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冰消期气候控制中国海相烃源岩有机碳富集

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摘要 【意义】气候作用影响着海洋有机碳富集, 现有文献主要探讨高日照量和温暖湿润气候下有机碳富集机理、总结富有机质沉积与天文周期期间的关系, 极少涉及冰消期海相烃源岩发育机理。我国在元古代和古生代冰消期发育了多套海相烃源岩, 通过研究和总结冰消期气候对盆地有机碳富集的作用机理, 有助于从地球系统的角度建立不同气候条件与有机质丰度之间的耦合关系模型。【进展】调研发现, 我国大型油气田对应的中生代和新生代主力烃源岩发育于中高纬度温室气候期, 而元古代和古生代主力烃源岩主要发育于中低纬度冰川消融期。冰消期烃源岩分布在新元古代、埃迪卡拉纪—寒武纪转换期、奥陶纪—志留纪转换期和二叠纪四个时代, 其特殊的气候条件对海洋有机碳富集具有重要作用。【结论与展望】米氏旋回控制下的高日照量、升温 and 波动气候导致的岩石风化增强、广泛的海侵作用、强烈的上升流作用和间冰期频繁的火山活动, 共同导致了冰消期海洋生产力提高和缺氧还原的水体环境, 进而促进有机碳富集和烃源岩形成。这一冰消期气候与烃源岩形成的关系模式, 体现了气候旋回控制下海洋—陆地—大气地球系统对有机碳富集的控制作用, 未来可结合气候模拟和定量计算的结果, 对大页岩油气田分布做出一定预测。

关键词 冰消期; 有机碳; 烃源岩; 古气候; 风化作用; 上升流; 火山作用

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0 引言

烃源岩有机碳富集主要由初级生产力和氧化还原条件控制, 高的初始生产力和有利于有机质保存的缺氧水体条件, 促使富有机质烃源岩的形成 (Demaison and Moore, 1980; Pedersen and Calvert, 1990; Sageman *et al.*, 2003; Schoepfer *et al.*, 2015)。前人对于烃源岩有机碳富集机制的研究主要集中在沉积盆地的古地理和古环境方面, 通过沉积地化手段恢复沉积期的古生产力和氧化还原条件, 进一步探究其主控因素 (Caplan and Bustin, 1999; Rimmer, 2004)。水体的初始生产力主要取决于表层水体中 P、Cu、Zn、Ni 等营养元素含量, 营养物质海洋输入的影响因素包括上升流输入、温盐环流输入和海侵输

入 (Caplan and Bustin, 1999; Hofmann *et al.*, 2001; Wei *et al.*, 2012); 营养物质的陆源输入对水体生产力有一定补充, 陆源输入包括陆源有机质和陆源营养元素输入 (Jiwarungrueangkul *et al.*, 2019; Xu *et al.*, 2020); 此外光照量对海洋初级生产力也有一定的影响 (Gao *et al.*, 2012; Huang *et al.*, 2021a; Striebel *et al.*, 2023)。氧化还原条件的控制因素包括局限的水体环境、最小含氧带 (OMZ) 扩张上移和水体氧消耗, 局限水环境主要指潟湖等低能水体较封闭的沉积环境, OMZ 扩张上移主要是海侵导致, 水体氧消耗包括生物大量繁殖耗氧和还原性气体反应耗氧 (Demaison and Moore, 1980; Calvert and Pedersen, 1993; Pichevin *et al.*, 2004)。因此, 烃源岩的发育在一定程度上与温

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度、洋流、大陆风化等因素具有相关性。

已有研究表明,全球碳循环与气候有着密切的关系(Dixon and Turner, 1991),而有机碳富集埋藏作为碳循环中的重要环节,与气候也存在一定的耦合关系。从较大尺度上看,Craig *et al.* (2013)曾提出烃源岩发育与海平面升降和气候变化之间存在较好的对应关系,全球性冰期之后发生快速海侵,伴随着裂谷活动,发育局限盆地(Cai *et al.*, 2022),有利于富有机质烃源岩沉积,因此烃源岩的发育可能与大尺度的冰期旋回有耦合关系。Huang *et al.* (2021a)在温暖湿润的晚白垩世松辽盆地TOC时间序列中广泛检测到米兰科维奇旋回,突出了受倾角控制的季节性日照强度的影响,高地轴倾角对应着夏季高日照量和高降水量,而日照量变化会影响生物生长能力并导致地表温度、冰川、洋流等一系列气候变化,进而导致海洋初始生产力提高和有机碳富集沉积。赵文智等(2019)认为元古宙分层海洋仅在若干个间冰期时间段内才有发育,是爆发性、间断性的,说明可能是某种具有旋回性的因素控制了气候、大气、海洋乃至生物的演化,并最终控制了烃源岩形成。此外,Zhang *et al.* (2015)提出轨道驱动的ITCZ周期性迁移控制了哈德来环流动力学变化以及下马岭组沉积期的降雨强度、信风强度和海洋上升流速率,因此认为TOC含量等沉积物地化特征的周期性变化是由导致ITCZ周期性迁移的米兰科维奇周期控制的。由此可以看出,前人认为温室期和间冰期的高日照量和高温气候有利于有机碳的富集(Craig *et al.*, 2013; Algeo *et al.*, 2014),且有机碳富集存在某种旋回性规律,但目前对于其相关关系的研究较少,主要停留在规律性的总结与假设阶段。由于全球主要烃源岩发育的时代和地区跨度较大,气候特征较复杂,针对大范围的气候与烃源岩相关关系的研究和规律性总结较少,且工作量较大。因此,本文选取我国主要油气藏不同时代海相烃源岩为研究对象,这些烃源岩具有地层时代跨越大、古地理分布相对较广且形成于研究相对较少的冰川消融时期等特点,研究气候对这些烃源岩有机碳富集的控制作用。

1 中国烃源岩发育

1.1 中国主要烃源岩发育情况

通过对中国烃源岩分布、深时古气候和古环境大量调研发现,从元古代到新生代的各个时代我国

均有大量烃源岩发育,其中250 Ma之后的中生代和新生代烃源岩对应的油气资源量占我国油气总资源量的70%左右,元古代和古生代的烃源岩资源量贡献约为30%(腾格尔等, 2010)。目前已有大量研究表明我国中、新生代的烃源岩主要发育于中高纬度地区和温室气候条件下,广泛分布在各个时代,且大多为陆相烃源岩。而250 Ma之前的元古代和古生代主要烃源岩集中发育于中低纬度地区和气候转折时期,多为冰消期的海相烃源岩(图1)。

对于我国元古代和古生代地层,安岳气田、塔河油田、长宁气田和双鱼石气田等亿吨级大型油气田的主力烃源岩主要分布在新元古代、埃迪卡拉纪—寒武纪转换期(E-C转换期)、奥陶纪—志留纪转换期(O-S转换期)和二叠纪四个时代;这四个时代烃源岩均形成于全球性大冰期后间冰期冰川消融期,对应着全球海侵阶段(图1)。这里的冰消期指紧随全球性大冰期后的冰融时期,但中国主要烃源岩发育地区不一定有相应的冰碛岩存在,目前仅新元古代大塘坡组和陡山沱组烃源岩之下发现有铁丝坳组和南沱组冰川沉积(Bao *et al.*, 2018; Shen *et al.*, 2021; Shen *et al.*, 2022b),其他烃源岩均发育于距离冰川沉积较近的受冰消期气候影响的地区。

古地理重建表明,冰消期四个时代的烃源岩均沉积于北半球中低纬度地区,太阳光照充足,气温相对较高(图2)。其中新元古代(大塘坡组沉积时期)华南板块位于15° N附近,新元古代(陡山沱组二段沉积时期)华南板块位于10° N附近;晚埃迪卡拉—早寒武世(玉尔吐斯组和筇竹寺组沉积时期)塔里木板块位于赤道附近,华南板块位于10° N附近;晚奥陶世—早志留世(五峰组—龙马溪组沉积时期)华南板块位于15° N附近;中二叠世(栖霞组沉积时期)华南板块位于赤道附近。当间冰期冰川融化时,这些较低纬地区往往会发生明显的气温升高,对应着转折期复杂且剧烈的气候变化。

1.2 主要烃源岩分布与冰消期的关系

华南宜昌地区在陡山沱组钻遇页岩气,陡山沱组烃源岩对华南安岳气田也有一定贡献(朱光有等, 2021),陡山沱组二段烃源岩(621±7 Ma)形成于Marinoan冰期后(Zhang *et al.*, 2005),对应华南南沱冰期(654~635 Ma; 636±4.9 Ma)(Zhang *et al.*, 2008; 胡蓉, 2016)。塔里木盆地塔中、塔河油田主力烃源岩下寒武统玉尔吐斯组(538.2±1.5 Ma)(Yao *et al.*, 2005;

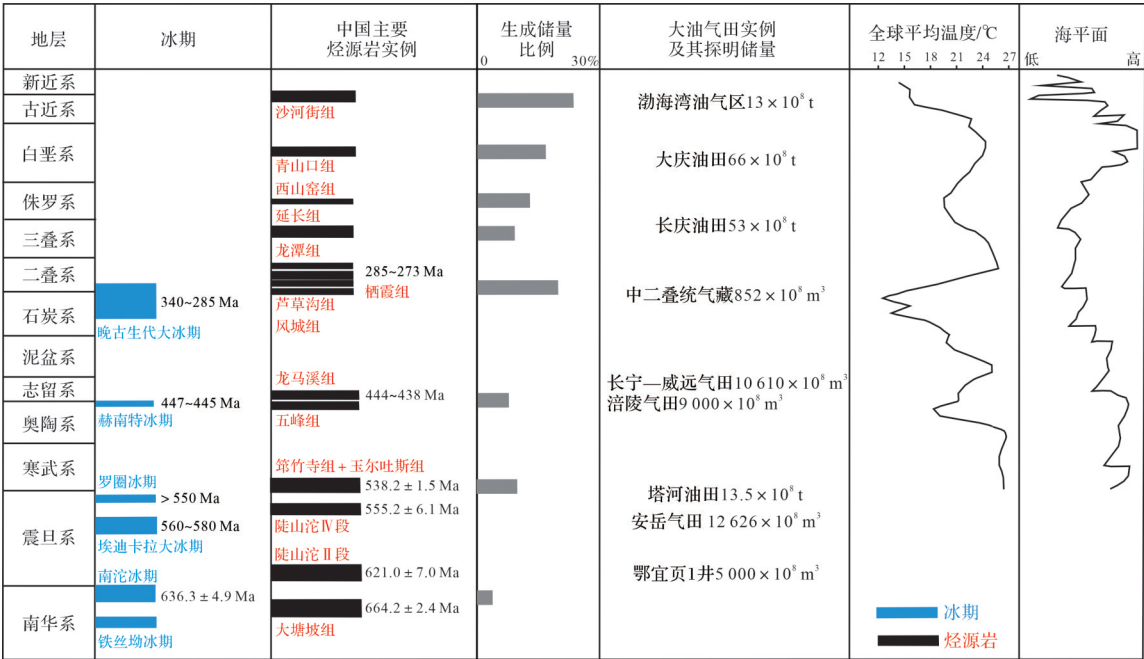


图1 中国主要烃源岩与冰期分布

年龄数据参考 Whetten, 1965; Garzanti and Sciunnach, 1997; Jones and Fielding, 2004; Yao *et al.*, 2005; Zhang *et al.*, 2005, 2008; Delabroye and Vecoli, 2010; Chen *et al.*, 2015; 胡蓉, 2016; 杨兵等, 2016; 陈旭等, 2017; Qie *et al.*, 2019; Wang *et al.*, 2021a; Huang *et al.*, 2021b; Wang *et al.*, 2021b; Sun *et al.*, 2022; Wang *et al.*, 2023b; 油气储量数据参考张健等, 2018; 戴金星, 2022; 全球平均温度参考 Scotese *et al.*, 2021; 全球平均海平面变化参考何登发等, 2015

Fig.1 Distribution of major source rocks and glaciation in China

Data of age are from Whetten, 1965; Garzanti and Sciunnach, 1997; Jones and Fielding, 2004; Yao *et al.*, 2005; Zhang *et al.*, 2005, 2008; Delabroye and Vecoli, 2010; Chen *et al.*, 2015; Hu, 2016; Yang *et al.*, 2016; Chen *et al.*, 2017; Qie *et al.*, 2019; Wang *et al.*, 2021a; Huang *et al.*, 2021b; Wang *et al.*, 2021b; Sun *et al.*, 2022; Wang *et al.*, 2023b; data of oil and gas reserves are from Zhang *et al.*, 2018; Dai, 2022; global average temperature refers to Scotese *et al.*, 2021; global average sea level change refers to He *et al.*, 2015

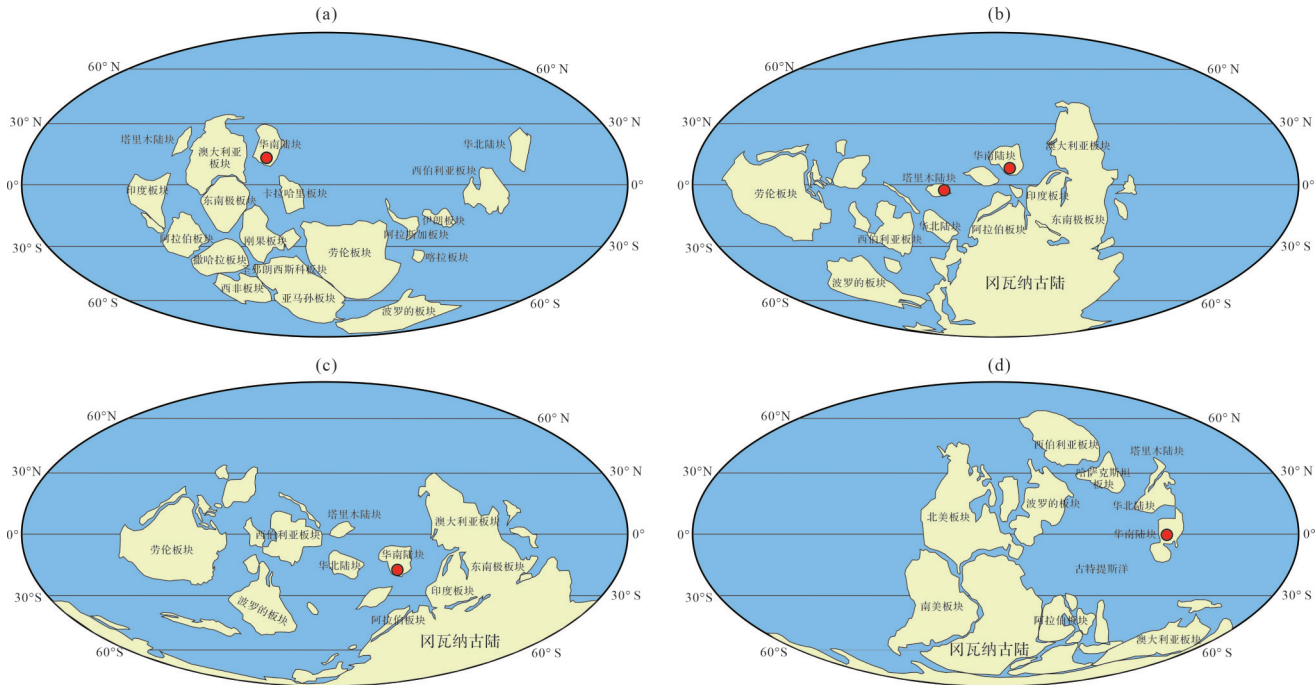


图2 中国冰消期海相烃源岩古地理分布(据 Harper and Servais, 2013; 李江海和姜洪福, 2013 修改)

Fig.2 Paleogeographic distribution of marine source rocks during deglaciation in China
(modified from Harper and Servais, 2013; Li and Jiang, 2013)

Cai *et al.*, 2009; Cai *et al.*, 2015)、威远和安岳气田主力烃源岩下寒武统筇竹寺组 and 上埃迪卡拉陡山沱组四段烃源岩(555.2±6.1 Ma)(Zhang *et al.*, 2005), 对应早寒武世气候较寒冷阶段, 当时塔里木盆地气候寒冷、风化作用弱(Zhang *et al.*, 2021), 同时小于 550 Ma 时期华北地区发育罗圈冰期(Wang *et al.*, 2021a), 此外 Wang *et al.* (2023b) 提出在 560~580 Ma 期间全球存在持续超过 20 Myr 的埃迪卡拉大冰期(GEG)。四川盆地东南部长宁—威远、威荣、涪陵大气田区探明储量已达万亿立方米, 上奥陶统一志留统五峰组—龙马溪组是该区各气田的重要烃源岩层, 其中龙马溪组烃源岩(444.43~438.13 Ma)(Chen *et al.*, 2015)形成于赫南特冰期(447.62~445.16 Ma; 447.02~444.4 Ma)(Delabroye and Vecoli, 2010; Chen *et al.*, 2015)之后。华南板块四川盆地双鱼石气田等二叠系天然气藏的主力烃源岩之一为中二叠统栖霞组(285~273 Ma; 286±10 Ma)(Shen *et al.*, 2019; 文龙等, 2021; 何文渊等, 2022), 形成于晚古生代全球性大冰期(340~285 Ma)后的冰川消融期(Qie *et al.*, 2019)。

虽然地质数据和模拟结果大多认为早寒武世地球处于缺乏永久极地冰盖的温室气候状态(Hearing *et al.*, 2018), 但仍有一些证据表明早寒武世期间中高纬度地区极有可能发生了冰川作用(Lindström, 1972; Landing and MacGabhann, 2010)。这说明早寒武世时期全球气温还并没有完全达到温室状态, 仍处于极地冰川消融阶段。同时, 新元古代末期在处于中低纬度的中国华北地区发现了罗圈组冰期沉积, 这也说明新元古代末期到早寒武世时期中国所处的华南、华北和塔里木三大陆块并非温室气候, 而是处于元古代大面积冰川事件后的冰川消融期。

2 冰消期烃源岩特征

(1) 新元古代: 新元古代有多期全球性冰期发育, 其冰消期发育多套烃源岩, 年龄最小的南华系大塘坡组和埃迪卡拉陡山沱组烃源岩分别是 Sturtian、Marinoan 冰期后的富有机质沉积。华南南华系大塘坡组烃源岩主要为含锰黑色炭质页岩, 夹有菱锰矿和凝灰岩(尹崇玉等, 2006), 有效烃源岩厚度多大于 50 m, TOC 含量大多分布在 3%~5%, 最高可达 10% 以上(李婷婷等, 2021; 宋腾等, 2022), 其下伏铁丝坳组冰碛岩。华南震旦系陡山沱组二段烃源岩主要岩性为黑色泥页岩, 有效烃源岩厚度 5~20 mm, TOC 含

量介于 1%~10%, 最高可达 19%(Jiang *et al.*, 2011; Liu *et al.*, 2012; 朱光有等, 2021)。

(2) E-C 转换期(新元古代—早寒武世): E-C 转换期烃源岩包括华南陡山沱组四段、塔里木盆地玉尔吐斯组、华南筇竹寺组和牛蹄塘组, 整体上形成于雪球地球冰川消融后, 也对应于华北罗圈冰期之后。陡山沱组四段主要岩性为泥质碳酸盐岩和黑色页岩, 有效烃源岩厚度多介于 20~50 m, TOC 含量介于 1%~4%(Jiang *et al.*, 2011; Liu *et al.*, 2012; 朱光有等, 2021); 陡山沱组沉积时期共发生了三次与洋流上升有关的广泛成磷事件, 分别为陡二段的下磷层、中磷层和陡四段的上磷层, 且发育多层火山灰蚀变黏土层, 证明陡山沱时期有多次火山作用事件(杨爱华等, 2015)。塔里木盆地玉尔吐斯组烃源岩为黑色页岩, 厚度介于 10~15 m, TOC 含量介于 2%~16%(Zhu *et al.*, 2016); 玉尔吐斯组第三层硅质岩中发现大量的磷结核, 其中的大量的磷元素可能来自上升流(Yeasmin *et al.*, 2017)。

(3) O-S 转换期(晚奥陶世—早志留世): 华南板块发育的五峰—龙马溪组烃源岩, 形成于 O-S 大冰期后, 主要烃源岩层为黑色页岩, 富有机质段厚度介于 10~60 m(Qiu and Zou, 2020), TOC 含量介于 1.5%~5.0%(邱振等, 2020)。五峰组以硅质页岩和碳质页岩为主, 层内常见笔石化石(贾敏, 2019), 发育超过 20 层的火山灰层; 龙马溪组分为上下两段, 底部发育大量的钾质斑脱岩层, 主要烃源岩层为下段的黑色硅质和碳质页岩。

(4) 二叠纪: 华南板块发育中二叠世晚古生代大冰期后栖霞组烃源岩, 形成于晚古生代大冰期后, 包括泥质岩烃源岩和碳酸盐岩烃源岩, 厚度介于 10~70 m, TOC 介于 0.5%~2.0%(黄士鹏等, 2016), 其中栖霞组二段的黑色泥质灰岩是最主要的富有机碳段(韦恒叶等, 2011)。栖霞组存在上升流区特有的冷/温水型属种四射珊瑚和腕足类、硅质结核和放射虫等生物类型(吕炳全等, 2010); 未见明显火山灰沉积, 但其对应时期世界各地存在频繁的火山作用, 且大气 CO₂ 迅速增加。

上述四个时期的烃源岩均为有机碳丰度较高的黑色泥页岩(图 3), 平均 TOC 含量均大于 3%。新元古代和 E-C 转换期的大塘坡组和陡山沱组烃源岩分别发育于铁丝坳冰碛岩和南沱组冰碛岩之上, 而 O-S 转折期的五峰组—龙马溪组和二叠系栖霞组、龙潭组烃源岩之下未找到直接的冰碛岩沉积。

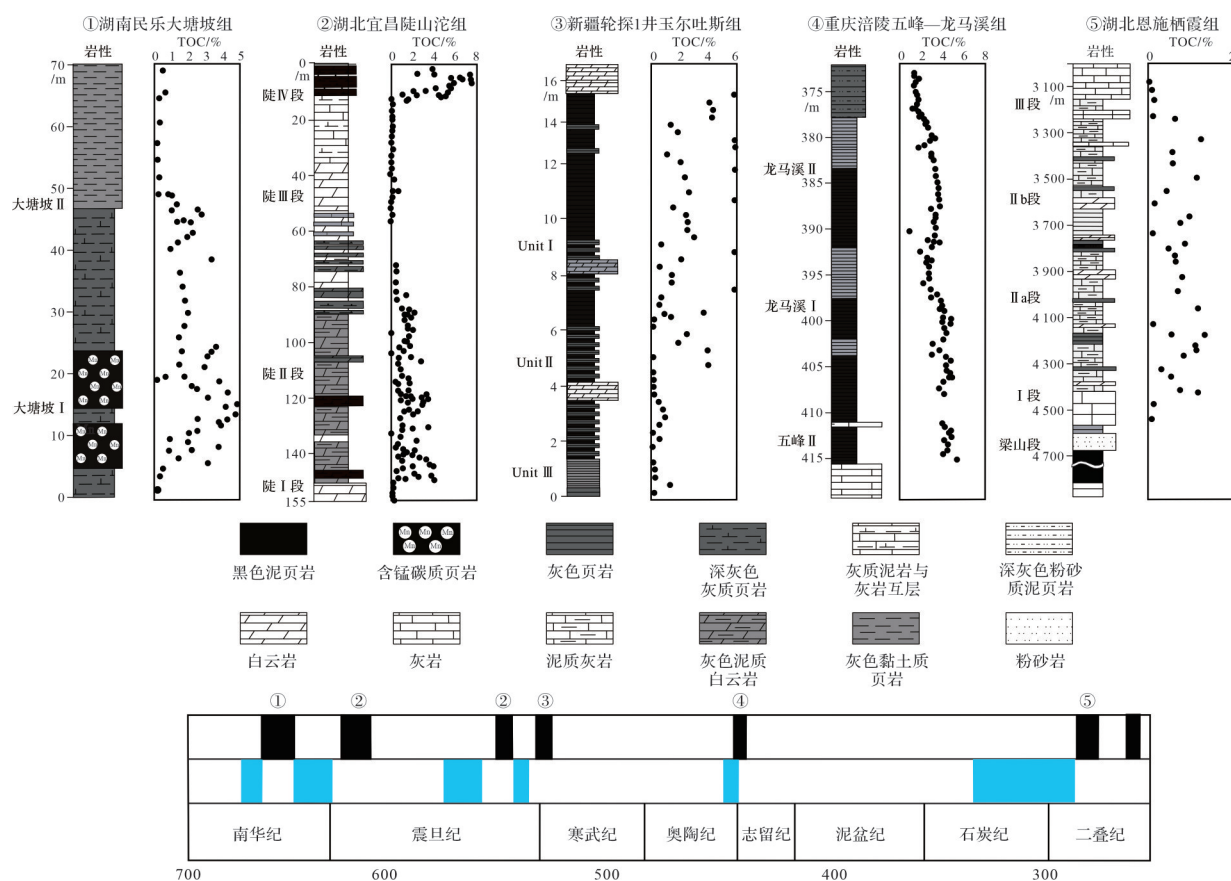


图3 中国冰消期海相烃源岩剖面及 TOC 含量

大塘坡组数据引自赵文智等, 2019; 陡山沱组数据引自 McFadden *et al.*, 2008; 玉尔吐斯组数据引自 Zhu *et al.*, 2016; 五峰组—龙马溪组数据引自邱振等, 2020; 栖霞组数据引自韦恒叶等, 2011

Fig.3 Marine source rock profiles and total organic carbon (TOC) contents during deglaciation in China

Data of the Datangpo Formation are cited from Zhao *et al.*, 2019; data of Doushantuo Formation are from McFadden *et al.*, 2008; data of Yurtus Formation are from Zhu *et al.*, 2016; data of Wufeng Formation-Longmaxi Formation are from Qiu *et al.*, 2020; data of Chixian Formation are from Wei *et al.*, 2011

3 冰融后气候控制有机碳富集

目前仅有几项关于间冰期气候影响有机碳富集的成果,认为间冰期有机碳富集主要机理包括,天文旋回导致的日照量增加、构造裂谷导致的局限盆地形成和升温导致的陆地风化增加(赵文智等, 2019; Huang *et al.*, 2021a)。但这几种解释都是针对烃源岩形成于整个间冰期而言,特别是日照量和风化增加在间冰期中期的高日照温湿气候下作用最明显,对中、新生代温室期形成的烃源岩影响较大,而与元古代和古生代冰川期末期到间冰期冰川消融初期的烃源岩情况并不完全相符。因此,需要针对冰期—间冰期过渡期特殊的冰融气候,结合与其相关联的地球系统气候变化、海洋变化和地质事件进一步探究气候对有机碳富集的控制作用。

3.1 气候特征及其作用

3.1.1 冰消期温度、湿度特征

冰消期作为从冰室气候向温室气候转变的特殊时期,其气温明显回升、气候变化较为剧烈,而气候的变化往往会影响生物生长和物源风化,会对有机碳的富集产生较大的影响,因此各烃源岩富集时代的温度和湿度特征研究至关重要。化学蚀变指数(CIA)常用来反映物源区的化学风化程度,计算公式为: $CIA = Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100$, 主要反映了长石相对于黏土矿物的含量(Nesbitt and Young, 1982; Fedo *et al.*, 1995; 赵占仑等, 2018)。化学风化与气候有着强烈的正相关关系,炎热湿润的气候条件往往对应较强的化学风化程度,因此 CIA 指数还广泛用于反映沉积时的气候条件。

新元古代大塘坡组烃源岩直接沉积在铁丝坳冰碛岩之上,其烃源岩 CIA 值介于 50~70, 化学风化作

用中等,为温暖湿润气候伴有间歇性的寒冷干旱。其中大塘坡 I 段 CIA 值介于 50~70,波动较大,而大塘坡组 II 段的 CIA 值介于 60~70,气温较高、气候相对平稳,大塘坡组沉积时期整体风化作用较强,营养物质陆源输入贡献明显(李婷婷等,2021)。Wei *et al.* (2020)通过大塘坡组烃源岩 Li 含量和 Li 同位素研究,也同样指出大塘坡组 I 段气候波动、风化作用较强,II 段气温较高、化学风化较强。

E-C 转换期陡山沱组烃源岩的 CIA 值大多介于 60~80,其 C 值介于 0.45~0.65,表明它们经历了中等程度的化学风化作用,沉积于温暖湿润的气候条件下(Zhai *et al.*, 2018; 朱光有等, 2021; 陆卓等, 2022)。“雪球地球”假说表明,在元古代冰川作用之后地球迅速过渡到温室气候条件(Hoffman *et al.*, 1998; Shields, 2005),因此埃迪卡拉纪—寒武纪转换期的构造、气候和海洋特征变化剧烈(Zhai *et al.*, 2018),且通常伴随着化学风化作用的增强(Shields *et al.*, 1997, 2007; Peters and Gaines, 2012)。但也有研究表明在寒武纪早期可能发生化学风化强度的短期降低(Li *et al.*, 2013)。华南寒武纪初期沉积的黑色页岩具有异常低的 CIA 值,且其 CIA 值与 TOC 之间呈负相关关系,而陆源输入指标 Ti/Al 与 TOC 仍呈正相关关系(Zhai *et al.*, 2018),这说明华南地区早寒武初期存在短时间的低温期,化学风化较弱,但由于其气温波动大导致其物理风化较强,仍然导致了陆源输入增加和生产力提高。

上奥陶统赫南特阶沉积期对应着多次短时冰期,此时华南板块位于冈瓦纳大陆西北侧的中低纬度热带、亚热带地区。赫南特冰期时沉积的观音桥段 CIA 值介于 50~65,指示较寒冷和干燥的气候;赫南特阶末期冰消期的下志留统鲁丹阶龙马溪组烃源岩的 CIA 值骤升为 65~75,指示温暖湿润的气候特征,气温波动较大(Detian *et al.*, 2010; Zou *et al.*, 2018)。因此,华南龙马溪组烃源岩发育于典型的升温波动的冰消期气候之下。

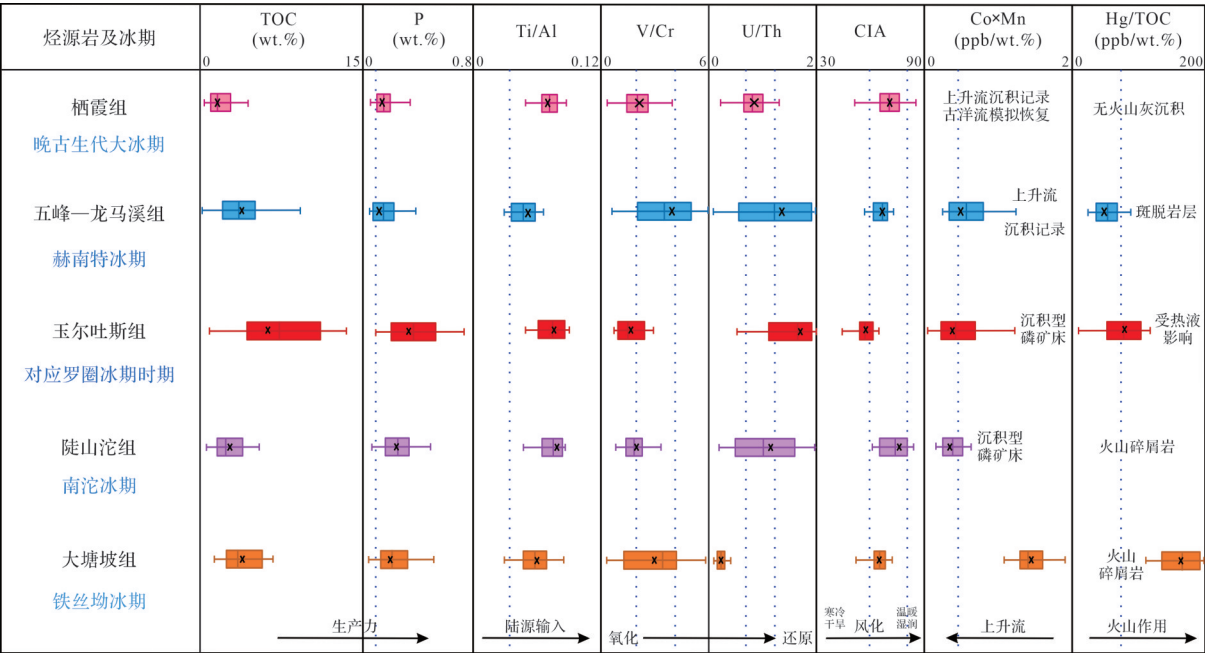
晚古生代冰期(LPIA)是显生宙最长和最强烈的冰川期,期间冈瓦纳大陆的主要陆块均可见冰碛岩分布(王洪浩等,2014),在早二叠世全球温度开始升高,冰川大面积融化,冰期结束。华南板块在中二叠世处于赤道附近,脱离冈瓦纳大陆,没有发现直接的冰期沉积,但其仍受转折期冰消时特殊的气候条件影响。栖霞组的 CIA 值介于 50~90,数值变化大,平

均值介于 70~80,指示了其整体沉积于温暖湿润的气候条件下,但气候波动较大(李明隆等, 2020; Sun *et al.*, 2023)。其中 TOC 含量较低的栖霞组一段和三段 CIA 值较低,对应寒冷干燥条件下较弱的化学风化作用;栖霞组二段高 TOC 灰岩对应温暖湿润气候下较高的化学风化作用。

3.1.2 作用机制

综合来看,冰消期烃源岩 CIA 值从冰期的极低值上升到烃源岩形成期的平均 60 以上(图 4),升温的同时对应着化学风化作用的增强,而化学风化作用往往会导致物源区岩石溶蚀和陆源营养元素输入海洋,进而导致海洋生产力提高,有利于有机质大量生成和富集。冰消期烃源岩的 CIA 值与陆源输入和生产力指标大多呈正相关关系,如栖霞组烃源岩的 CIA 值与陆源输入指标 Al、Ti 呈正相关关系,与生产力指标 P 含量也具有正相关关系(图 5),说明其化学风化作用增强导致了冰消期生产力的陆源输入增加。同样,五峰组—龙马溪组烃源岩的观音桥段处于冰期,化学风化作用弱,对应低的 TOC 含量;而龙马溪组温度升高对应风化作用增强,TOC 含量明显升高(图 6)。

同时,冰融时冰川覆盖区的温度在零摄氏度上下波动,反复的冷热交替导致岩石发生冻融风化损伤(李宇白, 2020)(图 7),而受冰消期不稳定气候影响的无冰川覆盖区也会因为温度反复波动发生温差风化损伤,使岩石的物理风化增强(Hori and Morihiro, 1998; Nicholson and Nicholson, 2000),进而促进岩石化学风化增强,陆源营养物质输入增加。中国冰消期烃源岩的 CIA 值在 50~90 之间波动较大,指示了冰消期气候的剧烈波动,而波动气候导致的反复循环的较大温差会使岩石的风化作用增强,陆源物质输入增加。如大塘坡组烃源岩在 TOC 丰度较高的 I 段,其 CIA 值在 50~70 之间反复波动,致使冻融风化增强,岩石物理和化学风化剥蚀增强,陆源输入增加;TOC 含量极高的玉儿吐斯组下段烃源岩,其气候波动性也明显大于上段;观音桥段 CIA 值介于 50~65,而其上的龙马溪组烃源岩的 CIA 值骤然上升至 65~75,巨大的气候波动致使龙马溪组初期具有极高的 TOC 值(图 6)。因此,冰消期特殊的升温波动气候导致物源区岩石物理风化和化学风化相互促进,共同导致陆源输入增加和初始生产力增加。此外,有研究表明冻融作用也会导致冻土的可溶有机碳(DOC)增加(Schmitt *et al.*, 2008; 王娇月等, 2011),增



大塘坡组数据引自 Ai *et al.*, 2021; 李婷婷等, 2021; 裴冰冰等, 2023; 陡山沱组数据引自 Fang *et al.*, 2019; 朱光有等, 2021; 陆卓等, 2022; 玉尔吐斯组数据引自邓倩, 2021; 欧阳思琪等, 2022; 朱光有等, 2022; 五峰—龙马溪组数据引自 Detian *et al.*, 2010; Zou *et al.*, 2018; 邱振等, 2020; Qiu *et al.*, 2023; 栖霞组数据引自韦恒叶等, 2011; 刘喜停等, 2014; Sun *et al.*, 2023

Fig.4 Summary of geochemical indicators of marine source rocks in deglaciation
Data of the datangpo Formation are from Ai *et al.*, 2021; Li *et al.*, 2021; Pei *et al.*, 2023; data of the Doushantuo Formation are from Fang *et al.*, 2019; Zhu *et al.*, 2021; Lu *et al.*, 2022; data of the Yuertus Formation are from Deng, 2021; Ouyang *et al.*, 2022; Zhu *et al.*, 2022; data of the Wufeng-Longmaxi Formation are from Detian *et al.*, 2010; Zou *et al.*, 2018; Qiu *et al.*, 2020; Qiu *et al.*, 2023; data of Chihhsian Formation are from Wei *et al.*, 2011; Liu *et al.*, 2014; Sun *et al.*, 2023

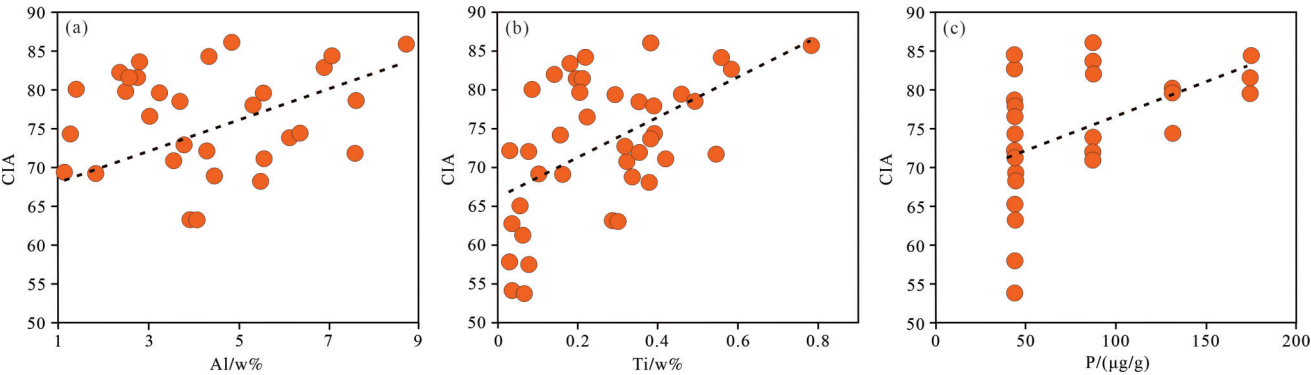


Fig.5 Relationship between chemical index of alteration (CIA) value and terrigenous input of source rock in Chihhsian Formation (data are from Sun *et al.*, 2023)

加的有机碳部分会随冰川融水和陆表径流流入海洋,致使海洋的有机碳陆源输入增加,有利于有机碳的富集埋藏。

3.2 气候相关事件作用

3.2.1 构造运动和海侵作用

万博等(2023)提出由于板块构造运动导致的海陆分布变化会极大地影响地表温度和生物发育,其

中热带区陆地面积增加不利于地表能量再分配,会导致地表温度的显著降低。而本研究中的元古代和古生代冰消期刚好对应南方陆块裂解并向北穿越低纬区时段,其热带大陆面积增加,对应全球地表温度降低。此时中国陆块进入了低纬度热带、亚热带地区,低纬地区相对温暖的气候保证了海洋生物大量繁殖,有利于有机质生成和富集。

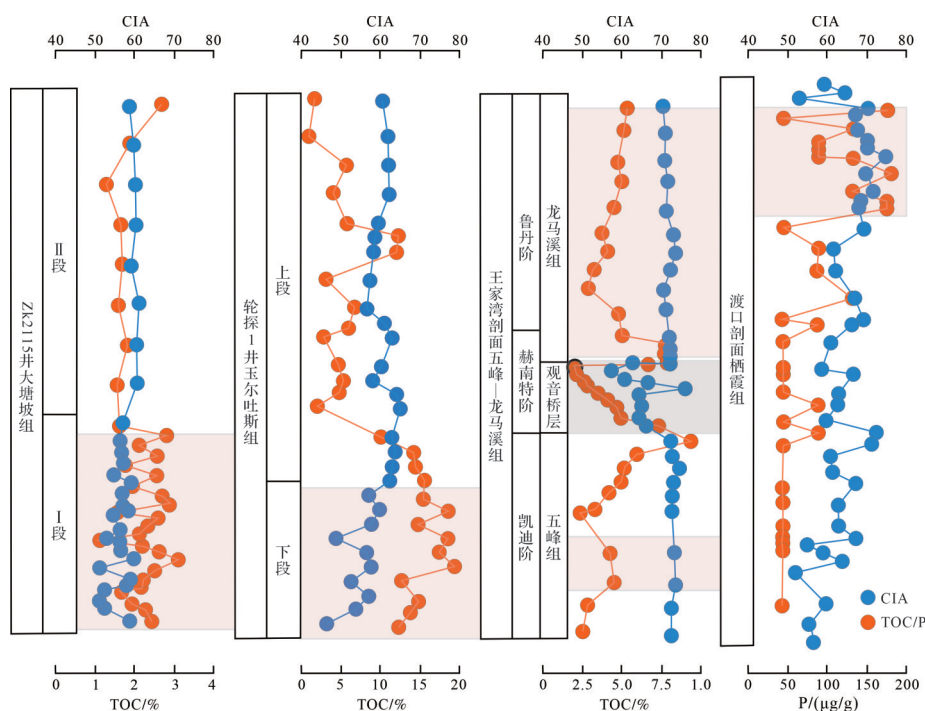


图6 冰消期烃源岩的古气候与生产力变化(数据引自 Yan *et al.*, 2009; Detian *et al.*, 2010; Wang *et al.*, 2020; 朱光有等, 2022; Sun *et al.*, 2023)

Fig.6 Paleoclimate and productivity change of source rock during deglaciation (data are from Yan *et al.*, 2009; Detian *et al.*, 2010; Wang *et al.*, 2020; Zhu *et al.*, 2022; Sun *et al.*, 2023)

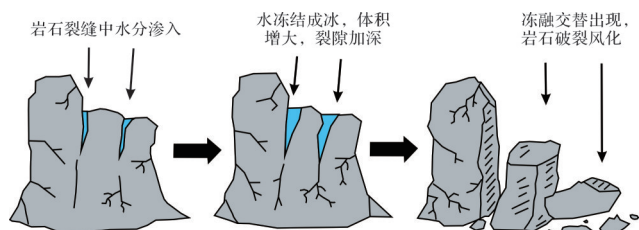


图7 岩石冻融作用的损伤机制(据路亚妮, 2013 修改)

Fig.7 Damage mechanisms caused by rock freeze-thaw processes (modified from Lu, 2013)

随着全球板块运动,热带区陆地面积逐渐减少,全球气温上升,大冰期冰川消融,两极和高山的大量冰川融水会流入海洋,导致全球海平面显著上升,海侵导致深部富营养元素的流体上涌,表层生产力提高;同时表层生产力勃发会导致浮游生物大量繁殖和表层水体氧气消耗,加之海侵引起的水体的分层和OMZ扩张,使得沉积水体缺氧,沉积界面处于氧化—还原界面之下,提高有机质埋藏量和保存率(张茜, 2020)。

这些冰川融水本身也会携带丰富的营养物质输入海洋, Raiswell *et al.* (2006)发现高山和极地冰川沉积物中(羟基)氧化铁纳米颗粒无处不在,这表明冰川融水中含有丰富的可作为营养物质的纳米铁颗

粒。在全球性大冰期的冰消期,大量的冰川沉积物通量会显著提升 Fe_{HR} 进入海洋的输送率,以提高海洋生产力。同时,冰川融水会释放大量封存氧气,导致海水含氧量增加,有利于海洋生物的生存(Hoffman *et al.*, 2017; Shen *et al.*, 2021)。特别是冰消期冰退时,高效的融水供应和排水系统,大量融水氧会被输送到冰架水域,导致海水氧化(Jenkins, 1999; Lechte *et al.*, 2019),如冰川融氧是“雪球地球”时期古海洋真核生物生存的必要条件,为后期生物爆发提供了条件(Shen *et al.*, 2022b)。因此,冰融初期的冰川融水氧输入虽然会导致海水氧含量增加,不利于深部有机质保存;但相对于生产力极低的冰期,其对生产力提高的影响更大,有利于有机质的富集。此外,大面积的冰川融化也会形成大量的陆表径流,陆表径流会导致岩石中水分渗入的增加,进而导致源区岩石风化作用的加剧,从而使陆源输入的营养物质增加。目前的研究表明,中国的四个富烃源岩的冰融时代中元古代大塘坡组和陡山沱组烃源岩下伏有明确的冰川沉积物(Bao *et al.*, 2018; Shen *et al.*, 2021; Shen *et al.*, 2022b),其极有可能是受冰川融水的直接影响,使得其营养物质输入进一步增强。

3.2.2 洋流作用

海洋中的营养物质除了陆源输入外还有海洋自身的洋流输入,与海洋营养物质输送相关的洋流主要是温盐环流和上升流。温盐环流是指海水在空间上存在着的温度差和盐度差导致的海水密度差异,进而导致的深层海水大尺度的缓慢运动(周天军等, 2000)。在冰期中后期海水密度差增大时,温盐环流会增强,以加强极地与赤道的热量交换,从而导致冰川消融,在此过程中两极的低温富营养流体向中低纬度运移,提高了中低纬度地区的海水初级生产力(张喜等, 2021),进而促进了冰融初期中低纬度地区的有机碳富集和烃源岩形成。张喜等(2021)提出上奥陶统一志留统的五峰组—龙马溪组烃源岩沉积受到温盐环流导致的大量营养物质输入影响。海洋—大气模型也表明五峰组—龙马溪组沉积时期天文旋回和大气环流导致了华南板块所在的低纬地区形成了富营养的北东向洋流(图8),导致其生产力提升(Zhang *et al.*, 2020; 张喜等, 2021)。

大量研究表明上升流的存在也对有机碳富集起着重要作用(Erich *et al.*, 1996; 张水昌等, 2005; 陈代钊等, 2011)。上升流是一种从深层向海表运移的涌升流,常因地形、季风、大洋环流或火山等作用而产生(张俞, 2021),热液上升流和风成上升流是最常见的上升流类型(Gao *et al.*, 2012)。由于冰川事件时期全球海表风强度往往更大,持续时间也更久(Porter and An, 1995; Jansen, 2017),因此在冰融初期也存在较强的沿岸风,沿岸风在科里奥利力的作用下即会导致沿岸上升流的形成(图9)。同时冰消期中国大

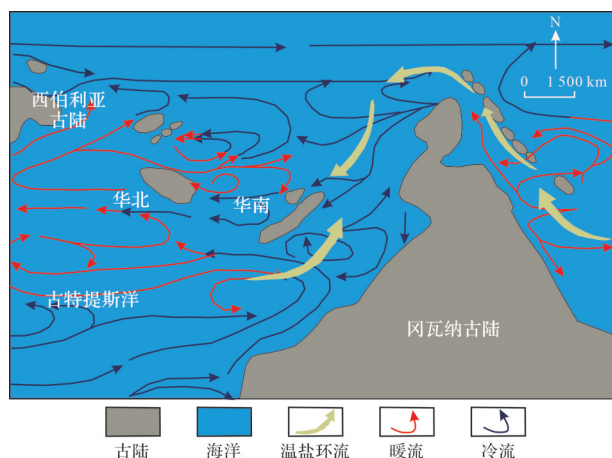


图8 晚奥陶世—早志留世海洋循环系统
(据 Pohl *et al.*, 2016; 张喜等, 2021 修改)

Fig.8 Ocean circulation system of Late Ordovician-Early Silurian (modified from Pohl *et al.*, 2016; Zhang *et al.*, 2021)

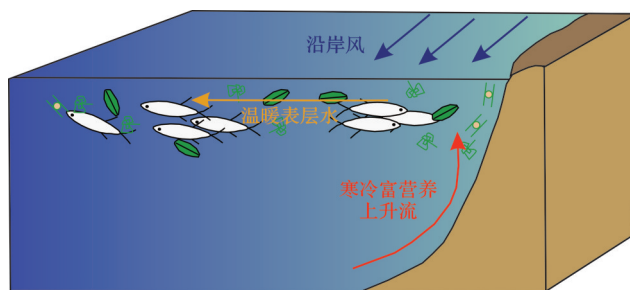


图9 沿岸上升流示意图

(据 Rykaczewski and Checkley, 2008 修改)

Fig.9 Schematic diagram of coastal upwelling
(modified from Rykaczewski and Checkley, 2008)

陆大多位于中低纬赤道辐射带附近,赤道流、赤道潜流存在也易形成强烈的上升流作用。上升流从海洋深部向表层输送大量锌、铜、镍、磷酸盐和硝酸盐等营养物质,使钙质和硅质生物快速繁殖(Sweere *et al.*, 2016),在促进初级生产力方面发挥了重要作用(Schoepfer *et al.*, 2013)。同时,上升流导致的深部缺氧水体补偿上升和表层生物勃发大量耗氧,使得缺氧还原的水体环境形成(刘峰等, 2011)。

上升流作用地区往往富集磷酸盐和生物硅质,因此常用沉积型磷矿和硅藻土指示上升流的存在。Co×Mn也常被用作上升流指标,上升流作用下的沉积物Co×Mn值通常小于0.4 (μg/g)·wt.%,因为上升流传送带增加了Co×Mn的去除率(Böning *et al.*, 2004; Schoepfer *et al.*, 2013; Sweere *et al.*, 2016)。前人研究表明,E-C转换期塔里木盆地玉尔吐斯组和华南陡山沱组均存在沉积型磷矿,热液活动和其引起的上升流作用对陡山沱组、玉尔吐斯组和牛蹄塘组等烃源岩的形成起到了重要作用(刘树根等, 2008; 陈代钊等, 2011; 贾智彬等, 2018)。此外,华北中上元古界和华南上奥陶统均发现有大量古上升流沉积记录,其中华北上元古界的上升流沉积中识别出富镁碳酸盐岩夹燧石薄层、黑色页岩和叠层石岩石组合(张尚锋等, 2012)。五峰组—龙马溪组高生物硅丰度和低Co×Mn值(Qiu *et al.*, 2023),说明同时存在温盐环流和上升流作用。虽然研究区观音桥段缺乏上升流的证据,但五峰组和龙马溪组烃源岩沉积期受到间冰期季节性上升流的影响(Qiu *et al.*, 2023)。上升流区特有的冷/温水型属种生物以及古气候—海洋模拟的结果均表明中二叠世赤道地区发育广泛的上升流,当海平面上升时,赤道上升流将赤道潜流中的营养元素翻涌到表层,促进了初级生产的提升,进而导致了栖霞组有机碳富集(吕炳全等, 2010; 刘喜停等, 2014)。

3.3 火山活动作用

火山活动与大地构造变化和气候变化有密切的联系(Robock, 2000), 火山作用与冰期旋回也有着较好的对应关系, 具体表现在冰川消融往往与火山作用具有正反馈关系(Huybers and Langmuir, 2009)。一方面, 冰融过程中陆地冰川会卸载、减压, 从而促进软流圈地幔的减压部分熔融, 陆相火山活动通常会加强(Huybers and Langmuir, 2009)。另一方面, 火山活动增强会导致大气二氧化碳含量升高, 进一步促进气温变暖、冰川融化。而火山作用与冰川消融之间正反馈作用的触发因素则可能是宏观尺度上的板块运动和天文旋回。因此, 冰川消融往往和频繁的火山活动伴随发生, 冰融气候下的富有机碳烃源岩往往发育火山灰沉积。这一观点已有大量实例可以证明, 本研究中四个冰消期烃源岩沉积时代也均发现有较频繁的火山活动。新元古代大塘坡组的顶底均有凝灰岩层, 是罗迪尼超大陆分裂过程中的火山喷发的记录(Wang and Shi, 2019); 陡山沱组发现有火山灰沉积层(Liu *et al.*, 2019), 且其受火山热液影响较大。在E-C过渡时期主要板块发生构造重构, 并伴随有频繁的火山作用(Kirschvink *et al.*, 1997; Doblas *et al.*, 2002), 在中国贵州早寒武世牛蹄塘组烃源岩底部发现有钾质斑脱岩, 指示该地区发生了3期火山作用(周明忠等, 2011)。上奥陶世一下志留世转换期为全球性大规模火山喷发期, 在瑞典、美国和中国华南等地区均发现了火山灰沉积物, 中国扬子地区五峰组—龙马溪组富有机质页岩中广泛夹斑脱岩层, 主要分布在凯迪阶上部、赫南特阶上部及鲁丹阶下部(邱振等, 2019; 张喜等, 2021)。在中二叠纪期, 华南板块栖霞组未找到直接的火山灰沉积证据, 但其同时期的塔里木、羌塘、潘伽等地存在大规模的火山喷发, 且导致了栖霞期大气CO₂迅速增加, 加速了从晚古生代大冰期(LP1A)冰室到温室气候的过渡(Sun *et al.*, 2023; Zhang *et al.*, 2023)。

以上研究表明, 烃源岩发育时段往往伴随着强烈的火山活动, 通常认为火山作用的存在有利于烃源岩的形成。但实际上火山作用对有机质富集的影响是较复杂的, 一方面火山活动释放的大量温室气体和有毒气体(CO₂、CH₄和SO₂等)会造成海洋水体硫化和含氧量降低, 对海洋生物造成灾难性影响(Grasby *et al.*, 2017), 同时提高有机碳的保存效率; 另一方面火山活动输入营养物质、造成全球变暖, 会

提高海洋的初级生产力。此外, 岩浆和热液的高温作用也会促进有机质的热分解和无机输入(焦鑫等, 2021)。因此, 要确定冰消期火山作用对有机碳富集的作用机理还需进一步探究各时期的火山作用强度、陆源输入生产力和氧化还原环境。指示火山作用存在的最直接证据是火山灰沉积, 地质历史时期火山活动虽然广泛存在, 但真正埋藏成岩的火山灰沉积却很少, 所以需要更精细的指标来指示火山作用及其强度。火山作用是非人为汞的最大输入来源(Pirrone *et al.*, 2010), 沉积岩中的Hg元素常被用来示踪火山作用的时限和强度(Pyle and Mather, 2003; Fan *et al.*, 2020; Shen *et al.*, 2022a); 不活动微量元素(Zr与Hf)也可用于记录火山物质的信息, 并且其不易受沉积与成岩作用影响, 可有效从泥页岩中识别火山物质(Yang *et al.*, 2022)。

冰消期各烃源岩沉积剖面的Hg含量显示, 大塘坡组、玉尔吐斯组烃源岩的Hg/TOC值较高(Zhou *et al.*, 2021; Wang *et al.*, 2023a), 均大于100(μg/kg)/wt.%, 指示火山活动的发生, 且其火山碎屑沉积段对应着高Hg/TOC值、高TOC含量、高P和高Ti/Al值, 说明火山活动导致了其古生产力增加, 进而促进有机碳富集。虽然五峰组—龙马溪组烃源岩的Hg/TOC值较低, 但却有明显的斑脱岩沉积, 仍说明其有较强的火山作用, 而其火山活动对古生产力的提升并不明显(邱振等, 2019); 其火山灰富集段对应沉积水体还原层段, 海水的氧化还原状态与五峰—龙马溪组烃源岩的有机碳含量密切相关, 说明火山作用对五峰—龙马溪组沉积期主要通过调节大洋含氧量来控制有机碳的保存效率, 导致了有机碳的富集(张喜等, 2021)。栖霞组烃源岩没有明显的火山灰沉积, 火山作用对有机质富集没有直接的生产力输入或致使水体还原的贡献, 但同时期全球活跃的火山活动释放巨量CO₂, 所引起的气候环境改变会对其有机碳富集有一定影响(Sun *et al.*, 2023; Zhang *et al.*, 2023)。

3.4 差异性因素分析

虽然中国冰消期烃源岩均处于寒冷干旱气候到温暖湿润气候的过渡期, 气温波动较大, 但各时代的平均气温仍有侧重性的差异。新元古代大塘坡组和陡山沱组烃源岩直接发育于冰碛岩之上, 整体气温相对其他时代更低, 为温暖湿润气候伴有间歇性的寒冷干旱, 化学风化作用中等, 但由于较强的冻融风化作用和冰川融水输入, 弥补了其化学风化的陆源

物质输入,气候对其生产力提升应具有较大贡献。E-C转换期存在短时的低温段,玉尔吐斯组烃源岩由于波动较大的气候和较强的海表风,较强的物理风化促进和弥补了化学风化,使陆源物质输入相对较高。而O-S转换期和中二叠统气候更偏温暖湿润,致使五峰组—龙马溪组和栖霞组的化学风化作用相对较强,营养物质陆源输入随温度升高而增强,同时由于其气温波动导致的温差风化损伤也有一定贡献。

本研究中各冰融时代均对应有明显的海平面上升,但其富营养流体的作用却有差异。新元古代大塘坡组和陡山沱组富营养流体来自冰融后的全球性海侵,有冰川融水和陆表径流的贡献,同时陡山沱组也受上升流影响。E-C转换期玉尔吐斯组和牛蹄塘组富营养流体主要来自较强的上升流作用。O-S转换期龙马溪组富营养流体来自冰融初期较强的温盐环流和上升流,导致其生产力提高和水体缺氧。二叠系栖霞组烃源岩受海侵导致的有机碳富集贡献较大,同时赤道上升流的营养物质贡献也导致了其生产力的提高。

四个时代的冰消期海相烃源岩中只有龙马溪组发育大规模的火山灰沉积,且其富有机质层段与火山作用时期对应良好,火山活动对其有机质富集起着较大作用,主要体现在火山物质输入致使水体缺氧还原,有利于有机质保存。新元古代大塘坡组和E-C转换期玉尔吐斯组也一定程度上受火山作用导致的营养物质直接输入和热液上升流输入作用影响,致使水体生产力提升。而二叠系栖霞组未发现火山灰沉积,烃源岩形成与火山作用关联性较小。

综上,冰消期烃源岩是在升温波动气候、海洋洋流变化以及火山活动等因素的综合作用下形成,三个因素对于烃源岩的古生产力均有贡献,洋流变化和火山活动对海洋氧化还原条件产生较大影响,但各因素单独都不是有机碳富集的充分条件。同时,从地球系统这个整体来看,这三个因素之间也有一定的相互影响,表现在火山作用喷出大量温室气体往往会导致气温上升和加剧气候波动,且冰消期的升温作用对海洋洋流变化有较大的影响。同时冰消期的大陆冰川卸载会导致火山作用增强,间冰期的火山作用频率明显大于冰期(Huybers and Langmuir, 2009)。各因素对冰消期各套烃源岩有机碳富集的作用对比和总结如表1。

4 国内外烃源岩富集对比

国外主要烃源岩分布与国内基本相似,约70%的油气贡献的烃源岩分布在中、新生代地层(图10),对应温室气候,其主要的有机质富集影响因素是温室期大量生物勃发导致的大量有机碳生成和埋藏,如波斯湾盆地侏罗系烃源岩、阿拉伯油气区白垩系烃源岩和尼日尔白垩系烃源岩(李江海等,2013)。同时,国外也在与中国冰消期烃源岩发育时代相对应的地层中发育烃源岩。如新元古代东西伯利亚地台里菲系页岩,E-C转折期Lena-Vilyuy盆地黑色页岩;在O-S转折期有全球性大量沉积的黑色页岩,如波斯湾地区和库夫拉盆地的下志留统和上奥陶统页岩;在二叠纪二叠盆地发育下二叠统页岩(李江海等,2013)。这些在冰消期生成的烃源岩也主要分布在中低纬地区,推测其发育机制大致与中国冰消期的几套烃源岩相似,受海侵事件、升温导致的化学风化增强、上升流活动和火山作用影响较明显。

国外烃源岩与国内烃源岩较大的区别在于中国独有的陆相生油方式,中国无论在中、新生代还是古生代均有大量的陆相烃源岩生油贡献,而国外则海相烃源岩占比极高。陆相烃源岩与海相烃源岩相比,更容易受到事件作用的影响,如火山活动和热液作用(马新涛等,2023),同时由于水体盐度、pH值和生物类型等因素的明显作用,陆相烃源岩受气候影响更为显著(焦鑫等,2021)。除中国C-P转折期的风城组和芦草沟组外,冰消期烃源岩在国内外均发育于海相地层。

5 冰消期烃源岩有机碳富集模式

冰融初期特殊的气候、环境、构造特征和地质事件等影响了生产力和氧化还原条件,从而控制海相烃源岩有机碳的富集。其中气候对有机碳富集的直接影响主要是与生物生长能力直接相关的温度、日照作用,以及与风化相关的湿度作用有关,温暖湿润的气候和高的日照量有利于生物生长繁殖,形成高的初级生产力。而相对于高温高湿的温室气候期,冰消期的气候优势并不明显,但由于整个地球系统的复杂性和各圈层耦合性,上升流、海侵、风化作用和火山作用等地质事件对全球平均温度相对较低的冰消期烃源岩发育也有较大的贡献。冰消期冰川融水输入导致的海侵作用、温差导致的上升流作用、升

表1 冰消期海相烃源岩有机碳富集模式对比总结
Table 1 Comparative summary of organic carbon enrichment patterns
in marine source rocks during the deglaciation

共性					差异					
控制因素	特征	形成原因	有机碳富集机理	具体控制机理	控制因素	烃源岩	特征	形成原因	有机碳富集机理	具体控制机理
气候作用	温度	较温暖	中低纬度、冰消期升温	利于生物生长	冰川消融	大塘坡组 陡山沱组	存在冰融	雪球地球 大冰期	生产力提高	冻融风化增强， 冰川融水输入
	日照	强度较强 时长较长	均分布于中低纬度	利于生物生长		玉尔吐斯组 龙马溪组 栖霞组	无冰碛岩	赤道附近冰期影响较弱	生产力 微弱提高	温差风化
其他相关作用	风化	增强	冰消期升温和气候波动	陆源营养物质输入	上升洋流	陡山沱组 玉尔吐斯组 五峰—龙马溪组 栖霞组	受上升流影响较大	冰融期强 海面风和洋流循环	生产力提高	深部低温 富营养海水上升
						大塘坡组	无上升流作用	受冰川融水输入影响	生产力提高	冻融风化形成大量富营养的冰融水
	海平面变化	海侵	构造运动、冰融水输入或构造挤压作用	保存条件改善	OMZ扩张， 深层水体缺氧	火山	陡山沱组 玉尔吐斯组 五峰—龙马溪组 大塘坡组	频繁	气候转折期和同冰期火山作用频繁	生产力提升，保存条件改善
					栖霞组		无直接证据	局部地区 无火山活动	—	—

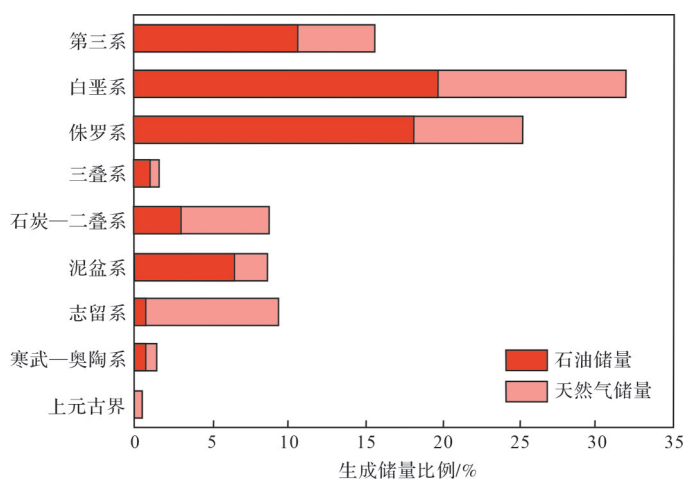


图10 世界烃源岩地层分布及其对油气地质储量的贡献比例(据腾格尔等, 2010 修改)

Fig.10 Distribution of source rock strata in the world and its contribution ratio to oil and gas geological reserves (modified from Teng *et al.*, 2010)

温波动气候下较强的风化作用以及频繁的火山作用共同导致了海洋初级生产力的提升,同时海侵、上升流和火山灰输入也可导致海底氧含量的降低,促进有机质的保存。

因此,冰消期海相烃源岩发育的模式可以总结为以下三点。其一,升温和剧烈波动的气候可导致岩石风化作用增强,陆源输入增加,生产力提高,更有利于有机碳富集。其二,冰融导致的冰川融水、海平面上升和中低纬活跃的洋流变化(上升流和温盐环流)会提高海洋的初级生产力,且生成的大量有机质分解耗氧将导致沉积水体的缺氧还原,有利于有

机碳的富集和保存。其三,冰消期活跃的火山作用会向海洋输送大量营养物质并导致水体的缺氧,提高海洋生产力并提高有机碳保存效率。这三个因素是整个地球系统在冰期—间冰期旋回中对冰消期气候的响应,而整个冰期—间冰期旋回是在米兰科维奇旋回和地球板块构造变化的共同作用下形成(图11)。然而,这一模式中的所有影响因素并非在所有冰消期海相烃源岩中均适用,各套烃源岩由于古地理的差异,控制有机质富集的主导因素各不相同,影响程度也不同。目前关于深时古气候的相关研究较为粗略,未来还需结合深时古气候模拟结果,进一步

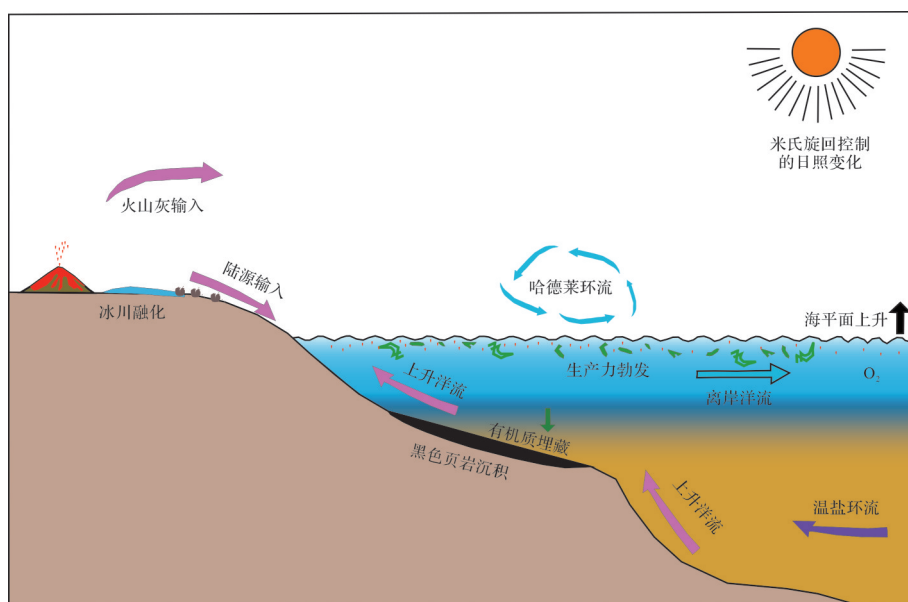


图11 冰消期气候控制下的富有机碳烃源岩形成模式图

Fig.11 Pattern of the formation of organic-rich source rocks under a deglaciation climate

验证冰消期气候对有机碳富集的控制机理及影响因素,以及定量分析各因素对有机质富集的贡献程度,以期对大页岩油气田分布做出一定预测。

6 结论

(1) 中国主要烃源岩在中、新生代发育于温室气候条件下,而在元古代和古生代发育于较寒冷的冰融气候条件下,且冰消期烃源岩均分布在中低纬度地区。

(2) 中国间冰期冰川消融期的烃源岩主要分布在新元古代、埃迪卡拉纪—寒武纪转换期、奥陶纪—志留纪和二叠纪四个时代。

(3) 米氏旋回控制下的高日照量、升温和波动气候导致的岩石风化增强、广泛的海侵作用、强烈的上升流作用和频繁的火山作用共同导致了冰消期水体生产力提高和缺氧还原的水体环境,进而导致了有机质富集和保存,体现了海洋—陆地—大气的协同变化。

(4) 本研究揭示了冰消期气候对烃源岩有机碳富集的控制机理,未来还需结合古气候模拟结果和生产力模型,进一步验证冰消期气候对有机碳富集的控制机理及影响因素。

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Climate of Deglaciation Controls the Organic Carbon Enrichment of Marine Source Rocks in China

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Abstract: [Significance] Climate plays an important role in controlling marine organic carbon enrichment, but rele-

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vant studies have primarily focused on the mechanism of organic carbon enrichment under high insolation and a warm humid climate, summarized the relationship between organic-rich basin sedimentation and astronomical cycle, and have rarely involved the development mechanism of marine source rocks during deglaciation. Several sets of marine source rocks were deposited during the deglaciation of Proterozoic and Paleozoic in China. Studying and summarizing the mechanism of climate on organic carbon enrichment in basins during deglaciation is helpful for establishing a coupling relationship model between different climatic conditions and organic matter abundance from the perspective of Earth system. **[Progress]** Research has found that the main source rocks of Mesozoic and Cenozoic corresponding to large oil and gas fields in China were developed in the greenhouse climate period of middle and high latitudes, whereas the main source rocks of Proterozoic and Paleozoic were mainly developed in deglaciation of middle and low latitudes. Abundant dating data indicate that the source rocks of the deglaciation period were distributed in the Neoproterozoic, Ediacaran-Cambrian transition, Ordovician-Silurian transition, and Permian. The source rock of the second member of the Doushantuo Formation in the Neoproterozoic was formed after the Nantuo glaciation. The Yurtus Formation and Qiongzhusi Formation of the early Cambrian were formed in the cold stage of the early Cambrian, after the North China Luoquan and Ediacaran glaciations. The Longmaxi Formation of the Early Silurian was formed after the Hernant glaciation. The Chihshian Formation of the Middle Permian was formed after the Late Paleozoic global ice age. Through the study of the paleoenvironment, paleoclimate, and productivity of source rocks in each periods, it is found that the unique climatic conditions in the deglaciation period played an important role in the organic carbon enrichment of marine source rocks. High temperatures and humidity in the middle and low latitudes, and high insolation corresponding to high obliquity during the deglaciation favor biological growth, reproduction, and organic carbon enrichment. Glacial meltwater input during deglaciation can cause transgression and import nutrients to the ocean. The chemical index of alteration (CIA) values, which rise sharply and fluctuate significantly between 50 and 90 in each period, reflect the warming and unstable climate characteristics during the deglaciation, corresponding to enhanced chemical and freeze-thaw weathering, leading to increased terrestrial nutrient input and productivity enhancement. During the initial stages of ice melting, strong equator-polar temperature differences and sea surface wind lead to intense upwelling, increasing surface water primary productivity, whereas surface biological blooms and oxygen consumption create a reducing environment conducive to organic matter preservation. Volcanism is more intense during interglacial deglaciation, the input of nutrients from volcanic eruptions increases the productivity of the marine surface, and the input of reducing substances improves the preservation conditions of organic matter. **[Conclusions and Prospects]** Under the control of Milankovitch cycles, high insolation, warming, and fluctuating climate lead to enhanced rock weathering, extensive marine transgression, intense upwelling, and frequent volcanism, collectively resulting in increased water productivity and anoxic reduction during deglaciation, thereby promoting organic carbon enrichment and source rock formation. This relationship model between climate and source rock formation during deglaciation reflects the control of the ocean-land-atmosphere earth system on organic carbon enrichment under the control of climate cycles. In the future, combining climate simulations and quantitative calculations, certain predictions can be made regarding the distribution of large shale oil and gas fields.

Key words: deglaciation; organic carbon; source rock; paleoclimate; weathering; upwelling; volcanism