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中国东部咸化湖盆始新统混积页岩岩相及有机质富集机制

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摘要:中国东部新生代断陷湖盆是重要的油气富集区,始新统页岩(约54~32 Ma)为主要储层。尽管各湖盆沉积时代相近,但在岩相特征、湖水盐度及有机质丰度方面差异显著,形成机制尚不明确。以渤海湾盆地东营凹陷、辽河凹陷、江汉盆地和南襄盆地为研究对象,综合岩相分类、矿物组成、元素与同位素特征,探讨富有机质页岩的沉积环境与富集机制。结果表明,早古近纪东亚夏季风增强导致气候强烈波动,约40 Ma各湖盆普遍达到最大湖深。炎热气候引起盐度周期性变化,形成多类型混积岩。岩相类型主要包括层状灰岩/白云岩、钙质-白云质泥岩、长英质页岩、钙质/白云质混合细粒岩。辽河凹陷以含泥方沸石微晶白云岩为特征,江汉盆地以白云岩-泥质钙芒硝岩为主。矿物组成总体呈北少南多的硅质、钙质递增规律。古气候转变控制湖水盐度与氧化还原环境,湿热气候促进生物繁盛,而高盐度增强水体分层与还原性,有利于有机质保存。济阳拗陷页岩TOC(总有机碳)含量较高(1.5%~4.5%),潜江与辽河页岩较低(0~3%),表明盐碱环境是有机质富集的关键控制因素。

关键词:咸化湖盆;混积页岩;页岩岩相;有机质富集;始新统

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Lithofacies and organic matter enrichment mechanism of Eocene mixed shale in the salinized lake basins, eastern China

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Abstract: The eastern China Cenozoic rifted lacustrine basins are important hydrocarbon-rich regions, with the Eocene shale (ca. 54–32 Ma) serving as a major reservoir. Although the depositional ages of these basins are similar, significant differences exist in lithofacies characteristics, lake water salinity, and organic matter abundance, and their formation mechanisms remain unclear. This study focuses on organic-rich shales from the Jiyang and Liaohe sags in the Bohai Bay Basin, the Jiangnan Basin, and the Nanxiang Basin. Through integrated lithofacies classification, mineralogical, elemental, and isotopic analyses, the depositional environments and enrichment mechanisms of organic-rich shales were investigated. Results show that the intensified East Asian summer monsoon during the early Paleogene caused pronounced climatic fluctuations, with all basins reaching their maximum lake depth around 40 Ma. Cyclic changes in salinity under extreme heat led to the development of multiple mixed lithofacies, including laminated limestone/dolostone, calcareous-dolomitic mudstone, felsic shale, and calcareous/dolomitic mixed fine-grained rocks. The Liaohe Sag is characterized by muddy analcime microcrystalline dolostone, whereas the Jiangnan Basin is dominated by dolostone-marly glauberite rocks. Overall, mineral compositions show a north-to-south

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increase in siliceous and calcareous contents. Paleoclimatic transitions controlled lake salinity and redox conditions: warm - humid climates enhanced bioproductivity, while high-salinity stratified waters strengthened reducing conditions and promoted organic matter preservation. The Jiyang Sag exhibits relatively high TOC contents (1.5 - 4.5%), while the Qianjiang and Liaohe sags show lower values (0 - 3%), indicating that saline - alkaline conditions were the dominant factor controlling organic matter enrichment.

Keywords: Salted lake basin; Mixed shale; Shale lithology; Organic matter enrichment; Eocene epoch

目前,东部盆地是中国陆相页岩油勘探开发主战场^[1-2]。相较于海洋沉积环境,湖泊环境对气候更为敏感,短时期内即可发生干湿交替和湖平面剧烈波动,致使湖相页岩表现出强非均质性和高黏土矿物含量的特征,也对湖相页岩油气资源的富集带来巨大影响^[3-5]。除了海相页岩油,深湖环境生成的页岩油也占很大比例,典型的湖相页岩包括美国尤因塔盆地的巴肯段和澳大利亚澳大利亚库珀盆地的罗斯尼思组、伊普西隆组和默特里组,巴基斯坦科哈特盆地的巴哈杜尔—凯尔组、印度阿萨姆—阿拉干盆地的科皮里组,以及中国茂名盆地油柑窝组、珠江口盆地文昌组、北部湾盆地流沙港组、依兰盆地达连河组、柴达木盆地的下干柴组、渤海湾盆地的沙河街组、江汉盆地的潜江组和南襄盆地的核桃园组。中国东部古近纪始新世发育了多套富有机质页岩,包括渤海湾盆地的沙河街组、江汉盆地的潜江组和南襄盆地的核桃园组。不同盆地显示出不同的盐度特征,页岩有机物富集、油气生成和保存特征方面也存在较大差异,可能受到纬度、气候、海侵和火山影响的差异。

目前研究表明:①对于始新统混合页岩岩相的研究已从单一矿物分类,发展到综合矿物组分、沉积构造和有机质丰度的多因素分类。例如,济阳拗陷始新统页岩被划分为4个大类、9个小类岩相^[6]。②有机质富集受环境控制明显,影响要素包括生产力、保存条件,盐度、水深等多因素耦合作用,有机质富集是高初级生产力和强还原保存条件共同作用的结果。咸化水体易形成盐度分层,底层缺氧利于有机质保存。但不同盆地有机质富集的主控因素存在差异^[7-8],例如柴达木盆地地下干柴沟组上段因营养供给不足和沉积速率快,导致TOC(总有机碳)含量偏低^[9]。③泥质纹层和灰质纹层通过控制黏土矿物转化和碱性矿物溶蚀-再沉淀对页岩生烃产生影响。目前,多数研究是针对单个盆地或凹陷的案例分析,对于古气候等具有广泛区域性影响的认识不一致,导致认识混乱。亟待从更宏观角度,系统性对比分析影响页岩沉积的核心参数,厘清参数的适用性条件,从而形成更科学的认识和结论。

以中国东部始新统咸化湖盆为研究对象,以古新世—始新世极热期至始新世—渐新世过渡期等全球重大气候事件和东亚季风为背景,从古气候、古环境、古氧化还原条件和风化强度的角度,分析对比渤海湾盆地辽河拗陷和济阳拗陷沙河街组三段(以下简称沙三段)至沙河街组四段(以下简称沙四段)、南襄盆地泌阳拗陷核桃园组三

段(以下简称核三段)至核桃园组四段(以下简称核四段)、江汉盆地潜江拗陷潜江组二段(以下简称潜二段)至潜江组三段(以下简称潜三段)TOC含量和生烃潜力的差异。以整个东部盆地的湖相页岩为研究对象,通过参数对比和比较,总结4个盆地始新统页岩有机质富集和生烃机制,所得结论具有广泛的推广价值,对东部盆地新页岩区块勘探和开发具有重要帮助。

1 地质与气候背景

1.1 地质背景

以中国东部盆地新近系始新统湖相页岩为研究对象,从北向南依次为渤海湾盆地辽河凹陷沙河街组、渤海湾盆地济阳拗陷沙河街组、南襄盆地泌阳凹陷核桃园组、江汉盆地潜江拗陷潜江组(如图1所示)。

渤海湾盆地辽河凹陷是位于渤海湾盆地东北部的新生代断陷湖盆,凹陷区位于断层控制下的新生代长期沉降带,以大幅度深陷为特征,古近系地层发育,具有良好的油气生成和储集条件^[10],发育多套湖相暗色泥岩。根据岩性、电性和生物组成特征,沙河街组自下而上可分为沙四段、沙三段、沙河街组二段(以下简称沙二段)和沙河街组一段(以下简称沙一段)。以浅湖、半深湖相泥页岩及扇三角洲相砂砾岩、砂岩沉积为主,局部发育湖相碳酸盐岩。始新世中期沙三段,辽河拗陷整体处于裂谷拉张深陷期,沉积了巨厚的半深湖—深湖相砂泥岩地层,地层在西部凹陷、东部凹陷和大民屯凹陷广泛分布。

济阳拗陷在构造上属于渤海湾盆地中的次级负向构造单元,经历了多期构造运动,其构造演化过程可大致分为古生代挤压变形阶段、中生代的断陷阶段以及新生代的断裂拉张构造运动3个演化阶段,新生代是渤海湾盆地伸展裂陷的主要阶段。东营凹陷古近纪地层为煤和油页岩等非常规能源矿产的重要赋存层位,此次研究的主要层段为沙三下亚段、沙四上亚段^[11]。

南襄盆地形成于中生代,位于新生代扬子地台与秦岭—大别造山带交汇发育的陆相断陷盆地,盆地可进一步划分为3个凹陷和4个凸起,即襄枣凹陷、南阳凹陷和泌阳凹陷,新野凸起、师岗凸起、社旗凸起和唐河低凸起^[12]。南襄盆地核桃园组处于强烈断陷期沉积的地层,厚度介于2 000~3 000 m,可划分为三段:核三段为主力

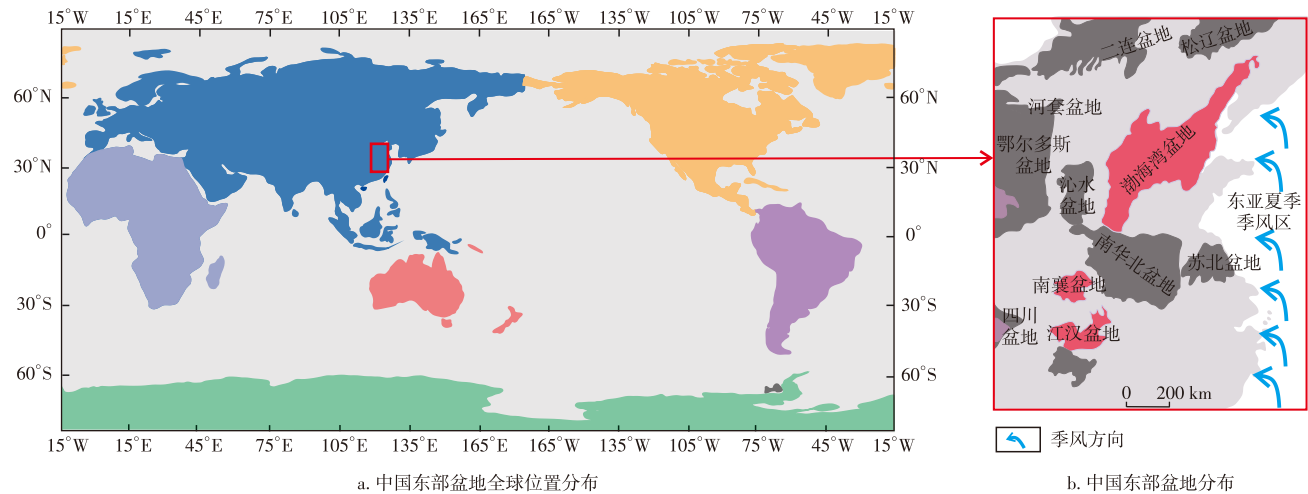


图1 中国东部盆地在全球及国内的位置分布(据文献[19-22]修改)

Fig. 1 Distribution of eastern China basins at global and domestic scales (modified from references[19-22])

含油层系,该段厚度介于1 100~2 000 m,其下部和中部为深灰色泥岩夹泥质白云岩、白云岩和砂岩,上部为碱性白云岩;核二段厚度介于700~800 m,岩性主要为泥质白云岩、白云质泥岩、泥岩和油页岩;核一段厚度介于400~500 m,岩性主要为灰绿色泥岩、白云岩、油页岩。局部与下伏的大仓房地层呈局部不整合接触^[13]。

江汉盆地是位于中扬子地块内的中生代大型裂谷盆地^[14]。盆地目前的地理特征主要形成于晚侏罗世至早白垩世,当时由于中国东部的陆内造山运动,周围山脉带和地块经历了强烈的隆起^[15-16]。从晚白垩世到古近纪,

江汉盆地经历了太平洋板块回滚和南亚碰撞引起的上地幔活跃上涌。这种环境导致了多阶段裂谷作用,并在盆地中形成了广泛的硅质碎屑沉积物、蒸发岩和大量玄武岩流沉积物。江汉盆地包括十几个次级凹陷,其中潜江凹陷是位于盆地中部的富烃凹陷(图2)。从晚白垩世到古近纪,潜江凹陷经历了2个不同的伸展裂谷阶段,以玄武岩熔岩流的多次幕式喷出为特征^[14]。江陵凹陷古近系沉积序列中存在多种类型岩石,包括碎屑岩、碳酸盐岩、蒸发岩和油页岩,这些岩性的存在表明了湖泊环境^[17],在古新世至始新统早期,潜江凹陷以蒸发岩特征显著^[18]。

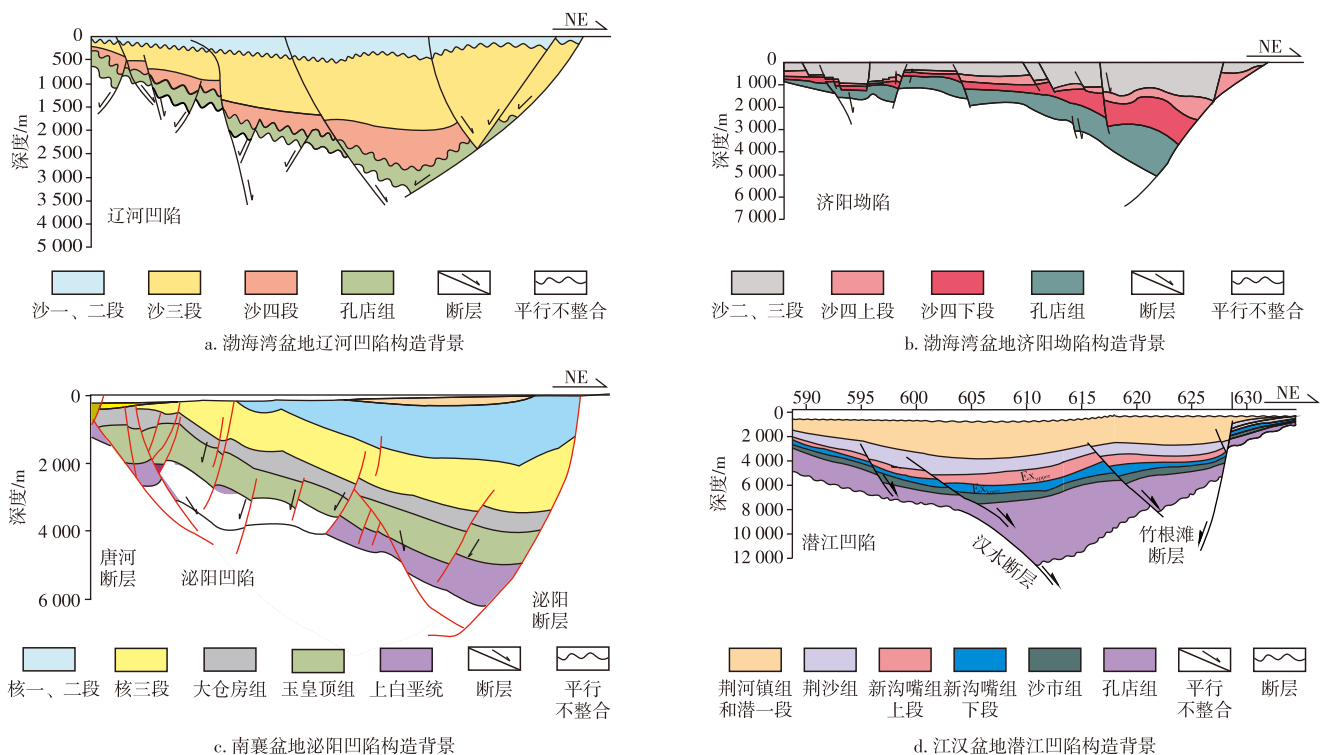


图2 中国东部主要盆地构造背景(据文献[19-22]修改)

Fig. 2 Tectonic setting of major eastern China basins (modified from references[19-22])

1.2 气候影响要素

1.2.1 东亚夏季风

始新世时期,亚洲东部是显著的季风区^[23]。东亚季风主要受太阳辐射、大气环流及陆海热力差异等多重因素的综合控制,具有显著的大陆性、季节性和复杂性特征。结合前人花粉记录与古气候重建结果可知,在晚白垩世至古新世期间,中国地区存在一条自西向东延伸的广泛干旱带^[24],表明当时气候格局呈现出明显的干湿分带特征,东亚季风体系尚未形成或仍处于早期阶段。随后,中国东部地区在渐新世与中新世的分界期气候由干旱转变为湿润气候。气候分带的基线变化通常被解释为全球大气环流格局由行星环流向季风环流的转型标志^[25]。多项研究表明,东亚夏季风的建立与加强使来自海洋的水汽得以大规模输送至中国东部地区,从而显著增强了区域降水,推动了气候的湿润化演化^[26]。这一过程不仅重塑了中国东部的古气候格局,也对沉积环境演化和有机质富集过程产生了深远影响。之前研究比较了氧同位素值与东亚夏季风强度之间的关系,并利用济阳坳陷沙河街组第三至第四段氧同位素的纵向分布,研究了始新统期间中国东部广大地区东亚夏季风的变化趋势(图2)。

1.2.2 极热事件

始新世是地质历史的关键时间间隔,始新世时期发生了一系列全球气候事件,包括古新世—始新世极热事件(Paleocene–Eocene Thermal Maximum, PETM)、早始新世极热事件(Early Eocene Climatic Optimum, EECO)、中始新世极热事件(Middle Eocene Climatic Optimum, MECO)以及晚始新世—早渐新世全球气候变冷事件。研究表明,古近纪主要发生2次全球性的气候变化,分别为PETM和始新世—渐新世变冷事件。

PETM是巨量碳注入到地球表层系统所导致的一次快速增温事件^[27–30],发生在距今55 Ma的始新世初,在一个地质年代时期内全球平均气温上升5~8 °C,陆地生态系统的初级生产力在PETM事件后得到大幅上升。虽然历时短暂,只有约200 ka^[31–32],地球保持温暖时间持续了80~200 ka,但对整个始新世的气温都产生了巨大影响,整个始新世期间直到渐新世都是偏温暖的气候。

发生PETM后,始新世期间又发生了2次极热事件,即EECO和MECO。PETM和第二次始新世极热事件(Eocene Thermal Maximum 2, ETM-2)为短周期的极热事件,持续时间介于10~200 ka;EECO和MECO为长周期极热事件,但每个独立的热事件持续时间较短^[23–24,27]。

始新世—渐新世时期极冷事件(Eocene–Oligocene Extreme Cold Event, EOT)发生在34 Ma前后,是新生代最显著的气候变冷事件之一,标志着地球气候由“温室”进入“冰室”^[33]。中始新世气候最适期,即MECO在40 Ma前发生持续时间约500 Ka的广泛海洋—大气变暖事件,主要表现为大气CO₂含量上升、生物变化和深海碳酸盐溶解时间延长^[34–36]。

1.2.3 火山活动

渤海湾盆地辽河坳陷沙河街组三段和江汉盆地潜江坳陷潜三段、潜四段发现了火山活动的痕迹。火山喷发会释放大量的SO₂与火山灰。SO₂在大气中转化形成酸雨,促进了陆源物质的加速风化,从而增强了陆源碎屑及营养物质向湖泊体系的输入。与此同时,火山灰的分解也可释放出丰富的营养元素,为湖泊沉积体系提供了额外的物质来源。这2种途径所提供的丰富营养物质显著提升了湖盆的初级生产力,促进了有机质的沉积与富集。在研究区江汉盆地潜江凹陷地区,火山灰沉降释放的营养元素进一步促进了湖盆的生物繁盛,但随之而来的高温与盐度升高的环境条件,也可能对水生生物的生长造成一定限制。

1.2.4 海侵事件

始新世时期,中国东部多个盆地受到不同程度的海侵影响,例如研究区中渤海湾盆地泌阳凹陷以东地区^[37–43],已有研究认为海侵过程有利于湖盆中优质烃源岩的形成与保存^[44–46],其主要机制包括:①海水的进入携带丰富的营养物质,提升了湖泊初级生产力;②海侵增强了湖水分层,使深水区氧气补给受限,从而导致底层水体的氧化还原条件发生变化,有助于有机质的富集与保存^[47–48]。

沙河街组四段上部发生海侵的证据是发现有各种大量的海相和海陆过渡相化石,沙河街组三段下部主要包括各种大量孔虫和甲藻的海相化石,说明在渤海湾盆地中最富油气的烃源岩层段,即沙河街组三段、四段受到海洋影响。这些层段的烃源岩被认为比纯湖相层段烃源岩具有更高的TOC含量(2%~>10%)和更优质的有机质类型(I型或II型干酪根)^[44–45]。济阳坳陷海相侵入影响段烃源岩含有丰富的藿烷,TOC含量大于2%,S₁+S₂(S₁为游离烃的含烃量,S₂为裂解烃的含烃量,S₁+S₂用来表示生烃潜力)含量为20 mg/g^[44–45]。泌阳凹陷核桃园组三段通过古生物学、微量元素和生物标志物被证实有海侵现象发生。

1.2.5 CO₂含量变化

研究区全球大气CO₂含量与东亚夏季风强度的变化如图1所示。总体来看,始新世期间大气CO₂含量呈先升后降的变化趋势,其转折点出现在EECO。从EECO至晚EOT,CO₂含量总体处于持续下降阶段,仅在MECO出现短暂回升。东亚夏季风强度的变化趋势与CO₂含量具有良好对应关系,同样表现为先增强后减弱的特征,其转折期也与MECO时期对应。全球大气CO₂含量的波动及东亚夏季风强度的演化与始新世关键气候事件密切相关,大气中CO₂含量升高也可能和EECO高温加速了硅酸盐风化有关^[49],产生了足够厚碳酸钠蒸发岩所需碱性较高的水体条件,这种条件下的化学风化作用增强解释了美国和中国在始新世时期碳酸钠蒸发岩群的形成过程^[50]。

2 方法与数据来源

研究以中国东部盆地典型断陷咸化湖盆为研究对象,结合始新世时期中国东部的沉积构造背景和气候变化背景,对渤海湾盆地辽河拗陷和济阳拗陷沙三段—沙四段、南襄盆地泌阳凹陷核二段—核三段和江汉盆地潜江凹陷潜三段—潜四段的陆相页岩开展岩相、矿物、有机质和古气候比较和研究。开展典型井分析,包括X射线衍射分析矿物组成、X射线荧光光谱法元素分析、碳氧同位素分析、TOC含量和岩石热解分析,并结合大量前人分析数据,系统分析中国东部盆地页岩岩相和元素组成的纵向变化,依据元素变化分析始新世时期古气候变化,以及古气候对古环境、有机质富集和生烃的影响,最后形成始新世时期中国东部地区咸化湖盆形成模式。

3 页岩岩相与元素组成

3.1 矿物成分和岩相

渤海湾盆地辽河拗陷沙三段至沙四段的矿物主要由碳酸盐矿物和黏土矿物组成,黏土矿物含量介于50%~100%,碳酸盐矿物含量介于50%~100%,硅酸盐矿物含量介于25%~75%(图3),碳酸盐矿物包括方解石、白云石和方沸石。渤海湾盆地济阳拗陷沙三段至沙四段矿物主要由碳酸盐矿物和硅酸盐矿物组成,碳酸盐矿物含量介于50%~100%,硅酸盐矿物含量介于50%~100%,黏土矿物含量介于20%~80%。南襄盆地泌阳凹陷核桃园组中,矿物成分包括碳酸盐矿物、硅酸盐矿物和黏土矿物,含量介于50%~100%,碳酸盐矿物包括方解石、白云石、方沸石和石膏。江汉盆地潜江拗陷潜江组的矿物成

分主要集中在高碳酸盐岩含量(50%~100%)、高硅酸盐岩含量(75%~100%)和相对较低的黏土矿物含量,碳酸盐矿物包括石膏、方解石、白云石和硝酸钙,以及岩盐矿物。

4个研究区的始新统地层都包含混合岩相的区域,但都位于碳酸盐矿物含量高的区域,这与盐湖泥页岩的特征有关。除混合岩相区分布外,渤海湾盆地济阳拗陷沙三段至沙四段和江汉盆地潜江拗陷潜江组也分布在碳酸盐矿物含量高的地区,另外渤海湾盆地辽河拗陷的沙三段至沙四段也分布在黏土矿物含量高的地区。

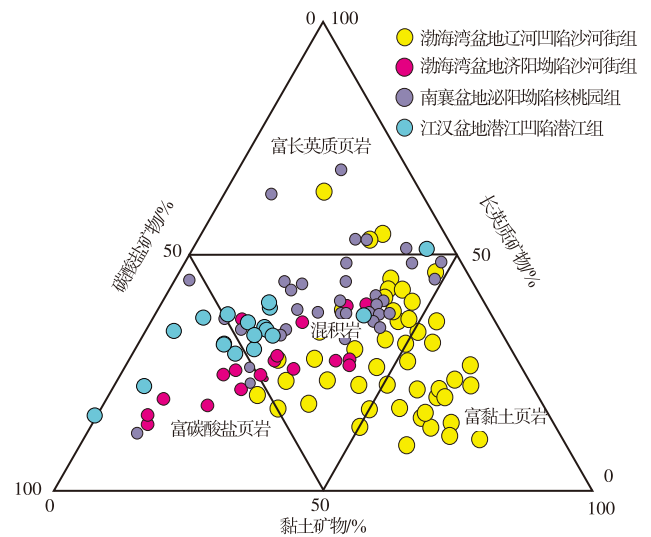


图3 中国东部盆地始新统页岩矿物组成(据文献[51-54]修改)

Fig. 3 Mineral composition diagram of Eocene shale in the basins of eastern China (data from references[51-54])

从北到南,黏土矿物含量逐渐降低,硅质矿物含量逐渐增加。从岩相组成来看,渤海湾盆地辽河拗陷沙三段至沙四段的砂岩岩相包括黏质泥岩、泥质泥岩、混合岩性页岩、粉砂质混合页岩和钙质混合页岩^[59-61]。渤海湾盆地济阳拗陷沙三段至沙四段的岩相组成包括层状灰岩、互层灰岩、层状黏土岩、层状细粉砂岩、层状泥质细粒混积岩、层状粉质黏土细粒混积岩。南襄盆地泌阳凹陷核三段的岩相包括块状硅质泥岩、块状泥质泥岩、层状砂质页岩、层状黏土质页岩、层状钙质页岩、层状泥质页岩和砂岩^[13]。江汉盆地潜江拗陷的潜三段至潜四段岩相包括灰色泥岩石膏、泥质石膏、灰色泥岩/泥岩、浊/钙质石膏、浊混积岩、灰色混积岩,泥质混积岩和硫酸盐混积岩以及盐岩(图4)。

4个研究区在始新统页岩层段均有泥页岩、灰质页岩、云质页岩,济阳拗陷还包括粉砂岩、灰岩,泌阳拗陷还包括粉砂岩,潜江拗陷还包括云岩、钙芒硝岩和石盐岩。从北往南,从矿物组成和岩相上看,咸化程度逐渐增强,从咸水-半咸水逐渐转化为咸水到盐湖环境。

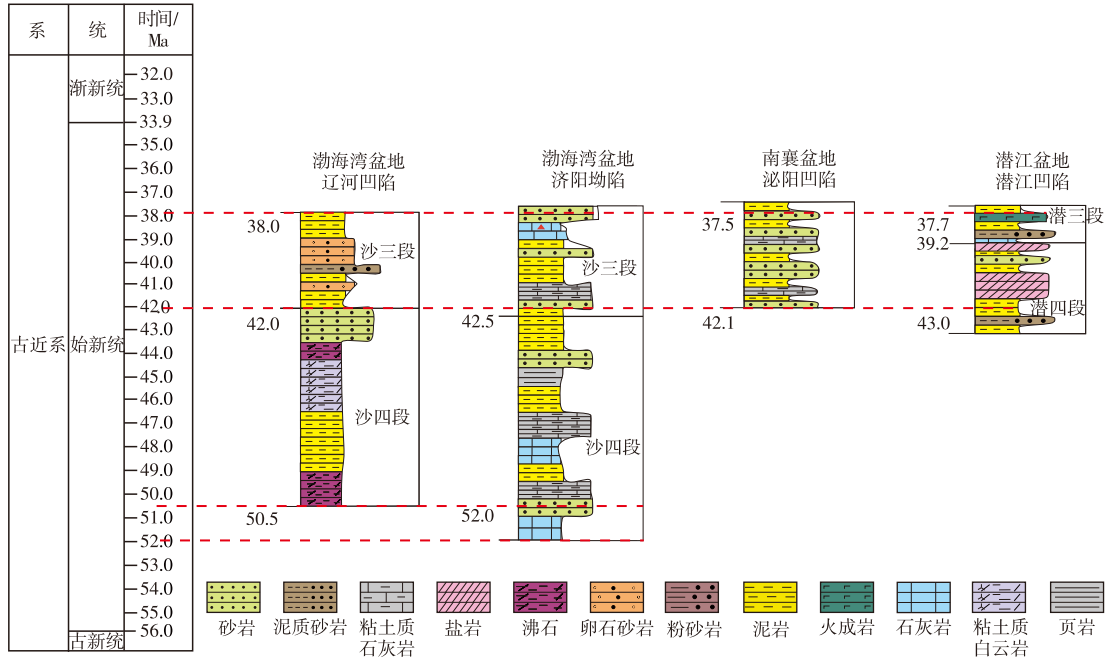


图4 地层岩相垂性分布(据文献[55-58]修改)

Fig. 4 Vertical distribution map of stratigraphic lithofacies (Modified from literature[55-58])

3.2 主、微量元素分布

在湖泊沉积物中,通常使用主、微量元素分布来指示古沉积环境,包括古盐度、古氧化还原条件、古气候等(表1)。通过运用对沉积环境反应敏感的Sr、Ba、Cu、Mn、Ca、Ni、V、Th、U、Ti、Mg等元素,结合相应的主、微量元素参数比值对中国东部盆地典型页岩层系(渤海湾盆地辽河凹陷沙河街组、渤海湾盆地济阳拗陷沙河街组、南襄盆地泌阳凹陷核桃园组和江汉盆地潜江凹陷潜江组)形成的古环境进行综合研究,包含古盐度、古气候、古水深、古氧化还原性等方面。

在古盐度方面,常用的参数有 $\omega(\text{CaO})/(\omega(\text{CaO}) +$

$\omega(\text{Fe}))$ 、 $\omega(\text{Sr})/\omega(\text{Ba})$ 、 $1000 \times \omega(\text{Rb})/\omega(\text{K})$ 和 $\omega(\text{B})/\omega(\text{Ga})$ ^[48]。在天然水中,Sr元素在相同条件下比Ba元素运移更远。在淡水与盐水混合时,淡水中的Ba²⁺会与盐水中的SO₄²⁻结合形成BaSO₄,然后发生沉淀。SrSO₄具有很强的溶解度,在生物作用下发生进一步运移和沉淀^[60-62, 66-67]。Ba和Sr在岩石埋藏成岩过程中会发生显著改变,一些含Sr矿物会在成岩作用过程中释放出Sr²⁺,如长石的钠长石化和蒙脱石的脱水过程^[68]。此外,Ba在埋藏成岩过程中也很容易迁移^[69-70]。在成岩作用的早期阶段,富含有机质的沉积物通中常含有大量的重晶石,这些重晶石在缺氧的底层水或孔隙水中发生还原性溶解^[71],导致了Ba²⁺的释放^[13]。

表1 古沉积环境参数指标(据文献[62-65]修改)

Table 1 Paleosedimentary Environmental Parameter Indicators (Modified from literature[62-65])

参数类型	参数指标	参数划分		
		淡水湖相	微咸湖相	咸湖相
古盐度	$\omega(\text{Sr})/\omega(\text{Ba})$	<0.2	0.2~0.5	>0.5
	$\omega(\text{CaO})/[\omega(\text{CaO})+\omega(\text{Fe})]$	<0.2	0.2~0.5	>0.5
	$1000 \times \omega(\text{Rb})/\omega(\text{K})$	<4	4~6	>6
	$\omega(\text{B})/\omega(\text{Ga})$	<3	3~6	>6
参数类型	参数指标	参数划分		
		气候温暖湿润	气候半湿润	气候干燥炎热
古气候	$\omega(\text{Sr})/\omega(\text{Cu})$	<5	5~10	>10
	气候指数C	>0.8	0.2~0.8	<0.2
参数类型	参数指标	参数划分		
		氧化环境	贫氧环境	还原环境
古氧化还原	$\omega(\text{Ni})/\omega(\text{Co})$	<5	5~7	>7
	$\omega(\text{U})/\omega(\text{Th})$	<0.75	0.75~1.25	>1.25
	$\omega(\text{V})/\omega(\text{Cr})$	<2.00	2.00~4.25	>4.25

在古氧化还原方面, $\omega(V)/\omega(V)+\omega(Ni)$ 、 $\omega(Ni)/\omega(Co)$ 和 $\omega(V)/\omega(Ni)$ 常被作为恢复古水体氧化还原条件的地球化学指标。在氧化环境中, Ni以Ni⁺的形式存在, 而Co以Co²⁺的形式溶解在水中。古氧化还原条件反映了沉积期湖水的含氧量。V、Ni和Cr对沉积环境中的氧化还原变化很敏感, 能够反映古环境的氧化还原条件^[72-73]。 $\omega(V)/\omega(V+Ni)$ 值介于0.84~0.89, 表明水体分层, 底层水中存在H₂S厌氧环境。中等V/(V+Ni)值(0.54~0.82)表示水体分层不明显的厌氧环境。低V/(V+Ni)值(0.46~0.60)反映了水体弱分层的贫氧环境^[74]。

古气候影响水位变化和水环境条件。古温度、湿度和日照量控制着碳酸盐种类的多样性、生成量和沉积过程。此外, 温暖的气候条件往往能提供充足的降雨, 使河流能够将营养物质和有机质输送到湖泊, 从而进一步提高初级生产力^[75]; 然而也会导致分层、流动循环弱和地表水中氧气含量高。在古气候方面, 气候指数为C和古盐度恢复采用 $\omega(Sr)/\omega(Cu)$, 其中 $C = \sum(Fe, Mn, Cr, Ni, V, Co) / \sum(Ca, Mg, K, Na, Sr, Ba)$, Sr是喜干元素, Cu是喜湿元素。在干旱条件下, 由于供水减少和水质碱度增加, Ca、Mg、K、Na、Sr、Ba等元素大量沉淀和沉积; 在潮湿的气候条件下, 岩石中存在更多的元素, 如Fe、Mn、Cr、Ni、V、Co。

通常在温暖潮湿的条件下, 降雨量充足, 而在干旱条件下, 淡水输入减少和蒸发强度增加会导致湖水含量增加, 可能会增加Mg/Ca比值, 并随后导致碳酸盐(白云石)的沉淀。因此, 较高的Mg/Ca比值表示在干燥气候条件下水分蒸发强度更强^[13]。

NESBITT等^[63]首次提出了化学侵蚀指数(CIA)来定量评估古代沉积岩(泥岩)的风化历史, 用于定量评估泥质岩的化学风化强度与物源区风化历史^[64-65, 76-79]。该指

标的理论基础在于化学风化过程中长石类矿物的分解及其向黏土矿物的转化过程。

$$\chi(CIA) = Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O) \times 100 \quad (1)$$

式中: $\chi()$ 是用来表示摩尔分数, %。

CIA常用于表征源区化学风化强度: CIA介于50%~60%表示初级风化作用, 60%~80%表示中等程度风化, 而80%~100%则反映了强烈化学风化过程。另外, CIA并非单纯反映化学风化程度, 还可能受到多种因素的影响, 包括沉积物物源差异、水动力条件下的粒度分选效应以及沉积后期K⁺的加入(如成岩伊利石化或交代作用)。在富含碳酸盐的泥质岩中直接采用CIA评估风化强度可能导致偏差, 因为碳酸盐矿物中的CaO会干扰硅酸盐系统中CaO摩尔分数计算, 从而降低指数的准确性^[80-82]。

4 气候对沉积环境的影响

从始新世早期开始, 4个盆地都具有较高的盐度, 这与盆地的干热气候有关。在干旱气候的影响下, 古湖水不断蒸发浓缩, 在凹陷内形成了咸水沉积体系。与岩相对应, 江汉盆地盐度较高, 渤海湾盆地次之。江汉盆地潜江组具有碳酸钙和盐岩等特征性盐湖矿物, 而渤海湾盆地辽河拗陷具有石膏等特征性盐湖矿物。渤海湾盆地在始新世早期至47 Ma的盐度相对较高, 从47 Ma到始新世末期, 表现出微咸水的特征。在古气候方面, 这4个地区在始新世期间均表现为干热气候, 而渤海湾盆地的气候在45~47 Ma期间经历了从干旱到湿润、半湿润的转变。东营凹陷和泌阳凹陷的Sr/Cu值相对较小, 反映了相较于辽河凹陷和潜江凹陷更湿润的气候, 而潜江凹陷则处于干热气候中(图5)。在页岩发育区间内, Sr、B、V元

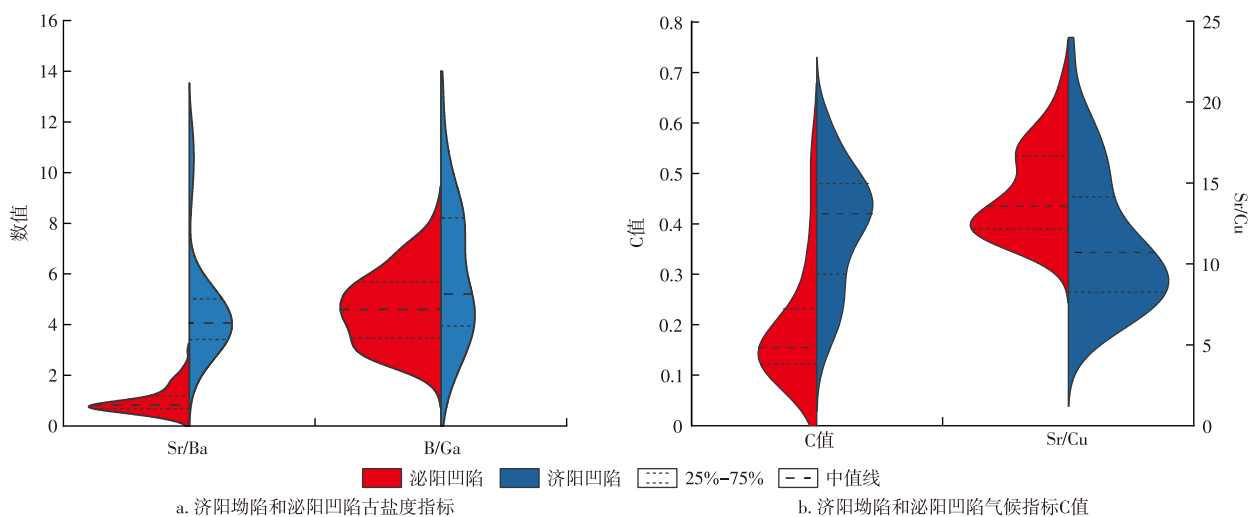


图5 济阳拗陷和泌阳凹陷古环境多指标比较(据文献[21,83]修改)

Fig. 5 Comparison of multiple indicators of paleoenvironment between the Jiyang Depression and Biyang Sag (modified from literature [21,83])

素在泌阳凹陷核桃园组三段下部相对富集较多, Sr/Cu 值普遍大于 10, V/Cr 值普遍大于 2, 反映了这个时期主要为干热气候, 沉积环境为微还原的咸水环境; 核桃园组三段的上部与下部相反, Sr、B 和 V 元素含量显著降低(图 6-图 7)。Sr/Cu 值一般小于 10, V/Cr 值大多小于 2, 表明气候主要为温暖湿润。潜江组第四段沉积期, 古气候指标中的化学蚀变指数小于 0.2, Sr/Cu 值极高, 表明干热气候; 潜江组第三段沉积期 Sr/Cu 值下降, 表明气候向温暖湿润开始转变(图 8)。

在古氧化还原条件方面, 40 Ma 期间, 4 个盆地均表现出由还原环境向氧化环境过渡的趋势(图 9)。从氧化-还原的角度来看, 从图 9 中可以看出, 潜江凹陷的 V/(V+Ni) 值最高, 均处于还原环境, 而泌阳凹陷的 V/(V+Ni) 值最小, 大多是在强氧化条件下。核桃园组三段下部的 V 元素相对富集, V/Cr 值普遍大于 2, 表明该时期的沉积环境是一个相对还原的咸化环境; 核桃园组第三段上部与下部相反, V 元素含量显著降低, V/Cr 值大多小于 2, 表明沉积环境是弱氧化的淡水环境。52~47 Ma 时期, 风化程度逐渐增强, 与始新世早期全球气温的短暂上升有关。经过一段时间后风化程度开始减弱, 在 42 Ma 左右再次增强。在这 4 个研究区中, 辽河凹陷始新世的风化程度最弱, 大部分时期属于弱风化。东营凹陷和潜江凹陷的风化程度较强, 东营凹陷最强, 这与古盐度参数 Sr/Ba 的趋势相似(图 10)。在岩性方面, 4 个地区的岩性在垂向上自下而上表现出砂泥比逐渐增大的趋势, 由深湖的纯泥岩转变为半深湖的含砂夹层泥岩。在 40 Ma 左右的 MECO 事件中, 存在厚层砂岩夹层, 砂泥比显著增加。气候变热后, 沉积速率呈增加趋势, 季节差异变大, 夏季降雨量增加, 导致河流等来源的陆地碎屑输入增加, 同时也提高了湖泊的生产力。

碳氧同位素是湖泊开放程度的良好指标。因为湖泊中的藻类会消耗 ^{12}C , 从而增加水中的 $\delta^{13}\text{C}$, 而有机质的氧化会产生 $^{12}\text{CO}_2$, 导致水中 $\delta^{13}\text{C}$ 减少。此外, 淡水的 $\delta^{13}\text{C}$ 远低于湖水, 淡水流入会降低湖水的 $\delta^{13}\text{C}$, 而蒸发会增加湖水的 $\delta^{13}\text{C}$ ^[94]。在氧同位素中, 较轻的 ^{16}O 更有可能从水面逃逸到空气中, 增加湖水的 $\delta^{18}\text{O}$, 而潮湿的气候和降雨将使湖水的 $\delta^{18}\text{O}$ 接近淡水中通常记录的值^[95]。根据研究结果整合了已发表的碳氧同位素数据(图 10), 在现代开放/封闭湖泊中通过同位素研究建立开放/封闭湖泊图解^[96-97]。

非碱性微咸水湖是指在大多数时期水体盐度已达到碳酸盐饱和, 但未达到硫酸盐和氯化物饱和的湖泊。非碱性咸水湖的典型例子包括始新世—渐新世渤海湾盆地(沙河街组沉积时期)东营凹陷^[98-100]和松辽盆地(嫩江组和青山口组沉积时期)^[101-103]。碱性微咸水湖是指水体碱

度高(pH 值大于 9)、矿化度相对较低、碳酸钠矿物欠饱和的湖泊。

根据含白云岩层序中是否存在丰富的同时代火山岩和凝灰质岩, 中国碱性微咸水湖分为富凝灰岩型和贫凝灰岩型两种类型。两种碱性微咸水湖的白云岩具有相似的碳氧同位素组成, 表明其白云岩在成因上是有联系的。碱性微咸水湖白云岩的 ^{13}C 值为正, 介于 0~10 ‰^[104], 而其 $\delta^{18}\text{O}$ 值大多为负值, 介于 -20‰~<0^[105-113](图 11)。渤海湾盆地辽河凹陷在古近系沙河街组沉积期间为贫凝灰岩型碱性微咸水湖^[108]。碱性微咸水湖泊中的白云岩主要赋存于湖中心沉积物中, 包括纹层状方沸石白云岩、钠长石白云岩、白云质方沸石、泥质白云岩和白云质泥岩等岩相。除了方沸石和自生钠长石外, 钠长石、重晶石和地开石在这些碱性微咸水湖沉积物中也很常见^[106]。

碱性盐湖被称为“苏打湖”, 其特征是在湖中心广泛沉积层状碳酸钠。中国碱性盐湖包括核桃园组沉积期的南襄盆地泌阳凹陷^[104]。准噶尔盆地玛湖凹陷碱性盐湖与泌阳凹陷不同(图 1a), 还含有丰富的火山岩和凝灰岩物质^[114]。碱性盐湖中的白云石矿物主要以孤立分散的晶体或聚集体赋存于白云质泥岩和白云质凝灰岩中^[115-116]。碱性盐湖白云岩的 $\delta^{13}\text{C}$ 值介于 0~7 ‰, $\delta^{18}\text{O}$ 值介于 5‰~15‰(图 11)^[114, 116, 117-119]。

根据 4 个凹陷碳氧同位素的平面分布来看, 渤海湾盆地辽河凹陷沙 3 段至沙 4 段水体为碱性微咸水湖, 渤海湾流域东营凹陷沙 3 段至沙 4 段水体为非碱性盐湖和碱性咸化湖泊, 南襄盆地泌阳坳陷核 1 段—核 2 段水体为碱性盐湖, 江汉盆地潜江凹陷潜 3 段—潜 4 段水体为非碱性咸湖。

5 气候对有机质富集及含油性的影响

渤海湾盆地辽河凹陷烃源岩 TOC 含量相对较低, 主要集中在 0~3%, 表现出明显的两段式分布特征。第一阶段为 42.4~39.2 Ma, 有机质富集程度最高时间在 42.0 Ma 左右(TOC 含量为 2.5%), 第二阶段为 39.1~38.0 Ma, 有机质富集度峰值在 38.5 Ma 左右(TOC 含量为 2.8%)。渤海湾盆地东营凹陷沙河街组沙三段页岩的 TOC 含量主要分布在 1.5%~4.5%, 有机质含量普遍较高。从下到上, 表现为 2 个长期变化。第一阶段为 42.4~39.2 Ma, 有机质富集度最高时间在 41 Ma 左右(TOC 含量为 4.5%), 第二阶段为 39.1~38.0 Ma, 有机质富集度出现峰值时间在 38.5 Ma 左右(TOC 含量为 3.0%)。南襄盆地泌阳凹陷核桃园组第三段 TOC 含量相对较高, 主要分布在 0~6%, 在 42.1~37.5 Ma 呈现出波动增加的趋势, 在 39.2~38 Ma 处于大规模有机质富集阶段, TOC 含量主要

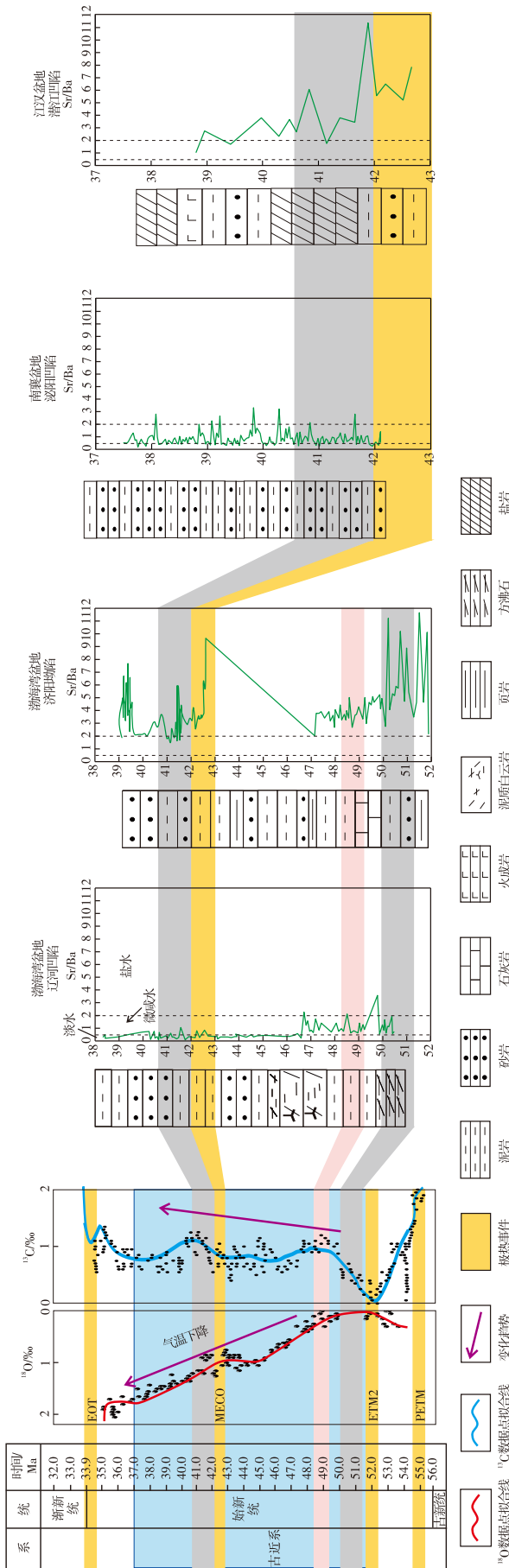


图6 中国东部盆地始新世时期 Sr/Ba 值变化趋势(据文献[21,83-85]修改)

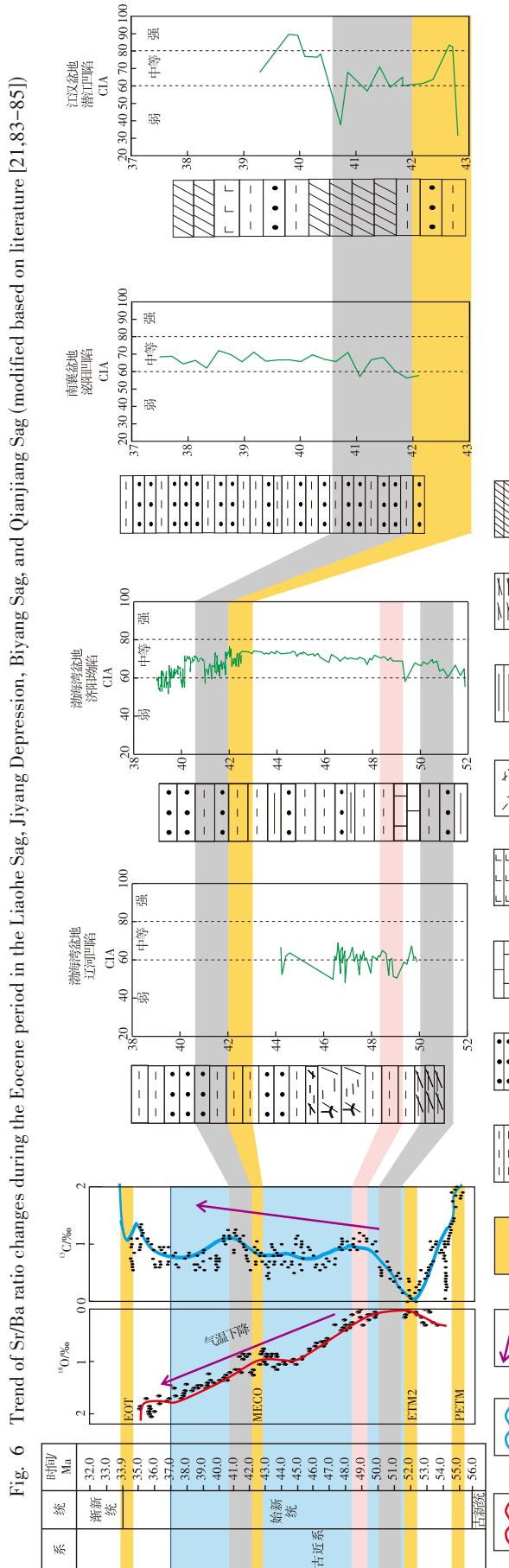


图7 中国东部盆地始新世时期 CIA 值变化趋势(据文献[86-89]修改)

Fig. 6 Trend of Sr/Ba ratio changes during the Eocene period in the Liaohé Sag, Jiyang Depression, Biyang Sag, and Qianjiang Sag (modified based on literature [21,83-85])

Fig. 7 Trend of CIA value changes during the Eocene period in the Liaohé Sag, Jiyang Depression, Biyang Sag, and Qianjiang Sag (modified based on literature [86-89])

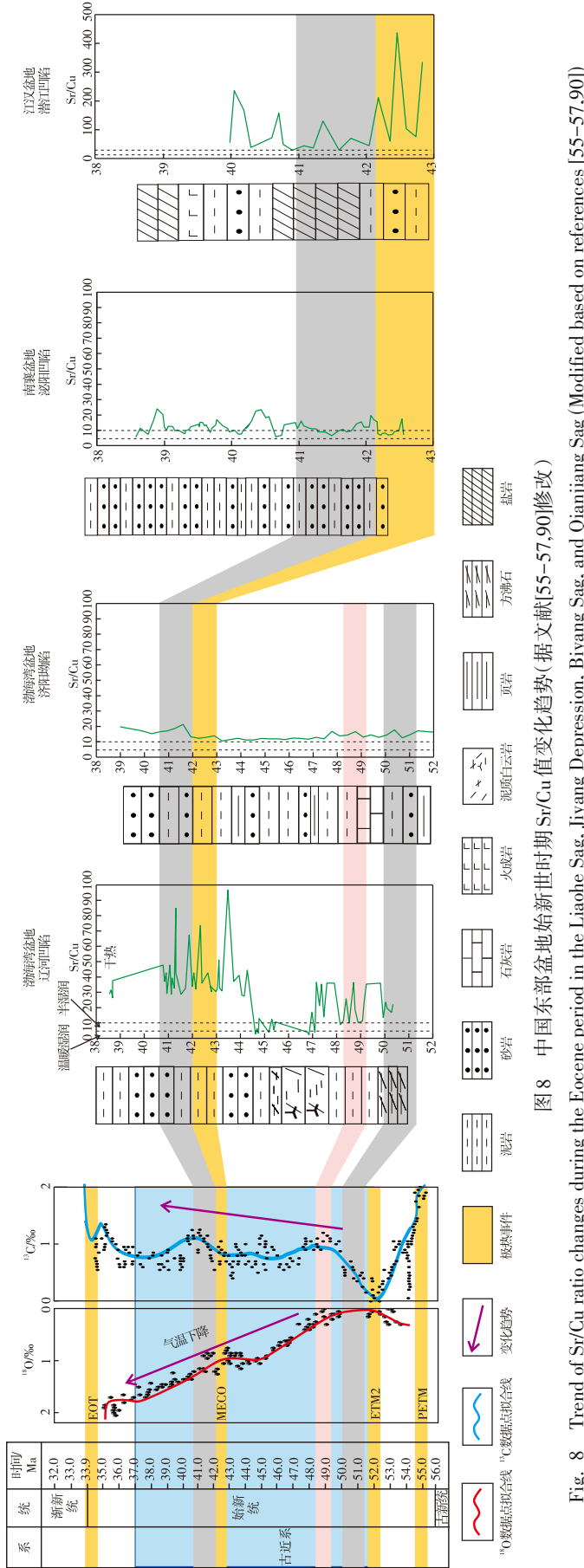


图 8 中国东部盆地始新统时期 Sr/Cu 值变化趋势 (据文献[55-57,90]修改)

Fig. 8 Trend of Sr/Cu ratio changes during the Eocene period in the Liaobe Sag, Jiyang Depression, Biyang Sag, and Qianjiang Sag (Modified based on references [55-57,90])

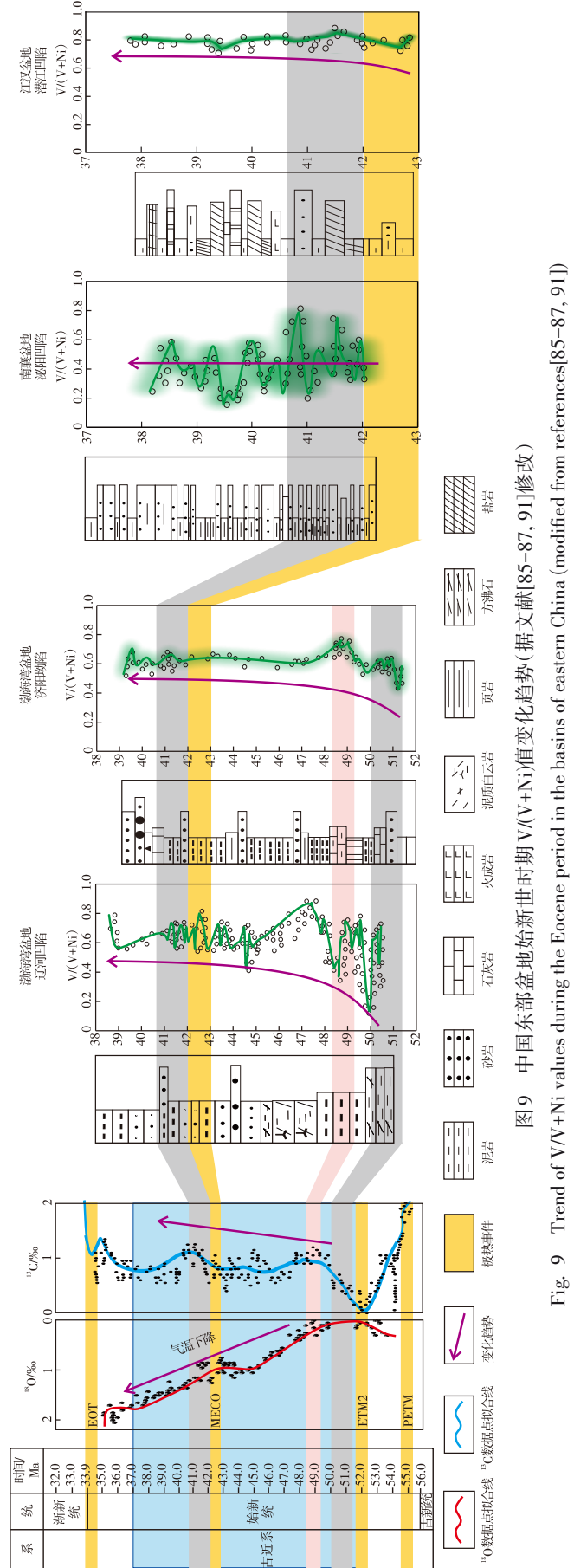


图 9 中国东部盆地始新统时期 V/(V+Ni) 值变化趋势 (据文献[85-87, 91]修改)

Fig. 9 Trend of V/(V+Ni) values during the Eocene period in the basins of eastern China (modified from references[85-87, 91])

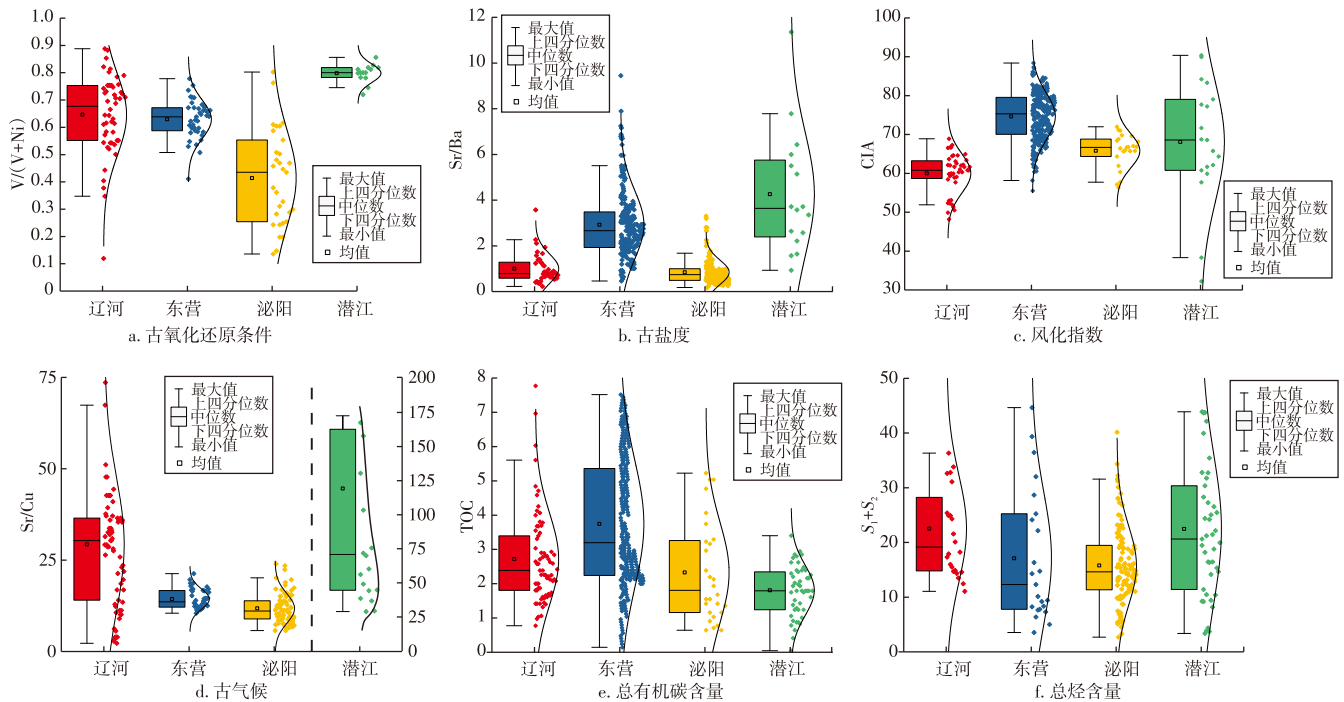


图10 中国东部盆地始新统页岩地球化学参数箱线图(据文献[55-57, 70, 78-80, 85-90, 92-93]修改)

Fig. 10

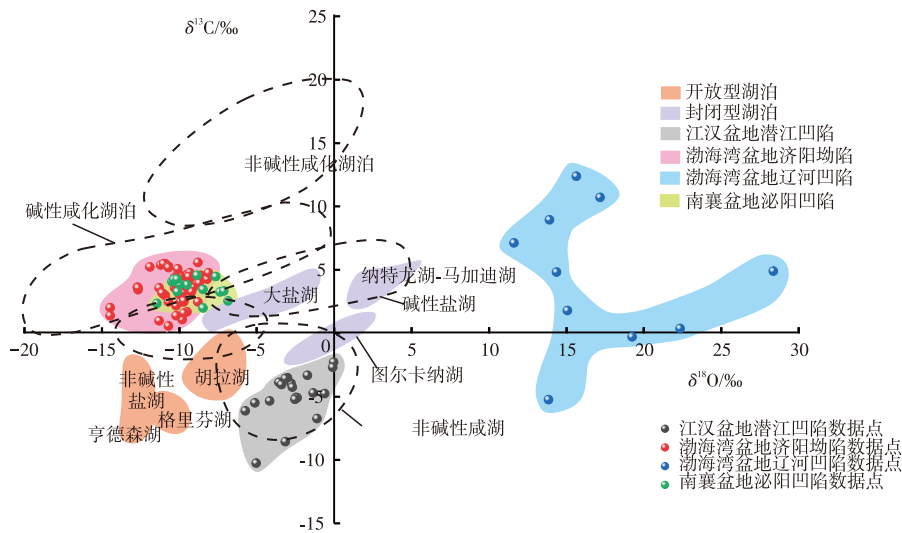


图11 湖盆类型分布(据文献[120-124]修改)

Fig. 11 Distribution map of lake basin types (modified from literature[120-124])

介于2%~6%。江汉盆地潜江凹陷烃源岩TOC含量也相对较低,主要分布在0~4%。整体表现出较大的波动,在39.2 Ma时达到最大值3.8%(图12)。4个研究区页岩的有机质类型都以I型和II₁型为主,为生油型有机质^[125-128]。

在4个地区的始新统页岩中,从下到上总有机碳含量逐渐降低,对应于大约55 Ma前PETM导致的全球变暖,向大约34 Ma前EOT导致全球变冷的转变。全球气温升高会增强风化过程,温暖的气候有利于生物繁殖,使有机质来源更丰富。中始新世气候适宜期(MECO)发生

在大约40 Ma前,全球气温短暂上升,39 Ma至41 Ma前4个地区均有TOC明显短暂上升的现象。

横向对比4个盆地的TOC含量,渤海湾盆地辽河凹陷沙三段沙四段的TOC含量最低,江汉盆地潜三组一潜四组的TOC含量也很低,南襄盆地核桃园三段的TOC含量相对较高。古盐度高的地区TOC含量较低,这可能与盐作为催化剂促进有机质热演化过程有关。同时,盐可以隔离有机质与氧气之间的接触,有利于有机质的保存。

综合比较4个研究区的TOC和S₁+S₂含量,东营凹陷的TOC含量最高,但S₁+S₂的平均值和中值最低,反映了

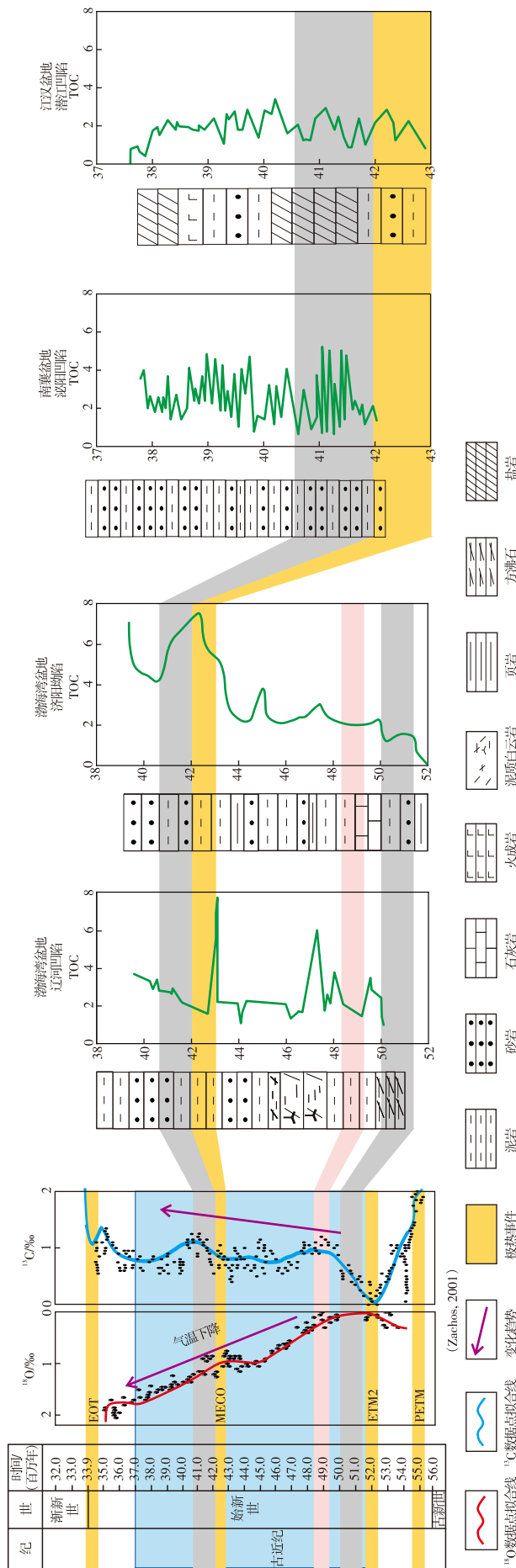


图 12 中国东部盆地始新世时期 TOC 含量变化趋势 (据文献[57, 92-93, 129]修改)
Fig. 12 Trend of Total Organic Carbon (TOC) content variation in the basins of eastern China during the Eocene period (modified based on references[57, 92, 93, 129])

渤海湾盆地东营凹陷的生烃转化率较低。南襄盆地泌阳凹陷TOC含量排第二,但 S_1+S_2 含量最低,也具有生烃转化率低的特点。辽河凹陷和潜江凹陷具有相反的特征,TOC含量较低,但 S_1+S_2 含量较高,反映了这2个地区的高油气转化率(图13),这一现象可能与海侵作用将更多有机质输入到东营凹陷和泌阳凹陷中有关。其中,东营凹陷距离海洋较近,有机质输送更多。这2个地区都具有相对潮湿的环境,有利于细菌生长,有机质分解作用更强,不利于有机质转化为油气,导致生烃转化率较低。

在有机质聚集后的早期成岩阶段,有机物发生强烈降解作用的同时,火山活动的影响使湖水中形成了缺氧—富硫化氢的水化学环境,从而增强了有机质的运移与保存条件,有利于优质烃源岩的形成^[130]。前人研究认为,火山活动增强了陆源物质的风化作用,加速了风化产物的搬运与输入,从而导致进入湖泊的碎屑物质显著增加。与此同时,火山活动可能诱发湖盆内生物生产力的短期爆发,使黑色页岩在高生产力条件下沉积。火山喷发过程还会消耗环境中的氧气,使湖盆水体处于缺氧—富硫化环境,有利于有机质的保存。

在海侵的影响下,泌阳凹陷核桃园组有机质富集的3个主要因素(即初级生产力、保存和沉积速率)发生了变化。随着海侵程度的增加,有机质的初级生产力增加,有机质保存环境变得更加恶化,沉积速率降低,这一过程导致有机质丰度增加和有机质质量提高,含油性增强,意味着海侵对湖相烃源岩的形成有积极影响^[43]。

从页岩油可动性分布来看,潜江凹陷的页岩油可动性最好,其次是济阳坳陷、泌阳凹陷和辽河凹陷。潜江凹陷和济阳坳陷的OSI(含油饱和度指数)大部分数据点大于100 mg/g,而辽河凹陷的OSI的数据点大多小于75 mg/g。从生烃潜力的分布可以看出,4个地区TOC与生烃潜力

之间的相关性都很好, R^2 (决定系数,取值0~1,值越大表示模型拟合越好)大于0.77,相邻拟合曲线之间的斜率差小于2,表明4个地区的生烃转化率相似。从含油性来看,潜江凹陷含油量最高,TOC和 S_1+S_2 含量较高,油气转化率最高,其次是泌阳凹陷、济阳坳陷,辽河凹陷含油性最差。

6 始新世咸化湖盆形成模式

典型咸化湖相页岩中有机质的富集受多种因素共同控制,主要包括古氧化还原条件、陆源输入、古生产力、古盐度、古气候以及风化强度等(图14)。而对于油气富集而言,有机质的热演化转化效率和后期油气保存条件同样是决定性因素。

渤海湾盆地辽河凹陷位于较高纬度地区,在始新世时期受东亚夏季风影响较弱,风化程度较低,且未受到海侵作用。该地区火山活动频繁,对湖盆沉积环境产生显著影响。火山物质输入导致水体盐度偏低,有机质含量较低,但沉积过程中形成的还原环境有利于有机质热解转化,从而使生烃效率较高,页岩含油量相对较高(图15)。

渤海湾盆地东营凹陷地处近海区域,在始新世时期受海侵作用显著。海水入侵使湖水矿化度升高,同时东亚夏季风作用增强,导致中等风化强度的干热气候条件。沉积环境从弱氧化逐渐过渡到还原环境,为有机质的保存提供了良好条件。该区烃源岩有机质丰度高,页岩油含量大,且富含碳酸盐矿物,有利于形成优质储层并促进油气的生成与保存(图15)。

南襄盆地泌阳凹陷在始新世时期也受到一定程度的海侵影响,但受东亚夏季风的影响相对较小。由于该区靠近内陆,风化程度低,湖水矿化度较低,气候以半湿

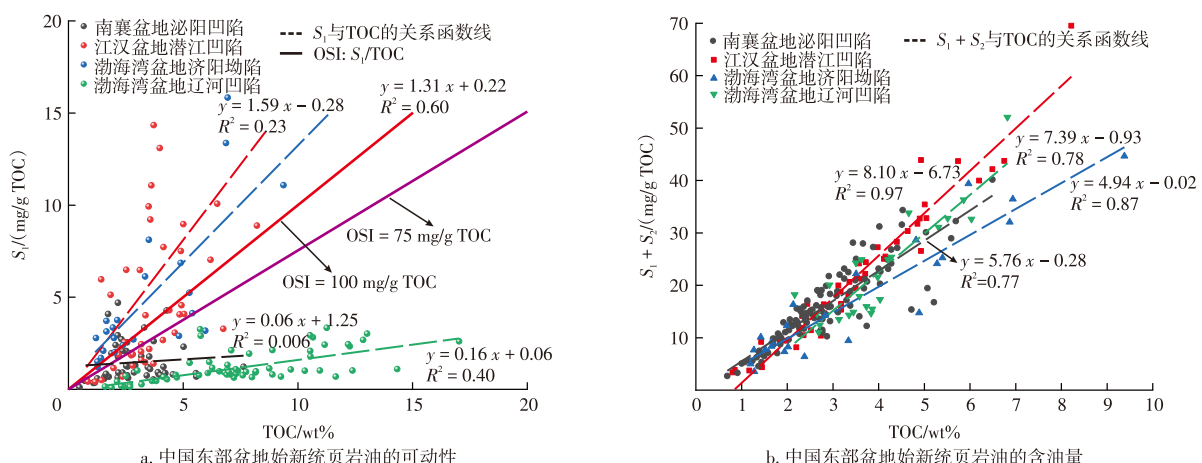


图13 中国东部盆地始新统页岩油的可动性和含油量(据文献[131-135]修改)

Fig. 13 Mobility and oil content of Eocene shale oil in the basins of eastern China(data from references[131-135])

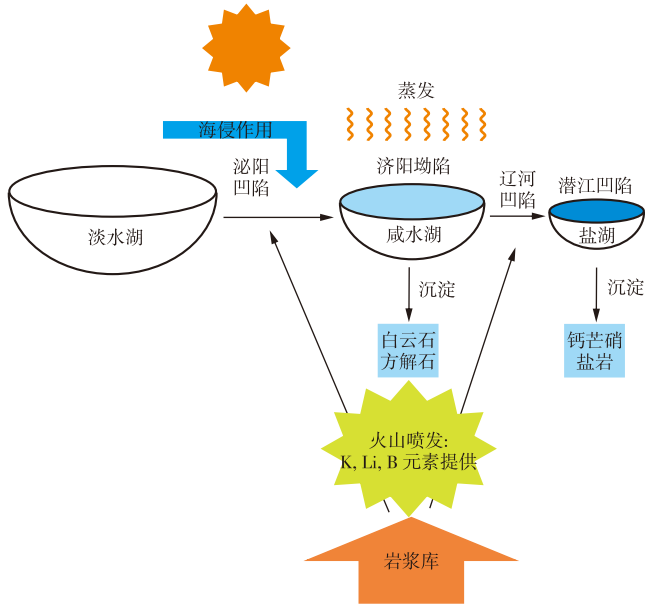


图 14 中国东部盆地盐湖形成模式

Fig. 14 Formation model of salt lakes in basins in eastern China

润-干旱为主。沉积环境以弱氧化至氧化环境为主,不利于有机质的保存与转化,因而烃源岩 TOC 含量和含油量均较低(图 15)。

江汉盆地潜江凹陷虽然位于内陆地区,但地处较低纬度,始新世时期受到强烈的东亚夏季风影响。该区气候干燥炎热,蒸发作用强烈,湖泊环境整体表现为高盐度特征。此外,潜江凹陷在始新世还受到频繁的火山活动与热液活动的双重影响。研究表明,火山灰降落与热液流体释放均能显著提升湖泊初级生产力^[136-137]。火山及热液物质输入通过携带大量营养元素促进水体中浮游生物的繁殖,同时增加湖水盐度,强化水体分层,从而有利于有机质的沉积与保存^[137]。此外,火山灰沉积所形成的水体分层阻隔了氧气的供给,减少了有机质的氧化作用,并在一定程度上防止了底层沉积物的扰动^[138]。因此,潜江凹陷的页岩虽然整体 TOC 含量较低,但其生烃转化效率较高,表现出较强的生烃潜力(图 15)。

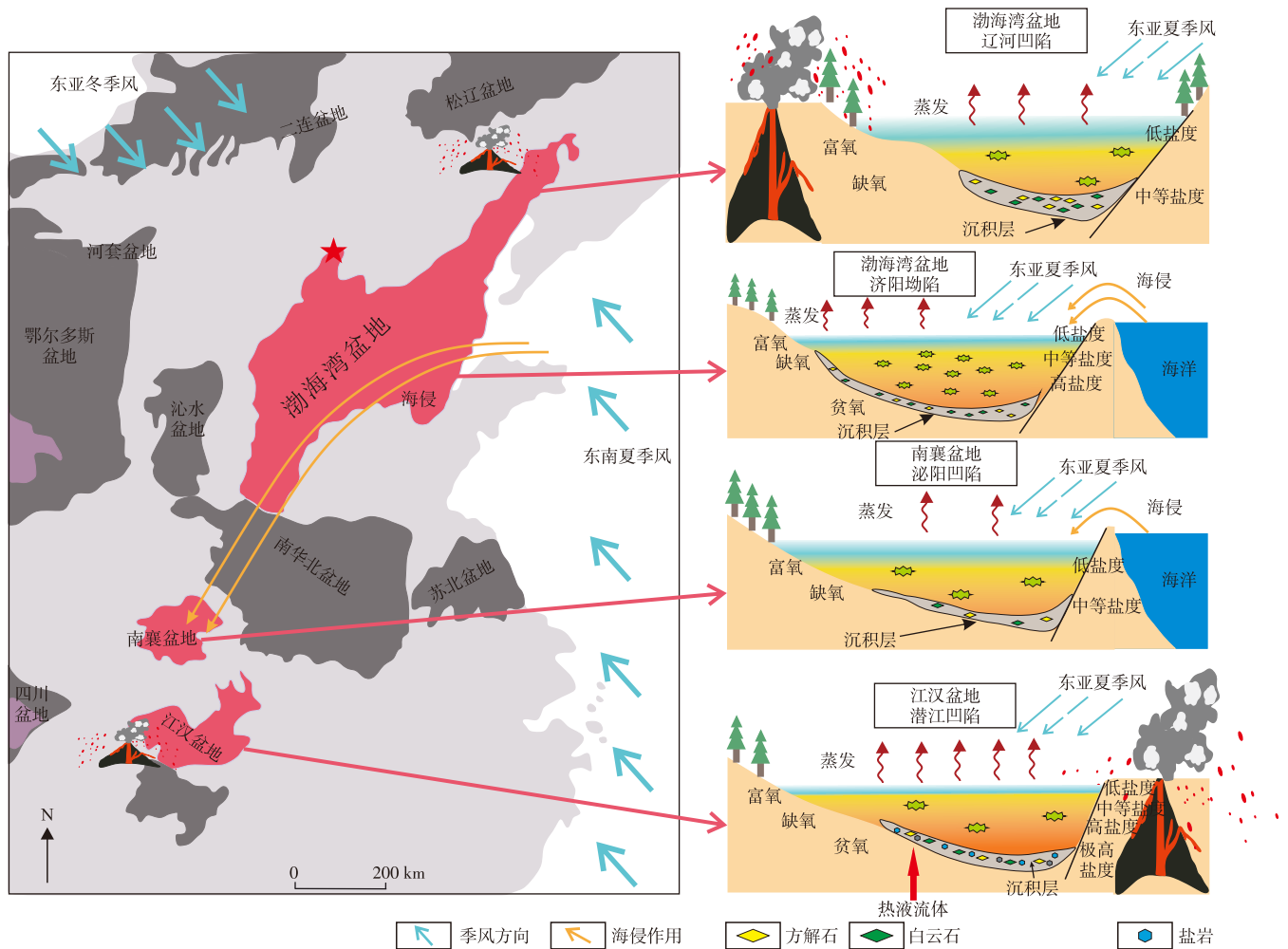


图 15 中国东部盆地始新统页岩有机质富集模式

Fig. 15 Organic Matter Enrichment Model of Eocene Shale in Basins of Eastern China

7 结论

对盐湖盆地始新统混合页岩的岩相特征及有机质富集机制进行了系统研究。以中国东部辽河、济阳、泌阳及潜江等典型湖盆为代表,结合地球化学、沉积学与气候事件分析,对构造—气候—沉积耦合条件下的岩相差异与有机质富集规律进行了综合探讨。主要结论如下:

1) 全球气候变化、大气CO₂含量波动及东亚夏季风强度与各湖盆地球化学参数具有显著对应关系。在中始新世暖期(MECO, 约41~39 Ma),古气候、盐度及氧化还原条件均出现突变,反映湖泊体系对全球气候事件的敏感响应。

2) 各凹陷在响应模式上整体一致,但区域差异明显。辽河与潜江凹陷受火山活动影响显著,干热气候与火山灰沉积共同作用下有机质含量偏低,但火山灰覆盖有利于抑制有机质氧化与促进生烃转化。济阳坳陷与泌阳凹陷受海侵作用影响,咸水输入提高湖盆盐度并携带外源有机质,使页岩TOC含量较高。整体上,始新世湖盆表现出风化及还原性由北向南增强的规律。

3) 盐度变化对有机质的保存、生烃及油气运移具有关键控制作用。盐度与古气候—氧化还原条件的协同变化共同促进了富有机质页岩的形成。未来应加强古盐度重建及其与有机质分布的定量耦合研究,以深化对盐湖盆地页岩油成藏模式及控制机制的认识。

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