

渤海湾盆地沧东凹陷古近系孔店组二段 页岩高丰度有机质富集模式

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摘要:渤海湾盆地沧东凹陷古近系孔店组二段(孔二段)页岩有机质丰度高,具有良好的页岩油勘探潜力,但由于缺乏精细的地球化学研究,有机质富集机理尚不清晰。通过开展全岩X射线衍射、全岩光片显微组分、岩石热解、总有机碳含量(TOC)、饱和烃色谱-质谱、单体烃碳同位素、主量元素与微量元素分析测试,研究了沧东凹陷孔二段页岩有机质富集的影响因素与模式。研究结果表明:孔二段页岩有机质富集受陆源碎屑输入、古生产力、古气候、古水深和古盐度多种因素影响,这些影响因素通过控制湖盆中菌藻类生物的生长、发育,在五级层序T-R旋回转换期形成高丰度有机质富集段。陆源碎屑输入为湖盆带来的丰富营养物质提高了湖盆生产力;古气候、古水深与古盐度主导了湖盆中水生/陆源有机质贡献比例的变化;细菌活动对有机质的改造提高了页岩H/C原子量比与“腐泥化”程度。以C₃开发层序T-R旋回转换期为主的⑧号小层页岩形成于温湿气候、低盐度和水体较深的沉积古环境,TOC平均为2.7%,游离烃含量(S₁)为3.7 mg/g,可动油指数(OSI)为215 mg/g,有机质丰度高、有机质类型较好,是页岩油有利靶窗。

关键词:生烃母质;沉积环境;有机质富集;页岩油;孔店组;古近系;沧东凹陷;渤海湾盆地

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Enrichment model of high-abundance organic matter in shales in the 2nd member of the Paleogene Kongdian Formation, Cangdong Sag, Bohai Bay Basin

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Abstract: Shales in the 2nd member of the Paleogene Kongdian Formation (also referred to as the Kong 2 Member) in the Cangdong Sag contain high-abundance organic matter, showing great potential for shale oil exploration. However, the mechanisms underlying the organic matter enrichment are yet to be clarified due to the lack of fine geochemical research. Given this, we investigate the factors influencing organic matter enrichment and the enrichment model in the Kong 2 Member shale using whole-rock X-ray diffraction, maceral identification on polished surfaces of whole-rock shale samples, rock pyrolysis, measurement of the total organic carbon (TOC) content, chromatography-mass spectrometry of saturated hydrocarbons, carbon isotopic analysis of monomer hydrocarbons, and the analyses and tests of major and trace elements. The results indicate that the organic matter enrichment in the Kong 2 Member shale is influenced by multiple factors including terrigenous clastic input, paleoproductivity, paleoclimate, paleo-water depth, and paleosalinity. These factors govern the growth and development of algae and bacteria in the lacustrine basin of the Cangdong Sag, contributing to the formation of organic matter enrichment horizons with high TOC content during the T-R cycle transition period of the fifth-order sequence. Specifically, the terrigenous clastic input introducing abundant nutrients enhanced the biological productivity of the lacustrine basin. The paleoclimate, paleo-water depth, and paleosalinity largely determined the terrigenous/aquatic ratio (TAR) of the lacustrine basin. Furthermore, bacterial activity transformed organic matter, increasing the H/C atomic ratio and the saprofication degree of the shale. Shales in

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sublayer ⑧, primarily taking shape during the T-R cycle transition, of the C_3 layer under development are formed under paleoenvironmental conditions of a warm and humid climate, low salinity, and deep water. This sublayer, with an average TOC content of 2.7%, S_1 of 3.7 mg/g, and producible oil index (POI) of 215 mg/g, boasts high abundance and favorable organic matter types, proving to be favorable landing zone for horizontal wells.

Key words: hydrocarbon-generating parent material, sedimentary environment, organic matter enrichment, shale oil, Kongdian Formation, Paleogene, Cangdong Sag, Bohai Bay Basin

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近年来,多个领域页岩油勘探获得重要发现,陆相页岩受到国内外众多学者的关注^[1–6]。陆相页岩在中国鄂尔多斯盆地延长组、准噶尔盆地芦草沟组、渤海湾盆地沙河街组及孔店组均广泛分布^[4–6],其中渤海湾盆地沧东凹陷古近系孔店组二段(孔二段)发育“纹层型”页岩油^[6],是目前中国陆相页岩油勘探开发的重要层位之一。

沧东凹陷孔二段沉积时期为拗陷型封闭湖盆,周围发育十大物源体系,具有短物源供给、相变快的特点,这导致纵向上页岩岩相组合与有机质丰度表现出较强的非均质性^[7–8]。前人使用层序地层学、岩石学对孔二段不同岩相、沉积旋回有机质的分布特征开展了大量研究。其中赵贤正^[9–11]等认为五级R旋回与T旋回不同的沉积环境、矿物含量、母质组成控制了有机质的丰度与类型;蒲秀刚等^[12]认为孔二段具有韵律性有机质富集特征,有机质富集受陆源输入的影响。陆相页岩分布不同于海相,古环境变化频繁^[10–11],有机质富集更易受多种因素制约^[13–17]。目前沧东凹陷孔二段页岩缺乏系统的地球化学精细研究,控制有机质分布的影响因素与富集的机理尚不清晰。为此,本文主要通过有机地球化学与元素地球化学方法,探讨了沧东凹陷孔二段页岩高丰度有机质的富集机理与模式,为页岩油甜点的精准预测提供理论依据。

1 区域地质背景

沧东凹陷位于渤海湾盆地南部,夹持于沧县隆起、徐黑凸起及孔店凸起之间,面积约1 800 km²(图1a)。沧东凹陷经历了古近纪同裂谷期和新近纪以来的后裂谷期,在中生界基底自下而上沉积了孔店组、沙河街组和东营组^[18–19]。其中,孔二段是在半干旱–潮湿、咸化沉积环境下沉积的一套以暗色泥页岩为主,夹薄层粉砂岩、中–细砂岩与泥质白云岩的地层,厚度为400 ~

600 m,分布稳定,面积约500 km²,是目前沧东凹陷页岩油的主要勘探层位。孔二段可分为4个亚段:①孔二四亚段[$Ek^{2(4)}$],湖泛初期,水体开始加深,沉积物粒度较粗,各物源口发育辫状河三角洲–滨浅湖沉积,半深湖–深湖及湖底扇沉积不发育;②孔二三亚段[$Ek^{2(3)}$],进入湖侵期,水体变深、湖盆面积扩大,以辫状河三角洲–半深湖沉积为主,局部可见湖底扇;③孔二二亚段[$Ek^{2(2)}$],湖盆可容空间进一步扩大、后期达到最大,以深湖–半深湖沉积为主,局部可见辫状河三角洲和湖底扇沉积;④孔二一亚段[$Ek^{2(1)}$],湖盆进入萎缩期,物源供给减缓,以辫状河三角洲–滨浅湖沉积为主^[20]。赵贤正、蒲秀刚等^[21–22]依据岩性组合、测井特征和小波分析等建立了孔二段页岩高频层序地层格架,将孔二段页岩进一步划分为 C_1 – C_7 共7个页岩油开发层系和21个开发小层(图1b)。

2 样品与方法

针对G108–8井孔二段2 915 ~ 3 415 m深度的低熟页岩进行了500 m连续取心,由于低热演化程度对页岩的有机地球化学参数影响较小,为本次研究提供了良好样本。选取1 096个样品开展全岩X射线衍射与烃源岩热解测试,对孔二段页岩进行含油性与甜点评价。从 $Ek^{2(2)}$ 与 $Ek^{2(3)}$ 页岩中挑选出32个样品开展全岩X射线衍射、有机碳含量、主量元素、微量元素、饱和烃色谱–质谱分析化验联测确定页岩矿物特征、有机碳含量和沉积环境。由于孔二段页岩生物标志化合物中具有丰富的 C_{30} 藿烷($C_{30}H$),为此挑选8块样品开展饱和烃单体化合物碳同位素分析确定 C_{30} 藿烷来源。此外,对27个样品进行干酪根元素分析确定页岩有机质类型;对19个样品进行全岩光片显微组分鉴定确定页岩母质特征。所有测试均在长江大学油气资源与勘探技术教育部重点实验室完成。

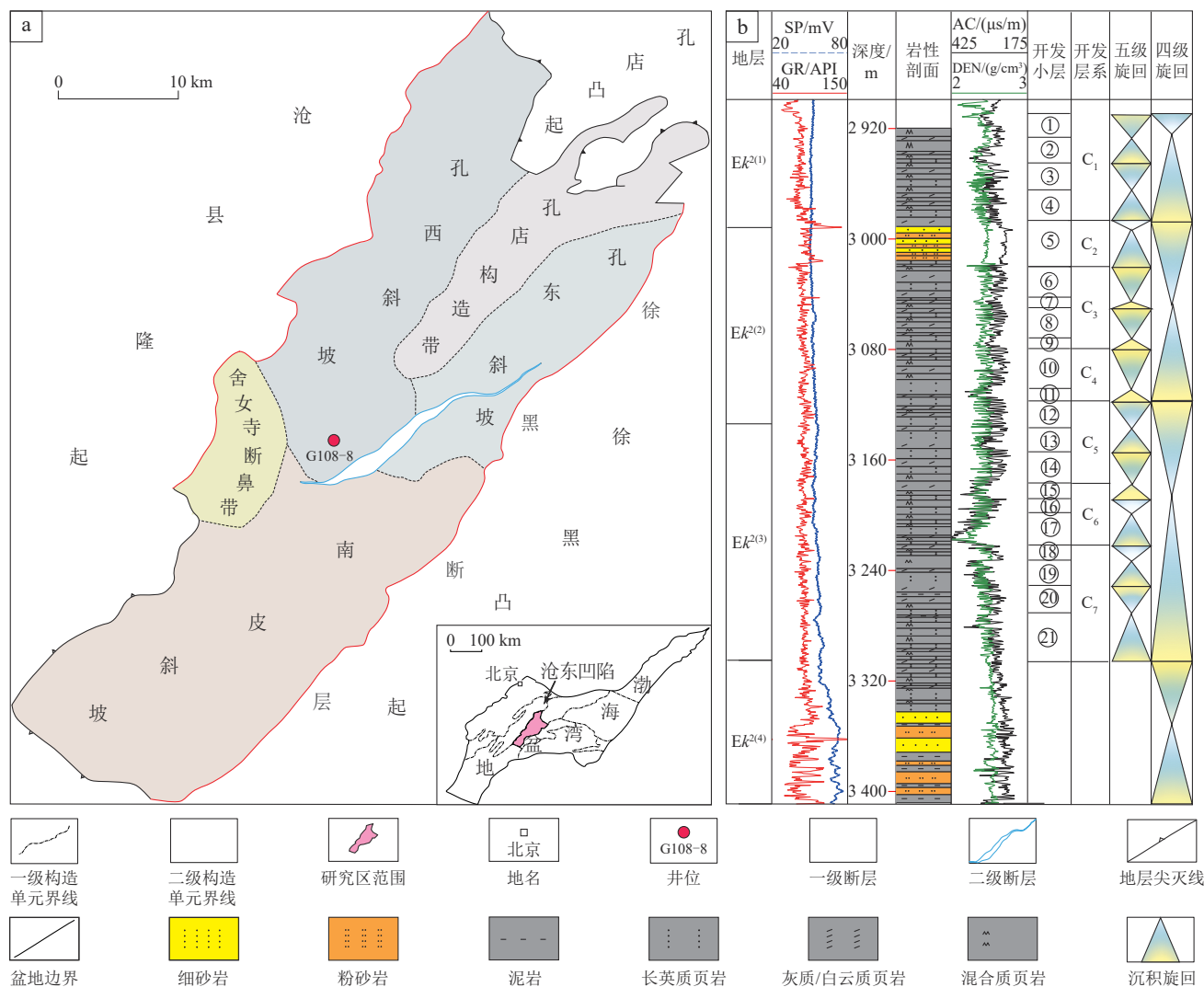


图1 沧东凹陷构造单元划分(a)与孔二段层序地层划分柱状图(b)

Fig. 1 Map showing the structural units in the Cangdong Sag (a) and stratigraphic column of the Kong 2 Member within the sag (b)

3 结果

3.1 岩石学特征

全岩X射线衍射(XRD)实验结果显示(图2a),孔二段页岩矿物组成含量以长石(9.0%~29.0%,平均14.8%)、石英(11.0%~24.0%,平均15.3%)为主,铁白云石(0~49%,平均18.3%)、方解石(0.0~23.0%,平均9.5%)次之,黏土矿物含量较低(8.0%~31.0%,平均16.3%)。此外,孔二段还存在方沸石(平均22.0%)及少量菱铁矿(平均1.5%)。依据细粒沉积岩长英质矿物含量、碳酸盐矿物含量和黏土矿物含量三端元命名法,可以识别出孔二段发育长英质页岩、混合质页岩和灰质/白云质页岩3种岩石类型(图2b)。

3.2 有机碳含量与干酪根元素特征

沧东凹陷孔二段页岩总有机碳含量(TOC)介于0.13%~13.09%,平均3.40%。其中TOC<1%的样品占比仅为23.8%,TOC>4%样品占比可达38.8%(图3a)。孔二段页岩干酪根H/C与O/C原子比值分别介于1.06~1.91和0.01~0.12,以I型与II₁型干酪根为主(图3b)。

3.3 有机显微组分特征

本次采用石油行业标准(SY/T6414—2014)中的有机显微组分的分类方法^[23],将孔二段页岩显微组分划分为腐泥组、壳质组、镜质组、惰质组、次生有机组、动物有机碎屑组和矿物沥青基质。结果显示,腐泥组在有机显微组分中占比最高,多以结构藻类

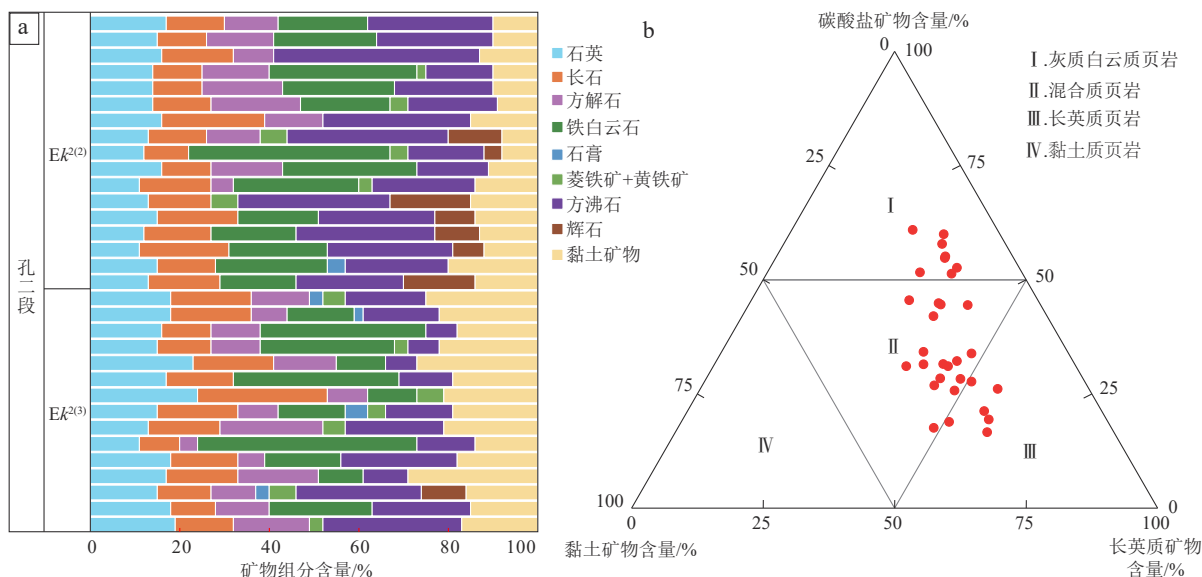


图2 沧东凹陷孔二段页岩矿物组成(a)与矿物组分含量三端元图(b)

Fig. 2 Diagram showing the mineral composition (a) and ternary plot of the mineral content (b) of the Kong 2 Member shales within the Cangdong Sag

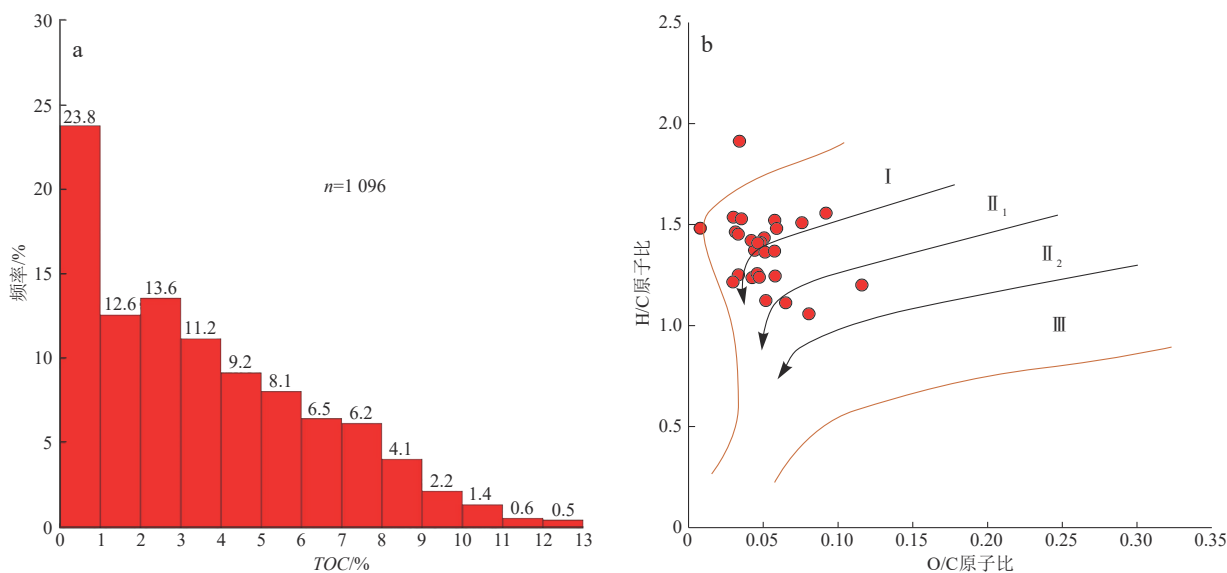


图3 沧东凹陷孔二段页岩有机碳含量分布频率直方图(a)与干酪根类型划分(b)

Fig. 3 Frequency histogram of the TOC content (a) and diagram showing kerogen types (b) for the Kong 2 Member shales within the Cangdong Sag

体与层状藻类体的形式产出(图4b,d,h),含量介于15.5%~57.0%,平均38.1%;矿物沥青基质含量仅次于腐泥组,平均22.1%,以细小有机质与细小黏土矿物相伴生的形式存在(图4a,c),为高等植物孢粉、表皮蜡质与低等植物、藻类中不稳定内含物与原生烃类经过细菌微生物改造后产物^[24-25];陆源有机质组分(壳质组+蜡质组+惰质组)中主要为镜质体与丝质体(图4e—g),平均含量为21.6%;沥青体与烃类体等次生组分平均含量为18.3%。综合表明,孔二段页岩母质来源以菌藻类低等生物为主,同

时存在部分陆源有机质的输入,且细菌对有机质改造强烈。

3.4 分子地球化学特征

3.4.1 正构烷烃

陆生/水生有机质比值(TAR),定义为 $(nC_{27}+nC_{29}+nC_{31})/(nC_{15}+nC_{17}+nC_{19})$,可以表征页岩陆生与水生有机质的相对输入,TAR值随水生生物贡献增多而降低^[26-28]。生烃母质、成熟度与生物降解等因素均会影

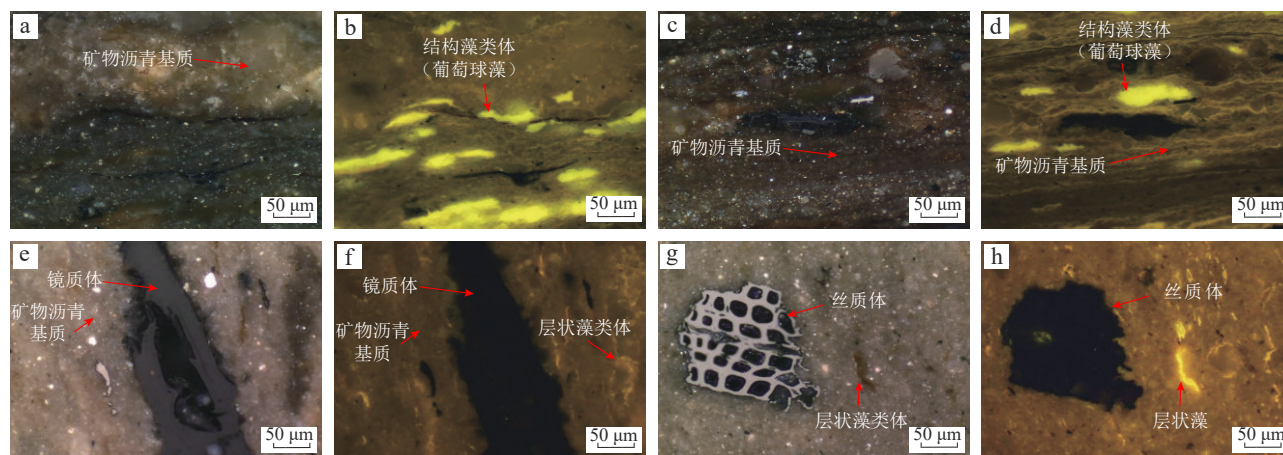


图4 沧东凹陷G108-8井孔二段页岩典型有机显微组分镜下特征照片

Fig. 4 Photomicrographs showing typical macerals in the Kong 2 Member shales in well G108-8 in the Cangdong Sag

a. 埋深3 050.26 m, 矿物沥青基质, 白光; b. 埋深3 050.26 m, 结构藻类体、矿物沥青基质, 荧光; c. 埋深3 092.76 m, 矿物沥青基质, 白光; d. 埋深3 092.76 m, 结构藻类体、矿物沥青基质, 荧光; e. 埋深3 162.57 m, 镜质体、矿物沥青基质, 白光; f. 埋深3 162.57 m, 镜质体、层状藻、矿物沥青基质, 荧光; g. 埋深3 248.82 m, 丝质体、层状藻类体, 白光; h. 埋深3 248.82 m, 丝质体、层状藻类体, 荧光

响正构烷烃的分布,从而导致 TAR 值变化^[29]。生物降解会导致正构烷烃和多环芳烃化合物缺失引起基线漂移,出现一个明显的由不可分辨化合物(unresolved complex mixture, UCM)组成的鼓包,孔二段页岩正构烷烃分布完整,无UCM鼓包^[30],表明样品未遭受生物降解(图5a, b),且样品热演化程度较低。这表明, TAR 值差异主要为生烃母质差异导致,可以有效指示页岩陆生与水生有机质的相对输入。

孔二段页岩 TAR 值分布范围较广(0.44 ~ 2.00),正构烷烃的分布具有明显差异。高 TAR 值样品,正构烷烃奇碳优势,主峰碳数为 nC_{23} — nC_{24} ,高碳数正构烷烃含量相对较高(图5a);低 TAR 值样品, nC_{13} — nC_{20} 正构烷烃奇偶优势不明显, nC_{22+} 正构烷烃呈现明显奇碳数优势,主峰碳数为 nC_{18} — nC_{19} (图5b)。纵向上,正构烷烃的分布规律与五级沉积旋回具有高度相关性,低 TAR 值位于五级层序每个水进旋回(T旋回)—水退旋回(R旋回)转换期,高 TAR 值则位于五级层序R—T旋回转换期(图6)。

3.4.2 生物标志化合物

生物标志化合物记录了生油母质生物骨架,是指示沉积环境与生烃母质的可靠手段^[31-32]。伽马蜡烷(Ga)指数($Ga/C_{30}H$)常用于表征高盐度沉积环境^[33]。沧东凹陷孔二段页岩伽马蜡烷发育(图5c),伽马蜡烷指数介于0.07 ~ 0.37,均值为0.22。

生烃母质方面,孔二段页岩饱和烃色谱—质谱总离子流图(TIC)普遍存在 C_{30} 藿烷为最高峰的特征

(图5e)。离子 m/z 191与 m/z 217质量色谱叠合图表明:孔二段页岩具有高 C_{30} 藿烷含量、低甾烷(S)含量的特征(图5f)。通常认为 C_{30} 藿烷主要来自于细菌,包括蓝细菌、异养细菌、甲烷营养菌和化学自养菌等,而甾烷主要来自藻类和高等植物。因此,甾烷/ C_{30} 藿烷($C_{30}H$)常用于指示有机质来源中藻类和陆源有机质与细菌的相对贡献^[34-35]。孔二段 $S/C_{30}H$ 值介于0.045 ~ 1.200,均值为0.420,指示了细菌对沉积有机质的强烈改造。这与显微镜下观察到大量矿物沥青基质反映的结果相吻合。

孔二段页岩中 C_{27} 、 C_{28} 和 C_{29} 规则甾烷中 C_{29} 规则甾烷占明显优势(图4d)。一般认为 C_{27} 和 C_{28} 甾烷主要来源于低等水生藻类^[36-37],而 C_{29} 甾烷既可来源于绿藻、也可来源于高等植物^[38-40]。干酪根元素与全岩光片显微组分分析表明,孔二段页岩有机质类型好且母质输入以水生生物为主,因此认为 C_{29} 规则甾烷可能存在绿藻的贡献。

3.4.3 单体化合物碳同位素特征

孔二段检出的藿烷类单体化合物碳同位素均偏轻,其中 C_{30} 藿烷碳同位素值为 -84.08‰ ~ -65.53‰ 。前人认为^[41-44]起源于化学自养菌的 C_{30} 藿烷碳同位素值为 -51.40‰ ~ -37.70‰ ,来源于甲烷营养菌的 C_{30} 藿烷碳同位素更加偏轻,碳同位素值为 -69.00‰ ~ -51.90‰ 。由于成熟度对同位素值的影响在2‰ ~ 3‰,推断孔二段藿烷化合物的形成与甲烷营养菌的活动有关。

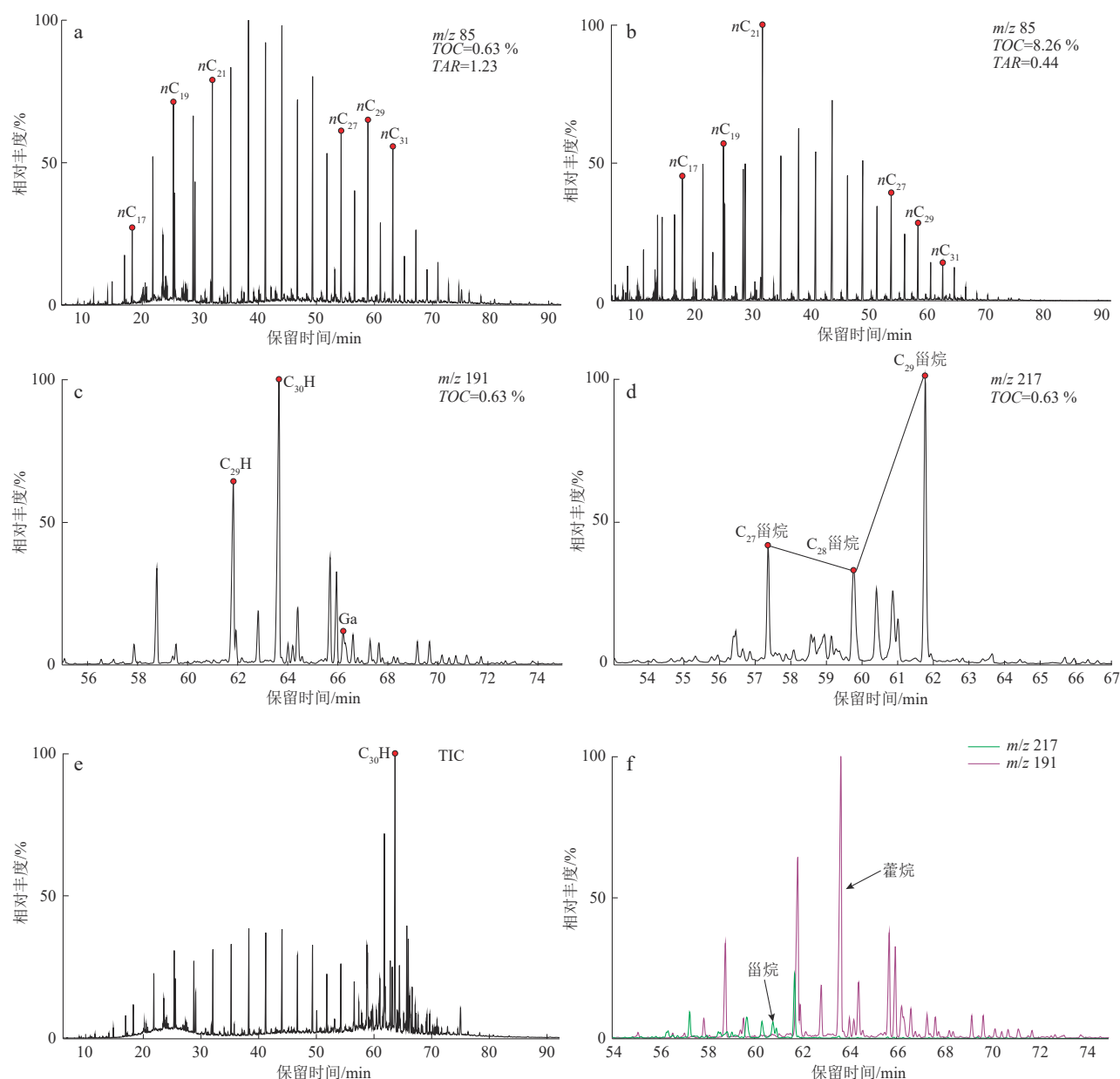


图5 沧东凹陷G108-8井孔二段页岩正构烷烃与生物标志化合物特征

Fig. 5 Characteristics of n-alkanes and biomarkers in shales in the Kong 2 Member in well G108-8 in the Cangdong Sag

a. 埋深3 020.09 m,页岩抽提物饱和和烃正构烷烃质量色谱图;b. 埋深3 162.57 m,页岩抽提物饱和和烃正构烷烃质量色谱图;c. 埋深3 020.09 m,页岩抽提物藿烷和伽马蜡烷质量色谱图;d. 埋深3 020.09 m,页岩抽提物甾烷质量色谱图;e. 埋深3 020.09 m,页岩抽提物饱和和烃色谱—质谱总离子流图(TIC);f. 埋深3 020.09 m,页岩抽提物饱和和烃藿烷与甾烷质量色谱叠合图

3.5 页岩元素地球化学特征

页岩元素地球化学保存了丰富的古环境信息,是分析有机质富集的重要手段之一,主量元素Al,Ti,Mn与微量元素V,U,Th,Sr,Ba,Cu,Zn,Zr在不同沉积环境中富集程度不同,可以作为恢复古沉积环境的参数^[45-46]。沧东凹陷孔二段页岩岩心样品X射线荧光光谱显示,常量元素Al,Ti和Mn元素含量分别为3.10%~8.10%,0.20%~0.50%和0.04%~0.20%;微量元

素V,Sr,Ba,Zr和Ni含量分别为 $(7.49 \sim 107.14) \times 10^{-6}$, $(189.85 \sim 2\,392.44) \times 10^{-6}$, $(172.26 \sim 673.03) \times 10^{-6}$, $(86.50 \sim 412.30) \times 10^{-6}$ 和 $(8.00 \sim 429.00) \times 10^{-6}$;营养元素Zn含量为 $(76.50 \sim 186.70) \times 10^{-6}$ 。盐度指标Sr/Ba元素含量比值介于0.45~5.25,均值为1.80;氧化还原指标V/(V+Ni)元素含量比值介于0.19~0.83,均值为0.56;陆源碎屑输入指标Ti/Al元素含量比值介于0.04~0.07,平均0.05;气候指标Sr/Cu元素含量比值介于1.80~12.10,平均6.10;古水深参数Zr/Al元素含量比值

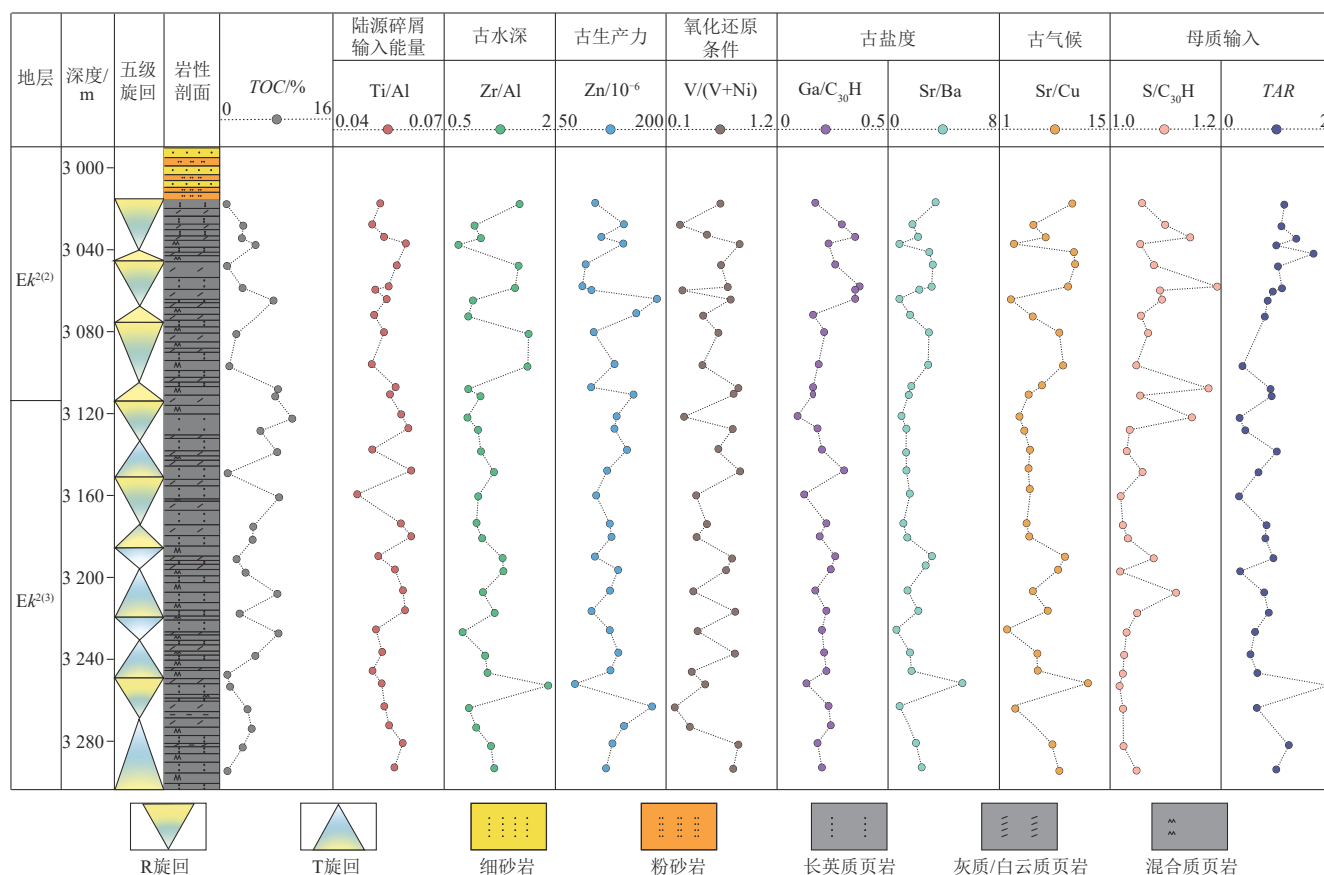


图6 沧东凹陷孔二段页岩微量元素指标与生物标志化合物参数纵向变化特征

Fig. 6 Vertical variations in the trace element indices and biomarker parameters of shales in the Kong 2 Member, Cangdong Sag

介于0.70~1.90,平均1.10(图6)。

纵向上地化参数与 TOC 在8个完整五级旋回上呈现规律性频繁的高一低变化。其中,营养元素 Zn 含量与 TOC 的变化趋势一致,水深参数 Zr/Al 、气候参数 Sr/Cu 、盐度参数 Sr/Ba 与 TOC 的变化趋势则完全相反。 T 旋回 TOC 增大, Cu 和 Zn 含量增高, Zr/Al 、 Sr/Cu 和 Sr/Ba 比值降低(图6)。

4 讨论

4.1 有机质富集影响因素

4.1.1 陆源碎屑输入与古生产力

陆源碎屑输入对有机质富集主要存在两个方面的影响:①陆源碎屑输入对有机质具有稀释作用;②陆源碎屑输入携带生物必要的营养物质,提高了湖盆的生产力进而促进生物勃发。 Ti 和 Al 两种元素可以有效反映沉积碎屑流入, Ti/Al 元素含量比值用于指示沉积物输入能量的大小与沉积物来自非铝硅酸盐来源的

程度^[47-50],且通常高的 Ti/Al 比值可能反映了沉积环境为沉积物提供了更高的运输能量^[51]。 Ti/Al 比值与 TOC 弱相关,表明了陆源碎屑输入对孔二段有机质的稀释作用影响有限(图7a)。

古生产力即为湖盆的初级生产力,是为生物繁衍提供能量、营养物质的能力。 Zn 元素被认为是主要的营养元素,是生物繁衍的物质基础,高 Zn 含量往往代表湖盆具有较高的初级生产力^[52-54]。孔二段页岩陆源碎屑长英质矿物含量与 Zn 元素相关性分析表明(图7f),湖盆的古生产力受陆源碎屑输入控制。陆源碎屑的输入为湖盆带来了丰富的营养元素,从而提高了湖盆的生产力,这为藻类等水生生物繁盛提供了物质基础,有利于有机质富集。

4.1.2 氧化还原条件

微量元素含量比值 $V/(V+Ni)$ 可以用于识别古氧化还原条件,当 $V/(V+Ni) < 0.45$ 时为富氧环境^[55-58]。孔二段 $V/(V+Ni)$ 平均0.56,指示其以贫氧还原环境为主。 TOC 与 $V/(V+Ni)$ 无相关性(图7b),且在氧化与还原条件下均存在高 TOC 样品,这表明氧化还原条件不是孔二

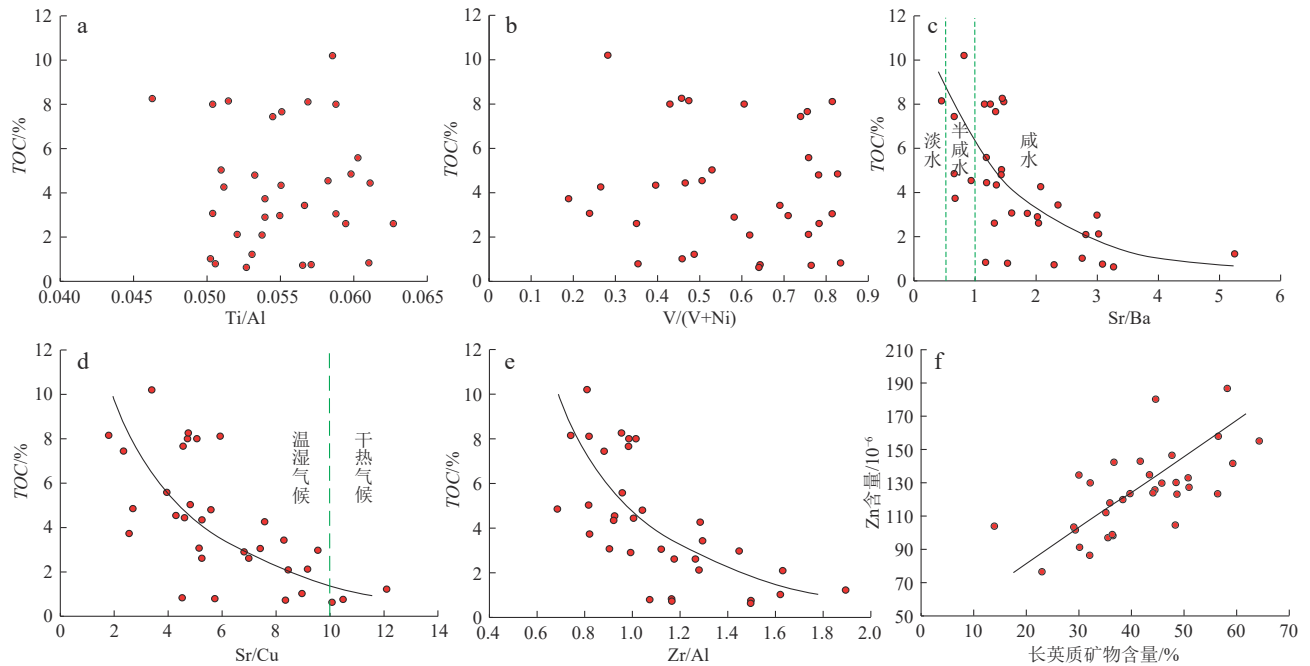


图7 沧东凹陷G108-8井孔二段页岩TOC与陆源碎屑输入(a)、氧化还原条件(b)、盐度(c)、古气候(d)、古水深(e)相关性及其长英质矿物含量与Zn元素含量关系(f)

Fig. 7 TOC content vs. terrigenous clastic input (a), redox conditions (c), salinity (d), paleoclimate (e), and paleo-water depth (f) and felsic mineral content vs. Zn content (b) for shales in the Kong 2 Member in well G108-8 in the Cangdong Sag

a. 埋深3 019 ~ 3 300 m, 陆源碎屑输入参数Ti/Al和TOC关系; b. 埋深3 019 ~ 3 300 m, 氧化还原参数V/(V+Ni)和TOC关系; c. 埋深3 019 ~ 3 300 m, 古盐度参数Sr/Ba和TOC关系; d. 埋深3 019 ~ 3 300 m, 古气候参数Sr/Cu和TOC关系; e. 埋深3 019 ~ 3 300 m, 古水深参数Zr/Al和TOC关系; f. 埋深3 019 ~ 3 300 m, 长英质矿物含量和Zn元素含量关系

段有机质富集的主控因素, 有机质富集受其他因素控制。

4.1.3 古盐度

伽马蜡烷含量与Sr/Ba元素含量比值可以表征页岩沉积环境中的分层水体, Sr/Ba比值小于0.6、介于0.6~1.0和大于1.0分别指示淡水、半咸水和咸水沉积环境^[59-60]。沧东凹陷孔二段页岩伽马蜡烷发育且样品Sr/Ba比值介于0.32~5.25, 仅有5个样品Sr/Ba比值介于0.60~1.00, 表明孔二段页岩为半咸水-咸水沉积环境。TOC与Sr/Ba比值呈现明显的负相关, 在淡水与半咸水条件下TOC较高(>4%), 随着湖水盐度升高TOC逐渐降低(图7c)。

4.1.4 古气候与古水深

沉积物中因古气候与水深变化, 不同微量元素丰度会出现迁移和富集, 因此微量元素含量及其比值是恢复古气候与水深的有效手段^[61-63]。Sr/Cu元素含量比值是重要的古气候判识参数之一, 当Sr/Cu比值介于1~10指示温湿气候, 大于10指示干热气候^[61]。Zr是典型的亲陆性元素, 通常存在于浅水沉积区域, 而Al

元素含量随着水深增加而增加, 因此Zr/Al元素含量比值增大, 指示水体变浅^[62-63]。

孔二段页岩Sr/Cu比值介于1.8~12.1, 平均为6.1, 表明孔二段沉积时期为温暖湿润气候, 半深水-深水沉积环境。TOC与古气候、古水深参数交会图表明(图7d,e), 温湿气候下, 湖水深度增加, TOC较高; 干旱气候下, 湖水深度降低, 页岩中TOC较低。因此, 古气候与古水深是孔二段有机质富集的主控因素, 且温湿气候、水体深度增加有利于有机质富集。

4.1.5 生烃母质构成

上述可知, 孔二段页岩有机质富集影响因素包括: 陆源碎屑输入、古生产力、古盐度、古气候与古水深。这些因素通过影响湖盆中菌藻类等水生生物的数量进而控制了有机质的富集。

水生、陆源有机质贡献比例不同, 其有机碳含量具有明显差异, 高有机碳含量页岩因具有较高的水生生物贡献而呈现出低TAR值的特征, 而随着水生有机质贡献降低, TAR值增大, 页岩有机碳含量降低(图8a)。温湿气候、深水环境下, 水动力条件充足, 丰富的地表水携带的营养元素注入湖泊提高了其生产力, 同时低

盐度水体有利于多种生物的繁衍,此地质背景下有利于形成高丰度有机质页岩(图8b,c)。随着气候干旱,水体深度降低,盐度升高,仅有少量的水生生物可以适应高盐度环境,不利于水生生物的繁衍,故页岩有机碳含量较低。

孔二段强烈的甲烷营养菌活动对有机质富集影响较小,但细菌对藻类、陆源有机质的再加工,提高了页岩H/C原子比(图8d)和“腐泥化”程度,改善了页岩的品质。这与前人总结的细菌微生物活动对生烃的认识^[64-66]相吻合,细菌类脂物成分代谢产物加入改变了有机质的结构使有机质热降解、脱官能团以及加氢生烃反应所需的活化能降低,这可能是孔二段页岩有机质类型好的原因之一。

4.2 有机质富集模式

在陆源碎屑输入、古生产力、古气候、古盐度等多种因素周期性变化的共同影响下,沧东凹陷孔二段页岩呈现出高TOC集中段与低TOC集中段交替变化的特征(图9)。五级层序尺度上不同沉积阶段地化参数

具有明显的差异,在T-R旋回转换期,地化参数呈现出低TAR、低Sr/Cu、低Zr/Al、低Sr/Ba和高Zn含量的特征(图9)。深水、低盐度、温湿环境和高生产力导致湖盆中水生生物大量繁衍,有机质含量高。与之相反,R-T旋回转换期,地化参数呈现出高TAR、高Sr/Cu、高Zr/Al、高Sr/Ba和低Zn含量的特征,此时页岩有机碳含量较低。这表明,高丰度有机质页岩主要形成于温湿气候、低盐度、较高水体深度、高生产力的T-R转换期。为此,总结出沧东凹陷孔二段五级沉积旋回T-R旋回转换期与R-T旋回转换期两种页岩有机质富集模式(图9b,c)。

T-R旋回转换期气候温湿,水动力条件强,充沛的陆源碎屑输入为湖盆带来Cu和Zn等营养物质,提高了湖盆生产力;较弱蒸发作用及充足的地表水、河流注入导致水体变深,盐度降低,湖盆中大量的菌藻类生物繁衍,此时页岩有机质含量较高,生烃母质中水生有机质比例升高(图9b)。R-T旋回转换期气候干热,水动力条件弱,陆源碎屑供给减少导致对湖盆营养物质输入减弱,降低了湖盆生产力,同时强烈的蒸发作用导致

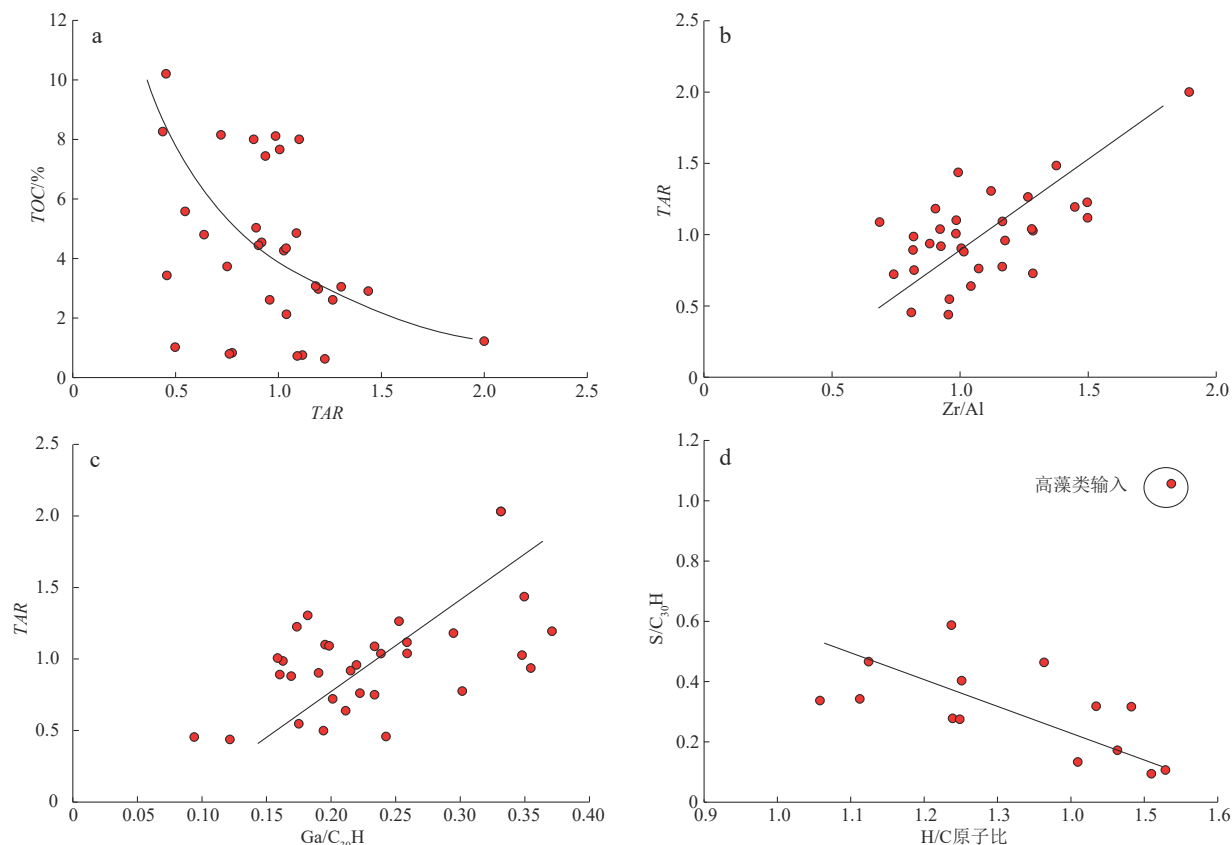


图8 沧东凹陷G108-8井孔二段页岩陆源/水生比参数TAR与TOC(a)、水深变化参数Zr/Al与TAR(b)、盐度参数Ga/C₃₀H(c)及干酪根C/H原子比与甾/藿比(S/C₃₀H)(d)关系

Fig. 8 TAR vs. TOC content (a), the Zr/Al ratio denoting water depth variation (b), and salinity parameter Ga/C₃₀H (c) and the H/C atomic ratio of kerogen vs. the sterane/hopane (S/C₃₀H) ratio (d) for shales in the Kong 2 Member in well G108-8 in the Cangdong Sag

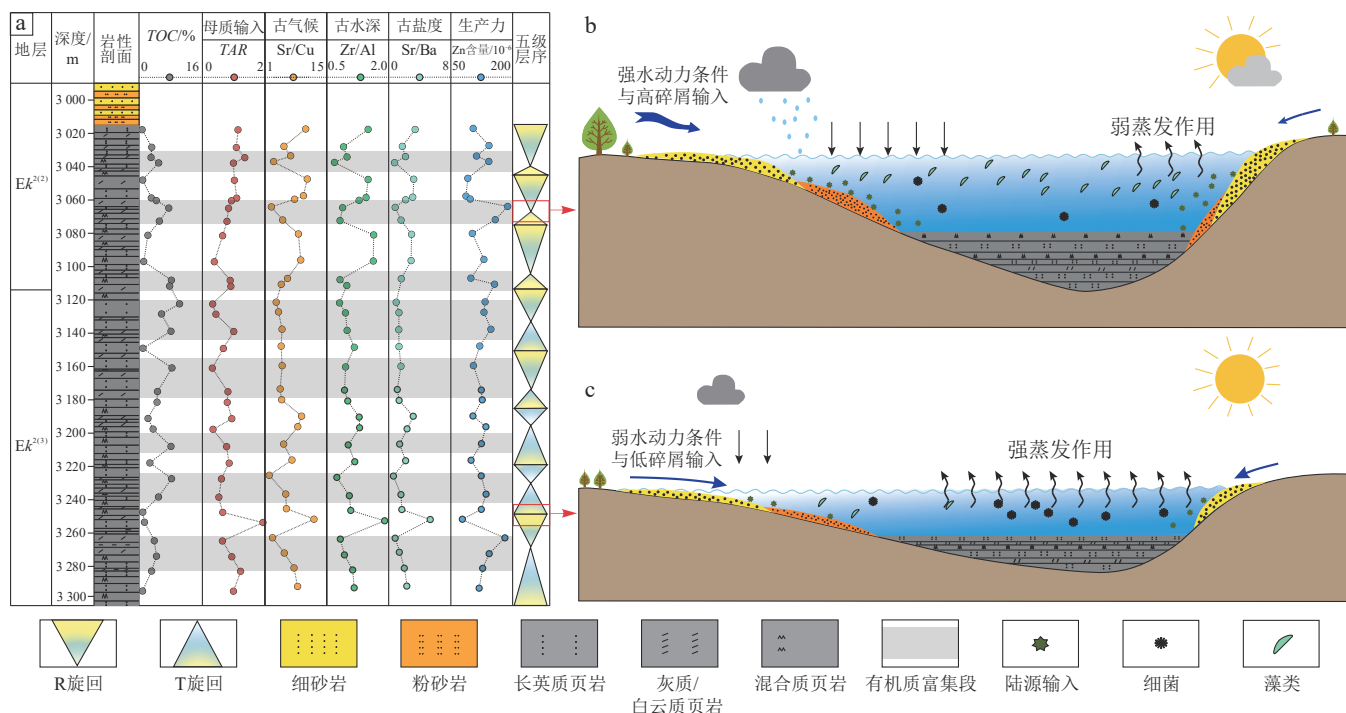


图9 沧东凹陷孔二段页岩有机质富集段纵向分布特征(a)、T-R旋回转换期页岩有机质富集模式(b)和R-T旋回转换期页岩有机质富集模式(c)

Fig. 9 Vertical distribution of organic matter enrichment horizons (a) and organic matter enrichment model during the T-R and R-T cycle transition periods (b, c) for shales in the Kong 2 Member within the Cangdong Sag

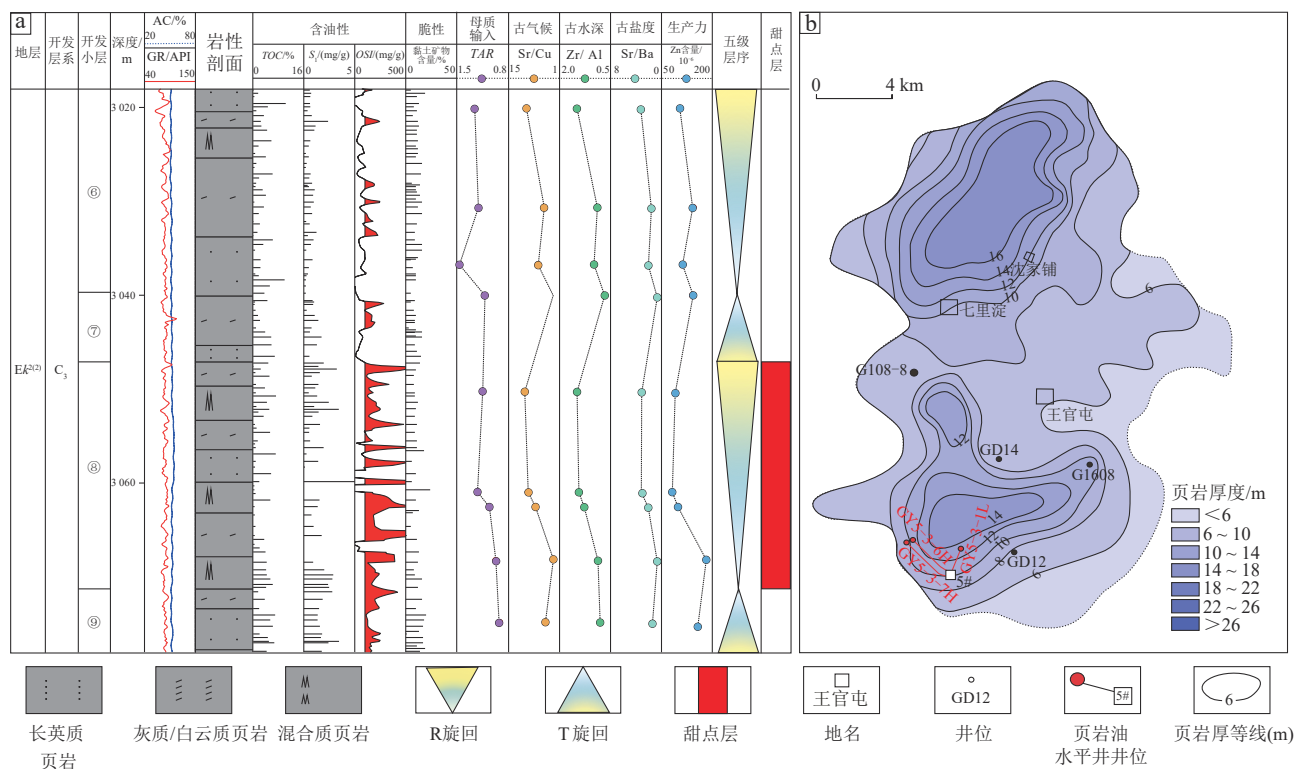


图10 沧东凹陷孔二段C₃页岩甜点层评价(a)与⑧号开发小层页岩厚度等值线图(b)

Fig. 10 Evaluation of shale sweet spots in layer C₃ (a) and isopach map of shales in sublayer ⑧ (b) in the Kong 2 Member within the Cangdong Sag

水体变浅,盐度升高,只有少量水生生物能适应高盐度环境,导致湖盆中菌藻类生物较少,此时页岩有机碳含量较低且生烃母质中陆源有机质比例升高(图9c)。

5 应用成效

孔二段页岩 TOC 是评价页岩甜点的关键指标之一。国内外已经证实, S_1/TOC (即可动油指数, OSI) 可反应页岩中滞留烃可动性的大小,在含油性评价中具有良好的应用效果。按照沧东凹陷古近系页岩甜点分类评价标准^[11],优选出 C_1 -②, C_2 -⑤, C_3 -⑧, C_4 -⑪, C_5 -⑬, C_6 -⑰和 C_7 -⑲7 个小层为 I 类甜点靶层。本研究以 C_3 开发层系为例,以 T-R 旋回转换期为主的⑧号小层页岩形成于温湿气候、低盐度和水体较深古环境条件, TOC 平均为 2.7%, S_1 为 3.7 mg/g, OSI 为 215 mg/g,且黏土矿物含量较低,是页岩油有利靶窗(图10a)。

沧东凹陷官东地区2021年对 C_3 -⑧号开发小层钻探的 GY5-3-1L 井(图10b),3 mm 油嘴直径测试单井峰值日产 56 t,目前稳定生产 962 d,稳产油 16 785 t。2022年在 GY5-3-1L 井取得良好勘探开发的基础上,钻探 GY5-3-6H 和 GY5-3-7H 两口页岩油水平井(图10b),3~4 mm 油嘴直径测试单井峰值日产 70.2~96.5 t,预测单井最终可采储量(EUR)可达 $(4.34 \sim 4.47) \times 10^4$ t。目前,官东5号平台投产的5口先导试验水平井已连续稳定生产 393~422 d,累产油达 7×10^4 t,并实现单井首年累产油平均超 1×10^4 t,达到了油价 50 美元/bbl 下的效益开发条件,展现了中国东部断陷盆地页岩油的良好发展前景。

6 结论

1) 沧东凹陷孔二段页岩有机质丰度高,干酪根以 I 型与 II₁ 型为主,生烃母质来源以菌藻类低等生物为主,同时存在部分陆源有机质输入。

2) 五级层序 T-R 转换期充沛的陆源碎屑输入提高了湖盆生产力;温湿气候和低盐度为菌藻类生物大量繁衍提供了良好的生存条件,是高丰度页岩有机质富集的主要部位。

3) 页岩有机质富集机理有效指导了官东地区孔二段5号平台页岩油水平井的部署,并取得了良好勘探效果,实现了油价 50 美元/bbl 下的效益开发,展现了孔二段良好的页岩油勘探前景。

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