有冰,再到双极有冰的转变,增强了两极与周围大洋的

温度差异,为亚洲季风的出现提供了大的气候背景条件。

3 新生代亚洲季风发育过程

青藏高原在新生代的形成以及横向和垂向生

长,改变了原先亚洲中低纬地区的纬向气候环流,影响了大气环流模式(Wu et al., 2022),同时使高原在夏季和冬季分别作为热源、冷源存在,加强了与周缘大洋的海陆热力学差异,有利于季风性气候的形成(Lu et al., 2023a)。同时,阻挡源于印度洋和太平洋的暖湿气流向亚洲内陆的输送,并在高原北侧形成下沉气流,影响亚洲内陆干旱化过程(Barbolini et al., 2020),并反过来进一步增强与周缘大洋的海陆热力学差异,导致原有季风区的季风强度加强。国内外地学工作者在南亚和东亚的陆上和海洋的沉积盆地中开展叶片、孢粉、同位素地球化学分析,同时运用数值模拟结果,结合地层的沉积时代重建新生代南亚和东亚季风的演化过程。

3.1 新生代南亚季风的发育

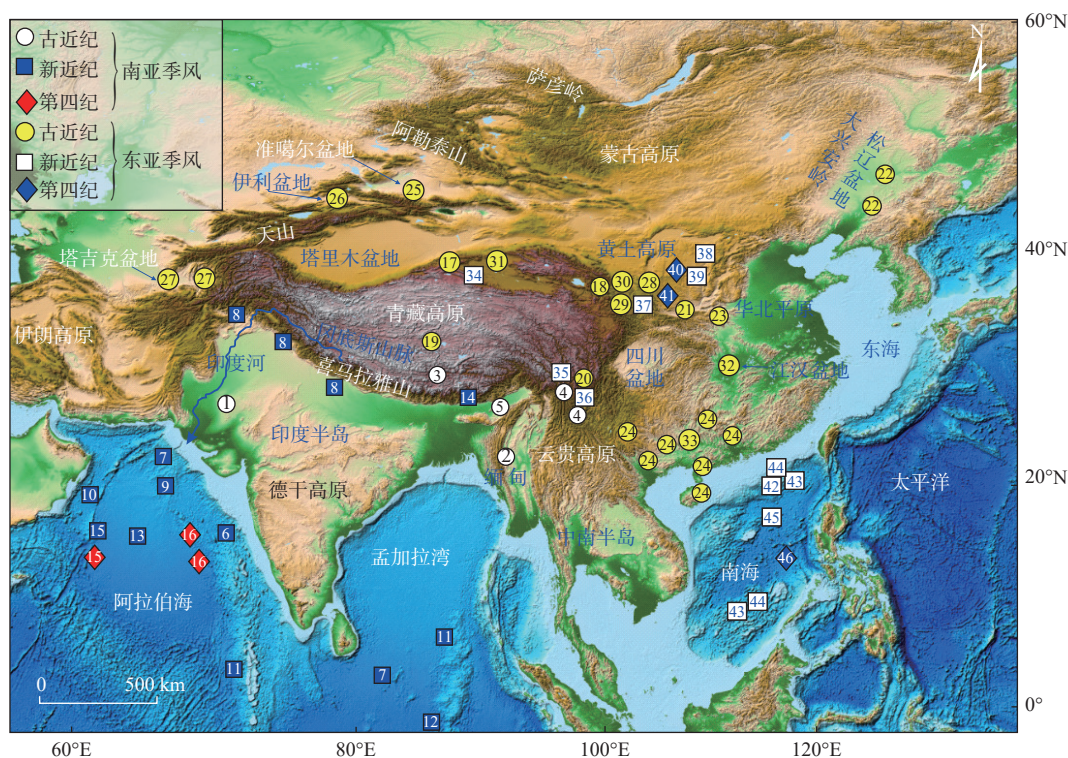
印度热带地区发现的始新世早期(55~52 Ma)植物化石显示出该地区的气温和降水都具有明显的季节变化(Shukla et al., 2014; Bhatia et al., 2021; 图 6①);缅甸始新世(55~34 Ma)腹足类化石和哺乳动物化石的氧同位素以及孢粉化石随着季节发生规律性变化(Licht et al., 2014; Huang et al., 2023; 图 6②);青藏高原冈底斯山脉始新统地层的动植物化石氧同位素呈现出的季节性变化(Ding et al., 2017; 图 6③);岩相学、孢粉学、碳酸盐和腹足类碳氧同位素结果共同表明,横断山脉地区在始新世(41 Ma)受到南亚季风的影响(Fang et al., 2021; 图 6④)。古印度河在始新世已经开始发育,这主要得益于其北部源头青藏高原的隆升和印度半岛出现的季风气候(Lu et al., 2023b; Najman et al., 2023)。印度板块漂移速率的急剧下降和俯冲型洋壳熔融岩浆活动的结束,可能指示印度板块与亚洲板块的全面碰撞,加上阿拉伯板块与亚洲大陆南缘发生碰撞(Sun et al., 2023a),导致中亚新特提斯洋急剧向西后退、青藏高原南界快速北移和中部唐古拉山地区快速抬升,耦合全球海平面快速下降,共同导致了亚洲陆地面积急速扩大,强化了海陆热力对比,从而可能导致热带印度季风在始新世晚期稳定存在(Fluteau et al., 1999; Spicer et al., 2016; Tada et al., 2016),这与气候模拟结果一致(Liu et al., 2017; Tardif et al., 2023)。

印度半岛东北部的植物叶片化石古温度重建结果表明,类似现今的南亚季风气候在渐新世晚期增强,导致区域内出现明显的干—湿季节交替(Srivastava et al., 2012; 图 6⑤)。在阿拉伯海东部钻孔渐新统一下中新统地层的地球化学和沉积学结

果表明,喜马拉雅山脉输入的陆源碎屑物质在 23 Ma 显著增加,Beasley et al.(2021)将其归结为南亚季风增强所致(图 6⑥)。阿拉伯海和孟加拉湾的地层沉积记录表明,喜马拉雅山脉在 23~15 Ma 侵蚀加剧(Clift et al., 2008; 图 6⑦),表明喜马拉雅山脉的剥蚀过程与中新世南亚季风增强之间存在相关性(Ding et al., 2017; Retallack et al., 2018)。

喜马拉雅山脉前陆盆地保存的西瓦里克组沉积序列是重建南亚季风在中新世晚期至更新世晚期演化过程的重要载体。大量的代用指标记录显示南亚季风存在多个增强阶段,分别出现在 10 Ma、5.5 Ma 和 3 Ma,季风强度随后下降到与现代相似的水平(Sanyal and Sinha, 2010; 图 6⑧)。中新世中期是印度河冲积扇沉积速率最快的时期,可能反映了南亚季风的加强导致源区喜马拉雅山脉地表快速剥蚀(Clift et al., 2002; 图 6⑨)。阿拉伯海西部海洋钻孔中总有机碳含量的增加,以及底栖有孔虫碳氧同位素显著负偏,都指示现今南亚季风系统在中新世晚期(13~7 Ma)处于增强阶段(Gupta et al., 2015; 图 6⑩)。孟加拉湾深海钻孔沉积物的年代测定结合有孔虫碳氧同位素以及地球化学分析结果表明,南亚季风在 15~13 Ma(Betzler et al., 2016; Bretschneider et al., 2021; 图 6⑪)和 10~8 Ma 突然增强(Gupta et al., 2004; 图 6⑫)。气候实验模拟结果揭示,在轨道参数、构造因素、冰川活动和大气 CO₂ 浓度变化 4 个主要影响因素中,南亚季风对构造因素的响应最直接,青藏高原在中新世晚期(8 Ma)的快速隆升导致类似现今南亚季风的出现(Prell and Kutzbach, 1992),这也进一步得到阿拉伯海沉积钻孔中地球化学和古生物化石(Tripathi et al., 2017; 图 6⑬)和喜马拉雅山前西瓦里克组植物叶片化石等结果的印证(Khan et al., 2019; 图 6⑭)。

阿拉伯海东部钻孔黏土矿物的微量元素和 Sr-Nd 同位素和粒度数据结果表明,当印度夏季风增强时(3.3~2.7 Ma 和 1.2~0 Ma),来自德干高原的硅屑沉积物供应增加,物源变化与印度夏季风强度的变化相关联(Cai et al., 2020; 图 6⑮)。随后 Lu et al.(2020)对阿拉伯海东部的深海沉积钻孔开展了全岩 Sr-Nd 同位素和碎屑锆石 U-Pb 年龄物源示踪,以及赤铁矿含量和粒度分析,发现钻孔中的物质主要来自青藏高原南部和德干高原,南亚季风降水量在 3.4~2.4 Ma 期间较低,在 1.8~1.1 Ma 南亚季风降雨增加,在 1.1~0.1 Ma 南亚季风降雨减少(图 6⑯)。



①Shukla et al.(2014), Bhatia et al.(2021); ②Licht et al.(2014), Huang et al.(2023); ③Ding et al.(2017); ④Fang et al.(2021); ⑤Srivastava et al.(2012); ⑥Beasley et al.(2021); ⑦Clift et al.(2008); ⑧Sanyal and Sinha(2010); ⑨Clift et al.(2002); ⑩Gupta et al.(2015); ⑪Betzler et al.(2016), Bretschneider et al.(2021); ⑫Gupta et al.(2004); ⑬Tripathi et al.(2017); ⑭Khan et al.(2019); ⑮Cai et al.(2020); ⑯Lu et al.(2020); ⑰Li et al.(2018a); ⑱Dupont-Nivet et al.(2007), Licht et al.(2014); ⑲Su et al.(2020); ⑳Sorrel et al.(2017), Zheng et al.(2022), Yuan et al.(2024); ㉑Lyu et al.(2021); ㉒Quan et al.(2011), Meng et al.(2018a); ㉓Su et al.(2022); ㉔Xie et al.(2020b); ㉕Sun et al.(2010); ㉖Hellwig et al.(2018); ㉗Wang et al.(2020); ㉘Lin et al.(2015); ㉙Wu et al.(2017); ㉚Miao et al.(2013); ㉛Yan et al.(2018); ㉜Huang and Hinnov(2019); ㉝Ren et al.(2021), Vormlocher et al.(2021); ㉞Miao et al.(2011); ㉟Jacques et al.(2011); ㊱Li et al.(2019); ㊲Guo et al.(2002); ㊳An et al.(2001); ㊴Ao et al.(2016); ㊵Meng et al.(2018b); ㊶Song et al.(2013); ㊷Jia et al.(2003), Ding et al.(2021); ㊸Wan et al.(2007); ㊹Chen et al.(2003), Holbourn et al.(2021); ㊺Wang et al.(2003b), Zheng et al.(2004); ㊻Wang et al.(2003b); Gai et al.(2020)

图6 亚洲季风研究结果位置分布图

Fig. 6 Location distribution of research results of the Asian monsoon

有关南亚季风的起源时间,陆地的植物叶片大化石的研究结果和地球化学元素、气候模拟结果大致吻合,即在始新世已经稳定存在,从印度半岛向东经过缅甸,一直延伸到横断山脉的西侧,和南亚季风现今的分布范围已经十分接近。除了前文分析的原因以外,印度半岛与印度洋的陆-海分布关系确立较早也是重要的驱动因素,确保了向印度半岛内部稳定输入湿润气团(Tardif et al., 2023)。进入新近纪,随着青藏高原的整体隆升和全球降温,南亚季风出现阶段性增强(Sarr et al., 2022)。印度半岛的陆地剖面记录的时间明显早于其周围海洋的沉积记录,一方面原因是叶片大化石等直观的沉积记录很难在动荡的海洋环境中保存,另一方面研究者采用的来自阿拉伯海、孟加拉湾的钻孔深度有

限。因而,在今后的研究过程中,需要加强深海钻孔的研究力度,从而实现海-陆交互检验,建立更加详细的南亚季风演化过程。

3.2 新生代东亚季风的发育

青藏高原北部索尔库里盆地存在沉积连续的始新世(51~39 Ma)风成沉积物,指示东亚季风气候在此期间出现,这与全球整体降温过程相关,而不是青藏高原隆升所致(Li et al., 2018a; 图6⑰)。西宁盆地记录亚洲内陆在40~34 Ma出现明显干旱化,这可能指示青藏高原隆升、副特提斯海后退、东亚季风的强弱变化是导致这次干旱事件出现的因素之一(Dupont-Nivet et al., 2007; Licht et al., 2014; 图6⑱)。化石分析结果表明西藏中部始新世中期(47 Ma)属于湿润的亚热带生态系统,经历了明显

的季风气候(Su et al., 2020; 图 6¹⁹)。但是 Fang et al. (2022)在青藏高原东南部的囊谦盆地的分析结合模拟结果,认为亚洲夏季风直到 35 Ma 才影响该地区,在此之前的始新世早—中期主要受西风带影响。青藏高原东南部剑川盆地的沉积学结果说明在 36 Ma 时季风性气候特征较为显著(Sorrel et al., 2017; Zheng et al., 2022; Yuan et al., 2024; 图 6²⁰), Fang et al. (2021)的研究将这一时间提前至 41 Ma, 但认为主要受南亚季风的影响。剑川盆地的位置处于东亚季风和南亚季风的交汇地带(Tardif et al., 2023), 尽管对于该地区出现季风气候的时间存在一定争议,但是说明季风气候在始新世晚期已经出现在云贵高原。

渭河盆地新生代河湖相地层黏土矿物含量结果表明,随着新生代全球气温的下降和沉积物不断堆积,盆地化学风化强度逐渐减弱,东亚季风气候逐渐形成,这是对始新世—渐新世过渡时期全球变冷事件的响应(Lyu et al., 2021; 图 6²¹)。东北平原多个剖面的叶片化石数据结果表明,东亚季风在 41~40 Ma 已经出现,这主要归结为大兴安岭以及青藏高原的隆升作用(Quan et al., 2011; Meng et al., 2018a; 图 6²²)。豫西潭头盆地古新世晚期至始新世早期孢粉组合的分析结果表明,该地区在此阶段出现针阔叶混交林,年降水量不低于 800 mm,气候经历了从温暖湿润到相对凉爽干燥的变化,表现出季风气候的特征(Su et al., 2022; 图 6²³)。华南地区的百色、南宁和茂名等 7 个盆地的古近系孢粉记录,揭示中始新世东亚季风对区域内生态系统的影响(Xie et al., 2020b; 图 6²⁴)。气候模拟结果表明,始新世时青藏高原的隆升高度对亚洲季风的影响相对较弱(Huber and Goldner, 2012; Tardif et al., 2023)。气候模拟结果揭示中国西部始新世早期出现纬向/带状干旱沙漠/草原气候带,但由于始新世晚期西太平洋副热带高压向西扩张,中国东部降水增加;新特提斯洋向西退却(Sun et al., 2023b)、蒙古高原、天山和帕米尔高原的隆升阻挡了西风带的湿润气流(Tardif et al., 2023),西北内陆开始发育风成沉积物(Sun and Windley, 2015),其纬向气候带很可能在始新世晚期消失(Li et al., 2018b)。

准噶尔盆地(Sun et al., 2010; 图 6²⁵)、伊利盆地(Hellwig et al., 2018; 图 6²⁶)和塔吉克盆地(Wang et al., 2020; 图 6²⁷)的研究结果表明,风成沉积物和干旱化过程形成于 25~24 Ma, 中亚地区至少自渐新

世晚期普遍存在与现在相似的气候模式。六盘山寺口子剖面渐新世至中新世沉积地层记录区域古气候在中新世早期从干旱向湿润转变,这主要归因于东亚夏季风的影响(Lin et al., 2015; 图 6²⁸)。临夏盆地地层记录东亚季风可能始于 26.5 Ma(Wu et al., 2017; 图 6²⁹)。兰州盆地的孢粉谱结果表明,东亚季风在渐新世早期的晚期出现在盆地地区,从而达到现代亚洲夏季风的西部边界(Miao et al., 2013; 图 6³⁰)。柴达木盆地新生代地层的植物化石说明,东亚季风在渐新世对盆地内的生物环境塑造起重要作用(Yan et al., 2018; 图 6³¹)。江汉盆地潜江组和荆河镇组的沉积记录表明,盆地自渐新世早期(34 Ma)出现东亚夏季风增强和西北冬季风减弱的现象,响应青藏高原的隆升(Huang and Hinnov, 2019; 图 6³²)。广西南宁盆地的化石氧同位素分析结果支持东亚季风在渐新世晚期出现,当时的降水量要比现今该地区更加丰富(Ren et al., 2021; Vornlocher et al., 2021; 图 6³³)。

柴达木盆地在中新世中期气候最适期(18~14 Ma)以后旱生植物类群百分比逐渐增加,针叶树类群百分比逐渐减少,指示东亚冬季风逐渐增强和东亚夏季风减弱共同推动了柴达木地区的干旱化过程(Miao et al., 2011; 图 6³⁴)。云南临沧盆地新近纪地层中的叶片化石记录了青藏高原东南缘在中新世晚期已经存在季风环境(Jacques et al., 2011; 图 6³⁵)。青藏高原东南缘昭通盆地的黏土矿物含量结果表明,在 8.8 Ma 时气候相对温暖湿润,6.2~2.8 Ma 的气候相对凉爽和潮湿,2.8~2.6 Ma 气候相对寒冷湿润,体现了亚洲季风的阶段性变化(Li et al., 2019; 图 6³⁶)。

黄土高原的风尘沉积(新近纪红黏土和第四纪黄土)因其沉积连续性好、年代准确且分布范围广而成为研究东亚季风演化的宝贵材料。黄土高原西部的秦安剖面记录的亚洲季风在早中新世(22 Ma)已经稳定出现(Guo et al., 2002; 图 6³⁷),在黄土高原中部出现的时间集中在中新世晚期(10~7 Ma; An et al., 2001; 图 6³⁸)、上新世(4.2~2.6 Ma; Ao et al., 2016; 图 6³⁹)和更新世早期(2.2~1.7 Ma; Meng et al., 2018b; 图 6⁴⁰)、更新世中期(1.2~0.6 Ma, Song et al., 2014; 图 6⁴¹)。

南海盆地在中生代—新生代经历了裂前、裂谷、沉降和断块升降 4 个阶段,是西太平洋陆缘海的重要组成部分,沉积了巨厚的陆源碎屑沉积物,

同时处于东亚大陆和西太平洋的交汇位置,对东亚季风的演化反映灵敏且详细(Wang and Li, 2009)。从现在已经报道的深海钻孔数据结果来看,东亚季风处于阶段性演化的时间节点集中在 25~22 Ma (Jia et al., 2003; Ding et al., 2021; 图 6④), 20~15 Ma (Wan et al., 2007; 图 6④), 12~8 Ma (Chen et al., 2003; Holbourn et al., 2021; 图 6④)、3.6~3 Ma (Wang et al., 2003b; Zheng et al., 2004; 图 6④)和 0.6~0.4 Ma (Wang et al., 2003b; Gai et al., 2020; 图 6④)。

东亚地区从东北平原、渭河盆地到青藏高原北部的索尔库里盆地的高纬地区,在新生代早期出现的纬向湿润带;在华中地区和青藏高原内部的中纬地区存在干旱、半干旱带(Guo et al., 2008)。气候模拟结果显示当时东亚地区的风和降水季节变化仍然较弱(Liu et al., 2019),这与现代季风气候的特点明显不同。东亚季风气候在始新世的起源时间与南亚季风具有同步性,但是局限于低纬度地区,并未向东亚内陆深入,这可能和东亚大陆边缘海(南海、日本海和鄂霍次克海)打开的时间较晚有关(Wang, 2004)。而东亚季风真正出现的标志是东亚

内陆中纬度地区结束新生代早期以西风带为水汽来源,随即转变为受东亚冬季风控制出现干旱、半干旱带,而东亚沿海从低纬度到高纬度地区出现以风向季节性稳定改变和丰沛的夏季降雨为特征的季风气候。由于南海完全打开的时间在渐新世,加上渤海、黄海和东海都是陆架海,因而来自海洋记录的东亚季风起源时间和东亚陆地的沉积记录相比明显滞后。但自渐新世以来,东亚地区的陆地剖面 and 海洋(南海)钻孔记录的东亚季风演化时间具有空间同步性。

4 亚洲季风演化阶段

新生代早期,随着印度板块与亚洲大陆南缘发生碰撞,改变了亚洲的海陆分布,导致青藏高原发生初始隆升,南亚和东亚均出现了季风性气候(图 7)。随着印度和阿拉伯板块持续向北俯冲,导致新特提斯洋向西退却,青藏高原持续隆升,结合全球其他区域的海峡打开导致的气候变化,南亚季风和东亚季风逐渐增强,但此时的东亚地区依然主要受控于

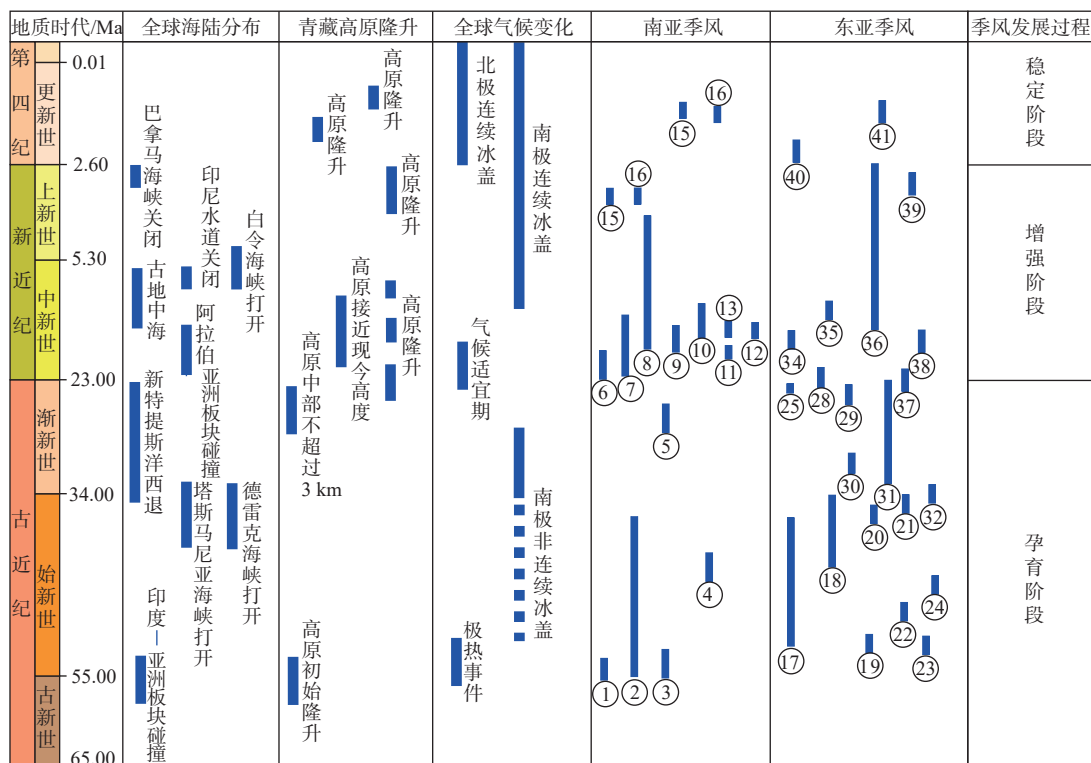
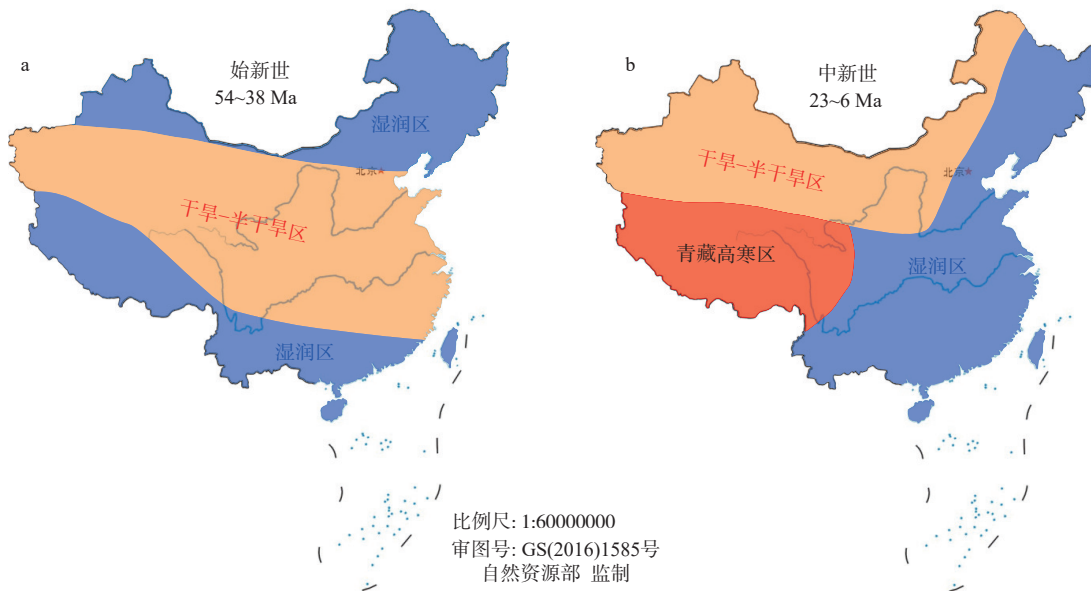


图 7 新生代南亚和东亚季风演化过程与全球海陆分布、青藏高原隆升和全球气候变化的对应关系(图中数字与图 6 的位置一一对应,蓝色矩形框的长度代表时间跨度)

Fig. 7 Correspondence between the evolution of the Cenozoic South Asian and East Asian monsoons and the global land-sea distribution, the uplift of the Tibetan Plateau, and global climate change (The numbers in the figure correspond to the positions in Figure 6; the length of the blue rectangular box represents the time)

行星风系(Guo et al., 2008)。在其北部中纬度地区,盛行西风从新特提斯洋带来了丰沛的降水,导致区域内出现湿润气候(Sun and Wang, 2005; 图 8a)。而在华中地区,受控于副热带高压下沉气流和沿海山脉引起的雨影效应的综合作用的控制,出现干旱、

半干旱的气候(Xie et al., 2020a)。南亚季风此时的影响范围可能比东亚季风更大,后者仅呈条带状局限分布于华南板块南缘的低纬度地区。此时的东亚季风无论分布区域和气候特征都表明其处于孕育发展阶段。



a—始新世气候格局分布图; b—中新世气候格局分布图

图 8 新生代东亚气候演变过程图(据 Guo et al., 2008 修改)

Fig. 8 Climate evolution in East Asia during the Cenozoic era (modified after Guo et al., 2008)

(a) Eocene climate pattern distribution map; (b) Miocene climate pattern distribution map

到了中新世早期,随着新特提斯洋退至欧洲,增加了亚洲大陆的面积,此时青藏高原处于强烈隆升阶段,其整体平均海拔已经接近现代。因而导致南亚季风和东亚季风在这一时期处于增强阶段,驱动印度河、雅鲁藏布江、澜沧江和长江等大河的演化(Zheng et al., 2013; Nie et al., 2018; Lu et al., 2023b; 林旭等, 2023),因而阿拉伯海、孟加拉湾、南海、东海的碎屑物质输入量急剧增加(Métivier et al., 1999; Clift et al., 2004; Song et al., 2023)。东亚地区古近纪受控于行星风系的气候特征在古近纪晚期—新近纪早期被打破(Sun and Windley, 2015),中国西北内陆由先前的湿润气候转变为干旱、半干旱气候(Sun et al., 2010),青藏高原出现高寒气候,而中国东部主要受控于季风气候(Guo et al., 2002)。迄今从时间和空间角度获取的各类证据基本可以确定,中国的气候格局至少在中新世中期已经形成(图 8b)。

自中新世中期以来,受控于南极和北极连续性冰盖形成的影响,加上全球关键地点的海峡和水道

的关闭,以及青藏高原阶段性的隆升,南亚季风和东亚季风在中新世晚期、上新世和更新世又出现了几期增强过程(刘东生等, 1998),导致发源于青藏高原的大河稳定出现(Zheng et al., 2013; Nie et al., 2018; Lin et al., 2024b),紧靠青藏高原的海上和陆上盆地又出现沉积物粒度变粗、沉积速率加快的现象(Li et al., 2014),这都说明亚洲季风已经进入稳定阶段(Wu et al., 2022; Lu et al., 2023a),深刻塑造了途径区域的地质、地貌。

5 结论

亚洲季风的两个子系统南亚季风和东亚季风的出现与东亚和南亚的海陆分布、亚洲地貌演化过程、全球气候变化等构造和气候活动紧密相关。在古近纪,东亚季风处于孕育形成阶段,而南亚季风的发育则相对成熟。但随着青藏高原在中新世的整体隆升并接近现今的海拔高度,南亚季风和东亚

季风进入增强阶段,强烈影响了区域内的地貌演化过程。自中新世中期以来,受控于青藏高原隆升、南北极冰盖的发育,亚洲季风经历了多期次的波动稳定发展阶段。在纵向时间上,南亚季风和东亚季风的发展过程相似,均主要经历了古近纪的孕育阶段、新近纪的增强阶段和第四纪的稳定阶段。在横向空间分布上,南亚季风和东亚季风的发展同步。未来有关亚洲季风研究的主要焦点应关注印度洋的海洋沉积记录与南亚陆地剖面的时空对比,实现海-陆相互检验。加强南亚季风和东亚季风的演化的对比研究,从而深入理解自新生代以来南亚和东亚地区的海陆分布、青藏高原隆升和全球气候变化对区域气候变化的影响。

References

- ALEKSEEV M N, DROUCHITS V A, 2004. Quaternary fluvial sediments in the Russian arctic and subarctic: late Cenozoic development of the Lena River system, northeastern Siberia[J]. *Proceedings of the Geologists' Association*, 115(4): 339-346.
- AN Z S, KUTZBACH J E, PRELL W L, et al., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan Plateau since Late Miocene times[J]. *Nature*, 411(6833): 62-66.
- AN Z S, 2014. Late Cenozoic climate change in Asia: loess, monsoon and monsoon-arid environment evolution[M]. Dordrecht: Springer.
- AN Z S, WU G X, LI J P, et al., 2015. Global monsoon dynamics and climate change[J]. *Journal of Earth Environment*, 6(6): 341-381. (in Chinese with English abstract)
- AO H, ROBERTS A P, DEKKERS M J, et al., 2016. Late Miocene-Pliocene Asian monsoon intensification linked to Antarctic ice-sheet growth[J]. *Earth and Planetary Science Letters*, 444: 75-87.
- BAHR A, KABOTH-BAHR S, KARAS C, 2023. The opening and closure of oceanic seaways during the Cenozoic: pacemaker of global climate change?[J]. *Geological Society, London, Special Publications*, 523(1): SP523-2021-54.
- BARBOLINI N, WOUTERSEN A, DUPONT-NIVET G, et al., 2020. Cenozoic evolution of the steppe-desert biome in Central Asia[J]. *Science Advances*, 6(41): eabb8227.
- BEASLEY C, KENDER S, GIOSAN L, et al., 2021. Evidence of a South Asian proto-monsoon during the Oligocene-Miocene transition[J]. *Paleoceanography and Paleoclimatology*, 36(9): e2021PA004278.
- BETZLER C, EBERLI G P, KROON D, et al., 2016. The abrupt onset of the modern South Asian Monsoon winds[J]. *Scientific Reports*, 6(1): 29838.
- BHATIA H, KHAN M A, SRIVASTAVA G, et al., 2021. Late Cretaceous-Paleogene Indian monsoon climate vis-à-vis movement of the Indian plate, and the birth of the South Asian Monsoon[J]. *Gondwana Research*, 93: 89-100.
- BRETSCHNEIDER L, HATHORNE E C, HUANG H, et al., 2021. Provenance and weathering of clays delivered to the Bay of Bengal during the middle Miocene: Linkages to tectonics and monsoonal climate[J]. *Paleoceanography and Paleoclimatology*, 36(2): e2020PA003917.
- CAI M J, XU Z K, CLIFT P D, et al., 2020. Long-term history of sediment inputs to the eastern Arabian Sea and its implications for the evolution of the Indian summer monsoon since 3.7 Ma[J]. *Geological Magazine*, 157(6): 908-919.
- CANE M A, MOLNAR P, 2001. Closing of the Indonesian seaway as a precursor to east African aridification around 3-4 million years ago[J]. *Nature*, 411(6834): 157-162.
- CHEN J L, HUANG R H, 2006. The comparison of climatological characteristics among Asian and Australian monsoon subsystems. Part I. The wind structure of summer monsoon[J]. *Chinese Journal of Atmospheric Sciences*, 30(6): 1091-1102. (in Chinese with English abstract)
- CHEN M H, WANG R J, YANG L H, et al., 2003. Development of East Asian summer monsoon environments in the late Miocene: radiolarian evidence from site 1143 of ODP Leg 184[J]. *Marine Geology*, 201(1-3): 169-177.
- CHUNG S L, LO C H, LEE T Y, et al., 1998. Diachronous uplift of the Tibetan plateau starting 40 Myr ago[J]. *Nature*, 394(6695): 769-773.
- CLIFT P, GAEDICKE C, EDWARDS R, et al., 2002. The stratigraphic evolution of the Indus Fan and the history of sedimentation in the Arabian Sea[J]. *Marine Geophysical Researches*, 23(3): 223-245.
- CLIFT P D, LAYNE G D, BLUSZTAJN J, 2004. Marine sedimentary evidence for monsoon strengthening, Tibetan uplift and drainage evolution in East Asia[M]//CLIFT P, KUHN T W, WANG P, et al. Continent-ocean interactions within East Asian marginal seas. Washington DC, USA. American Geophysical Union: 255-282.
- CLIFT P D, PLUMB R A, 2008. The Asian monsoon: causes, history and effects[M]. Cambridge: Cambridge University Press.
- CLIFT P D, HODGES K V, HESLOP D, et al., 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity[J]. *Nature Geoscience*, 1(12): 875-880.
- CLOTTEN C, STEIN R, FAHL K, et al., 2019. On the causes of Arctic sea ice in the warm Early Pliocene[J]. *Scientific Reports*, 9(1): 989.
- DENG T, WANG X M, WU F X, et al., 2019. Review: implications of vertebrate fossils for paleo-elevations of the Tibetan Plateau[J]. *Global and Planetary Change*, 174: 58-69.
- DING L, SPICER R A, YANG J, et al., 2017. Quantifying the rise of the Himalaya orogen and implications for the South Asian monsoon[J]. *Geology*, 45(3): 215-218.
- DING L, KAPP P, CAI F L, et al., 2022. Timing and mechanisms of Tibetan Plateau uplift[J]. *Nature Reviews Earth & Environment*, 3(10): 652-667.
- DING W J, HOU D J, GAN J, et al., 2021. Palaeovegetation variation in response to the late Oligocene-early Miocene East Asian summer monsoon in the Ying-Qiong Basin, South China Sea[J]. *Paleogeography, Paleoclimatology, Palaeoecology*, 567: 110205.
- DING Y H, CHAN J C L, 2005. The East Asian summer monsoon: an over-

- view[J]. *Meteorology and Atmospheric Physics*, 89(1-4): 117-142.
- DING Y H, SUN Y, LIU Y Y, et al., 2013. Interdecadal and interannual variabilities of the Asian summer monsoon and its projection of future change[J]. *Chinese Journal of Atmospheric Sciences*, 37(2): 253-280. (in Chinese with English abstract)
- DUK-RODKIN A, BARENDREGT R W, FROESE D G, et al., 2004. Timing and extent of Plio-Pleistocene glaciations in north-western Canada and east-central Alaska[J]. *Developments in Quaternary Sciences*, 2: 313-345.
- DUPONT-NIVET G, KRIJGSMAN W, LANGEREIS C G, et al., 2007. Tibetan plateau aridification linked to global cooling at the Eocene-Oligocene transition[J]. *Nature*, 445(7128): 635-638.
- EHRMANN W U, MACKENSEN A, 1992. Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 93(1-2): 85-112.
- FANG X M, YAN M D, ZHANG W L, et al., 2021. Paleogeography control of Indian monsoon intensification and expansion at 41 Ma[J]. *Science Bulletin*, 66(22): 2320-2328.
- FANG X M, GUO Z T, JIANG D B, et al., 2022. No monsoon-dominated climate in northern subtropical Asia before 35 Ma[J]. *Global and Planetary Change*, 218: 103970.
- FLUTEAU F, RAMSTEIN G, BESSE J, 1999. Simulating the evolution of the Asian and African monsoons during the past 30 Myr using an atmospheric general circulation model[J]. *Journal of Geophysical Research: Atmospheres*, 104(D10): 11995-12018.
- GAIC C C, LIU Q S, ROBERTS A P, et al., 2020. East Asian monsoon evolution since the late Miocene from the South China Sea[J]. *Earth and Planetary Science Letters*, 530: 115960.
- GALLAGHER S J, WALLACE M W, LI C L, et al., 2009. Neogene history of the West Pacific warm pool, Kuroshio and Leeuwin currents[J]. *Paleoceanography*, 24(1): PA1206.
- GLADENKOV A Y, OLEINIK A E, MARINCOVICH JR L, et al., 2002. A refined age for the earliest opening of Bering Strait[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 183(3-4): 321-328.
- GUO Z T, RUDDIMAN W F, HAO Q Z, et al., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China[J]. *Nature*, 416(6877): 159-163.
- GUO Z T, SUN B, ZHANG Z S, et al., 2008. A major reorganization of Asian climate by the early Miocene[J]. *Climate of the Past*, 4(3): 153-174.
- GUPTA A K, SINGH R K, JOSEPH S, et al., 2004. Indian Ocean high-productivity event (10-8 Ma): Linked to global cooling or to the initiation of the Indian monsoons? [J]. *Geology*, 32(9): 753-756.
- GUPTA A K, YUVARAJA A, PRAKASAM M, et al., 2015. Evolution of the South Asian monsoon wind system since the late Middle Miocene[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 438: 160-167.
- HALL R, 2009. Southeast Asia's changing palaeogeography[J]. *Blumea: Biodiversity, Evolution and Biogeography of Plants*, 54(1-3): 148-161.
- HAO Q Z, ZHANG R H, WANG P X, et al., 2016. Monsoons across multi-scales: summary of fourth conference on Earth system science[J]. *Advances in Earth Science*, 31(7): 689-699. (in Chinese with English abstract)
- HELLWIG A, VOIGT S, MULCH A, et al., 2018. Late Oligocene to early Miocene humidity change recorded in terrestrial sequences in the Ili Basin (south-eastern Kazakhstan, Central Asia)[J]. *Sedimentology*, 65(2): 517-539.
- HOLBOURN A, KUHNT W, CLEMENS S C, et al., 2021. A ~ 12 Myr Miocene record of east Asian monsoon variability from the South China Sea[J]. *Paleoceanography and Paleoclimatology*, 36(7): e2021PA004267.
- HSÜ K J, RYAN W B F, CITA M B, 1973. Late Miocene desiccation of the Mediterranean[J]. *Nature*, 242(5395): 240-244.
- HUANG C J, HINNOV L, 2019. Astronomically forced climate evolution in a saline lake record of the middle Eocene to Oligocene, Jiangnan Basin, China[J]. *Earth and Planetary Science Letters*, 528: 115846.
- HUANG H S, MORLEY R J, LICHT A, et al., 2023. A proto-monsoonal climate in the late Eocene of Southeast Asia: evidence from a sedimentary record in central Myanmar[J]. *Geoscience Frontiers*, 14(1): 101457.
- HUBER M, GOLDNER A, 2012. Eocene monsoons[J]. *Journal of Asian Earth Sciences*, 44: 3-23.
- JACQUES F M B, GUO S X, SU T, et al., 2011. Quantitative reconstruction of the Late Miocene monsoon climates of southwest China: a case study of the Lincang flora from Yunnan Province[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 304(3-4): 318-327.
- JIA G D, PENG P, ZHAO Q H, et al., 2003. Changes in terrestrial ecosystem since 30 Ma in East Asia: stable isotope evidence from black carbon in the South China Sea[J]. *Geology*, 31(12): 1093-1096.
- KARAS C, NÜRNBERG D, BAHR A, et al., 2017. Pliocene oceanic seaways and global climate[J]. *Scientific Reports*, 7(1): 39842.
- KEIGWIN L D JR, 1978. Pliocene closing of the Isthmus of Panama, based on biostratigraphic evidence from nearby Pacific Ocean and Caribbean Sea cores[J]. *Geology*, 6(10): 630-634.
- KHAN M A, BERA M, SPICER R A, et al., 2019. Palaeoclimatic estimates for a latest Miocene-Pliocene flora from the Siwalik Group of Bhutan: Evidence for the development of the South Asian Monsoon in the eastern Himalaya[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 514: 326-335.
- KNIES J, CABEDO-SANZ P, BELT S T, et al., 2014. The emergence of modern sea ice cover in the Arctic Ocean[J]. *Nature Communications*, 5(1): 5608.
- LAWVER L A, GAHAGAN L M, 2003. Evolution of Cenozoic seaways in the circum-Antarctic region[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 198(1-2): 11-37.
- LI J J, FANG X M, SONG C H, et al., 2014. Late Miocene-Quaternary rapid stepwise uplift of the NE Tibetan Plateau and its effects on climatic and environmental changes[J]. *Quaternary Research*, 81(3): 400-423.
- LI J P, WU Z W, JIANG Z H, et al., 2010. Can global warming strengthen the East Asian summer monsoon? [J]. *Journal of Climate*, 23(24): 6696-6705.
- LI J X, YUE L P, ROBERTS A P, et al., 2018a. Global cooling and enhanced Eocene Asian mid-latitude interior aridity[J]. *Nature Communications*,

- 9(1): 3026.
- LI P, ZHANG C X, GUO Z T, et al., 2019. Clay mineral assemblages in the Zhaotong Basin of southwestern China: Implications for the late Miocene and Pliocene evolution of the South Asian monsoon[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 516: 90-100.
- LI X F, ZHANG R, ZHANG Z S, et al., 2018b. Do climate simulations support the existence of East Asian monsoon climate in the Late Eocene?[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 509: 47-57.
- LICHT A, VAN CAPPELLE M, ABELS H A, et al., 2014. Asian monsoons in a late Eocene greenhouse world[J]. *Nature*, 513(7519): 501-506.
- LIN X, QIAN W H, 2012. Review of the global monsoon and monsoon marginal zones[J]. *Advances in Earth Science*, 27(1): 26-34. (in Chinese with English abstract)
- LIN X, LIU J, PENG B F, et al., 2017. A review of low-temperature thermochronology on bedrock and detritus from rivers around the Tibetan Plateau[J]. *Seismology and Geology*, 39(6): 1091-1110. (in Chinese with English abstract)
- LIN X, CHENG Y R, FENG Y F, et al., 2019. A review on regressive time in southwest Tarim Basin and its forming mechanism[J]. *Marine Geology & Quaternary Geology*, 39(3): 84-93. (in Chinese with English abstract)
- LIN X, TIAN Y T, DONELICK R A, et al., 2019. Mesozoic and Cenozoic tectonics of the northeastern edge of the Tibetan plateau: evidence from modern river detrital apatite fission-track age constraints[J]. *Journal of Asian Earth Sciences*, 170: 84-95.
- LIN X, JOLIVET M, LIU-ZENG J, et al., 2021. Mesozoic-Cenozoic cooling history of the Eastern Qinghai Nan Shan (NW China): Apatite low-temperature thermochronology constraints[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 572: 110416.
- LIN X, LIU J, LIU W M, et al., 2023. Development and evolution of the Yellow River and Yangtze River[M]. Beijing: Geology Press. (in Chinese)
- LIN X, HU C W, WU R T, et al., 2024a. How was the late Neogene red clay formed in the Ordos Plateau (Northwest China)?[J]. *Minerals*, 14(6): 537.
- LIN X, LIU-ZENG J, JOLIVET M, et al., 2024b. Sedimentary provenance constraints on the Cretaceous to Cenozoic palaeogeography of the western margin of the Jiangnan Basin, South China[J]. *Gondwana Research*, 125: 343-358.
- LIN X B, WYRWOLL K H, CHEN H L, et al., 2015. An active east Asian monsoon at the Oligocene-Miocene boundary: evidence from the Sikouzi Section, Northern China[J]. *The Journal of Geology*, 123(4): 355-367.
- LIU T, ZHENG M P, GUO Z T, 1998. Initiation and evolution of the Asian Monsoon system timely coupled with the ice-sheet growth and the tectonic movements in Asia[J]. *Quaternary Sciences*, 18(3): 194-204. (in Chinese with English abstract)
- LIU X D, DONG B W, YIN Z Y, et al., 2017. Continental drift and plateau uplift control origination and evolution of Asian and Australian monsoons[J]. *Scientific Report*, 7: 40344.
- LIU X D, DONG B W, YIN Z Y, et al., 2019. Continental drift, plateau uplift, and the evolutions of monsoon and arid regions in Asia, Africa, and Australia during the Cenozoic[J]. *Science China Earth Sciences*, 62(7): 1053-1075.
- LIU-ZENG J, TAPPONNIER P, GAUDEMER Y, et al., 2008. Quantifying landscape differences across the Tibetan plateau: Implications for topographic relief evolution[J]. *Journal of Geophysical Research: Earth Surface*, 113(F4): F04018.
- LIU-ZENG J, ZHANG J Y, MCPHILLIPS D, et al., 2018. Multiple episodes of fast exhumation since cretaceous in southeast Tibet, revealed by low-temperature thermochronology[J]. *Earth and Planetary Science Letters*, 490: 62-76.
- LIVERMORE R, HILLENBRAND C D, MEREDITH M, et al., 2007. Drake passage and Cenozoic climate: an open and shut case?[J]. *Geochemistry, Geophysics, Geosystems*, 8(1): Q01005.
- LU H J, TIAN X B, YUN K, et al., 2018. Convective removal of the Tibetan Plateau mantle lithosphere by ~ 26 Ma[J]. *Tectonophysics*, 731-732: 17-34.
- LU H Y, GUO Z T, 2014. Evolution of the monsoon and dry climate in East Asia during late Cenozoic: a review[J]. *Science China Earth Sciences*, 57(1): 70-79.
- LU H Y, LIU R X, CHENG L H, et al., 2020. Phased evolution and variation of the South Asian monsoon, and resulting weathering and surface erosion in the Himalaya-Karakoram Mountains, since late Pliocene time using data from Arabian Sea core[J]. *Geological Magazine*, 157(6): 864-878.
- LU H Y, FENG H, LYU H Z, et al., 2023a. Formation and evolution of the Asian landscape during the Cenozoic[J]. *The Innovation Geoscience*, 1(2): 100020.
- LU H Y, ZHANG H Z, FENG H, et al., 2023b. Landform evolution in Asia during the Cenozoic revealed by formation of drainages of Wei River and Indus River[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 619: 111516.
- LYU H, LU H Y, WANG Y C, et al., 2021. East Asian paleoclimate change in the Weihe Basin (central China) since the middle Eocene revealed by clay mineral analysis[J]. *Science China Earth Sciences*, 64(8): 1285-1304.
- MA Y, ZHENG D W, ZHANG H P, et al., 2021. Plio-Pleistocene establishment of Irtysh river in Junggar, northwest China: implications for Siberian-Arctic River system evolution and resulting climate impact[J]. *Geophysical Research Letters*, 48(12): e2021GL093217.
- MCQUARRIE N, STOCK J M, VERDEL C, et al., 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions[J]. *Geophysical Research Letters*, 30(20): 2036.
- MENG Q T, BRUCH A A, SUN G, et al., 2018a. Quantitative reconstruction of Middle and Late Eocene paleoclimate based on palynological records from the Huadian Basin, northeastern China: evidence for monsoonal influence on oil shale formation[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 510: 63-77.
- MENG X Q, LIU L W, WANG X T, et al., 2018b. Mineralogical evidence of reduced East Asian summer monsoon rainfall on the Chinese loess plateau during the early Pleistocene interglacials[J]. *Earth and Planetary Science Letters*, 486: 61-69.

- MÉTIVIER F, GAUDEMER Y, TAPPONNIER P, et al., 1999. Mass accumulation rates in Asia during the Cenozoic[J]. *Geophysical Journal International*, 137(2): 280-318.
- MIAO Y F, FANG X M, HERRMANN M, et al., 2011. Miocene pollen record of KC-1 core in the Qaidam Basin, NE Tibetan Plateau and implications for evolution of the East Asian monsoon[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 299(1-2): 30-38.
- MIAO Y F, WU F L, HERRMANN M, et al., 2013. Late early Oligocene East Asian summer monsoon in the NE Tibetan Plateau: evidence from a palynological record from the Lanzhou Basin, China[J]. *Journal of Asian Earth Sciences*, 75: 46-57.
- MIAO Y F, FANG X M, SUN J M, et al., 2022. A new biologic paleoaltimetry indicating Late Miocene rapid uplift of northern Tibet Plateau[J]. *Science*, 378(6624): 1074-1079.
- NAAFS B D A, STEIN R, HEFTER J, et al., 2010. Late Pliocene changes in the North Atlantic current[J]. *Earth and Planetary Science Letters*, 298(3-4): 434-442.
- NAJMAN Y, ZHUANG G S, CARTER A, et al., 2023. When did the Indus River of South-Central Asia take on its “modern” drainage configuration?[J]. *GSA Bulletin*, 136(7-8): 2815-2830. NIE J S, RUETENIK G, GALLAGHER K, et al., 2018. Rapid incision of the Mekong River in the middle Miocene linked to monsoonal precipitation[J]. *Nature Geoscience*, 11(12): 944-948.
- O'DEA A, LESSIOS H A, COATES A G, et al., 2016. Formation of the isthmus of panama[J]. *Science Advances*, 2(8): e1600883.
- PEI J L, ZHAO Y, ZHOU Z Z, et al., 2021. Impact of Cenozoic Antarctic continent-ocean configuration patterns on global climate change[J]. *Journal of Geomechanics*, 27(5): 867-879. (in Chinese with English abstract)
- PRELL W L, KUTZBACH J E, 1992. Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution[J]. *Nature*, 360(6405): 647-652.
- QIANG X K, AN Z S, SONG Y G, et al., 2011. New eolian red clay sequence on the western Chinese Loess Plateau linked to onset of Asian desertification about 25 Ma ago[J]. *Science China Earth Sciences*, 54(1): 136-144.
- QUADE J, CERLING T E, BOWMAN J R, 1989. Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan[J]. *Nature*, 342(6246): 163-166.
- QUAN C, LIU Y S, UTESCHER T, 2011. Paleogene evolution of precipitation in northeastern China supporting the middle Eocene intensification of the East Asian monsoon[J]. *Palaiaos*, 26(11): 743-753.
- RAYMO M E, RUDDIMAN W F, 1992. Tectonic forcing of late Cenozoic climate[J]. *Nature*, 359(6391): 117-122.
- REN J B, SCHUBERT B A, LUKENS W E, et al., 2021. Low oxygen isotope values of fossil cellulose indicate an intense monsoon in East Asia during the late Oligocene[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 577: 110556.
- RETALLACK G J, BAJPAI S, LIU X M, et al., 2018. Advent of strong South Asian monsoon by 20 million years ago[J]. *The Journal of Geology*, 126(1): 1-24.
- ROWLEY D B, CURRIE B S, 2006. Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet[J]. *Nature*, 439(7077): 677-681.
- SANYAL P, SINHA R, 2010. Evolution of the Indian summer monsoon: synthesis of continental records[J]. *Geological Society, London, Special Publications*, 342(1): 153-183.
- SARR A C, DONNADIEU Y, BOLTON C T, et al., 2022. Neogene South Asian monsoon rainfall and wind histories diverged due to topographic effects[J]. *Nature Geoscience*, 15(4): 314-319.
- SHUKLA A, MEHROTRA R C, SPICER R A, et al., 2014. Cool equatorial terrestrial temperatures and the South Asian monsoon in the Early Eocene: evidence from the Gurha Mine, Rajasthan, India[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 412: 187-198.
- SONG Y G, FANG X M, KING J W, et al., 2014. Magnetic parameter variations in the Chaona loess/paleosol sequences in the central Chinese Loess Plateau, and their significance for the middle Pleistocene climate transition[J]. *Quaternary Research*, 81(3): 433-444.
- SONG Z H, WAN S M, COLIN C, et al., 2023. Enhanced weathering input from South Asia to the Indian Ocean since the late Eocene[J]. *Science Bulletin*, 68(3): 305-313.
- SORREL P, EYMARD I, LELOUP P H, et al., 2017. Wet tropical climate in SE Tibet during the Late Eocene[J]. *Scientific Reports*, 7(1): 7809.
- SPICER R A, YANG J, HERMAN A B, et al., 2016. Asian Eocene monsoons as revealed by leaf architectural signatures[J]. *Earth and Planetary Science Letters*, 449: 61-68.
- SPICER R A, SU T, VALDES P J, et al., 2020. Why ‘the uplift of the Tibetan Plateau’ is a myth[J]. *National Science Review*, 8(1): nwaa091.
- SPICER R A, FARNSWORTH A, SU T, et al., 2024. The progressive co-evolutionary development of the Pan-Tibetan highlands, the Asian Monsoon system and Asian Biodiversity[J]. *Geological Society, London, Special Publications*, 549(1): 180.
- SRINIVASAN M S, SINHA D K, 1998. Early Pliocene closing of the Indonesian Seaway: evidence from north-east Indian Ocean and Tropical Pacific deep sea cores[J]. *Journal of Asian Earth Sciences*, 16(1): 29-44.
- SRIVASTAVA G, SPICER R A, SPICER T E V, et al., 2012. Megaflora and palaeoclimate of a Late Oligocene tropical delta, Makum Coalfield, Assam: evidence for the early development of the South Asia Monsoon[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 342-343: 130-142.
- STRAUME E O, GAINA C, MEDVEDEV S, et al., 2020. Global Cenozoic paleobathymetry with a focus on the Northern Hemisphere oceanic gateways[J]. *Gondwana Research*, 86: 126-143.
- SU L F, ZHANG Q Q, SUN Y K, et al., 2022. New evidence of the emergence of the East Asian monsoon in the early Palaeogene[J]. *Scientific Reports*, 12(1): 20471.
- SU T, FARNSWORTH A, SPICER R A, et al., 2019. No high Tibetan plateau until the Neogene[J]. *Science Advances*, 5(3): eaav2189.
- SU T, SPICER R A, WU F X, et al., 2020. A Middle Eocene lowland humid subtropical “Shangri-La” ecosystem in central Tibet[J]. *Proceedings of*

- the National Academy of Sciences of the United States of America, 117(52): 32989-32995.
- SUN G Y, HU X M, GARZANTI E, et al., 2023a. Pre-Eocene Arabia-Eurasia collision: New constraints from the Zagros Mountains (Amiran Basin, Iran)[J]. *Geology*, 51(10): 941-946.
- SUN J M, YE J, WU W Y, et al., 2010. Late Oligocene–Miocene mid-latitude aridification and wind patterns in the Asian interior[J]. *Geology*, 38(6): 515-518.
- SUN J M, XU Q H, LIU W M, et al., 2014. Palynological evidence for the latest Oligocene-early Miocene paleoelevation estimate in the Lunpola Basin, central Tibet[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 399: 21-30.
- SUN J M, WINDLEY B F, 2015. Onset of aridification by 34 Ma across the Eocene-Oligocene transition in Central Asia[J]. *Geology*, 43(11): 1015-1018.
- SUN J M, SHEYKH M, AHMADI N, et al., 2021. Permanent closure of the Tethyan Seaway in the northwestern Iranian Plateau driven by cyclic sea-level fluctuations in the late Middle Miocene[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 564: 110172.
- SUN J M, SHA J G, WINDLEY B F, et al., 2023b. Late Eocene stepwise sea-water retreat from the Pamir-Tian Shan convergence zone (Alay Valley) in the western Tarim Basin, China[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 622: 111603.
- SUN X J, WANG P X, 2005. How old is the Asian monsoon system?—Palaeobotanical records from China[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 222(3-4): 181-222.
- TADA R, ZHENG H B, CLIFT P D, 2016. Evolution and variability of the Asian monsoon and its potential linkage with uplift of the Himalaya and Tibetan Plateau[J]. *Progress in Earth and Planetary Science*, 3(1): 4.
- TRIPATHI S, TIWARI M, LEE J, KHIM B K. 2017. First evidence of denitrification vis-à-vis monsoon in the Arabian Sea since Late Miocene[J]. *Scientific reports*, 7(1): 1-7.
- TARDIF D, SARR A C, FLUTEAU F, et al., 2023. The role of paleogeography in Asian monsoon evolution: a review and new insights from climate modelling[J]. *Earth-Science Reviews*, 243: 104464.
- TIAN Y T, KOHN B P, HU S B, et al., 2015. Synchronous fluvial response to surface uplift in the eastern Tibetan Plateau: implications for crustal dynamics[J]. *Geophysical Research Letters*, 42(1): 29-35.
- TURNER A G, ANNAMALAI H, 2012. Climate change and the South Asian summer monsoon[J]. *Nature Climate Change*, 2(8): 587-595.
- VORNLOCHER J R, LUKENS W E, SCHUBERT B A, et al., 2021. Late Oligocene precipitation seasonality in East Asia based on $\delta^{13}\text{C}$ profiles in fossil wood[J]. *Paleoceanography and Paleoclimatology*, 36(4): e2021PA004229.
- WAN S M, LI A C, CLIFT P D, et al., 2007. Development of the East Asian monsoon: mineralogical and sedimentologic records in the northern South China Sea since 20 Ma[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 254(3-4): 561-582.
- WANG B, WU R G, LI T M, 2003a. Atmosphere–warm ocean interaction and its impacts on Asian–Australian monsoon variation[J]. *Journal of Climate*, 16(8): 1195-1211.
- WANG C S, DAI J G, ZHAO X X, et al., 2014. Outward-growth of the Tibetan Plateau during the Cenozoic: A review[J]. *Tectonophysics*, 621: 1-43.
- WANG P X, JIAN Z M, ZHAO Q H, et al., 2003b. Evolution of the South China Sea and monsoon history revealed in deep-sea records[J]. *Chinese Science Bulletin*, 48(23): 2549-2561.
- WANG P X, 2004. Cenozoic deformation and the history of sea-land interactions in Asia[M]//CLIFT P, KUHN T W, WANG P, et al. Continent-ocean interactions within East Asian marginal seas. Washington DC, USA. American Geophysical Union: 1-22.
- WANG P X, LI Q Y, 2009. History of the South China Sea—a synthesis [M]//WANG P X, LI Q Y. The South China Sea: Paleogeography and sedimentology. Dordrecht: Springer: 487-496.
- WANG W T, ZHENG W J, ZHANG P Z, et al., 2017. Expansion of the Tibetan Plateau during the Neogene[J]. *Nature Communications*, 8: 15887.
- WANG X, CARRAPA B, SUN Y C, et al., 2020. The role of the westerlies and orography in Asian hydroclimate since the late Oligocene[J]. *Geology*, 48(7): 728-732.
- WILSON D S, POLLARD D, DECONTO R M, et al., 2013. Initiation of the West Antarctic Ice Sheet and estimates of total Antarctic ice volume in the earliest Oligocene[J]. *Geophysical Research Letters*, 40(16): 4305-4309.
- WU F L, FANG X M, MENG Q Q, et al., 2017. Magneto- and litho-stratigraphic records of the Oligocene-Early Miocene climatic changes from deep drilling in the Linxia Basin, Northeast Tibetan Plateau[J]. *Global and Planetary Change*, 158: 36-46.
- WU F L, FANG X M, YANG Y B, et al., 2022. Reorganization of Asian climate in relation to Tibetan Plateau uplift[J]. *Nature Reviews Earth & Environment*, 3(10): 684-700.
- XIE Y L, WU F L, FANG X M, et al., 2020a. Early Eocene southern China dominated by desert: evidence from a palynological record of the Hengyang Basin, Hunan Province[J]. *Global and Planetary Change*, 195: 103320.
- XIE Y L, WU F L, FANG X M, 2020b. A major environmental shift by the middle Eocene in southern China: evidence from palynological records[J]. *Review of Palaeobotany and Palynology*, 278: 104226.
- XIONG Z Y, LIU X H, DING L, et al., 2022. The rise and demise of the Paleogene Central Tibetan valley[J]. *Science Advances*, 8(6): eabj0944.
- YAN D F, ZHANG L, HAN L, et al., 2018. Podocarpium from the Oligocene of NW Qaidam Basin, China and its implications[J]. *Review of Palaeobotany and Palynology*, 259: 1-9.
- YAN M D, VANDERVOO R, FANG X M, et al., 2006. Paleomagnetic evidence for a mid-Miocene clockwise rotation of about 25° of the Guide Basin area in NE Tibet[J]. *Earth and Planetary Science Letters*, 241(1-2): 234-247.
- YANCHEVA G, NOWACZYK N R, MINGRAM J, et al., 2007. Influence of

- the intertropical convergence zone on the East Asian monsoon[J]. *Nature*, 445(7123): 74-77.
- YUAN T T, XU H, LIU G Z, et al., 2024. Eocene dry eolian system in the Jianchuan Basin, southeastern Tibetan Plateau: implications for regional wind regime and paleoclimate[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 635: 111949.
- ZACHOS J, PAGANI M, SLOAN L, et al., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present[J]. *Science*, 292(5517): 686-693.
- ZHENG D W, ZHANG P Z, WAN J L, et al., 2006. Rapid exhumation at ~ 8 Ma on the Liupan Shan thrust fault from apatite fission-track thermochronology: Implications for growth of the northeastern Tibetan Plateau margin[J]. *Earth and Planetary Science Letters*, 248(1-2): 198-208.
- ZHENG H B, POWELL C M, REA D K, et al., 2004. Late Miocene and mid-Pliocene enhancement of the East Asian monsoon as viewed from the land and sea[J]. *Global and Planetary Change*, 41(3-4): 147-155.
- ZHENG H B, CLIFT P D, WANG P, et al., 2013. Pre-Miocene birth of the Yangtze River[J]. *Proceedings of the National Academy of Sciences of the United States of America*, 110(19): 7556-7561.
- ZHENG H B, YANG Q, CAO S, et al., 2022. From desert to monsoon: irreversible climatic transition at ~ 36 Ma in southeastern Tibetan Plateau[J]. *Progress in Earth and Planetary Science*, 9(1): 12.

附中文参考文献

- 安芷生, 吴国雄, 李建平, 等, 2015. 全球季风动力学与气候变化[J]. *地球环境学报*, 6(6): 341-381.
- 陈际龙, 黄荣辉, 2006. 亚澳季风各子系统气候学特征的异同研究 I. 夏季风流场结构[J]. *大气科学*, 30(6): 1091-1102.
- 丁一汇, 孙颖, 刘芸芸, 等, 2013. 亚洲夏季风的年际和年代际变化及其未来预测[J]. *大气科学*, 37(2): 253-280.
- 郝青振, 张人禾, 汪品先, 等, 2016. 全球季风的多尺度演化[J]. *地球科学进展*, 31(7): 689-699.
- 林祥, 钱维宏, 2012. 全球季风和季风边缘研究[J]. *地球科学进展*, 27(1): 26-34.
- 林旭, 刘静, 彭保发, 等, 2017. 青藏高原周围河流基岩和碎屑矿物低温热年代学研究进展[J]. *地震地质*, 39(6): 1091-1110.
- 林旭, 程钰瑞, 冯一帆, 等, 2019. 塔西南盆地海退时间及其形成机制研究[J]. *海洋地质与第四纪地质*, 39(3): 84-93.
- 林旭, 刘静, 刘维明, 等, 2023. 黄河和长江发育与演化[M]. 北京: 地质出版社.
- 刘东生, 郑绵平, 郭正堂, 1998. 亚洲季风系统的起源和发展及其与两极冰盖和区域构造运动的时代耦合性[J]. *第四纪研究*, 18(3): 194-204.
- 裴军令, 赵越, 周在征, 等, 2021. 南极新生代海陆格局变迁对全球气候变化的影响[J]. *地质力学学报*, 27(5): 867-879.