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从晚古生代冰室到早中生代温室的气候转变：兼论东特提斯低纬区的沉积记录与响应

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摘　要　地球在晚古生代晚期—中生代早期经历最近一次从冰室到温室的气候转变，是理解未来地球冰川消融、全球变暖等气候转变的重要窗口。这一时期的沉积记录和气候模型研究揭示，冰川活动、大气 $p\mathrm{CO_2}$ 和气候状态间存在复杂的耦合和反馈机制，同时伴随发生陆表植被更替和生物迁移。随冰川消融、大气 $p\mathrm{CO_2}$ 升高和全球变暖，低纬大陆区干旱化趋势和季节性降雨增强，出现季风气候并在冰室之后的三叠纪温室盛行。华南和华北是位于东特提斯低纬区的主要大陆，其石炭—二叠系在沉积和生物特征上与 Pangea 超大陆西侧热带区差异显著，蕴含有丰富的深时气候变化信息。基于前人成果，在简述石炭—三叠纪全球气候变化的基础上，对东特提斯低纬区石炭—三叠纪沉积记录进行总结，阐明其深时古气候研究意义和研究前景。

关键词　深时古气候；晚古生代冰期；冰室—温室气候转变；Pangea 超大陆；季风气候

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0　引言

近现代人类活动导致大气 $\mathrm{CO_2}$ 浓度不断升高，在约 200 年间由工业革命前的 280 mL/m^3 激增到现在的 400 mL/m^3[1]。地球大气 $\mathrm{CO_2}$ 浓度上一次超过这一水平为新近纪上新世时期，距今约 260～530 万年，当时全球平均气候较现在高约 3℃～4℃。若 $\mathrm{CO_2}$ 的排放速率不能有效降低，按现在的增长速度，在本世纪末大气 $\mathrm{CO_2}$ 浓度可能达到近 34 Ma 以来的最高值[2]，人类生存、演化的冰室气候可能面临大陆冰川消融、温度升高等一系列气候环境变化。以第四纪冰室气候为基础的气候系统机制已不足以充分揭示未来气候的发展趋势，需要我们深入理解全球变暖背景下的气候系统和反馈机制。地球在显生宙以来整体以高大气 $p\mathrm{CO_2}$ 的温室和低大气 $p\mathrm{CO_2}$ 的冰室气候交替为特征[3-5]，有关过去的温室气候和气候转变的“深时”信息都蕴含于沉积记录中，因此基于沉积记录的深时古气候研究是全面理解地球气候转变过程和机制、改进气候模型并预测未来气候状态的关键[2,6-8]。在晚古生代晚期—中生代早期，地球经历了最近一次从冰室到温室的气候转变(图 1)，本文对该时期的古气候研究进展进行简述，并就此分析东特提斯低纬区华北

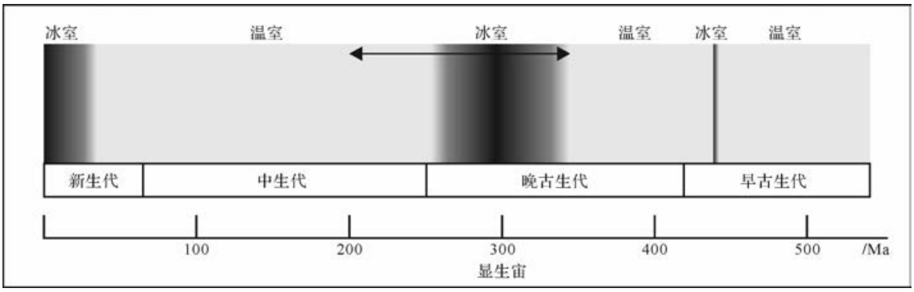

图 1　显生宙内冰室—温室气候交替变化的整体特征
(修改自文献[3])，黑色箭头指示从晚古生代冰室到早中生代温室的气候转变期

Fig.1　The icehouse-greenhouse climate alternations in the Phanerozoic with the black arrow showing the periods from the late Paleozoic ice age to the early Mesozoic greenhouse climate

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和华南的同期沉积记录的深时古气候意义。

1 晚古生代冰川活动

1.1 中—高纬冈瓦纳大陆及其北缘的冰川型沉积记录

作为晚古生代冰期最直接的证据,冰川型沉积记录广布于冈瓦纳陆块上[4],为一系列与冰川活动有关的沉积记录,包括块状—层状的杂砾岩、具刻痕/棱面的砾石、含落石的纹层状泥岩、软沉积变形等,它们形成于从冰缘到冰海/冰湖相多种沉积环境[9]。传统认为晚古生代冰川作用持续发育于南半球中高纬度地区,该冰川的扩张和消融引发中低纬度地区如欧美大陆边缘的高频海平面波动[10-13]。然而,近年来对这些冰川型沉积记录的研究表明,晚古生代冰川作用具有明显的阶段性,冰川沉积与非冰川沉积周期性叠置出现,且冰川中心随时间和空间发生变化[9,14-15]。通过对冈瓦纳大陆冰川型沉积地层的对比分析,Isbell *et al.*[9]将晚古生代冰川分为三期:Ⅰ期为晚泥盆—石炭纪早期,主要发育于南美洲西侧和非洲中部等地;Ⅱ期为石炭纪中期,主要发育于南美洲南部、澳大利亚东部和藏南等地;Ⅲ期为晚石炭世晚期—早二叠世早期(格舍尔阶—萨克马尔阶),广布于冈瓦纳大陆[15-17]及亲冈瓦纳地块群(如保山地块、腾冲地块、拉萨地块[18-23]等)之上。Ⅰ、Ⅱ期冰川活动分布范围小属山岳型冰川,受地势和雪线控制;而Ⅲ期冰川活动分布广泛,存在冰海/冰湖相沉积,具有大陆冰盖性质[9]。Fielding *et al.*[15]对澳大利亚东部石炭—二叠纪沉积的研究也揭示晚古生代冰川活动的多期性。石炭纪末—二叠纪初的冰川型沉积记录可达到35°~40°S的中纬度地区[24],甚至在Pangea超大陆西侧近赤道的北美中大陆高山地区也可能发育山岳型冰川活动和相关的黄土堆积[25-28],表明晚古生代冰川活动在这一时期达到最盛,分布范围最广[16,29](图2)。由于缺少必要的海相生物化石,这些冰川型沉积地层序列的时代约束明显不足,成为区域、全球气候对比的难点所在。近年来,对冰川型沉积序列所进行的火山灰层锆石U-Pb定年[30-31],特别是高精度热电离质谱U-Pb年代学研究[32-33],为提高地层年代精度、进行气候对比提供了必要保障。

1.2 低纬区海平面和气候变化的沉积指标记录

高纬冰川活动增强使大量降水储存于大陆表层,加上体积冷缩效应可导致显著的全球海平面下降,且冰川活动的强弱引发低纬区高频、高幅的海平面周期性变化,由此形成特征性的韵律性沉积序列[7]。同时,大量降水以冰川形式保存使冰量增大,可致使全球海水氧同位素组成发生变化,由此引发同期沉淀并与海水保持化学平衡的碳酸盐/磷酸盐矿物的氧同位素组成随之改变(也与海水温度存在相关性)。同时,冈瓦纳大陆冰川活动对应全球气候变冷,因海水温度是控制水体与沉积质间氧同位素分馏的重要因素,气候变冷也可通过降低海水温度而改变低纬区海相生物壳氧同位素组成。因此,低纬区的旋回性沉积序列和钙质生物壳氧同位素组成构成冰川活动的重要间接指标[45,47-50],晚古生代腕足壳和牙形石氧同位素的明显正偏与大规模冰川活动期大致吻合(图2)。此外,冰川活动在中低纬区的生态响应主要表现为植物的更替和海相生物的迁移、灭绝及生物多样性的降低,反映了生物对气候变化的响应[51-54]。在美国Illinois盆地, Smith *et al.*[55]发现晚维宪期沉积由以碳酸盐岩为主的序列突然转变为碳酸盐岩—碎屑岩混积序列,且深切谷—充填构造指示海平面下降幅度明显增大,达到约90 m,认为是冈瓦纳冰量突然增大的结果,指示冈瓦纳大规模冰川的启动。同期的海平面下降证据也见于华南右江盆地[56]。对比第四纪冰川的模型计算[57]和古地形重建研究[58]揭示,宾夕法尼亚亚纪冰川型海平面下降幅度在60~100 m。基于方解石质腕足壳氧同位素组成,Adlis *et al.*[59]估算宾夕法尼亚亚纪冰川型海平面最达下降幅度可达70 m,而基于磷灰石质牙形石氧同位素组成估算的同期海平面下降幅度大于120 m[60]。基于对大量晚古生代冰川型海平面波动研究总结,Rygel *et al.*[61]认为低纬区的旋回性沉积序列反映冈瓦纳冰川活动状态,即冰川型海平面变化幅度与冰川冰量有关,幅度越大对应冰量愈大。通过海侵地形重建,Sweet *et al.*[62]估算宾夕法尼亚亚纪早期最大冰川型海平变化约为20 m,尽管远低于上述估算值,作者认为该海平面变化幅度并不反映小冰盖的冰川活动,而可能指示大的稳定冰盖冰量的微小变化。然而,晚古生代冈瓦纳冰川多中心、多期次的活动属性似乎不足以支持大幅度(大于50~60 m)的海平面变化[9,29]。基于合理大气CO_2浓度的冰川—气候模型模拟也显示,晚古生代冰川型海平面变化幅度为25~33 m,很难大于50 m[63-64]。

2 冰室—温室气候转变

2.1 冰川活动的减弱与消亡

早二叠世冰盛期之后,全球气候开始转暖,澳大利亚东部等地萨克马尔阶之后的3次冰海型沉积指

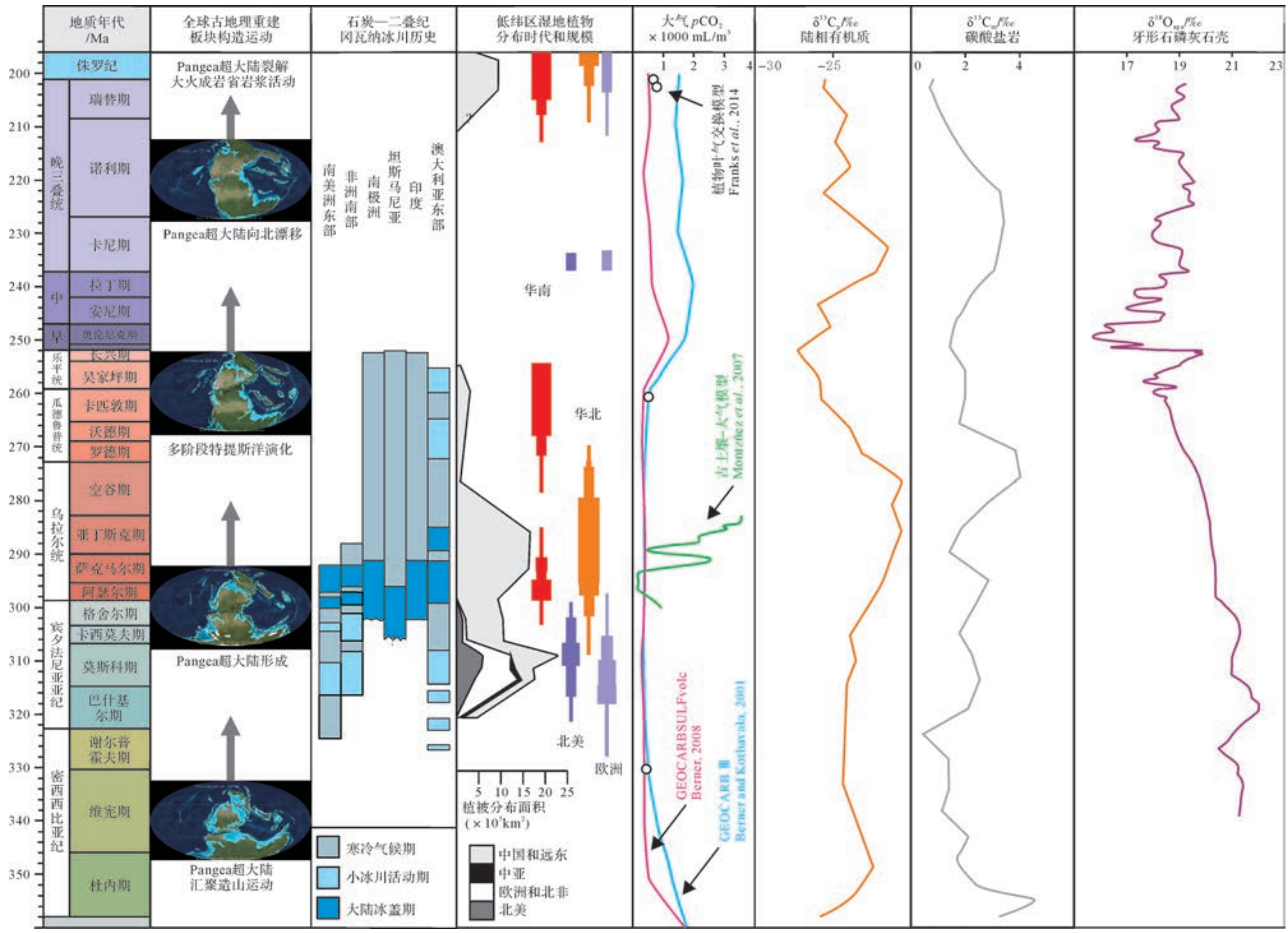

图 2　晚古生代冰室—早中生代温室气候转变期的全球板块古地理（https://deeptimemaos.com）、冈瓦纳冰川历史[9,15,17,29,33-34]、热带喜湿性植被分布[35-36]、大气 CO_2 浓度[37-39]、陆相有机质碳同位素[40]、碳酸盐碳同位素[41]和牙形石磷酸盐壳体氧同位素组成[42-46]变化对比图

Fig.2　Co-variation diagrams for the global plate palaeogeography (https://deeptimemaos.com), Gondwanaland glaciation[9,15,17,29,33-34], extent of tropical wetland vegetation[35-36], atmosphere CO_2 concentration[37-39], carbon isotopes of terrestrial organic materials[40], carbon isotopes of carbonates[41] and oxygen isotopes of conodont apatite shells[42-46] during the transition from the late Paleozoic Ice Age to the early Mesozoic greenhouse world

示全球转暖过程中阶段性的气候变冷事件[15]，与石炭纪冰川启动过程中存在阶段性的气候变冷一致，说明晚古生代冰期气候变化的渐进式特征[29]。随早二叠世向冰后期的转变，冈瓦纳大陆沉积记录发生明显变化：1）冰川相关沉积物（如冰碛杂砾岩、含落石的纹层状泥质岩等）被含煤砂泥岩、正常海相泥页岩和浅海碳酸盐岩沉积所取代[11,65]；2）碎屑沉积物的矿物成熟度提高，泥质岩中的高岭石增多[66]，大陆表层化学风化强度增大[67-70]；3）黑色泥页岩的有机碳同位素和碳酸盐岩—生物壳的 C-O 同位素也发生负偏—正偏大幅度波动[71-73]。对应于早二叠世气候变暖，全球范围内出现大规模海侵沉积序列[29]。Pangea 超大陆西侧热带区古土壤温度从约 22℃增大到约 35℃[74]，同时发生由暖湿性到干热性植物群落的更替[75]。古土壤形貌和化学组成及植物群落的研究表明，二叠纪冰川消融和全球变暖导致欧美大陆低纬区气候出现长时间尺度的干旱化趋势[76]，降雨的季节性增强。对应于二叠纪的冰川消融和全球变暖，低纬区海相碳酸盐沉积序列的碳氧同位素组成也发生负偏，指示大气 pCO_2 和表层水体温度升高[46,49,77-80]。对应于大陆冰盖的消融、解体和气候变暖，大气 pCO_2 从冰盛期的约 300 mL/m³ 增大到>1 000 mL/m³，且呈波动性增大，与晚古生代冰室气候向温室气候转变的渐进式特征一致。尽管在冰盛期之后的冰川活动期

大气 pCO_2 及海水温度均有所降低[38]，但没有降低至冰盛期的极限水平，而是因冰消期的快速升高达到气候状态发生转变的阈值，最终在二叠纪末次冰期[33]结束之后进入全球无/少冰的温室气候。

2.2 季风气候与低纬大陆区干旱化

沉积学和古生物学等研究表明，Pangea 超大陆古气候属于季风气候体制[81-83]，其发展、鼎盛与晚古生代冰川消融、冰室—温室气候转变存在密切联系。在石炭纪期间由于陆块还主要偏重于南半球，地表气流仍然以分带型为主，季风不明显。在二叠纪随着泛大陆的逐渐北移和冈瓦钠冰川的逐渐萎缩，季风气候逐渐增强。风成沉积和古土壤氧同位素研究揭示，在早二叠世出现从北东到北西的显著风向转变[84-85]。同时，季风强度也取决于高纬大陆冰川的扩张和消融，具有周期性变化[86]。模型研究表明，冈瓦纳大陆冰盖消融和全球变暖使得 Pangea 超大陆西侧热带区季风(西北风)增强[87]，并在晚古生代冰期结束之后的三叠纪达到最盛，形成贯穿整个热带低纬区的巨型季风系统[83]。欧美大陆沉积记录晚三叠世卡尼期的洪水—强降雨事件[88-89]。在晚古生代冰期强烈的上升流通常发生于大洋东岸[29]，而中晚三叠世在特提斯洋西侧出现西南向季风引发的上升流作用[90]，表明大洋环流也随气候状态的转变而发生显著变化。在晚三叠世晚期，北美大陆古土壤指示的古降雨量和地表古温度降低，欧美大陆结束季风性降雨而再次变为以风成沉积为主的干旱气候环境[91]。然而，一些学者对季风气候的存在仍持怀疑态度。Kent *et al.*[92]依据古地磁数据认为三叠纪依然存在明确的纬向气候分带，Berra[93]基于特提斯西岸碳酸盐岩台地—碎屑岩的沉积序列，认为晚三叠世发生海平面下降和全球变冷事件，由此导致气候带的迁移及降雨量的变化，与季风气候无关。

3 东特提斯低纬区(华南和华北)的沉积记录

3.1 沉积记录与冰川型海平面变化

晚古生代冰室气候时期，我国华北和华南与北美—欧洲类似，位于低纬度地区，因此广泛发育与冈瓦纳冰川增长和消融同步的海平面变化旋回是无疑的。在我国华南地区，刘本培等[94]和李儒峰等[95]根据碳酸盐岩沉积和生物地层序列，最早在晚石炭世地层中识别出了这种变化。之后，Ueno *et al.*[96]和 Wang *et al.*[97]对这种高频旋回沉积的宏观特征进行了较为细致的描述。通过对右江盆地北缘巴马孤立台地碳酸盐沉积微相研究，Liu *et al.*[98]在早二叠世末期发现了 7 个“高频”三级相对海平面变化旋回。最近，严雅娟等[99]记述了黔南地区早二叠世碳酸盐岩地层中记录的大幅度海平面下降导致的显著碳酸盐岩暴露构造；武思琴等[100]识别出了早二叠世快速海平面上升期陆源碎屑沉积体系的响应。华北地区在石炭—二叠纪经历由海相—海陆过渡相—陆相的盆地沉积转变，发育含煤碳酸盐岩—碎屑岩沉积旋回(图 3A,B)。依据多种沉积层序界面的确定和分析，华北石炭—二叠系沉积序列被认为与海平面变化存在成因联系[101-104]。华北石炭—二叠纪沉积记录显示的海平面变化具周期性和突发性，可识别出多个三级和四级海平面变化(图 3A)，与北美中大陆同期海平面变化可以对比，具全球性和等时性，属于冰川型海平面变化。吕大炜等[105-106]获得更多地层数据支持上述观点，并对海平面变化属性，即周期性和高频性进行较深入的剖析，认为旋回性沉积所指示的高频海平面受高纬冰川消长的控制。然而，与北美和俄罗斯台地相比[62,107-108]，华北地区在高精地层格架建立和海平面变化幅度定量化方面仍没有取得实质性进展；同时，华北和华南发育的旋回性沉积的特征以及与北美地区最早识别出的旋回层(cyclothem)的对比，仍然是一个值得深入研究的课题。因此，将来的研究可聚焦于华北晚石炭—早二叠世良好的地层记录和沉积序列(图 3B)，进行高精度放射性同位素定年和海平面变化定量估算等研究。

3.2 沉积记录与陆表气候变化

华北在石炭末—早二叠世全球变暖期仍发育含煤沉积，表明其与欧美大陆区同时期的干旱化气候明显不同。但自早二叠世晚期开始随板块北移，华北地区煤层减少、变薄并出现较多的杂色和紫红色泥岩，喜湿性植物群衰落而耐旱性植被逐渐繁盛[20,109]，在长时间尺度上也出现气候的干旱化趋势[110-114]。华南在石炭—二叠纪以碳酸盐岩沉积为主，发育两套含煤碎屑岩沉积，自下而上依次为早二叠世晚期梁山煤系和晚二叠世龙潭煤系。华南早二叠世铝质泥岩也发育旋回性沉积序列(大竹园组和梁山组，图 3C)，指示多期次的淡水林滤作用[115]，可能指示湿热气候条件下降雨的季节性特征。华南在二叠纪末开始至中晚三叠世经历了较长时期的干旱—半干旱性气候，发育蒸发岩和紫红色泥质岩沉积(图 4)，而晚三叠—早侏罗世含煤地层再次出现，表明湿润气候的重启和成

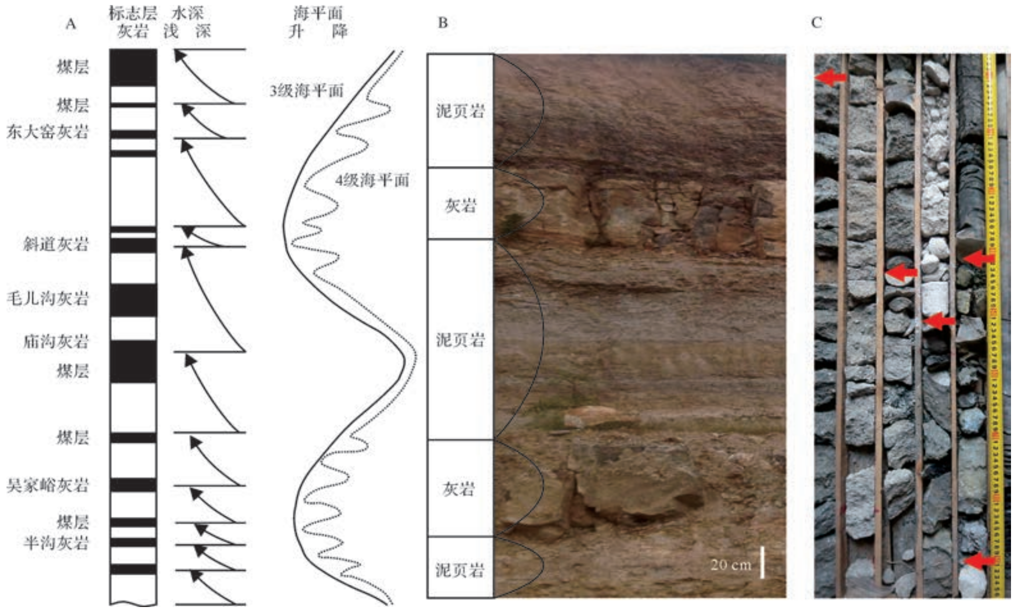

图 3　A.太原西山含煤沉积旋回和海平面变化曲线(改编自文献[104]);B.华北南缘太原组碳酸盐岩—泥页岩的旋回沉积;C.黔北早二叠世 Al 质泥岩—黑色泥岩的多旋回沉积序列(红色箭头指示颜色变化,显示多期淋滤特征)

Fig.3　A. coal-bearing cyclic sedimentation and related sea-level variation recorded in Xishan region, Taiyuan (revised from reference[104]); B. cyclothems of carbonate-mudstone depositions of Taiyuan Formation in Henan province; C. the early Permian Al-enriched mudstone-black mudstone cyclic sequence (red arrows mark the whiter-darker colour transitions) in northern Guizhou province

图 4　华南晚二叠世—三叠纪具气候指示意义的岩石地层野外照片

A.晚二叠世龙潭组含煤细碎屑岩;B.早三叠世飞仙关组紫红色泥岩和灰绿色泥岩;C.中三叠世巴东组紫红色粉砂质泥岩;D.晚三叠世九里岗组石英砂岩和灰黑色泥页岩

Fig.4　Field photos showing Late Permian-Triassic sedimentary sequences with climate significances in South China

A. late Permian coal-bearing fine-grained clastic sedimentary strata of Longtan Formation; B. early Triassic intercalated purple-red and grey-green mudstones of Feixianguan Formation; C.middle Triassic purple-red silty mudstones of Badong Formation; D. late Triassic quartz sandstones and dark-gray mudstones of Jiuliguang Formation

煤植物的繁盛。通过泥岩化学—矿物组成定量示踪陆表风化强度,Yang *et al.*[116]对华北南部陆表古温度状态进行了(半)定量重建。在早二叠世萨克马尔中—晚期,华北与冈瓦纳大陆及其北缘同期细屑岩的化学风化强度具有一致的升高趋势,表明全球大陆化学风化增强,对应于早二叠世的冈瓦纳冰川消融和全球变暖。萨克马尔期细屑岩具有与现代大河流河口泥岩一致的化学风化—纬度分布模式,基于纬度对陆

表温度的控制,推测也应具有相似的化学风化—陆表温度分布模式,据此估算早二叠世冰盛末期的低纬(华北,北纬~10°)与高纬(冈瓦纳,南纬50°~60°)间的陆表温度梯度为约20℃[116]。基于现代花岗质基岩表层土壤风化强度与气候条件的相关性统计分析,Yang *et al.*[117]建立了一个应用化学风化指数进行陆表年均温度估算的经验转换方程(图5)。在降雨量或湿度可以独立约束的条件下,该方程可用于深时陆表古温度的定量估算,据此推测华北南部在早二叠世萨克马尔期的陆表古温度为约20℃,为暖湿性气候,而Pangea超大陆西侧热带区则为干冷性气候(约4℃)(图5)。

毫无疑问,位于东特提斯低纬区的华南、华北地区发育较连续的碳酸盐岩沉积序列,可进行高分辨率的低纬区古海水化学成分和古温度研究[45-46,97](图1),发育碎屑岩沉积序列,便于进行陆表古气候恢复和重建[116-117];与中高纬的冰川型沉积序列和泛大陆西侧低纬区沉积记录对比研究,可深入理解全球和区域气候的转变机制和影响因素。此外,通过泥质岩风化地球化学和古土壤记录估算陆表温度和降雨量,进而与古海洋的海水化学组成和海表温度对比,可更好的理解深时地球气候系统。

4　存在的问题

4.1　低纬区海平面的变化幅度

低纬沉积序列的高频旋回特征是冰川型海平面变化的反映,大幅的海平面波动被认为代表大的冰盖扩张和消融事件[57]。基于地层记录定量估算的海平面变化幅度从小于40 m到大于100 m[13,55,58-59,61-62]。海平面波动的幅度在很大程度上取决于高纬区冰川的冰量大小,因此大幅的海平面波动指示大规模冰盖的存在。然而,晚古生代的冰川型沉积记录显示,高纬冰川活动以多中心、多期次、不连续为特征,基本没有形成统一的高纬冰盖,其冰川总量相对较小,可能不足以形成约大于50 m的海平面波动[29]。冰盖—气候模型模拟结果显示,若高纬冰盖体积足够导致如此大的海平面波动,会致使冰川表层温度过低而只有在异常高的大气$p\mathrm{CO_2}$驱动下才能有效消融[63]。基于地质参数模拟的海平变化幅度仅为25~40 m[63-64]。上述差异反映了数据与模型对冰量认识的差异,这种矛盾在一定程度上反映了基于地层记录海平面变化幅度估算的不确定性;比如,晚古生代边缘海具有比现代海洋相对小的密度跃层深度,因此类比现代海洋的密度跃层深度可能会高估海平面的变化幅度[13,29]。

4.2　低纬区热带气候的冷暖波动

在早二叠世冰盛期到之后的冰川消融期,Giles[49]利用腕足壳氧同位素变化趋势揭示热带海洋经历了从小于12℃大于20℃的明显冷—暖变化,温度变化幅度达到约10℃,认为高纬区冰盖扩展与消融对低纬区气候具有显著影响[118]。Soregahn *et al.*[26,28]在Pangean大陆西侧近赤道区识别出了可能指示低纬山岳冰川的杂砾岩和风成古黄土沉积,认为在晚古生代冰盛期热带大陆经历显著的温度降低。

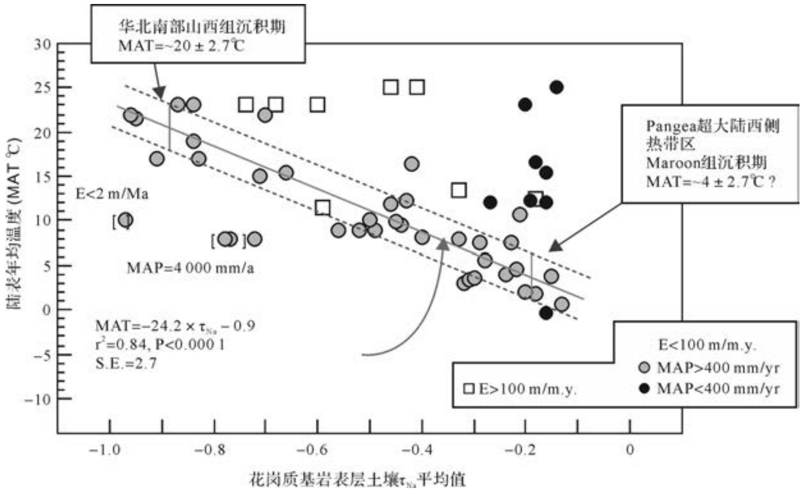

图5　现代花岗质基岩表层土壤风化强度与陆表年均温度(MAT)、年均降雨量(MAP)和物理剥蚀速率(E)间的相互关系(据文献[117]修改)

Fig.5　The co-variation of modern weathering intensity of surface soils developed on granitic basements with mean annual land surface temperature, mean annual precipitation and physical erosion rate (revised from reference [117])

模型研究也揭示 Pangean 中部山岳冰川的存在可能导致热带区广泛的低温和寒冷[119]。然而，同样基于腕足壳氧同位素温度估算的其他研究[120-121]则给出与现代低纬表层海水相近或更高的温度值（大于约 18℃），而且即使低大气 $p\mathrm{CO}_2$ 气候模型模拟的热带海水温度也接近或大于 20℃，最新的牙形石磷灰石氧同位素研究表明，尽管热带海水的温度存在波动，但整体均处于相对温暖的气候状态[46]。Tabor *et al.*[74]基于冰盛期古土壤矿物氢—氧同位素获得了 20℃～35℃的近地表成壤温度，认为可近似反映陆表温度的变化[75]，与低纬区山岳冰川沉积记录形成鲜明对比。Zambito *et al.*[122]计算了北美大陆早二叠世末岩盐流体包裹体的均一温度，其平均值在 20℃～45℃间变化。上述研究表明，对低纬热带区相应于高纬冰川活动是否发生显著的冷暖波动，学界还存在较大的分歧，主要关系到所用气候指标的有效性和准确性。例如，基于生物壳氧同位素计算的古海水表层温度很大程度上取决于周围海水 δ^{18}O 值，后者通常被假定为固定值（-1‰～1‰）；同时，海水的 pH 值和碱度也是氧同位素组成的重要控制因素，钙质壳气候指标的温度差异可能与边缘海的上升流活动有关[29]。

4.3　低纬区大陆干旱化的东西差异

自早二叠世早期，随冰川解体、大气 $p\mathrm{CO}_2$ 升高和全球变暖，欧美热带大陆区呈显著的干旱化趋势和强的季节性波动，且具有自西向东推进的空间规律[76,123-124]，指示赤道西风作用的季风气候特征[81]。这种赤道大陆的干旱化趋势与季风活动在东特提斯低纬大陆上出现较晚，华北和华南在早二叠世基本都具有聚煤作用发生的气候条件。华北在早二叠世晚期之后开始出现紫红色泥岩沉积，煤层减薄、层数减少，出现耐旱性植物组合，可能与板块北移至亚热带干旱气候带有关。华南在晚二叠世仍处于大规模成煤的无季节性分异的暖湿气候条件下，发育铝土矿和喜湿性植物群落，自二叠纪末—早三叠世开始出现代表干旱气候特征的沉积和植物组合。在热带大陆干旱化的同时，热带海洋—大气环流也发生变化[90,125]。目前，东特提斯低纬大陆的干旱化趋势研究较少，与 Pangea 大陆的对比还缺少足够的年代地层学和气候指标数据的支持，学界对这种全球尺度热带大陆干旱化的具体成因机制也不甚了解。与欧美大陆所处的 Pangea 超大陆相比，华北和华南具有对全球气候变化的不同沉积响应；更重要的是，这些东侧大洋内部地块上的古气候记录，是 Pangea 超大陆期间气候体系的一个重要组成部分，对深入、全面了解当时的气候区带展布和演化格局至关重要。

5　结束语

整体而言，我国对晚古生代冰室—三叠纪温室气候转变期的深时古气候学研究相对零散，缺乏系统性，原始创新不够。现有研究主要集中在区域古气候特征与演化、定性古气候判别等方面，在定量古气候重建和大气 CO_2 浓度恢复，特别是古气候模型和模拟方面尤为薄弱。我国具有很多连续的地质记录，很多剖面具有很好的多重地层研究基础，并在深时古气候系统中占据特殊且重要的古地理位置；同时，综合低纬区的华北和华南大陆与邻区多地块（如保山、腾冲等）的地质记录还可以构建跨区域性古气候断面。因此，我国具有系统开展和发展深时古气候学的良好条件[7]，结合上述晚古生代—早中生代的深时古气候问题，借助青年人才的培养和成长，有希望做出一些创新性的成果。

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The Earth's Penultimate Icehouse-to-greenhouse Climate Transition and Related Sedimentary Records in Low-latitude Regions of Eastern Tethys

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Abstract: During the Period of Pangea in the Carboniferous-Triassic time, there occurred the Earth's last climate transition from icehouse to greenhouse state, which provides an unique deeptime window to understand the climate impact of deglaciation and global warming in the near future. Studies on the sedimentary records of this period revealed that glaciation, atmosphere CO_2 concentration and climate have complicated coupling and feedback mechanisms along with floral replacement on lands and faunal migration in oceans. Low-latitude continents became drying with seasonal precipitation corresponding with Gondwana deglaciation, atmosphere pCO_2 rising and temperature increase especially in the west tropical Pangea and monsoon climate came into its acme during the Triassic when the landmass of Pangea symmetrically spreading across the equator. Both North China and South China were island land blocks in the low-latitude eastern Tethys region during the Carboniferous-Triassic era. There developed sedimentary and biological records quite different from the counterparts in the western tropical Pangea, achieving critical information for deeptime climate changes. In this contribution, we briefly review the Carboniferous-Triassic paleoclimate evolution and then discuss the related sedimentary records of North China and South China, pointing out several potential study topics for future deeptime paleoclimate research in China.

Key words: deeptime paleoclimate; Late Paleozoic ice age; icehouse-greenhouse climate transition; Pangea; monsoon climate