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石炭纪－二叠纪转折期重大地质事件与鄂尔多斯盆地东缘页岩气富集主控因素探讨

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摘　要:随着非常规油气富集与多地质(生物)事件耦合作用研究的不断深入,逐步证实了黑色页岩层系中非常规油气"甜点区/段"的沉积过程常伴随着多种全球或区域地质(生物)事件,如火山喷发、热液活动、大洋缺氧、气候突变、生物繁盛与灭绝等.鄂尔多斯盆地东缘石炭系－二叠系发育多套海陆过渡相页岩层系,是目前我国页岩气勘探开发的重要目标层段之一.通过梳理石炭纪－二叠纪转折期区域(鄂尔多斯盆地)和全球性重大地质、气候和生物事件,讨论其对鄂尔多斯盆地东缘页岩气富集的潜在影响.研究表明:石炭纪－二叠纪转折期海平面、古气候以及植被面貌等变化,在不同程度上影响着有机质生成的水体表层初级生产力以及有机质保存的水体底部氧化还原状态等条件.由于鄂尔多斯盆地东缘石炭系晋祠段(招贤页岩)和二叠系山$_2^3$亚段中页岩层段的含气量与*TOC*含量具有良好的正相关性,从有机质富集的角度探讨了古生产力和古水体氧化还原条件对海陆过渡相页岩气富集程度的影响,提出植物繁盛能够为有机质大量生成提供物质基础,相对海平面的上升易形成贫氧－缺氧水体环境,有利于有机质沉积富集,从而最终促进了该区页岩气"甜点段"形成.

关键词:有机质富集;地质(生物)事件;海陆过渡相页岩气;冰期－间冰期;晚古生代;非常规油气沉积学;石油地质.
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Discussion on Significant Geological Events during Carboniferous-Permian Transition and Main Controlling Factors of Shale Gas Enrichment in Eastern Margin of Ordos Basin

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Abstract: With the ongoing advancement of research on the coupling effect of unconventional oil and gas enrichment with multi-geological (biological) events, it has increasingly been confirmed that the deposition process of unconventional oil and gas "sweet spots" in black shale formations is frequently accompanied by volcanic eruptions, hydrothermal activities, ocean anoxia, climate change, biological prosperity, and extinctions, among various global or regional geological (biological) events. The Carboniferous-Permian transition in the eastern margin of the Ordos basin is endowed with multiple sets of marine-continental shale formations, which are significant targets for the exploration and development of shale gas in the country. In this paper it provides a review of the major geological events during the Carboniferous-Permian transition in order to discuss their potential impact on shale gas enrichment in the eastern margin of the Ordos basin. The Study shows that the changes in the glacial sea-level, paleoclimate during the Carboniferous-Permian transition have impacted on the surface primary productivity of organic matter and the bottom redox conditions in different degrees. Given the positive correlation between gas content and total organic carbon (*TOC*) content in the Carboniferous Jinci Section (Zhaoxian Shale) and Permian Shan_2^3 Subsection shale formations in the eastern margin of the Ordos basin, it discusses the potential influence of paleoproductivity and paleoenvironment on the enrichment of marine-continental transition shale gas deposits: vegetation flourished organic matter, and with the relative rise in sea level, a hypoxic-anoxic water environment is easily formed, conducive to the deposition and enrichment of organic matter, thereby ultimately facilitating the formation of the "sweet spots" for shale gas in the region.

Key words: organic matter enrichment; geological (biological) event; marine-continental transitional facies shale gas; glacial-interglacial period; Late Paleozoic; unconventional petroleum sedimentology; petroleum geology.

0 引言

石炭纪－二叠纪转折期是地球生态系统演化的重要时期，该时期发生了一系列的地质（生物）事件，包括晚古生代大冰期的出现和消亡（Fielding *et al.*，2008a；Isbell *et al.*，2012）、Pangea超大陆聚合（Zhao *et al.*，2018；Feng *et al.*，2021）、多次大火成岩省（Torsvik *et al.*，2008；Timmerman *et al.*，2009；Xu *et al.*，2014）和华夏生物大辐射（Fan *et al.*，2020）等等．这些重大地质（生物）事件对该时期的古气候和海平面等产生了不同程度的影响．在这一转折期，全球发育了富有机质页岩沉积（张光亚等，2019；邹才能等，2023），主要分布在北美南部、南美西部、欧亚大陆东北部以及我国华北等地区，包含巴拉纳盆地的Irati页岩（Cagliari *et al.*，2022）、二叠盆地的Wolfcamp页岩等．在华北鄂尔多斯盆地东缘沉积了多套富有机质页岩层系，包括本溪组、太原组、山西组等，沉积环境总体上为海陆过渡相（张琴等，2022；Zhang *et al.*，2023）．目前，鄂尔多斯盆地东缘的山$_2^3$亚段已获得了重要勘探突破，其中直井最高测试产量超过1.0×10^4 m^3/d，水平井最高测试产量超过6×10^4 m^3/d（焦方正等，2023）．该地区具有良好的勘探开发潜力，未来有望成为页岩气勘探开发的接替领域（匡立春等，2020；邹才能等，2024）．

研究发现页岩沉积中记录了火山喷发、生物灭绝、海/湖平面突变、海水缺氧/富氧等地质（生物）事件．这些地质（生物）事件与非常规油气的形成是否存在时空耦合关系？它们对非常规油气的富集，特别是“甜点区/段”的形成，是促进还是抑制作用？学者们对地质（生物）事件与页岩有机质富集的形成展开了相关探讨（邱振和邹才能，2020；柳蓉等，2021；Lu *et al.*，2021；Zou *et al.*，2022）．邱振和邹才能（2020）以四川盆地五峰组－龙马溪组和鄂尔多斯盆地延长组为例，研究了页岩沉积过程中各类地质事件（构造运动、海平面升/降、气候变冷、火山喷发、硫化缺氧及生物大灭绝等）对非常规油气资源富集的影响，提出非常规油气资源富集是全球性或区域性多种地质事件耦合的结果．柳蓉等（2021）总结了全国50个盆地、95个含矿区油页岩的成因和分布规律，揭示油页岩富集的有利因素包括藻类和生物繁盛、稳定的湖泊分层、适量的火山灰、热液事件、大洋缺氧事件、海侵事件和气候湿润事件，而不利因素主要包括重力流事件和频繁的火山活动．Zou *et al.*（2022）通过对4个典型油气盆地（四川盆

地、鄂尔多斯盆地、Appalachian盆地、Williston盆地)的分析,全面回顾了非常规油气系统中细粒沉积物的沉积和成岩作用,并探讨了重大地质事件的耦合沉积在控制非常规油气层段(区)形成中的作用.

笔者在梳理石炭纪—二叠纪转折期地质(生物)事件的前提下,以鄂尔多斯盆地东缘海陆过渡相页岩为例,分析了地质(生物)事件与海陆过渡相页岩有机质富集之间的耦合作用.基于含气量与有机质丰度(*TOC*)的相关关系,探讨了地质(生物)事件对海陆过渡相页岩气富集的影响;这不仅为石炭纪—二叠纪的气候变化和地质(生物)事件的耦合提供了新的认识,也是对海陆过渡相页岩气成因机制和非常规油气沉积学理论的重要补充.

1　地质概况

中国海陆过渡相页岩主要发育于上古生界,在鄂尔多斯盆地、沁水盆地、南华北盆地、四川盆地、贵州、下扬子地区以及准噶尔盆地的局部区域广泛分布(图1a;翟刚毅等,2020).其中,四川盆地和鄂尔多斯盆地的海陆过渡相页岩发育最为广泛,蕴含的资源量也最为可观(郭旭升等,2018;Yang and Guo,2021).由于构造活动时间上的差异,我国南、北方海陆过渡相页岩沉积盆地的海退时间存在间隔(Li *et al.*,2015;郭艳琴等,2019;刘雯等,2023),北方的海陆过渡相页岩主要分布在石炭系—二叠系本溪组、太原组和山西组(Jiang *et al.*,2016;蔡光银等,2022;Wang *et al.*,2023),而南方的海陆过渡相页岩主要发育在二叠系梁山组、小江边组和龙潭组(闫德宇等,2016;郭旭升等,2018).

鄂尔多斯盆地位于华北克拉通西部(图1b),面积约为25×10^4 km^2,可以分为6个二级构造单元,富含石油、天然气和煤炭资源(杨华等,2015).本文结合申博恒等(2022)修订的华北板块的生物地层格架和Yang *et al.*(2014,2020)、Wu *et al.*(2021)等采用的岩石地层单元及其标志层,建立了鄂尔多斯东缘的岩石地层(图1c).利用Yang *et al.*(2014,2020)和Wu *et al.*(2021)对华北板块北部扒楼沟剖面和南部永城煤田的太原组和山西组进行锆石U-Pb定年,构建了鄂尔多斯东缘高分辨率绝对年代学框架.

晚石炭世本溪组沉积期,华北地台处于沉降阶段,华北海从东北向侵入盆地东部,形成了滨浅海沉积环境,沉积了砂岩、页岩、碳酸盐岩和煤层.晚石炭世—早二叠世太原组沉积期,海侵范围扩大,覆盖了中央古隆起,形成了统一的陆表海沉积环境,主要沉积泥岩、页岩和碳酸盐岩.早二叠世山西组沉积期,受海西构造运动的影响,华北地台整体抬升,海水逐渐从盆地的东西两侧退出,进入海陆过渡相沉积阶段.在这一阶段,受潮汐作用影响,发育滨浅海—潟湖—潮控三角洲沉积体系,由于海陆过渡相沉积环境的快速变化,导致碳酸盐岩的发育程度减弱,形成了纵向上砂岩、粉砂岩、页岩和煤的多样岩性组合.到中二叠世的下石盒子组沉积期,海水完全退出,进入陆相淡水湖盆的沉积演化阶段(图1c;Jiang *et al.*,2016;Zhang *et al.*,2021;蔡光银等,2022;张琴等,2022;刘雯等,2023).

2　石炭纪—二叠纪转折期重大地质(生物)事件与鄂尔多斯盆地东缘页岩气富集分析

非常规油气资源沉积富集与重大地质环境突变关系密切,而重大地质环境突变是地球深部与表层相互作用产生,通过全球性或区域性地质(生物)事件影响非常规油气资源沉积环境;同时,全球性或区域性地质(生物)事件在时间上与空间上具有耦合关系(邱振和邹才能,2020).本文以鄂尔多斯盆地东缘海陆过渡相(山西组、太原组和本溪组)为例,分析重大地质(生物)事件驱动的环境变化对有机质富集的耦合作用,并探讨这种耦合作用对页岩气富集的影响(图2).

2.1　晚古生代冰期

地球在显生宙经历了奥陶纪末、晚古生代以及晚新生代等多个显著冰期.其中,晚古生代冰期是跨越晚泥盆世到晚二叠世早期的冰期事件,持续达近亿年,被认为是显生宙中持续时间最长、影响范围最广的冰期(Montañez *et al.*,2007).晚古生代冰期由多个冰期和间冰期组成(图2),石炭纪—二叠纪识别出多个冰期,包括谢尔普霍夫早期C1冰期、谢尔普霍夫晚期的C2冰期、巴什基尔中期的C3冰期、莫斯科中期C4冰期、阿瑟尔期—萨克马尔早期P1冰期、萨克马尔晚期—亚丁斯克早期P2冰期、空谷晚期—罗德期P3冰期以及卡匹敦期P4冰期(Fielding *et al.*,2008a;Isbell *et al.*,2012).石炭纪晚期—二叠纪早期晚古生代冰期达到顶峰,全球气候变冷、海平面下降,海水温度降低(Isbell *et al.*,

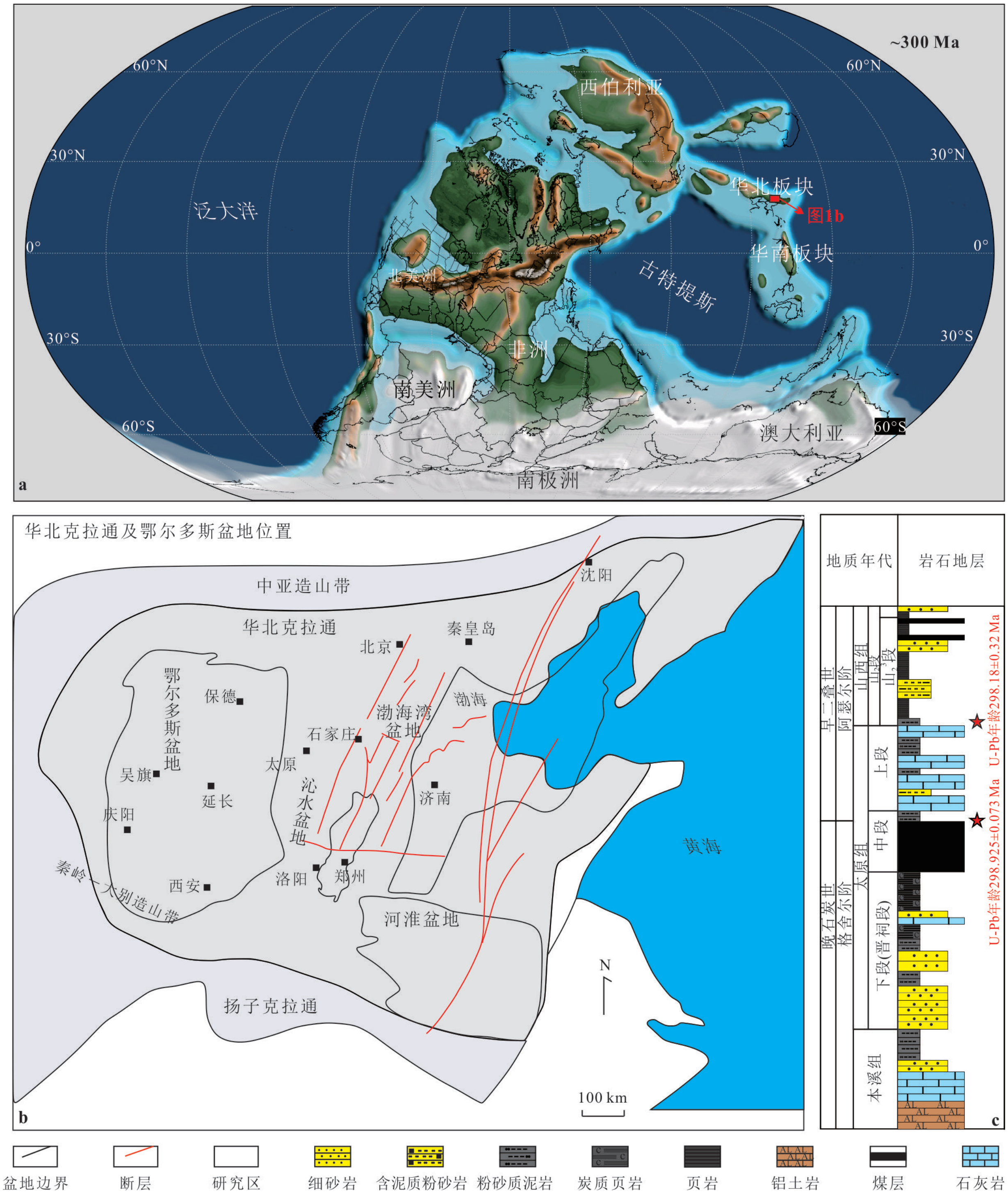

图 1　研究区位置及地层概况

Fig.1　Location and stratum survey of the study area

a.宾夕法尼亚晚期(~300 Ma)古地理图(Blakey,R.,Deep Time Maps,http://deep timemaps.com);b.鄂尔多斯盆地构造单元划分及研究区位置示意图据李勇等(2024)修改;c.鄂尔多斯盆地晚石炭世—早二叠世地层综合柱状图据武瑾等(2021);张琴等(2022);蔡光银等(2022)修改;CA-ID-TIMS-U-Pb年龄来自于Wu *et al.*(2021)

2003; Montañez and Poulsen, 2013; Chen *et al.*, 2016).萨克马尔晚期,冰川沉积的消失和海侵事件的增加,标志着晚古生代冰期主幕的结束,地球气候逐渐向温室气候转变(Isbell *et al.*,2003;Chen *et al.*,2016;Griffis *et al.*,2019;巩恩普等,2021;张诺等,2022).晚古生代冰期结束的驱动因素还存在许

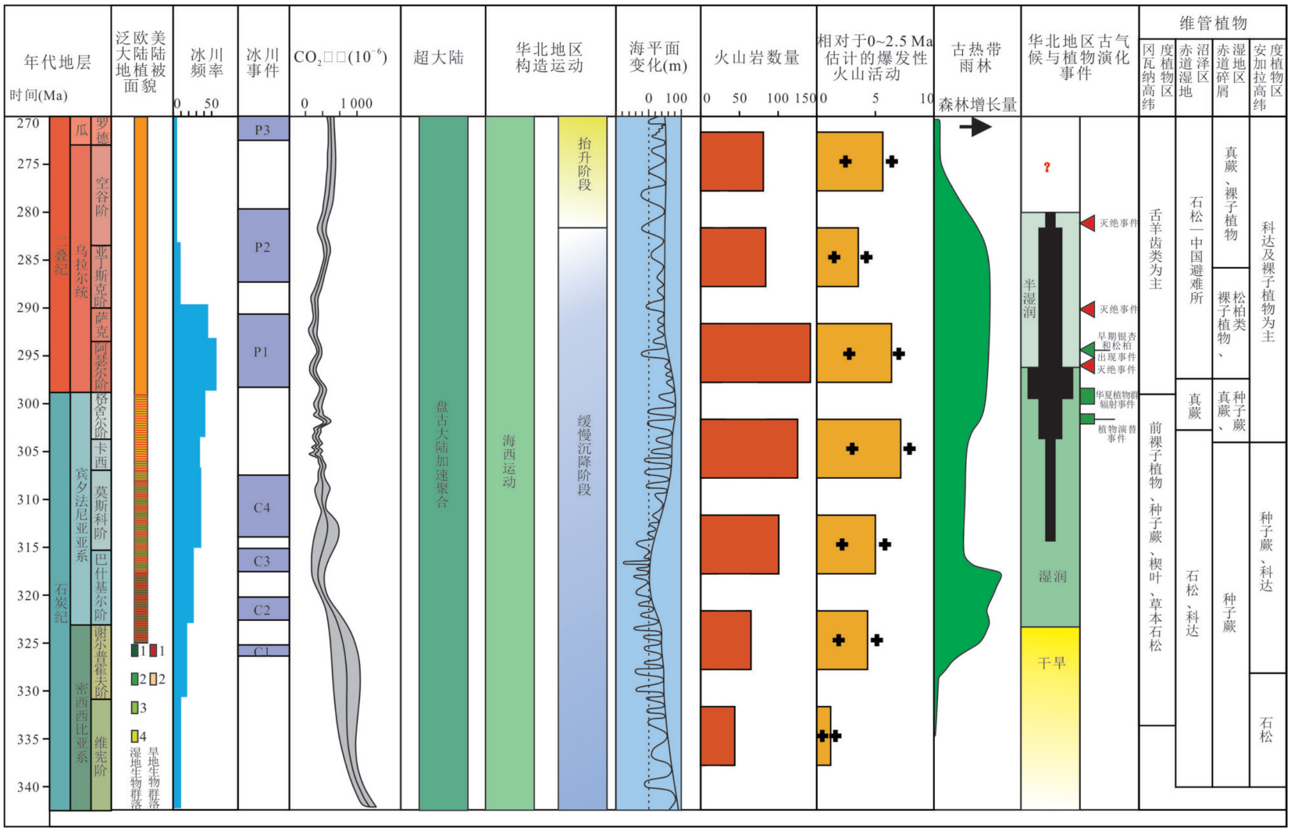

图 2　石炭纪－二叠纪地质(生物)事件

Fig.2　Carboniferous-Permian geological (biological) event

地质年代据 Gradstein *et al.*(2020)；CO_2 含量据 Montañez and Poulsen(2013)；冰川频率据 Soreghan *et al.*(2019)；冰川事件据 Fielding *et al.*(2008b)；超大陆构造事件据 Huang *et al.*(2018)；华北地区构造事件据石婧等(2024)；全球海平面变化据 Haq and Schutter(2008)；火山岩记录和相对于0～2.5 Ma估计的爆发性火山活动据 Soreghan *et al.*(2019)；古热带雨林据 Cleal and Thomas(2005)；殷鸿福等(2018)；华北地区古气候据张泓等(1999)；植物演化事件据 Wang(2010)；Stevens *et al.*(2011)；维管植物分布据殷鸿福等(2018)

多争议，目前普遍认为大气 CO_2 浓度增加(Montañez *et al.*，2007)、大火成岩省活动、地幔柱上升和板块运动(Goddéris *et al.*，2017)等因素是导致冰期消亡的主要原因．晚古生代冰期的影响不仅涉及岩石圈、水圈、大气圈和生物圈，也与非常规油气的富集密切相关．

鄂尔多斯盆地东缘晋祠段(招贤页岩)沉积时期，主要对应C4冰期至P1冰期之间，前人证实在此期间全球存在一次明显的变暖过程(Chen *et al.*，2018；Chen *et al.*，2022；岳超盛等，2024)．多指标重建的古大气 p_{CO_2} 记录显示其从背景值的 350×10^{-6} 上升到卡西莫夫末期的 700×10^{-6}(Richey *et al.*，2020)，而此时腕足壳氧同位素($\delta^{18}O$)和牙形石氧同位素($\delta^{18}O$)显示表层海水温度大幅度增加(Grossman *et al.*，2008；Chen *et al.*，2016)．海平面升高造成的缺氧环境为有机质保存提供了良好的条件．同时，低温的气候环境和稳定的构造地质背景也促进了植物的繁盛(Fan *et al.*，2020)，为有机质富集提供了物质来源．鄂尔多斯盆地东缘山西组沉积时期对应晚古生代冰期发育的顶峰，这一时期全球温度大幅度下降，冈瓦纳大陆冰川扩张，CO_2的浓度降到最低，低纬度地区海平面大幅度下降(Chen *et al.*，2018；Soreghan *et al.*，2019)．海平面的下降为盆地沼泽化和维管植物扩张提供了条件，继而增强了风化作用，提高了陆源碎屑的输入．尽管海平面的下降导致水体氧化，不利于有机质富集，但在山西组沉积过程中，华北地区发生了多次海侵，形成的河漫湖泊、潮上湿地和近岸海湾等贫氧－缺氧的沉积环境，使得以镜质组和惰质组为主要组成的有机质碎屑得到了良好的保存．

2.2　构造与海平面变化

石炭纪－二叠纪是Pangea超大陆聚合的关键时期(Zhao *et al.*，2018；Feng *et al.*，2021)，华北板块、塔里木板块以及柴达木板块等板块与西伯利

亚—东欧板块作为Pangea超大陆的一部分，古地理位置、古气候、沉积环境和大地构造背景都经历了重大的变化（Liu，1990；Zhang *et al.*，1999；Huang *et al.*，2018）. 由于加里东运动，华北地区缺失了奥陶系、志留系和泥盆系地层，沉积间断长达约138 Ma. 晚石炭世本溪组沉积时期，随着华北地台的持续下降，鄂尔多斯盆地开始接受沉积，在古亚洲洋（索伦洋）运动的作用下，盆地分布格局转变为“北隆南倾”，使得祁连海与华北海局部连通（张诺等，2022；石婧等，2024）；太原组沉积时期，盆地仍处于沉降阶段，盆地整体位于海平面以下；山西组沉积时期，盆地受到海西构造运动和北部古亚洲洋由西向东的“剪刀状”拼合、关闭的影响；同时，由于冰川发育规模的增大，海平面下降，导致海水从盆地东西两侧流出，使盆地进入海陆过渡相沉积阶段（Wang *et al.*，2022a）.

晚古生代海平面的变化受到了冰川作用和Pangaea超大陆聚合的共同影响（吕大炜等，2009）. 冰期—间冰期的周期性变化也影响了沉积相带组合、沉积地貌和旋回沉积厚度等变化. 在华北板块的石炭系—二叠系地层中，已经确认多个2至4级的海平面变化旋回（陈世悦和刘焕杰，1995；吕大炜等，2009），这些变化趋势与全球趋势相似，并已在东亚和北美等地区得到验证（Lee and Chough，2006；Nakazawa and Ueno，2009；Eros *et al.*，2012）. 然而，关于海平面变化的幅度仍存在较大争议：一些学者认为海平面变化的幅度主要集中在40 m到100 m之间（Crowley and Baum，1991；van der Meer *et al.*，2017）；另一些学者则通过地质记录和模拟结果推断华北地区的海平面在0到40 m之间变化（申博恒等，2022）.

鄂尔多斯盆地东缘招贤页岩沉积期，海平面开始上升，沉积环境转变为河漫湖泊、潮上湿地和近岸海湾（吕大炜等，2009；Shen *et al.*，2024）. 海洋中大量的水生浮游藻类生物（图3），为页岩沉积提供了丰富的有机物质来源，同时，缺氧的沉积环境有利于有机质的保存. 鄂尔多斯盆地东缘山西组沉积期，正值晚古生代冰期的顶峰，海平面大幅度下降，陆地表暴露，植物繁盛，陆地生产力升高（吕大炜，2009；Chen *et al.*，2020）. 古地理格局由陆表海逐渐演变为三角洲和潮坪，这为植被扩张提供了更好的条件，也为有机质富集提供了物质基础. 海侵作用形成的贫氧—缺氧的沉积环境也促进了页岩中有机质的富集.

2.3 大火成岩省

火山活动在地质历史的转折期中扮演着重要的角色，对全球古环境和生物生存都产生了极大的影响，如奥陶纪—志留纪（邱振和邹才能，2020）、泥盆纪末期（王玉珏等，2020）、二叠纪—三叠纪（Lu *et al.*，2021）、侏罗纪末期（Percival *et al.*，2015）等，而石炭纪—二叠纪的火山活动主要发生在古赤道周围，包括Skagerrak-Centered大火成岩省（～300～298 Ma；Torsvik *et al.*，2008；Timmerman *et al.*，2009；Hamilton and Pearson，2011）和塔里木大火成岩省（～300 Ma；Xu *et al.*，2014）. 在西北欧，通过 ^{40}Ar-^{39}Ar 和 U/Pb 等方法计算出 Skagerrak-Centered 大火成岩省喷发于～297 Ma（Torsvik *et al.*，2008）. 石炭纪—二叠纪时期，华北地区经历了剧烈的构造运动，包括拉张—挤压旋回，板块俯冲引起了大范围的火山活动（图2；李洪颜等，2009；Wang *et al.*，2022b），这些火山事件在一定程度上影响了鄂尔多斯盆地有机质的沉积过程. 钟蓉等（1996）通过地球化学方法确定了晚古生代华北地区火山来源的分布情况：早二叠世太原组沉积期，华北西缘火山源大致位于乌达以北，以酸性为主；而华北中部和东部可能位于大同东北等地，以酸性和中性岩体为主（张拴宏等，2010；张诺等，2022）. 晚石炭世—早二叠世的岩浆活动在华北地块北部边缘是持续的过程，与华北板块北部～306～308 Ma的岩浆侵入事件相一致（Zhang *et al.*，2009）. 研究发现，火山活动释放的营养元素有助于海洋生物的繁荣和初级生产力的提升，有利于有机物质的积累；然而，有毒物质的存在会对生物生存造成危害，并降低初级生产力. 低强度的火山活动促进生物繁殖，而剧烈的火山活动将不断加大生态环境的修复压力，最终可能导致不可逆的破坏（谢浩然等，2023）.

在华北板块石炭系—二叠系的地层中，火山岩记录较少，但在沉积岩记录中可以找到火山事件的迹象. 钟蓉等（1996）在华北板块中部和西北部识别出了火山事件的沉积序列和火山沉积层（Schmitz *et al.*，2021）. 研究发现，石炭纪—二叠纪时期，鄂尔多斯盆地东缘、南源和西源地区均发生了不同程度的火山活动（钟蓉等，1996）. 笔者在鄂东缘大吉3-4井山西组的2 148 m深度与煤层交界处还观察到火山碎屑岩，进一步证实了石炭纪—二叠纪存在火山活动（图4）；然而，由于在地层中观察到的火山沉积

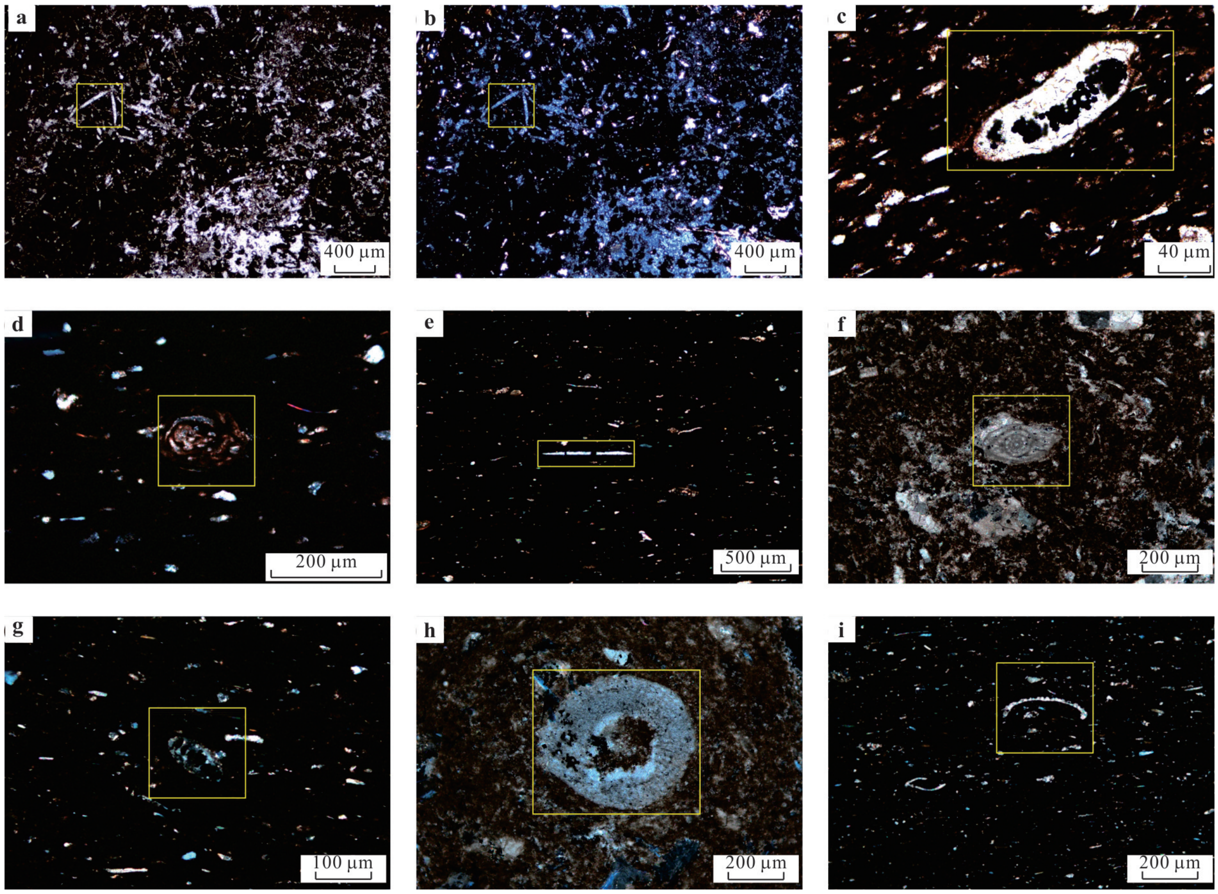

图 3　鄂尔多斯盆地东缘生物碎屑微观特征

Fig.3　Microscopic characteristics of biogenic debris in the eastern edge of the Ordos basin

a.海绵骨针，透射，大吉 3-4 井山$_2^3$亚段，2 142 m；b.海绵骨针，单偏，大吉 3-4 井山$_2^3$亚段，2 142 m；c.有孔虫，透射，大吉 3-4 井山$_2^3$亚段，2 144.74 m；d.有孔虫，已泥化保留其外形，呈玫瑰花状、卵圆状，正交偏光，大吉 3-4 井山$_2^3$亚段，2 143.33 m；e.具单轴双射的海绵骨针，正交偏光，大吉 3-4 井山$_2^3$亚段，2 145.57 m；f.䗴类（外形多呈纺锤形，旋壁发育，房室亮晶充填，隔壁泥晶结构，个体 0.1～0.7 mm），正交偏光，大吉 3-4 井山$_2^3$亚段，2 184.65 m；g.有孔虫，正交偏光，大吉 3-4 井山$_2^3$亚段，2 148 m；h.棘皮类（仅见具单晶结构的海百合茎，部分见中央茎结构，个体 0.07～2.50 mm），正交偏光，大吉 3-4 井山$_2^3$亚段，2 164.02 m；i.生物碎屑，正交偏光，大吉 3-4 井山$_2^3$亚段，2 145.21 m

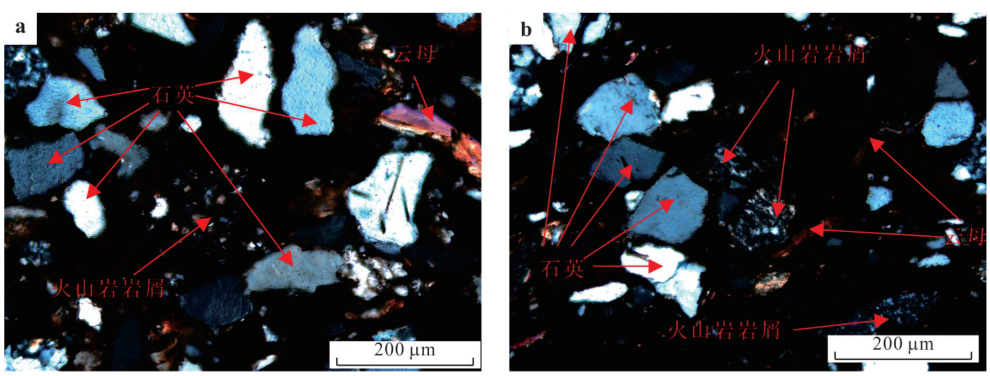

图 4　鄂尔多斯盆地东缘火山碎屑岩

Fig.4　Volcanic clastic rocks in the eastern margin of the Ordos basin

a.正交偏光：中酸性火山岩岩屑，大吉 3-4 井山$_2^3$亚段，2 148 m；b.正交偏光：中酸性火山岩岩屑，大吉 3-4 井山$_2^3$亚段，2 148 m

较少，因此区域性火山活动对华北地区富有机页岩沉积的影响因素还需要进一步研究.

2.4　生物群落繁盛

地质历史时期发生过多次生物大灭绝和生物

辐射事件(舒德干等,2009;沈树忠和张华,2017).石炭纪－二叠纪华夏生物大辐射与晚古生代大冰期的时间相吻合,温度降低和大气－海洋氧化被认为是生物大辐射的主要原因(Cleal and Thomas,2005;Hilton and Cleal,2007).

晚古生代冰期p_{CO_2}浓度大幅度下降,从中石炭世的600×10^{-6}下降至早二叠世的100×10^{-6}(体积百分含量)(Montañez *et al.*,2016),大气中的O_2在泥盆世晚期有了明显上升(Wallace *et al.*,2017),晚泥盆世大气增氧量与新元古代早期大成氧事件(NOE;650～525 Ma)的增氧量相当(Holland,2002;Campbell and Squire,2010),使大气氧含量达到了～31%,超过了当代水平(21%),即相当于150 PAL(Kump,2008).石炭纪－二叠纪的冰期事件与大气增O_2减CO_2时间相一致(Berner,2003).大气中O_2和CO_2含量占比的变化也引起了生态群落的变化,在泥盆纪之前,生态群落主要由绿藻类浮游生物构成;进入宾夕法尼亚纪早期的巴斯基尔期,植物群落开始由蕨类植物占主导地位,形成了相对简单的生态系统;进入莫斯科期晚期,植物群落的组成发生了显著变化,由原本以种子蕨纲为主逐渐过渡到以裸子植物(维管植物)为主导(Cleal and Thomas,2005).这些裸子植物属于高等植物,其根、茎、叶系统具有支撑功能,能够疏导水和营养物质,通过表皮和气孔进行光合作用的调节和保护;孢子具有强大的繁殖能力,显著增强了它们通过光合作用、风化和侵蚀作用来增加O_2、减少CO_2的能力.这些植物形成的热带雨林以石松植物为代表,含有大量木质素成分,其固碳能力极为强大,使有机碳能够迅速埋藏(Scholze *et al.*,2003;Cleal and Thomas,2005).

在鄂尔多斯盆地东缘太原组沉积期间,陆源碎屑(以陆地高等维管植物形成的腐－腐殖型有机质为主)和海洋藻类为富有机质页岩形成提供了有利的因素.山西组沉积期间,华北地区环境整体上为温暖潮湿,有利于高等植物(维管植物)具有更好生产、风化、侵蚀和固碳.此外,随着海平面下降,华北地区广布沼泽使这些植物固定的碳得以大量保存,也为富有机质页岩形成提供了丰富的有机质来源.

2.5 多地质(生物)事件耦合关系

地质(生物)事件的发生是相互作用和影响.晚古生代冰期、海平面变化、构造运动、火山活动、生物繁盛等在不同程度上影响了有机质的沉积和保存条件(图2).上文对鄂尔多斯盆地东缘海陆过渡相页岩沉积过程中的各类地质(生物)事件进行了分析,结果表明优质页岩储层的形成与全球性或区域性地质(生物)事件密切相关.本溪组－太原组沉积期为间冰期,随着海平面上升形成了河漫湖泊、潮上湿地和近岸海湾的沉积环境,丰富的水生浮游藻类生物和水体缺氧－贫氧的沉积环境促进了有机质富集.山西组沉积期处于冰期顶峰,海平面的下降,植物的繁盛和由海侵活动形成的贫氧－缺氧环境为山$_2^3$亚段页岩的形成提供了有利条件.在鄂尔多斯盆地东缘本溪组、太原组和山西组的页岩中,观察到火山活动的记录较少,因此区域性火山活动对鄂尔多斯盆地东缘页岩的影响还需要进一步的研究.

综上所述,从地质(生物)事件的角度分析,笔者认为鄂尔多斯盆地东缘海陆过渡相页岩的富集过程主要受到晚古生代冰期植物繁盛、海平面变化、海侵作用的影响,火山活动对页岩富集过程的影响还需要进一步的研究(图5).

3 页岩气富集主控因素探讨

页岩气的形成与富集受到水体沉积条件、有机质聚集等早期沉积环境及后期构造活动等因素的共同控制(Zhang *et al.*,2021).针对页岩气富集、高产模式及控制因素,研究人员提出(邹才能等,2015;邱振等,2020):早期富有机质页岩沉积是页岩气富集的基础;后期有效保存条件是高产的关键.本文对鄂尔多斯东缘石炭纪－二叠纪海陆过渡相页岩气的富集特征进行初步研究,尝试从有机质富集沉积的角度探讨其控制因素.含气量作为衡量页岩气富集程度的关键指标,其受多种因素影响,包括岩性、有机质类型、*TOC*、成熟度、石英、黄铁矿和黏土矿物含量、孔隙度以及后期保存条件等等(秦建中等,2014;Shurr and Ridgley,2002).研究表明,页岩*TOC*含量对含气量有着关键控制作用(邱振等,2020;王恩泽等,2022).基于此,本文对鄂尔多斯盆地海陆过渡相页岩(晋祠段和山$_2^3$亚段页岩)的含气量与*TOC*含量进行统计分析.结果显示含气量与*TOC*含量呈正相关性(图6;R^2=0.598).鄂尔多斯盆地属于构造稳定的克拉通盆地,断裂欠发育,天然气保存条件优越,加上页岩气自生自储的特性,因此,鄂尔多斯盆地海陆过渡相页岩含气量主要取决于*TOC*含量;基于以上因素,笔者以有机质富集的控制因素来探讨含气量富集的影响因素.

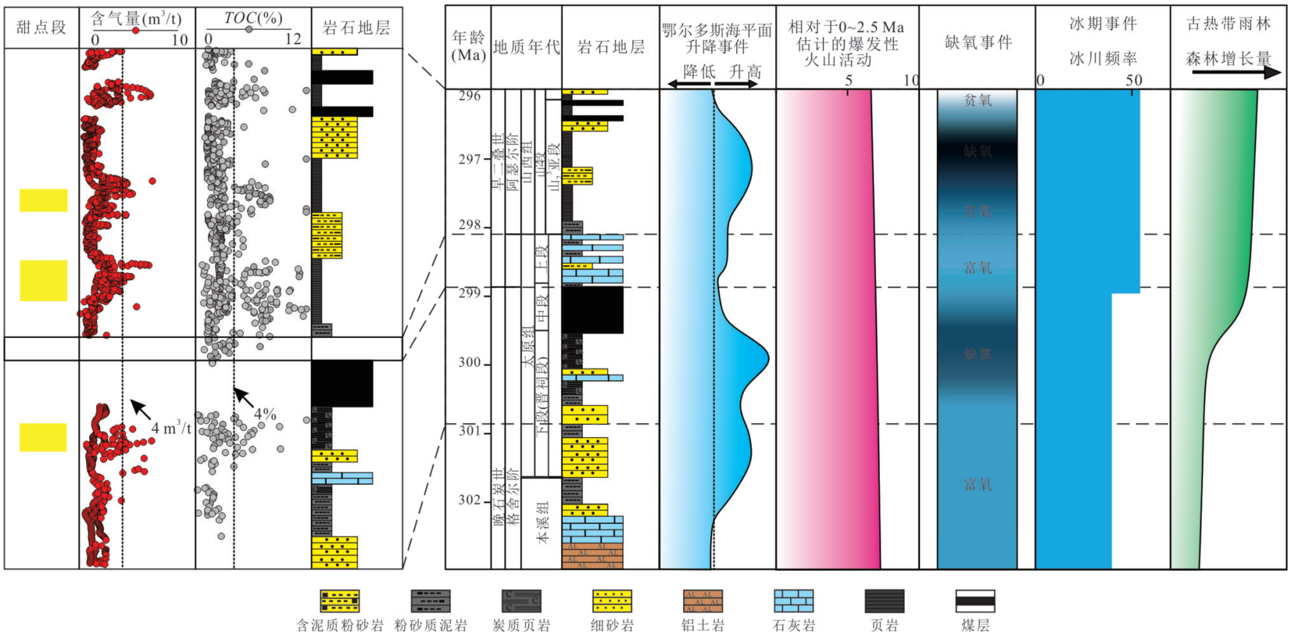

图5　鄂尔多斯盆地东缘晚石炭纪－早二叠纪之交地质(生物)事件及山西组、太原组、本溪组页岩气甜点段分布特征

Fig.5　Carboniferous-Permian geological (biological) events in the eastern margin of Ordos basin and the distribution characteristics of Shanxi, Taiyuan and Benxi formations shale gas dessert section

地质年代、岩性地层等据国际地层年代表(2023版)及申博恒等(2021，2022)；沈树忠等(2019)，综合岩石地层划分据武瑾等(2021)；张琴等(2022)；蔡光银等(2022)；鄂尔多斯盆地相对海平面变化据吕大炜等(2009)；火山活动据 Soreghan *et al.*(2019)；沉积水体缺氧程度趋势分布据 Mo_{EF} 和 U_{EF} 元素建立；冰期—间冰期特征据 Qie *et al.* (2019)；Fang *et al.* (2021)；Chen *et al.* (2018)修改；*TOC* 含量趋势图中数据部分来自武瑾等(2021)；张琴等(2022)；蔡光银等(2022)，其中红色圆点代表样品 *TOC* 含量大于12% 的样品；含气量趋势图据测井曲线建立

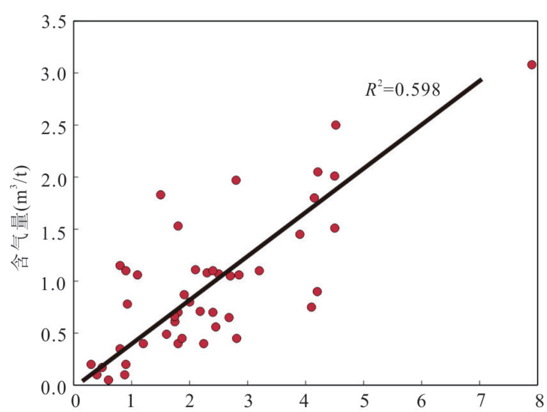

图6　鄂尔多斯盆地东缘石炭系－二叠系(晋祠段与山$_2^3$亚段)页岩层段的 *TOC* 含量与实测含气量交汇图

Fig.6　Intersection diagram of *TOC* content and measured gas content for Carboniferous-Permian (Jinci Formation and Shan$_2^3$ Subsection) shale intervals in the eastern margin of the Ordos basin

部分数据来自武瑾等(2021)；蔡光银等(2022)；张琴等(2022)；Zhang *et al.*(2023)

有机质富集影响因素众多，主要包括陆源碎屑的供应、古气候、古盐度、古生产力和古水体氧化还原环境等(刘翰林等，2023；田巍等，2019)．而有机质富集沉积的研究主要侧重于水体表层生产力和底部氧化还原条件，高生产力是有机质富集的前提，缺氧环境则有助于有机质的保存(邱振等，2020；刘翰林等，2023)．鄂尔多斯盆地东缘海陆过渡相页岩沉积过程中，湿热气候促进了藻类等浮游生物的光合作用，进而提升了碳合成速率；同时，高陆源风化营养元素通量背景下，大量陆源营养物质 P、N 经河流搬运作用进入潟湖，在一定程度上提高了初级生产力．同时，由于冈瓦纳冰川消长，触发了全球海平面的变化，在海平面相对上升期，形成河漫湖泊、潮上湿地和近岸海湾等有利于有机质沉积的环境，大量陆源碎屑对水体氧的消耗使得水体沉积环境转变为贫氧－缺氧，进一步促进了有机质的保存．

诸多研究已证实，水体初级生产力可以通过 Ba、P、Ni、Zn 等营养元素及 P/Ti 和 Ba/Al 等比值来指示(Qiu *et al.*，2022)；水体氧化还原条件的指标可以通过 U、V、Mo、Ni、Cu 等微量元素和它们与 Th、Cr 等微量元素的比值反映，如 U_{EF}，Mo_{EF} 等(田巍等，2019)；陆源风化的强度则可以通过 CIA 来反映(Zou *et al.*，2018；Algeo and Liu，2020)，基于上述的

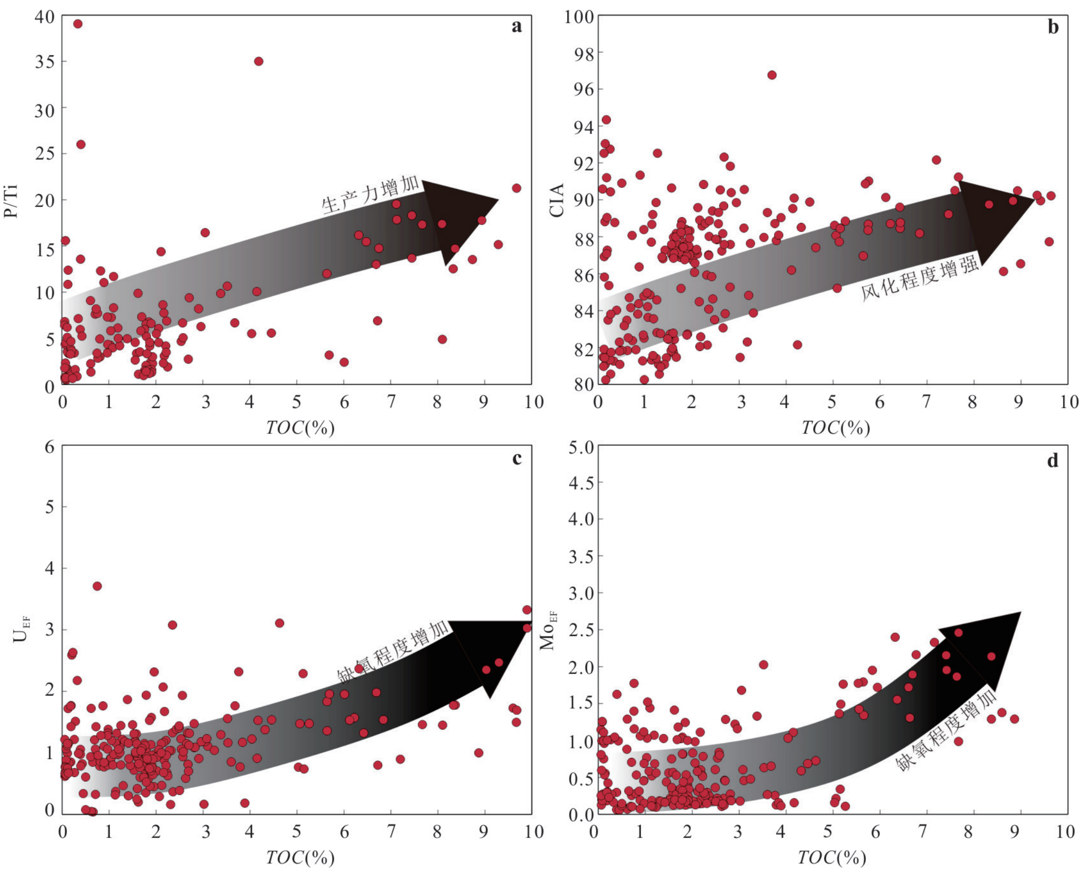

图7 鄂尔多斯盆地东缘石炭系—二叠系(晋祠段与山$_2^3$亚段)页岩层段的 *TOC* 含量与P/Ti交汇图(a)、CIA交汇图(b)、U_{EF}交汇图(c)、Mo_{EF}交汇图(d)

Fig.7 Intersection diagrams of *TOC* content with P/Ti (a), CIA (b), U_{EF} (c), and Mo_{EF} (d) for Carboniferous-Permian (Jinci Formation and Shan$_2^3$ Subsection) shale intervals in the eastern margin of the Ordos basin

部分数据来自武瑾等(2021);蔡光银等(2022);张琴等(2022); Zhang *et al*.(2023)

指标,本文分析了地质(生物)事件对页岩气富集的影响.统计分析招贤页岩、山$_2^3$亚段页岩的 *TOC* 含量与P/Ti、CIA、U_{EF}、Mo_{EF}指标表明(图7),鄂尔多斯盆地东缘页岩沉积过程中,植物繁盛和高陆源风化带来的陆源碎屑提高了水体的初级生产力,为有机质富集提供了物质基础;而相对海平面上升形成的贫氧—缺氧沉积环境为有机质的富集创造了适宜条件;两个因素的共同作用促进了鄂尔多斯东缘两套页岩气的富集.

4 结论

(1)石炭纪—二叠纪转折期鄂尔多斯盆地东缘页岩气富集受地质(生物)事件的多重影响.晚古生代冰期,广泛的陆地面积和相对稳定的构造背景使得华北地区最大规模的热带雨林系统形成,植物繁盛使得陆地生产力升高,为页岩有机质富集提供了条件.冰川作用和海平面变化影响着有机质的保存环境:相对海平面上升,形成的贫氧—缺氧环境,减小了有机质的氧化分解,使有机质得到了更好的保存.

(2)基于页岩气含气量这一关键因素,通过建立TOC含量与含气量的相关关系,从古生产力和古环境角度分析了页岩气与重大地质(生物)事件的相互关系:石炭纪—二叠纪时期,植物繁盛能够为有机质大量生成提供物质基础,相对海平面的上升易形成贫氧—缺氧水体环境,有利于有机质大量沉积富集,从而最终促进了该区页岩气"甜点段"形成.

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