第 36 卷　第 4 期
2016 年 7 月

第　四　纪　研　究
QUATERNARY　SCIENCES

Vol.36,　No.4
July, 2016

doi:10.11928/j.issn.1001-7410.2016.04.04　　　**文章编号**　1001-7410(2016)04-820-12

晚新生代以来中国西北植被演化及反映的干旱化过程*

祝淑雅①②　吴海斌①②　李　琴①③　张春霞①③
于严严①③　孙爱芝①②　郭正堂①②③

(①中国科学院地质与地球物理研究所, 新生代地质与环境重点实验室, 北京　100029; ②中国科学院大学, 北京　100049;
③中国科学院青藏高原地球科学卓越创新中心, 北京　100101)

摘要　亚洲内陆干旱化是全球新生代大陆环境变化中最引人瞩目的重大事件之一, 一直是古气候研究的热点。但到目前为止, 亚洲内陆干旱化的起源、演化及其机制仍存在争议。本文系统整理了具详细定年的 30 条孢粉序列, 利用生物群区化方法, 重建了晚新生代以来我国西北植被的时空演化历史, 探讨了干旱化过程。结果显示: 约 36~28Ma, 我国西北植被以森林为主, 气候湿润; 约 27~24Ma, 出现草原, 开始呈现干旱化趋势; 约 23~18Ma 荒漠扩张; 约 8Ma 以来, 大部分森林被荒漠、草原替代, 干旱程度显著增强。上述干旱化历史与全球变冷、青藏高原隆升及副特提斯海退缩在时代上有一定的关联性。因此认为, 亚洲内陆干旱化的起源可能与青藏高原隆升及副特提斯海的退缩有关, 而之后干旱化过程受全球变冷影响逐步加强, 约 8Ma 以来的急剧干旱化可能与北半球高纬变冷的关系更为密切。

主题词　生物群区　植被演化　干旱化　晚新生代　全球变冷　高原隆升

中图分类号　P534.62, P534.63, Q913.84, P532　　**文献标识码**　A

1　引言

亚洲内陆干旱化是与我国西部人类生存环境和社会可持续发展联系紧密的重大科学问题[1],其起始时间、演变过程及驱动机制是新生代北半球环境演化的研究热点之一[2~4],涉及全球变冷和青藏高原隆起等一系列重大科学问题[3~9]。

许多学者基于不同地质记录, 对亚洲干旱环境的起源和演化做了大量研究, 并取得重要进展。基于孢粉、岩性等地质记录对我国环境的研究[10~11]揭示,古近纪我国干旱环境大致呈东西带状分布,新近纪的干旱区则显示出与现今大致相似的宏观格局。精细的区域研究[4,12,13]也进一步指出,以内陆干旱为特征的非带状环境格局至少出现于中新世早期。近年来,黄土高原粉尘沉积序列的研究表明,亚洲内陆干旱化至少在晚渐新世-早中新世(约 25~22Ma)开始形成[3,4],此后干旱程度在约 14Ma、10Ma、8~7Ma 和 3.6Ma 逐步增强[14~20]。我国西北准噶尔盆地、塔里木盆地及周边地区的沉积记录也揭示,干旱气候在晚渐新世(约 24Ma)已经形成[21,22],在约 7Ma 和 4~2Ma 有加强的过程[23,24];西宁盆地沉积记录和蒙古黄土粉尘沉积序列进一步表明,在始新世-渐新世交界处(约 34Ma)就可能出现干旱环境[25~29],干旱气候的加强出现在约 20Ma、14Ma、7Ma 和 2Ma 等多个时期[30~33]。这些干旱化的起源和演化,可能与青藏高原隆升[2,5,34,35]、副特提斯海消亡[9,25,26,36]、全球变冷及北极冰盖形成演化[2~4,37~39]有关。以上结果表明,尽管已有研究取得了亚洲内陆干旱化起源和演化历史的框架性认识,但是由于不同区域、不同沉积记录所反应的干旱化过程可能存在差异[2,9,22,26,40], 要全面认识亚洲内陆的干旱化历史, 需从大的区域开展环境序列的集成研究。

陆地植被对气候变化反应灵敏, 且气候意义明

第一作者简介: 祝淑雅　女　26 岁　硕士研究生　第四纪地质学专业　E-mail: zhushuya@mail.iggcas.ac.cn

* 国家自然科学基金项目(批准号:41125011、41572165、41430531 和 41472319)和中国科学院战略性先导科技专项项目—应对气候变化的碳收支认证及相关问题(批准号:XDA05120700)共同资助

2016-03-17 收稿, 2016-05-20 收修改稿

确，在地层中又容易保存，是重建古气候的重要手段之一[41]。虽然，以往也有空间集成的古植被研究[41,42~45]，但这些研究多是定性的描述，且以“世”为单位，时段划分较粗略，缺乏对古植被时空演化的详细研究。而详细时间序列的古植被集成研究，对于干旱环境的演化认识是极为关键的。

本文基于东亚具准确年代控制的 30 条孢粉序列，重建了晚新生代以来我国植被、尤其是西北内陆植被的时空演化，并以此来探讨其干旱化过程。相对以往的工作，本次研究的进步之处在于：1）利用生物群区化方法[46]，定量化重建了晚新生代以来的古植被；2）根据最新的 2012 年标准极性柱年龄[47]，对各剖面的年代序列进行统一，实现具较准确年龄控制的空间对比。这为更全面地认识亚洲内陆干旱化提供证据。

2　数据和方法

2.1　数据来源

本文系统收集和整理了我国及周边区域晚新生代以来的孢粉序列。为了获得有效、可靠的植被演化序列，我们在数据选择上采取了如下标准：1）孢粉序列必须具有较准确的年代控制，如磁性地层年代、裂变径迹定年等，排除那些只有生物地层或岩相地层定年的孢粉数据，为较高精度的古植被演化及干旱化过程的区域对比研究奠定基础；2）孢粉数据必须具有详细的孢粉谱信息，保证生物群区化结果的可靠性。

基于上述标准，本次研究共选取了 30 条孢粉序列，孢粉点位的空间分布见图 1，数据信息见表 1。这些孢粉序列主要分布于黄土高原、青藏高原及新疆等区域，研究时段主要集中于晚渐新世以来。

2.2　数据处理

本次研究所收集的 30 条孢粉序列中[48~76]，有 20 条具有详细的磁性地层。由于这些磁性地层年龄有的是 1995 年的标准极性柱年龄[77]，有的是 2004 年的标准极性柱年龄[78]，与最新的 2012 年标准极性柱年龄有所不同[47]。为了准确进行时间对比，我们将磁性地层统一更新至 2012 年标准极性柱年龄。各极性控制点间的样品年龄，则通过线性内插的方法获得。其余 10 条孢粉序列，因原文献中只提供了基于磁性地层年代获得的孢粉随时间变化序列，未提供详细的原始磁性地层信息，所以无法对其年代进行更新；这部分孢粉序列仍使用原文献中的年代数据（表 1）。相对于以往的标准极性柱年龄，2012 年标准极性柱各极性年龄在新近纪以来的变化不超过 0.1Ma，36Ma 以来的古近纪极性年龄变化不超过 0.5Ma。由于本文探讨的植被演化时间分辨率为 1Ma，且集中于新近纪以来，因此上述变化对本研究的精度影响不大。

在孢粉数据质量控制方面：首先，通过数字化方法获得文献中孢粉谱上各种属的百分含量；其

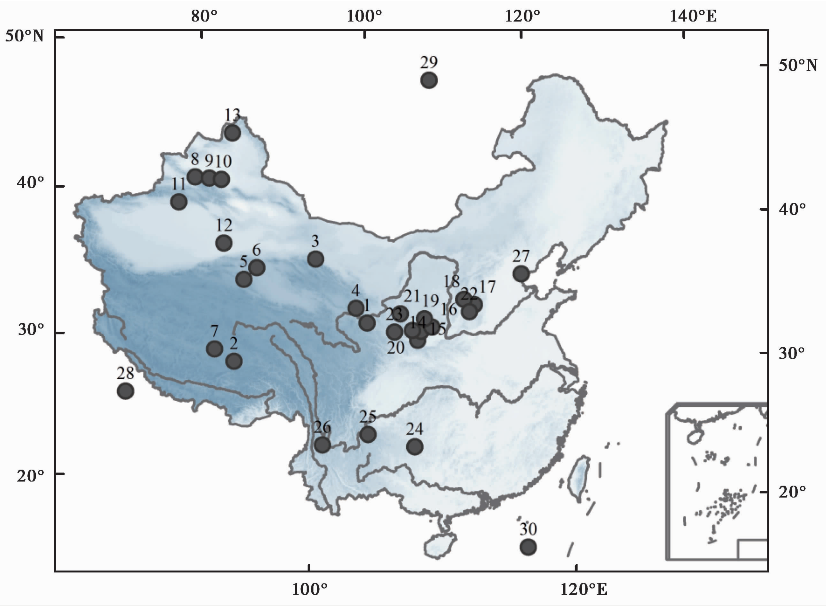

图 1　新生代以来东亚孢粉数据空间点位分布图

Fig. 1　Location of pollen sites in East Asia since the Cenozoic

表 1 孢粉数据信息表

Table 1 Detailed information about the palynological sequences

序号	采样点	经度/°E	纬度/°N	海拔/m	研究时段/Ma	参考文献
1*	临夏盆地毛沟	103.00	35.50	2280	30.6~5.0	[48]
2	青藏高原中部错鄂	91.50	31.48	4515	2.9~0	[49]
3	青藏高原北玉门老君庙	97.53	39.78	2501	13.00~2.21	[50]
4	西宁谢家	101.87	36.52	2367	52.5~17.0	[51]
5*	柴达木盆地西部 KC-1 钻孔	91.75	38.05	2820	18~5	[52]
6	柴达木盆地西部 SG-3 钻孔	91.75	38.38	2736	3.10~0.01	[53]
7	青藏高原中部伦坡拉	89.62	32.07	4607	25.5~19.8	[54]
8	天山北部独山子	84.67	44.23	1000	8.70~2.58	[55]
9	天山北部金沟河	85.46	44.17	913	28.0~4.2	[56]
10	天山北部塔西河	86.33	44.10	1538	26.5~2.6	[57]
11	天山南部库车塔吾	83.05	41.92	1388	13.3~2.6	[58]
12	罗布泊 Ls2 钻孔	88.38	39.78	817	7.1~5.3	[59]
13	准噶尔克孜勒托尕依	86.68	47.84	520	36.0~33.5	[60]
14*	关中石家湾	107.70	34.40	619	3.00~1.99	[61]
15*	甘肃灵台文王沟	107.74	35.07	900	6.5~3.4	[62]
16*	甘肃灵台小石沟	107.73	35.07	900	5.1~4.2	[62]
17	榆社盆地 96-IV 钻孔	113.00	37.00	1070	3.2~2.0	[63]
18*	榆社盆地小白	112.40	37.20	1264	5.5~2.5	[64]
19*	黄土高原中部西峰	107.97	35.88	1075	6.2~2.4	[65]
20	黄土高原中部朝那	107.20	35.12	1426	3~0	[66]
21*	六盘山东部寺口子	106.03	36.30	1591	20~0	[67]
22*	山西张村	112.85	36.97	1043	2.77~2.52	[68]
23	天水盆地燕湾	105.57	34.97	1540	17.1~6.1	[69]
24	云南鹤庆深钻	107.70	26.56	2190	2.78~0	[70]
25	云南昭通 ZT 钻孔	103.74	27.32	1918	8.8~2.6	[71]
26	云南大理大松坪	100.01	26.29	2366	6.9~1.5	[72]
27	天津东部 G2 钻孔	117.63	39.07	3	7.65~0	[73]
28	尼泊尔西瓦利克	83.00	27.50	1000	11.5~1.0	[74]
29	贝尔加湖 BDP-96-1 钻孔	108.35	53.70	456	3.60~2.35	[75]
30*	南海 1148 站	116.57	18.84	0	32.8~23.8	[76]

* 代表仍使用原文献年代的序列

次，去除孢粉谱中水生植物、蕨类和藻类等反映局地性的隐域类型，将陆生植物孢粉总数作为统计基数，对各孢粉种属重新进行百分比例统计；最后，结合已建立的年代序列，获得不同点位各种属百分含量序列，进行孢粉的生物群区化计算。

2.3 研究方法

依据中国第四纪孢粉数据库小组建立的生物群区化方案[46]，结合已获得的 30 条孢粉数据（表 1），完成孢粉的生物群区化。即将植物分类群×植物功能型矩阵、植物功能型×生物群区矩阵以及地层孢粉百分含量数据输入 PPPbase 软件[79]中，计算各生物群区类型得分值；然后，对各点位序列的生物群区类型得分值进行每 1Ma 时段的平均，选择得分最高的生物群区作为对应层位孢粉样品的植被类型，获得各点位每 1Ma 的植被类型；最后，利用地理信息系统软件 ArcGIS，实现每 1Ma 植被类型的空间成图，由此获得晚新生代以来我国植被时空演化历史（图 2）。

生物群区得分是通过计算分类群组合与给定生物群区之间的近似得分获得的，它可较好反映所有的植被信息总和[80]。一个生物群区的得分不是简单地取决于所有花粉的百分比含量，而是依赖于花粉种类的多少以及每种花粉百分比含量的大小[80]。因此，生物群区得分可以有效指示气候变化，如森林群区得分比草原/荒漠得分高时，可指示相对湿润的气候条件；反之亦然。此外，植被类型百分比可直观地展示植被类型随时间的变化，如草原/荒漠比例

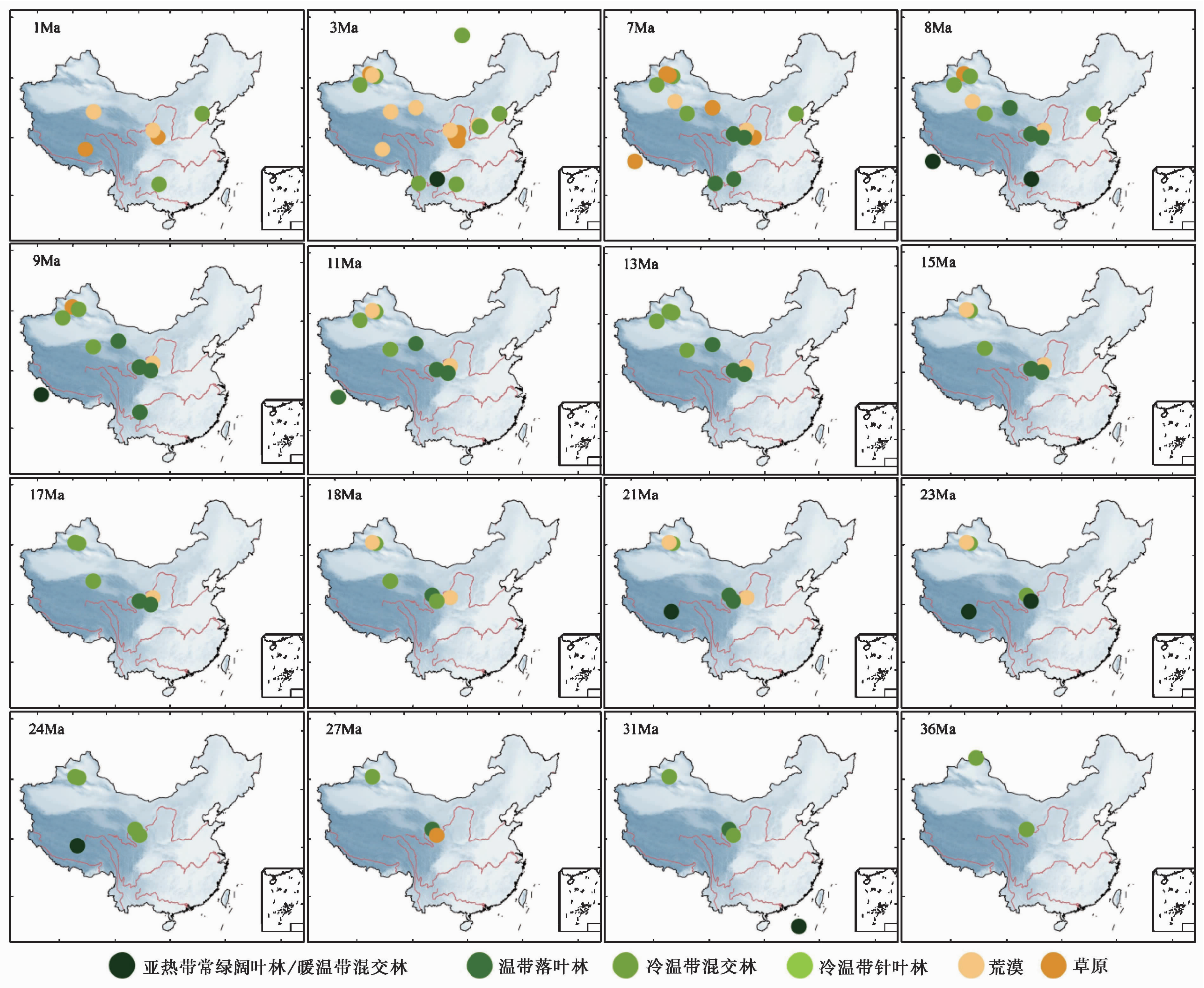

图 2　新生代以来我国植被时空演化图

Fig. 2　Spatial vegetation distributions in China since the Cenozoic

高于森林时，可指示相对干旱的气候条件；反之亦然[43,45]。

3　晚新生代以来西北植被演化和干旱化过程

结果表明（图 2），晚新生代以来，我国主要植被类型有：草原、荒漠、冷温带针叶林、冷温带混交林、温带落叶林、亚热带常绿阔叶林/暖温带混交林。空间植被演化表明，大约 36～28Ma，我国西北内陆植被主要以森林为主；约 27～24Ma，开始出现草原；约 23～18Ma，荒漠进一步在西北内陆扩张；约 18～8Ma，荒漠和草原分布未明显扩张；约 8Ma 以来森林显著减少，荒漠/草原增多，特别是约 3Ma 以来，西北内陆和黄土高原地区大部分森林转变为荒漠/草原。上述植被的时空演化反映了新生代以来我国西北内陆逐步干旱化的历史。

为了更好表达西北内陆干旱化的演化过程，我们集成了该区域 13 条孢粉序列（表 1 中序号 1～13）的生物群区得分，并对其每 1Ma 时间断面上出现的植被类型的点位数量进行频数统计，获得了西北地区植被类型百分比序列（图 3）。结果显示：约 36～32Ma，森林生物群区得分处于峰值，荒漠和草原得分较低（图 3a），且未出现荒漠/草原（图 3b和 3c），表明此阶段气候相对湿润，由于该时期的孢粉序列在数量上偏少，因此无法详细呈现西北区植被特征，详细重建还将依赖于今后序列重建的加强；约 31～26Ma，森林群区得分降低，呈现干旱化趋势；约 26～8Ma，荒漠和草原类型已在西北内陆较稳定分布，呈现干旱化状态；约 8Ma 以来，森林群区得分急剧降低，其百分比例也随之减小，荒漠、草原比例明显增多，指示西北内陆干旱程度显著增强。

4　讨论和结论

上述植被演化结果表明，约 36～28Ma，我国西

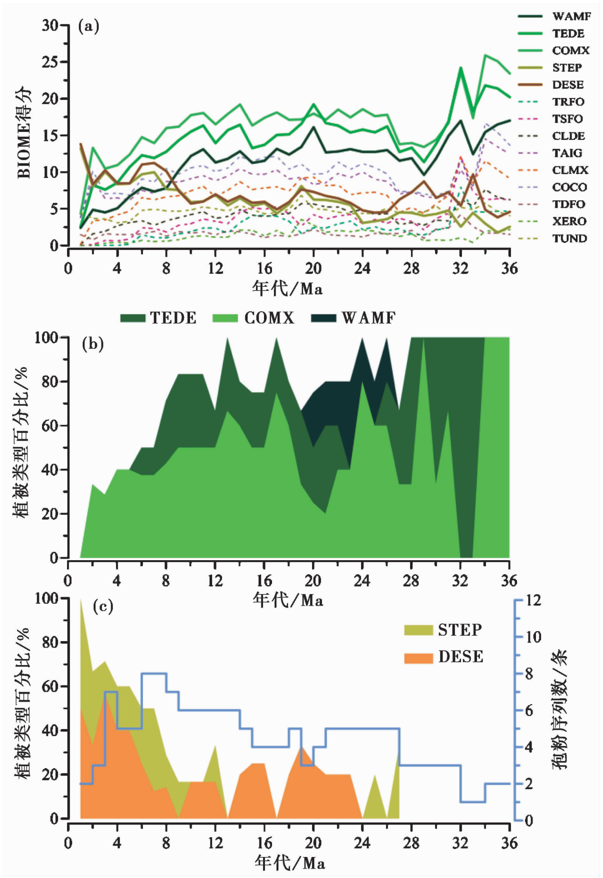

图 3　新生代以来我国西北内陆植被演化序列

(a)各植被类型生物群区得分变化；(b)各森林类型比例变化；(c)荒漠和草原比例变化及西北地区孢粉序列数

COCO，冷温带针叶林；COMX，冷温带混交林；TEDE，温带落叶林；WAMF，亚热带常绿阔叶林/暖温带混交林；TUND，苔原；STEP，草原；DESE，荒漠；TRFO，热带雨林；TSFO，热带季雨林；CLDE，寒温带落叶林；TAIG，泰加林；CLMX，寒温带混交林；TDFO，热带干旱森林/稀树草原；XERO，旱性疏林/灌丛

Fig. 3　Vegetation evolution sequences from Northwest China since the Cenozoic. (a) Biome scores of various vegetation types; (b) The changing proportion of forest; (c) The changing proportion of steppe and desert and the number of palynological sequence within Northwest China

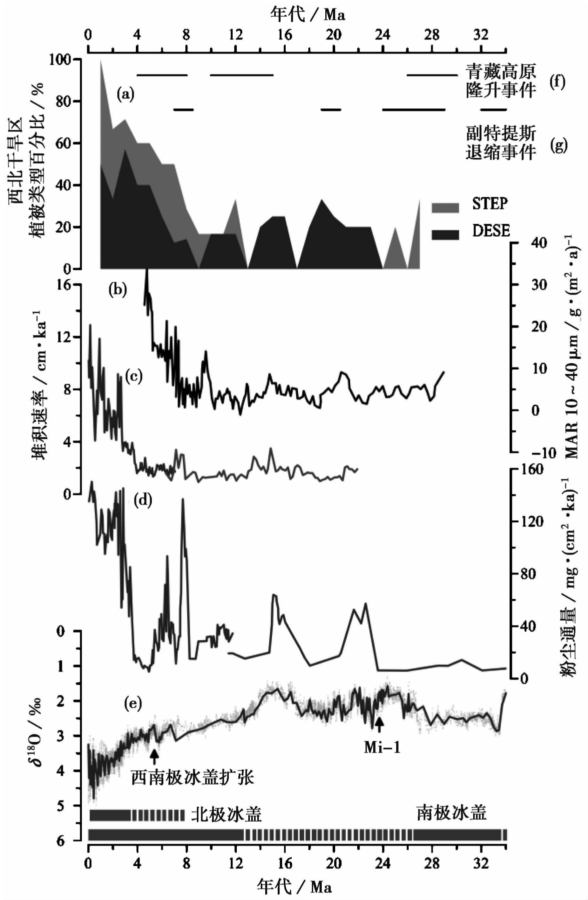

图 4　晚新生代以来我国西北内陆干旱化与全球不同地质环境记录的对比

(a)西北地区荒漠、草原比例；(b)临夏盆地毛沟剖面粒度质量累计比率(MAR)[86]；(c)粉尘堆积速率：7~0Ma 取自西峰剖面，22.0~6.2Ma 取自秦安剖面[2]；(d)北太平洋粉尘通量，其中 12~0Ma 取自 ODP 885/886 孔[85]，26~12Ma 取自 GPC3 孔[81]；(e)全球温度变化及南北极冰盖演化序列[106,107]；(f)青藏高原隆升事件[96~99]；(g)副特提斯退缩事件[102~104]

Fig. 4　Comparison of drying history from Northwest China with different geological records since Cenozoic. (a) The changing proportion of steppe and desert; (b) Grain size indexes records at Maogou profile, Linxia Basin; (c) Dust accumulation rate from Xifeng and Qin'an profiles; (d) Dust flux of north Pacific Ocean; (e) Global deep-sea oxygen records with the evolution of polar ice sheets; (f) Uplift events of Tibetan Plateau; (g) Retreat events of the Para-Tethys Sea

北气候相对较湿润，约 27~24Ma 内陆地区出现干旱环境，且约 8Ma 以来干旱化显著增强，并持续至今。这一气候演化与前人的研究结果[3,4,21,22,81~86]具有一定的可比性。

晚始新世，北太平洋粉尘通量[81,85]低(图 4d)，指示亚洲内陆干旱程度低；且晚始新世兰州以河湖相沉积物为主，风成物质百分含量低，也同样反映了相对湿润的气候特征[82]。此外，基于植物化石资料的定量化结果[83]显示，晚始新世西北地区年均降水约为 800~1000mm，相较于东北与南方地区略显干旱，但还没有达到草原/荒漠的干旱条件。Quan 等[84]基于植物化石资料的定量化结果也显示晚始新世青海西宁、甘肃玉门等地的年均降水高于 735mm。这与本文古植被所揭示的在约 36~28Ma 期间相对湿润的气候条件相似。

与前一时段相比，约 27~24Ma 我国环境有明显变化，突出的表现是内陆地区出现了干旱环境(图 4a)。这种干旱化历史，同样在北太平洋粉尘

通量(图 4d)、我国黄土粉尘堆积速率(图 4c)和其他地质记录中有所表现。约 24Ma 北太平洋粉尘通量急剧增加[81,85]，约 25~22Ma 黄土高原西部发育粉尘堆积[3,4]，表明亚洲内陆干旱化加剧。此外，来自亚洲内陆直接沉积记录的研究也表明，塔克拉玛干沙漠可能形成于约 26.7~22.6Ma[22]，且塔里木盆地及其周边地区的干旱气候至少在约 24Ma 也已经形成[21,22]，指示亚洲内陆干旱化已有一定规模。第三纪动植物标志、盐类沉积和煤层等地质环境指标的集成研究[4,10~13]也表明，晚渐新世-早中新世我国环境格局发生了重大变化，干旱环境集中于西北内陆地区。

约 24~8Ma，亚洲内陆的干旱程度总体上相对较低(图 4a)，这与黄土高原粉尘堆积速率(图 4c)、西北地区沉积物粒度质量累计比率(图 4b)反映的结果较一致。虽然北太平洋粉尘通量在约 14Ma 前后出现相对较高的时段[81,85]，指示亚洲内陆干旱程度的增加，但是本文古植被重建的结果并未表现出荒漠和草原植被类型百分比例的较明显增多。就整体趋势而言，粉尘堆积速率在中新世期间比第四纪要低得多，说明当时内陆干旱程度相对较弱，与本文重建结果总体相似。

约 8Ma 以来，北太平洋粉尘通量快速增加[81,85]，我国西北地区沉积物粒度质量累计比率增加[86](图 4b)，表明亚洲内陆干旱化的进一步加强；与此同时，黄土高原六盘山以东地区多个磁性地层结果表明，黄土下伏红粘土的年代为约 8~7Ma，指示粉尘沉积范围在不断扩大及搬运粉尘所需冬季风的加强，说明此阶段亚洲内陆干旱化的显著增长[16,17,87~92]；此外，古气候定量化结果显示，兰州地区晚中新世(约 8Ma)以来年均降水从 1150±350mm 减少至上新世的 500±100mm 及更新世的 240±40mm[93]；敦煌地区[94]和青海循化盆地[95]的古气候定量化结果也揭示，约 8Ma 以来年降水量逐渐减少，表明不断增强的干旱化趋势。

众多研究已表明，青藏高原隆升[3~6,34,96~100]、全球变冷[3,4,7,25,37,39]及副特提斯海的退缩[36,101~104]是导致亚洲内陆干旱化的重要原因。数值模拟结果认为，青藏高原隆起对来自印度洋的暖湿气流输送起着重要的阻挡作用，并在高原北侧形成下沉气流，影响亚洲内陆干旱化的过程[5,6,34]。高原隆升对西伯利亚高压也有加强作用，并加强了冬季风，是促进亚洲内陆干旱化的另一个途径[6,34,100]。另一方面，全球变冷会使大气中的水汽含量明显减少，导致亚洲内陆大陆度显著增加[7]；北极冰盖的发育也会加强西伯利亚高压，促进干旱气候的形成[5,105]；此外，副特提斯海在空间上的逐步西撤，改变了海陆热力差异，引起气压结构的重组，加强了东亚季风环流，导致亚洲内陆地区水汽急剧减少，从而引起欧亚大陆显著的干旱化[34,101]。

我国古植被演化表明(图 3 和图 4a)，亚洲内陆的干旱化可能始于晚渐新世(约 27~24Ma)，并在晚中新世(约 8Ma)急剧加强。由于全球温度在约 14Ma 前一直维持较高，虽然深海氧同位素记录了期间发生了几次重要的气候事件[106,107]，如早渐新世降温事件(Earliest Oligocene Glacial Maximum)、晚渐新世增温事件(Late Oligocene Warming)和中中新世适宜期(Mid-Miocene Climate Optimum)等，但是这一阶段并未发生约 27~24Ma 时段的明显阶段性降温(图 4e)。因此晚渐新世的亚洲内陆干旱化难以用全球变冷引起大气水汽含量降低导致亚洲内陆干旱化来解释。

青藏高原研究表明，约 28~26Ma，青藏高原南部可能已隆升到现今高度[98,108~110]；渐新世-中新世早期(约 29~24Ma)，东昆仑造山带快速隆升，并引起柴达木盆地与高原内部可可西里和风火山盆地的解体[111~113]；另一方面，多数盆地则在晚渐新世-中新世开始形成，如寺口子盆地形成于约 29Ma[114]、临夏盆地形成于约 29Ma[115]、共和盆地形成于约 22Ma[116]等。如前所述，此阶段高原隆升可能加强了对印度洋水汽输送的阻挡[5,6]，同时加强了西伯利亚高压[6,34,100]，进而导致亚洲内陆的干旱化。另一方面，在青藏高原不同隆升高度场景下对干旱区影响的数值模拟结果进一步显示[117]，当青藏高原隆升高度为 0m 时，副热带高压控制下干旱-半干旱区位于我国的中部，其核心区域为 30°N 左右；只有当高原隆升到一定阈值时(现今高度的 1/2)，我国内陆 40°N 以北地区才会出现明显的干旱环境。因此，我们认为晚渐新世西北内陆干旱环境的出现可能与该时段青藏高原隆升到一定高度有关。

另外，西北内陆的干旱化还可能与副特提斯海的退缩有关。许多研究表明，晚始新世开始副特提斯海可能从塔里木盆地退出[102~104,118]，虽其最后的退出时间还存在争议，但晚渐新世副特提斯海面积不断向西缩减是事实；缩减也使古地中海和副特提斯海之间的隔离状况更加严重[102~104]。上述因素改变了海陆热力差异，导致亚洲内陆地区水汽减少，

也可能促进了亚洲内陆干旱环境的形成。

约 8Ma 以来，尽管青藏高原隆升和副特提斯海进一步萎缩[104]，可能对亚洲内陆的干旱化也有一定的贡献；但是该时段全球温度急剧下降（图 4e），北半球高纬冰盖开始逐步发育[106,107]，与亚洲内陆干旱程度快速增强同步，说明这一阶段全球变冷，尤其是北半球降温对干旱环境的演化具有明显的影响。

综上所述，我们认为亚洲内陆约 27～24Ma 出现的干旱环境可能与青藏高原隆升及副特提斯海的退缩有关，之后干旱化过程受全球变冷影响逐步加强，约 8Ma 以来亚洲内陆的急剧干旱化可能与北半球高纬变冷的关系更为密切。

致谢 真诚感谢审稿老师建设性的修改意见，使文章得以完善和最终发表。

参考文献（References）

1 符淙斌，安芷生. 我国北方干旱化研究——面向国家需求的全球变化科学问题. 地学前缘，2002，**9**(2)：271～275
Fu Congbin, An Zhisheng. Study of aridification in Northern China——A global change issue facing directly the demand of nation. *Earth Science Frontiers*, 2002, **9**(2): 271～275

2 Guo Z T, Peng S Z, Hao Q Z *et al.* Late Miocene-Pliocene development of Asian aridification as recorded in an eolian sequence in Northern China. *Global Planet Change*, 2004, **41**(3～4): 135～145

3 Guo Z T, Ruddiman W F, Hao Q Z *et al.* Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. *Nature*, 2002, **416**: 159～163, doi: 10.1038/416159a

4 Guo Z T, Sun B, Zhang Z S *et al.* A major reorganization of Asian climate by the Early Miocene. *Climate of the Past*, 2008, **4**(3): 153～174

5 Ruddiman W F, Kutzbach J E. Forcing of Late Cenozoic Northern Hemisphere climate by plateau uplift in southern Asia and the American West. *Journal of Geophysical Research*: *Atmospheres*, 1989, **94**(15): 18409～18427

6 Kutzbach J E, Prell W L, Ruddiman W F. Sensitivity of Eurasian climate to surface uplift of the Tibetan Plateau. *The Journal of Geology*, 1993, **101**(2): 177～190

7 Felzer B, Oglesby R J, Webb T *et al.* Sensitivity of a general circulation model to changes in Northern Hemisphere ice sheets. *Journal of Geophysical Research*, 1996, **101**(14): 19077～19092

8 安芷生，张培震，王二七等. 中新世以来我国季风-干旱环境演化与青藏高原的生长. 第四纪研究，2006，**26**(5)：678～693
An Zhisheng, Zhang Peizhen, Wang Erchie *et al.* Changes of the monsoon-arid environment in China and growth of the Tibetan Plateau since the Miocene. *Quaternary Sciences*, 2006, **26**(5): 678～693

9 Dupont-Nivet G, Hoorn C, Konert M. Tibetan uplift prior to the Eocene-Oligocene climate transition: Evidence from pollen analysis of the Xining Basin. *Geology*, 2008, **32**(12): 987～990

10 Wang P X. Neogene stratigraphy and paleoenvironments of China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 1990, **77**(3～4): 315～334

11 刘东生，郑绵平，郭正堂. 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. 第四纪研究，1998，(3)：194～204
Liu Tungsheng, Zheng Mianping, Guo Zhengtang. Initiation and evolution of the Asian monsoon system timely coupled with the ice-sheet growth and the tectonic movements in Asia. *Quaternary Sciences*, 1998, (3): 194～204

12 张仲石，郭正堂. 根据地质记录恢复渐新世和中新世不同时期环境空间特征及其意义. 第四纪研究，2005，**25**(4)：523～530
Zhang Zhongshi, Guo Zhengtang. Spatial character reconstruction of different periods in Oligocene and Miocene. *Quaternary Sciences*, 2005, **25**(4): 523～530

13 Sun X J, Wang P X. How old is the Asian monsoon system? —Palaeobotanical records from China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2005, **222**(3～4): 181～222

14 Hao Q Z, Guo Z T. Magnetostratigraphy of an Early-Middle Miocene loess-soil sequence in the western Loess Plateau of China. *Geophysical Research Letters*, 2007, **34**(18): L18305, doi: 10.1029/2007GL031162

15 Qiang X, An Z S, Song Y *et al.* New eolian red clay sequence on the western Chinese Loess Plateau linked to onset of Asian desertification about 25Ma ago. *Science China Earth Sciences*, 2011, **54**(1): 136～144

16 Ding Z L, Xiong S F, Sun J M *et al.* Pedostratigraphy and paleomagnetism of a ～7.0Ma eolian loess-red clay sequence at Lingtai, Loess Plateau, north-Central China and the implications for paleomonsoon evolution. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 1999, **152**(1～2): 49～66

17 Ding Z L, Yang S L, Sun J M *et al.* Iron geochemistry of loess and red clay deposits in the Chinese Loess Plateau and implications for long-term Asian monsoon evolution in the last 7.0Ma. *Earth and Planetary Science Letters*, 2001, **185**(1～2): 99～109

18 Zhang Y B, Sun D H, Li Z J *et al.* Cenozoic record of aeolian sediment accumulation and aridification from Lanzhou, China, driven by Tibetan Plateau uplift and global climate. *Global and Planetary Chang*, 2014, **120**: 1～15, doi: 10.1016/j.gloplacha.2014.05.009

19 方小敏，徐先海，宋春晖等. 临夏盆地新生代沉积物高分辨率岩石磁学记录与亚洲内陆干旱化过程及原因. 第四纪研究，2007，**27**(6)：989～1000
Fang Xiaomin, Xu Xianhai, Song Chunhui *et al.* High resolution rock magnetic records of Cenozoic sediments in the Linxia Basin and their implications on drying of Asian inland. *Quaternary Sciences*, 2007, **27**(6): 989～1000

20 马小林，田　军. 15Ma 以来海陆记录的轨道-构造尺度东亚季风的演化以及西北内陆的干旱化. 第四纪研究，2015，**35**(6)：1320～1330

Ma Xiaolin, Tian Jun. East Asian monsoon evolution and aridification of Northwest China viewed from land and sea on the tectonic-orbital time scale since 15Ma. *Quaternary Sciences*, 2015, **35**(6): 1320~1330

21 Sun J M, Ye J, Wu W *et al.* Late Oligocene-Miocene mid-latitude aridification and wind patterns in the Asian interior. *Geology*, 2010, **38**(6): 515~518

22 Zheng H B, Wei X C, Tada R *et al.* Late Oligocene-Early Miocene birth of the Taklimakan Desert. *Proceedings of the National Academy of Sciences of the United States of America*, 2015, **112**(25): 7662~7667

23 Zheng H B, Powell C, An Z S *et al.* Pliocene uplift of northern Tibetan Plateau. *Geology*, 2000, **28**(8): 715~718

24 Tang Z H, Ding Z L, White P D *et al.* Late Cenozoic Central Asian drying inferred from a palynological record from the northern Tian Shan. *Earth and Planetary Science Letters*, 2011, **302**(3~4): 439~447

25 Dupont-Nivet G, Krijgsman W, Langereis C G *et al.* Tibetan Plateau aridification linke to global cooling at the Eocene-Oligocene transition. *Nature*, 2007, **445**, 635~638, doi: 10.1038/nature05516

26 Sun J M, Windley B F. Onset of aridification by 34Ma across the Eocene-Oligocene transition in Central Asia. *Geology*, 2015, **43**(11): 1015~1018

27 Xiao G Q, Abels H A, Yao Z *et al.* Asian aridification linked to the first step of the Eocene-Oligocene climate Transition (EOT) in obliquity-dominated terrestrial records (Xining Basin, China). *Climate of the Past*, 2010, **6**: 501~513, doi: 10.5194/cp-6-501-2010, 2010

28 Zhang C X, Guo Z J. Clay mineral changes across the Eocene-Oligocene transition in the sedimentary sequence at Xining occurred prior to the global cooling. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2014, **411**: 18~29, doi: 10.1016/j. palaeo. 2014.06.031

29 赵秀丽，张春霞，吴海斌等. 西宁盆地始新世/渐新世过渡期孢粉植物群特征及其意义. 第四纪研究，2015，**35**(6)：1489~1499

Zhao Xiuli, Zhang Chunxia, Wu Haibin *et al.* Significance of Eocene-Oligocene transition pollen record from Xining Basin, China. *Quaternary Sciences*, 2015, **35**(6): 1489~1499

30 Zhang X G, Xiao G Q, Guo Z T *et al.* Evidence of late Early Miocene aridification intensification in the Xining Basin caused by the northeastern Tibetan Plateau uplift. *Global and Planetary Change*, 2015, **128**: 31~46, doi: 10.1016/j. gloplacha. 2015.02.002

31 Long Liqun, Fang Xiaomin, Miao Yunfa *et al.* Northern Tibetan Plateau cooling and aridification linked to Cenozoic global cooling: Evidence from *n*-alkane distributions of Paleogene sedimentary sequences in the Xining Basin. *Chinese Science Bulletin*, 2011, **56**(15): 1569~1578

32 鹿化煜，安芷生，王晓勇等. 最近 14Ma 青藏高原东北缘阶段性隆升的地貌证据. 中国科学（D 辑），2004，**34**(9)：855~864

Lu Huayu, An Zhisheng, Wang Xiaoyong *et al.* Geomorphologic evidence of phased uplift of the northeastern Qinghai-Tibet Plateau since 14 million years ago. *Science in China* (Series D), 2004, **34**(9): 855~864

33 Wang X Y, Lu H Y, Vandenberghe J *et al.* Late Miocene uplift of the NE Tibetan Plateau inferred from basin filling, planation and fluvial terraces in the Huang Shui catchment. *Global Planet Change*, 2012, **88~89**: 10~19, doi: 10.1016/j. gloplacha. 2012.02.009

34 An Z S, Kutzbach J E, Prell W L *et al.* Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan Plateau since Late Miocene times. *Nature*, 2001, **411**: 62~66, doi: 10.1038/35075035

35 滕晓华，韩文霞，叶程程等. 柴达木盆地 SG-1 孔 1.0Ma 以来碳酸盐同位素记录的亚洲内陆干旱化及成因. 第四纪研究，2013，**33**(5)：866~875

Teng Xiaohua, Han Wenxia, Ye Chengcheng *et al.* Aridification of the Asian inland since 1.0Ma: Evidences from carbonate isotope records of deep core from the Qaidam Basin. *Quaternary Sciences*, 2013, **33**(5): 866~875

36 Ramstein G, Fluteau F, Besse J *et al.* Effect of orogeny, plate motion and land-sea distribution on Eurasian climate change over the past 30 million years. *Nature*, 1997, **386**: 788~795, doi: 10.1038/386788a0

37 郭正堂，彭淑贞，郝青振等. 晚第三纪中国西北干旱化的发展及其与北极冰盖形成演化和青藏高原隆升的关系. 第四纪研究，1999，(6)：556~566

Guo Zhengtang, Peng Shuzhen, Hao Qingzhen *et al.* Late Tertiary development of aridification in Northwestern China: Link with the Arctic ice-sheet formation and Tibetan uplifts. *Quaternary Sciences*, 1999, (6): 556~566

38 Lu H Y, Wang X Y, Li F L. Aeolian sediment evidence that global cooling has driven Late Cenozoic stepwise aridification in Central Asia. *Geological Society*, London, Special Publications, 2010, **342**(1): 29~44

39 Lu Huayu, Guo Zhengtang. Evolution of the monsoon and dry climate in East Asia during Late Cenozoic: A review. *Science China*: *Earth Sciences*, 2014, **57**(1): 70~79

40 方小敏，吴福莉，韩文霞等. 上新世-第四纪亚洲内陆干旱化过程——柴达木中部鸭湖剖面孢粉和盐类化学指标证据. 第四纪研究，2008，**28**(5)：874~882

Fang Xiaomin, Wu Fuli, Han Wenxia *et al.* Plio-Pleistocene drying process of Asian inland——Sporopollen and salinity records from Yahu section in the central Qaidam Basin. *Quaternary Sciences*, 2008, **28**(5): 874~882

41 Bette L, Bllesner B, Garland R *et al.* Vegetation-induced warming of high-latitude regions during the Cretaceous Period. *Nature*, 1997, **385**(6619): 804~807

42 Wang W M. Correlation of pollen sequences in the Neogene palynofloristic regions of China. *Palaeoworld*, 2006, **15**(1): 77~99

43 Jiang H, Ding Z. Spatial and temporal characteristics of Neogene palynoflora in China and its implication for the spread of steppe vegetation. *Journal of Arid Environments*, 2009, **73**(9): 765~772

44 Miao Y F, Herrmann M, Wu F L *et al.* What controlled Mid-Late Miocene long-term aridification in Central Asia? —Global cooling or Tibetan Plateau uplift: A review. *Earth Science Reviews*, 2012, **112**(3): 155~172

45 Tang Z H, Ding Z L. A palynological insight into the Miocene aridification in the Eurasian interior. *Palaeoworld*, 2013, **22**(3): 77~85

46 中国第四纪孢粉数据库小组. 表土孢粉模拟的中国生物群区. 植物学报, 2001, **43**(2): 201~209

Members of China Quaternary Pollen Data Base. Simulation of China biome reconstruction based on pllen data from surface sediment samples. *Acta Botanica Sinica*, 2001, **43**(2): 201~209

47 Gradstein F M, Ogg G, Schmitz M *et al.* The Geologic Time Scale 2012. Amsterdam: Elsevier, 2012. 85~113

48 马玉贞, 李吉均, 方小敏. 临夏地区30.6~5.0Ma红层孢粉植物群与气候演化记录. 科学通报, 1998, **43**(3): 301~304

Ma Yuzhen, Li Jijun, Fang Xiaomin. Palynoflora and climate evolution during 30.6~5.0Ma at Linxia. *Chinese Science Bulletin*, 1998, **43**(3): 301~304

49 Lu Houyuan, Wang Sumin, Wu Naiqin *et al.* A new pollen record of the last 2.8Ma from the Co Ngoin. central Tibetan Plateau. *Science in China* (Series D), 2001, **44**(1): 292~300

50 Ma Yuzhen, Fang Xiaomin, Li Jijun *et al.* The vegetation and climate change during Neocene and Early Quaternary in Jiuxi Basin, China. *Science in China* (Series D), 2005, **48**(5): 676~688

51 陈传飞. 青藏高原东北缘西宁盆地新生代孢粉记录与古生态环境演化. 兰州: 兰州大学硕士学位论文, 2009. 1~134

Chen Chuanfei. Cenozoic Pollen Records and Palaeoenvironmental Evolution in Xining Basin, Northeasten Tibetan Plateau. Lanzhou: The Master's Dissertation of Lanzhou University, 2009. 1~134

52 Miao Y, Fang X, Herrmann M *et al.* Miocene pollen record of KC-1 core in the Qaidam Basin, NE Tibetan Plateau and implications for evolution of the East Asian monsoon. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2011, **299**(1): 30~38

53 Cai M, Fang X, Wu F *et al.* Pliocene-Pleistocene stepwise drying of Central Asia: Evidence from paleomagnetism and sporopollen record of the deep borehole SG-3 in the western Qaidam Basin, NE Tibetan Plateau. *Global and Planetary Change*, 2012, **94~95**: 72~81, doi: 10.1016/j. gloplacha. 2012.07.002

54 Sun J, Xu Q, Liu W *et al.* Palynological evidence for the Latest Oligocene-Early Miocene paleoelevation estimate in the Lunpola Basin, central Tibet. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2014, **399**: 21~30, doi: 10.1016/j. palaeo. 2014.02.004

55 Sun J, Xu Q, Huang B. Late Cenozoic magnetochronology and paleoenvironmental changes in the northern foreland basin of the Tian Shan Mountains. *Journal of Geophysical Research*, 2007, **112**: B04107, doi: 10.1029/2006JB004653, 2007

56 Tang Z, Ding Z, White P D *et al.* Late Cenozoic Central Asian drying inferred from a palynological record from the northern Tian Shan. *Earth and Planetary Science Letters*, 2011, **302**(3): 439~447

57 Sun J, Zhang Z. Palynological evidence for the Mid-Miocene Climatic Optimum recorded in Cenozoic sediments of the Tian Shan Range, Northwestern China. *Global and Planetary Change*, 2008, **64**(1): 53~68

58 Zhang Z, Sun J. Palynological evidence for Neogene environmental change in the foreland basin of the southern Tianshan range, Northwestern China. *Global and Planetary Change*, 2011, **75**(1): 56~66

59 Hao H, Ferguson D K, Chang H *et al.* Vegetation and climate of the Lop Nur area, China, during the past 7 million years. *Climatic Change*, 2012, **113**(2): 323~338

60 Sun J, Ni X, Bi S *et al.* Synchronous turnover of flora, fauna, and climate at the Eocene-Oligocene boundary in Asia. *Scientific Reports*, 2014, **4**: 07463, doi: 10.1038/srep07463

61 Han J, Fyfe W, Longstaffe F J *et al.* Pliocene-Pleistocene climatic change recorded in fluviolacustrine sediments in Central China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 1997, **135**(1): 27~39

62 吴玉书. 甘肃灵台雷家河地区中新世晚期-上新世早期孢粉植物群. 植物学报, 2001, **43**(7): 750~756

Wu Yushu. Palynoflora at Late Miocene-Early Pliocene from Leijiahe of Lingtai, Gansu Province, China. *Acta Botanica Sinica*, 2001, **43**(7): 750~756

63 Liu G, Estella B L, Yun L *et al.* Palynological record of Pliocene climate events in North China. *Review of Palaeobotany and Palynology*, 2002, **119**(3): 335~340

64 Li X Q, Li C S, Lu H Y *et al.* Paleovegetation and paleoclimate in Middle-Late Pliocene, Shanxi, Central China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2004, **210**(1): 57~66

65 Wang L, Lu H Y, Wu N Q *et al.* Palynological evidence for Late Miocene-Pliocene vegetation evolution recorded in the red clay sequence of the central Chinese Loess Plateau and implication for palaeoenvironmental change. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2006, **241**(1): 118~128

66 Wu F, Fang X, Ma Y *et al.* Plio-Quaternary stepwise drying of Asia: Evidence from a 3Ma pollen record from the Chinese Loess Plateau. *Earth and Planetary Science Letters*, 2007, **257**(1): 160~169

67 Jiang H C, Ding Z L. A 20Ma pollen record of East-Asian summer monsoon evolution from Guyuan, Ningxia, China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2008, **265**(1): 30~38

68 Qin F, Ferguson D K, Zetter R *et al.* Late Pliocene vegetation and climate of Zhangcun region, Shanxi, North China. *Global Change Biology*, 2011, **17**(5): 1850~1870

69 Hui Z, Li J, Xu Q *et al.* Miocene vegetation and climatic changes reconstructed from a sporopollen record of the Tianshui Basin, NE Tibetan Plateau. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2011, **308**(3): 373~382

70 肖霞云, 沈 吉, 王苏民等. 鹤庆深钻孢粉记录揭示的2.78Ma以来的植被演替与气候变迁. 中国科学 (D辑), 2007, **37**(6): 778~788

Xiao Xiayun, Shen Ji, Wang Sumin *et al.* The plant diversity and its relationship with paleoenvironment since 2.78Ma revealed by pollen records in the Heqing deep drilling core. *Science in China* (Series D), 2007, **37**(6): 778~788

71 常 琳. 晚中新世-上新世中国西南季风区植被演化：来自云南昭通盆地的孢粉学证据. 北京：中国科学院大学博士学位论文，2015. 1~104

Chang Lin. Vegetation History during the Late Miocene-Pliocene in the Southwestern Monsoon Region of China: Pollen Evidence from Zhaotong Basin, Yunnan Province. Beijing: The Doctoral Dissertation of University of Chinese Academy of Sciences, 2015. 1~104

72 任祥斌，云南大理盆地晚中新世-上新世孢粉植物群演化. 青岛：山东科技大学硕士学位论文，2015. 1~50

Ren Xiangbin. Palynoflora Evolution during Late Miocene-Pliocene at Dali, Yunnan. Qingdao: The Master's Dissertation of Shandong University of Science and Technology, 2015. 1~50

73 杨吉龙，秦雅飞，胥勤勉等. 7.65Ma BP 以来天津滨海地区的植被演变特征. 地质学报，2015，**89**(6)：1134~1143

Yang Jilong, Qin Yafei, Xu Qinmian *et al.* Palaeovegetation evolution features of the Tianjin coastal region since 7.65Ma BP. *Acta Geologica Sinica*, 2015, **89**(6): 1134~1143

74 Hoorn C, Ohja T, Quade J *et al.* Palynological evidence for vegetation development and climatic change in the Sub-Himalayan Zone (Neogene, Central Nepal). *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2000, **163**(3): 133~161

75 Demske D, Mohr B, Oberhansli H *et al.* Late Pliocene vegetation and climate of the Lake Baikal region, southern East Siberia, reconstructed from palynological data. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2002, **184**(1): 107~129

76 Wu Guoxuan. Deep-water Oligocene pollen record from South China Sea. *Chinese Science Bulletin*, 2003, **48**(22): 2511~2515

77 Cande S C, Kent D V. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, 1995, **100**(B4): 6093~6095

78 Gradstein F, Ogg J, Smith A *et al.* A Geological Time Scale 2004. Cambridge: Cambridge University Press, 2004. 1~589

79 Guiot J, Goeury C. PPPBASE, a software for statistical analysis of paleoecological and paleoclimatological data. *Dendrochronologia*, 1996, **14**: 295~300

80 Prentice C, Guiot J, Huntley B *et al.* Reconstructing biomes from palaeoecological data: A general method and its application to European pollen data at 0 and 6ka. *Climate Dynamics*, 1996, **12**(3): 185~194

81 Rea D K, Leinen M, Janecek T R. Geologic approach to the long term history of atmospheric circulation. *Science*, 1985, **227**(4688): 721~725

82 Zhang Y B, Sun D H, Li Z J *et al.* Cenozoic record of aeolian sediment accumulation and aridification from Lanzhou, China, driven by Tibetan Plateau uplift and global climate. *Global and Planetary Change*, 2014, **120**: 1~15, doi: 10.1016/j. gloplacha. 2014.05.009

83 Wang Q, Spicer R A, Yang J *et al.* The Eocene climate of China, the early elevation of the Tibetan Plateau and the onset of the Asian monsoon. *Global Change Biology*, 2013, **19**(12): 3709~3728

84 Quan C, Liu Y S, Utescher T. Eocene monsoon prevalence over China: A paleobotanical perspective. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2012, **365~366**: 302~311, doi: 10.1016/j. palaeo. 2012.09.035

85 Rea D K, Snoeckx H, Jasoph L H. Late Cenozoic eolian deposition in the North Pacific: Asian drying, Tibetan uplift, and cooling of the Northern Hemisphere. *Paleoceanography*, 1998, **13**(3): 215~224

86 徐先海，方小敏，宋春晖等. 临夏盆地新生代沉积物粒度记录与亚洲内陆干旱化. 湖泊科学，2008，**20**(1)：65~75

Xu Xianhai, Fang Xiaomin, Song Chunhui *et al.* Grain-size records of Cenozoic lacustrine sediments from Linxia Basin and the aridification of Asian inland. *Journal of Lake Sciences*, 2008, **20**(1): 65~75

87 Sun D H, Shaw J, An Z S *et al.* Magnetostratigraphy and paleoclimatic interpretation of a continuous 7.2Ma Late Cenozoic eolian sediments from the Chinese Loess Plateau. *Geophysical Research Letters*, 1998, **25**(1): 85~88

88 Sun D H, An Z S, Shaw J *et al.* Magnetostratigraphy and palaeoclimatic significance of Late Tertiary aeolian sequences in the Chinese Loess Plateau. *Geophysical Journal International*, 1998, **134**(1): 207~212

89 Sun D H, Zhang F Y, Han F *et al.* Magnetostratigraphy and palaeoenvironmental records for a Late Cenozoic sedimentary sequence from Lanzhou, northeastern margin of the Tibetan Plateau. *Global and Planetary Change*, 2011, **76**(3): 106~116

90 Qiang X K, Li Z X, Powell C M *et al.* Magnetostratigraphic record of the Late Miocene onset of the East Asian monsoon, and Pliocene uplift of northern Tibet. *Earth and Planetary Science Letters*, 2001, **187**(1): 83~93

91 Song Y G, Fang X M, Torii M *et al.* Late Neogene rock magnetic record of climatic variation from Chinese eolian sediments related to uplift of the Tibetan Plateau. *Journal of Asian Earth Sciences*, 2007, **30**(2): 324~332

92 Zhu Y M, Zhou L P, Mo D W *et al.* A new magnetostratigraphic framework for Late Neogene Hipparion Red Clay in the eastern Loess Plateau of China. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2008, **268**(1): 47~57

93 王 飞，孙东怀，张月宝等. 过去 8Ma 兰州盆地古温度、古降水和古高度的半定量估算. 第四纪研究，2012，**32**(5)：1021~1035

Wang Fei, Sun Donghuai, Zhang Yuebao *et al.* Quantitative reconstruction of Late Cenozoic paleoclimate and paleoelevation of Lanzhou basin in north east Tibetan Plateau. *Quaternary Sciences*, 2012, **32**(5): 1021~1035

94 Liu Y S, Utescher T, Zhou Z K. The evolution of Miocene climates in North China: Preliminary results of quantitative reconstructions from plant fossil records. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 2011, **304**(3): 308~317

95 徐增连. 青藏高原东北缘循化盆地渐新世-中新世孢粉记录与东亚季风演化. 武汉：中国地质大学（武汉）博士学位论文，2015. 1~109

Xu Zenglian. Oligocene-Miocene Pollen Records in Xunhua Basin, Northeastern Tibetan Plateau and Its Implications for Evolution of the East Asian Monsoon. Wuhan: The Doctoral Dissertation of China University of Geosciences (Wuhan), 2015. 1～109

96 Molnar P, Boos W R, Battisti D S. Orographic controls on climate and paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau. *Annual Review of Earth and Planetary Sciences*, 2010, **38**(1): 77～102

97 Molnar P, Burchfiel B C, Zhao Z Y *et al.* The geologic evolution of northern Tibet: Results from an expedition to Ulugh Muztagh. *Science*, 1987, **235**(4786): 299～304

98 Molnar P, Houseman G A, England P C. Earth science: Palaeo-altimetry of Tibet. *Nature*, 2006, **444**: E4, doi: 10.1038/nature05368

99 Molnar P, Stock J M. Slowing of India's convergence with Eurasia since 20Ma and its implications for Tibetan mantle dynamics. *Tectonics*, 2009, **28**(3): TC3001, doi: 10.1029/2008TC002271

100 Manabe S, Terpstra T B. The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments. *Journal of the Atmospheric Sciences*, 1974, **31**(1): 3～42

101 Fluteau F, Ramstein G, Besse J. Simulating the evolution of the Asian and African monsoons during the past 30 Myr using an atmospheric general circulation model. *Journal of Geophysical Research: Atmospheres*, 1999, **104**(10): 11995～12018

102 Dercourt J, Ricou L E, Vrielynck B *et al.* Atlas Tethys, Paleoenvironmental Maps: Explanatory Notes. Pairs: Gauthiervillars, 1993. 1～307

103 Rogl F. Mediterranean and Paratethys, facts and hypotheses of an Oligocene to Miocene paleogeography (short overview). *Geologica Carpathica*, 1999, **50**(4): 339～349

104 Popov S V, Rogl F, Rozanov A Y *et al.* Lithological-paleogeographic maps of Parathys, 10 Maps Late Eocene to Pliocene. *Courier Forschungsinstitut Senckenberg*, 2004, **250**: 1～46

105 Ding Z L, Derbyshire E, Yang S L *et al.* Stepwise expansion of desert environment across Northern China in the past 3.5Ma and implications for monsoon evolution. *Earth and Planetary Science Letters*, 2005, **237**(1): 45～55

106 Zachos J C, Gerald R D, Richard E Z. An Early Cenozoic perspective on greenhouse: Warming and carbon-cycle dynamics. *Nature*, 2008, **451**(17): 279～283

107 Zachos J C, Pagani M, Sloan L *et al.* Trend, rhythms, and aberrations in global climate 65Ma to present. *Science*, 2001, **292**(5517): 686～693

108 Rowley D B, Currie B S. Palaeo-altimetry of the Late Eocene to Miocene Lunpola Basin, central Tibet. *Nature*, 2006, **439**(7077): 677～681

109 DeCelles P G, Quade J, Kapp P *et al.* High and dry in central Tibet during the Late Oligocene. *Earth and Planetary Science Letters*, 2007, **253**(3): 389～401

110 Ding L, Xu Q, Yue Y H *et al.* The Andean-type Gangdese Mountains: Paleoelevation record from the Paleocene-Eocene Linzhou Basin. *Earth and Planetary Science Letters*, 2014, **392**(15): 250～264

111 Yin A, Dang Y Q, Zhang M *et al.* Cenozoic tectonic evolution of Qaidam Basin and its surrounding regions (part 2): Wedge tectonics in southern Qaidam Basin and the Eastern Kunlun range. *Geological Society of America Special Papers*, 2007, **433**: 369～390, doi: 10.1130/2007.2433 (18)

112 Yin A, Dang Y Q, Wang L C *et al.* Cenozoic tectonic evolution of Qaidam Basin and its surrounding regions (part 1): The southern Qilian Shan-Nan Shan thrust belt and northern Qaidam Basin. *Geological Society of America Bulletin*, 2008, **120**(7～8): 813～846

113 Yin A, Dang Y Q, Zhang M *et al.* Cenozoic tectonic evolution of the Qaidam Basin and its surrounding regions (part 3): Structural geology, sedimentation, and regional tectonic reconstruction. *Geological Society of America Bulletin*, 2008, **120**(7～8): 847～876

114 Wang W, Zhang P, Kirby E *et al.* A revised chronology for Tertiary sedimentation in the Sikouzi Basin: Implications for the tectonic evolution of the northeastern corner of the Tibetan Plateau. *Tectonophysics*, 2011, **505**(1): 100～114

115 Fang X, Garzione C, Van der Voo R *et al.* Flexural subsidence by 29Ma on the N edge of Tibet from the magnetostratigraphy of Linxia Basin, China. *Earth and Planetary Science Letters*, 2003, **210**(3): 545～560

116 Craddock W, Kirby E, Zhang H. Late Miocene-Pliocene range growth in the interior of the northeastern Tibetan Plateau. *Lithosphere*, 2011, **3**(6): 420～438

117 Liu X D, Guo Q C, Guo Z T *et al.* Where were the monsoon regions and arid zones in Asia prior to the Tibetan Plateau uplift? *National Science Review*, 2015, **2**: 403～416, doi: 10.1093/nsr/nwv068

118 Sun J M, Windley B F, Zhang Z L *et al.* Diachronous seawater retreat from the southwestern margin of the Tarim Basin in the Late Eocene. *Journal of Asian Earth Sciences*, 2016, **116**: 222～231, doi: 10.1016/j.jseaes.2015.11.020

ARIDIFICATION IN NORTHWESTERN CHINA SINCE THE LATE CENOZOIC EVIDENCED BY THE VEGETATION CHANGE

Zhu Shuya①② Wu Haibin①② Li Qin①③ Zhang Chunxia①③
Yu Yanyan①③ Sun Aizhi①② Guo Zhengtang①②③
(①*Key Laboratory of Cenozoic Geology and Environment*, *Institute of Geology and Geophysics*, *Chinese Academy of Sciences*, *Beijing* 100029; ②*University of Chinese Academy of Sciences*, *Beijing* 100049; ③*CAS Center for Excellence in Tibetan Plateau Earth Sciences*, *Beijing* 100101)

Abstract

The aridification in the Asian Interior is one of the key climate events in the Cenozoic. Over the past score years, although numerous studies from separated locations within the continental interior obtain the fundamental framework for the aridification, discrepancy exists among various records from different areas, and the history of the aridification is still open to debate. To better constrain the evolution of aridification in inner Asia, a promising approach is to reconstruct a long-term, well-dated environmental history based on regional integrated analysis. In addition, Northwestern China is located in the internal arid area of Asian, with a typical continental climate, so the vegetation change in this region is more sensitive to the aridity.

In order to achieve reliable vegetation change data, our collected palynological records are selected based on the following criteria: 1) the record should be well dated. The records constrained solely on lithological correlations or pollenchronologies are removed from consideration, and the remaining records are dated mainly by detailed magnetostratigraphic ages; 2) palynological records must cover detailed pollen spectrum information to ensure the accuracy of the biomization. A total of 30 palynological sequences met these criteria and have been used within this study. Then the chronologies of the palynological sequences were unified to the 2012 Geomagnetic Polarity Time Scale.

Finally, we used the biomization method to reconstruct the vegetation changes in Northwestern China during the Late Cenozoic. The results show a relatively humid climatic condition with mainly forest in Northwestern China from ca.36Ma to 28Ma. Steppe started to expand during ca.27Ma and 24Ma, indicating an aridification trend, and changed to desert during the interval from ca.23Ma to 18Ma. Aridity was significantly increased since ca.8Ma, as evidenced by the replacement of forests by steppe and deserts. We attribute the early stepwise aridification to the retreat of the Paratethys Sea and to the uplift of Tibetan Plateau, and the subsequent gradual aridification trends to the ongoing Late Cenozoic global cooling. The significant aridification since ca. 8Ma may be linked with the enhanced cooling in the northern high latitudes.

Key words biome, vegetation evolution, aridification, Late Cenozoic, global cooling, Tibetan Plateau uplift