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柴北缘鱼卡地区大煤沟组七段页岩岩相特征及沉积演化模式

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摘要:近年来,中国陆相盆地页岩油成为油气勘探开发的热点和难点。笔者以柴达木盆地北缘鱼卡地区中侏罗统大煤沟组七段为研究对象,通过岩心、普通薄片观察、有机地化、X衍射等实验,研究了大煤沟组七段的岩相特征、沉积演化模式,为优质烃源岩的发育分布提供理论依据。研究表明,该段共发育6种岩相,垂向上可划分为3个沉积阶段。阶段A为温湿气候下的三角洲前缘、浅湖环境,发育贫有机质块状黏土质、硅质泥岩相,强陆源输入导致水体富氧,使该阶段页岩油气潜力较差,TOC平均为0.79%;阶段B为构造沉降作用下半深湖-深湖环境,发育富有机质块状黏土质泥岩相,深湖还原环境为有机质提供了良好保存条件,使该阶段页岩油气潜力较高,TOC平均为4.16%;阶段C为干旱气候、构造沉降共同控制的半深湖-深湖环境,发育富有机质纹层状钙质、富黏土钙质、黏土质泥岩相,湖水咸化分层提供了良好的有机质保存条件,适应性藻类勃发提供了高生产力,使该阶段页岩油气潜力最高,TOC平均为5.03%。

关键词:页岩油;有机质富集;沉积演化模式;大煤沟组七段;柴达木盆地北缘

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Facies Characteristics and Sedimentary Evolution Model of the 7th Member of Dameigou Formation in Yuqia Area, North Qaidam Basin

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Abstract: In recent years, shale oil in continental basins of China has become a hotspot in oil and gas exploration and development. This paper studied the lithofacies characteristics and sedimentary evolution model of the 7th member of the Dameigou Formation in the Yuqia area, North Qaidam Basin. The results show that there are 6 lithofacies in this section, which can be divided into 3 sedimentary stages. Stage A is a delta front and shallow lake environment under a warm and humid climate, developing silty clay and silty claystone lithofacies with poor organic matter, leading to high water body oxygen content due to strong continental input, resulting in poor shale oil potential, TOC average is 0.79%; Stage B is a semi-deep lake-deep lake environment under tectonic subsidence, developing clayey shale lithofacies with rich organic matter, deep lake reduction environment provides good preservation conditions for organic matter, resulting in higher shale oil potential, TOC average is 4.16%; Stage C is a semi-deep lake-deep lake environment controlled by arid climate and tectonic subsidence, developing clayey shale lithofacies with rich organic matter, brackish water stratification provides good preservation conditions for organic matter, and the proliferation of adaptive algae provides high productivity, resulting in the highest shale oil potential, TOC average is 5.03%.

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ry evolution model of the 7th member of Dameigou formation of Middle Jurassic in Yuqia area, north Qaidam Basin by means of observation of core and thin section, organic geochemistry and X-ray diffraction experiments. It provided theoretical basis for the development and distribution of high-quality source rocks. The results show that there are six types of lithofacies, which can be divided into three sedimentary stages in the vertical direction. Stage A is the delta front and shallow lake sedimentary environment under warm and humid climate, which develops massive poor-organic clay and siliceous mudstone facies. Strong terrestrial input leads to the oxygen-rich water body with an average TOC of 0.79%. Therefore, shale oil and gas potential is poor at this stage. Stage B is a semi-deep to deep lake sedimentary environment under tectonic subsidence, which develops the massive rich organic clay mudstone facies. The deep-lake reducing environment provides good condition for the preservation of organic matter. A higher potential of oil and gas appears with an average TOC of 4.16%. Stage C is a semi-deep to deep lake sedimentary environment jointly controlled by arid climate and tectonic subsidence, which develops the laminar calcareous organic-rich matter, calcareous clay-rich and clayey mudstone facies. Good preservation conditions of organic matter by lake salinity stratification and high productivity of adaptive algae make stage C the highest shale oil and gas potential with an average TOC of 5.03%.

Keywords: shale oil; organic enrichment; sedimentary evolution model; the 7th member of Dameigou formation; north of Qaidam basin

世界油气行业已处于从常规油气向非常规油气转化的阶段。目前,页岩气已成为全球非常规天然气勘探开发的热点(邹才能等,2013),而页岩油则是未来非常规油气发展的主要接替类型之一(宋明水等,2019)。随着技术的发展及研究的深入,发现细粒沉积岩具有极强的非均质性(Wang et al., 2019, 2020),众多学者开始关注其沉积岩相学、沉积环境、有机质富集机理等内容(黄小青等,2020;侯啓东等, 2020;王宏语等,2018)。

中国陆相细粒沉积岩具有较大的生烃潜力(Lin et al., 2013)。近年来,已经对渤海湾盆地沙河街组(Li et al., 2020)、鄂尔多斯盆地延长组(Lin et al., 2013)、准格尔盆地芦草沟组(Zhang et al., 2019)、江汉盆地潜江组(Hou et al., 2017)等层位有了一定的认识。与海洋环境相比,湖泊形成的细粒沉积岩垂向演化快,对气候等环境因素的变化更为敏感(邓远,2020)。

柴达木盆地北缘(简称柴北缘)侏罗系发育,湖相泥页岩生烃条件良好(Jin et al., 2002;姚宏鑫等, 2017),2013年中国地质调查局在柴北缘鱼卡地区进行了柴页1井的钻探,在中侏罗统钻遇富有机质页岩,并划分出3个有利层段(王胜建等,2016;郭天旭等,2017),笔者针对大煤沟组七段,对其岩相特征和沉积演化模式进行了研究。

1 区域地质概况

柴达木中生界盆地起始于中三叠世零星分布的小型山间坳陷(图1),早侏罗世末期—中侏罗世,塔里木板块相对于柴达木板块大规模东移,区域扩张环境向挤压环境转变,柴北缘南部开始隆起,沉积中心移至鱼卡地区(高先志等,2003;王晓鹏等,2016)。

鱼卡凹陷位于柴北缘中部,区内地势西高东低,西侧为赛什腾山,北侧和东侧为达肯大坂山,南侧为绿梁山(图2),为一呈北西向展布的断陷(白悦悦等, 2020),在整个中侏罗世表现出早期断陷、后期凹陷的构造特征(李猛,2014),有效勘探面积约430 km²。

根据柴页1井岩屑录井资料,结合岩性和沉积环境,将大煤沟组划分为7个小段,其中一到三段沉积于早侏罗世,四到七段沉积于中侏罗世,以三角洲及湖泊环境下沉积的砂岩、泥页岩及煤层为主(Guo et al., 2018;郭天旭等,2018)。大煤沟组七段(1 900~1 990 m)为笔者研究层位,其顶、底部以沉积粉砂岩、泥岩互层为主,中部为一段厚48 m的碳质页岩,其上发育厚约8 m的油页岩(图3)。在整个柴北缘发育连续且稳定,以凹陷中心向四周减薄为特征,沉积厚度最大可达200 m(付小东等,2014)。

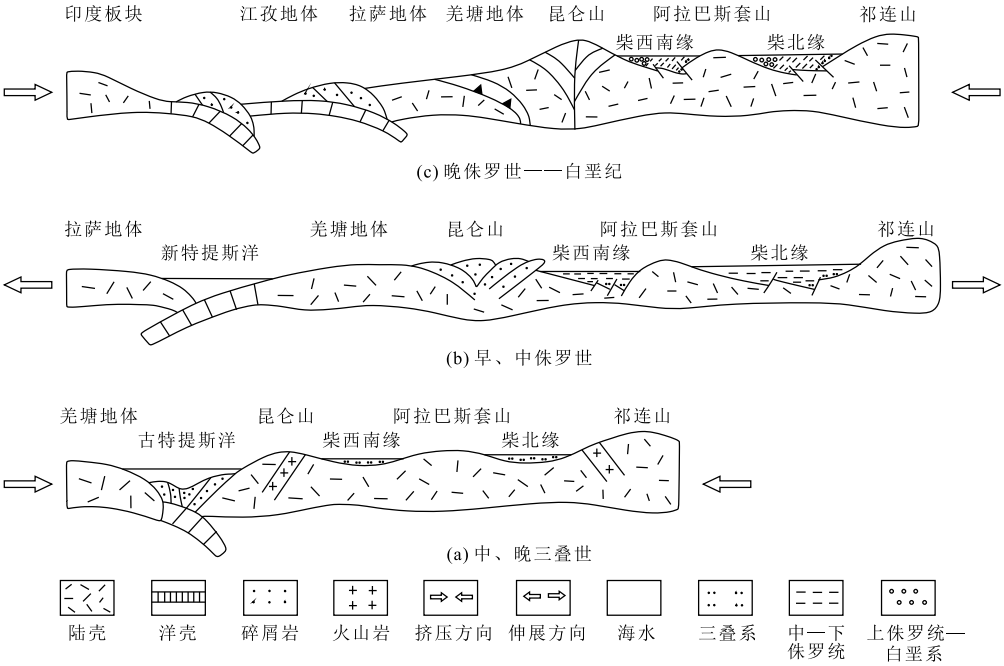


图 1 柴西及邻区中生界原型盆地演化示意剖面图(改自段宏亮等,2007)

Fig. 1 Schematic section of Mesozoic prototype basin evolution in the west of Qaidam basin and its adjacent area (Modified from Duan Hongliang et al. ,2007)

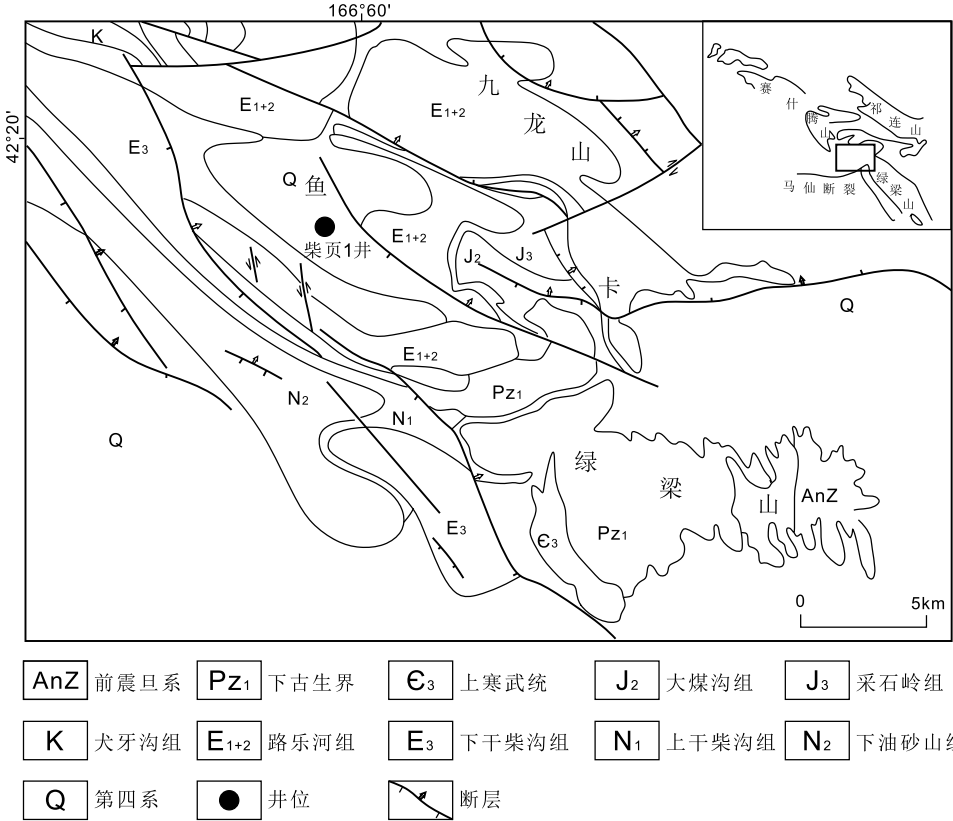


图 2 柴达木盆地北缘区域地质图(改自李浩涵等,2016)

Fig. 2 Regional geological map of the northern margin of Qaidam basin (Modified from Li Haohan et al. , 2016)

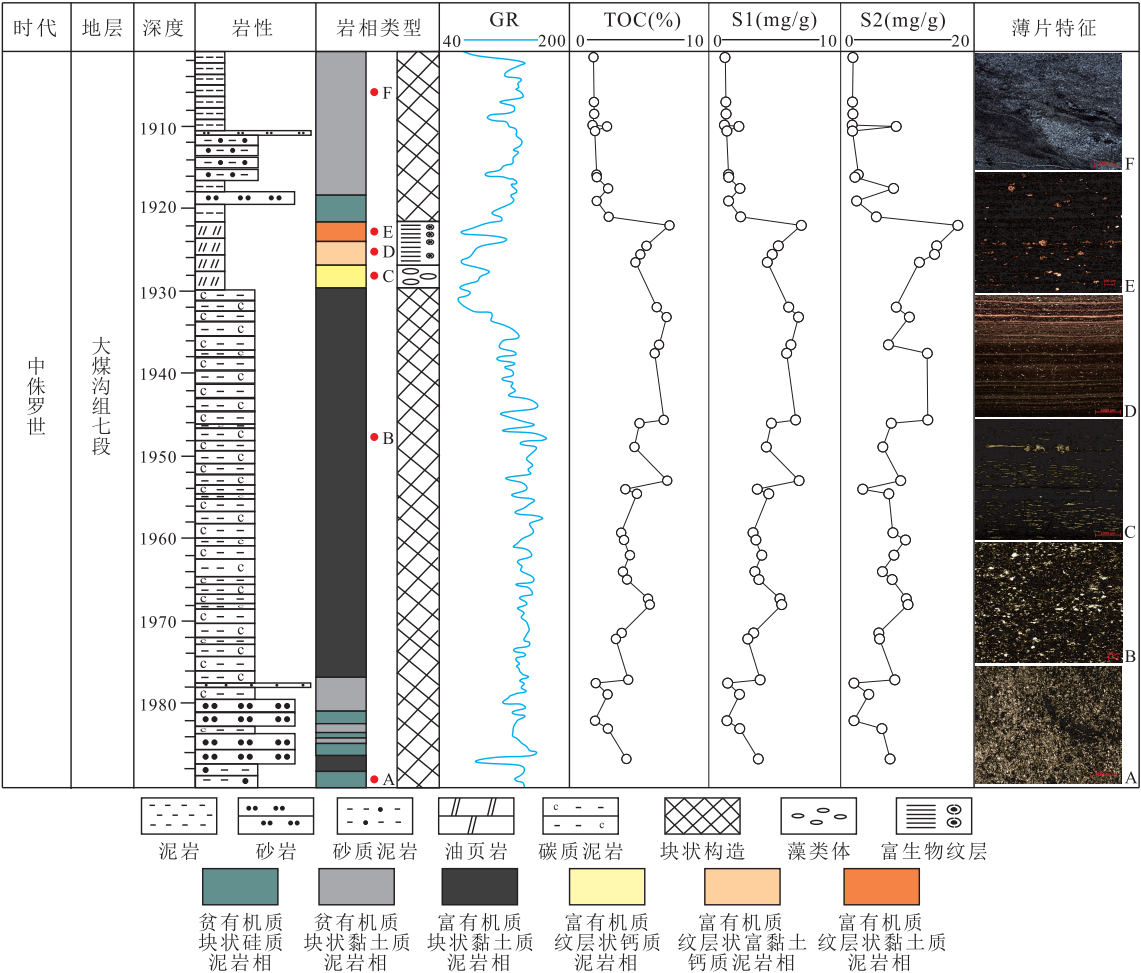


图 3 柴页 1 井柴达木北缘中侏罗统大煤沟组七段综合柱状图

Fig. 3 Comprehensive column chart of the 7th member of middle Jurassic Dameigou formation at the northern margin of Qaidam from Well CY1

2 样品及研究方法

在本次研究中,对柴页 1 井大煤沟组七段(1 900~1 990 m)连续取得岩心样 70 块,岩性包括粉砂岩、泥岩、碳质页岩和油页岩。其中 33 个样品岩心垂直于层理面切割为片状,用于制作普通薄片。利用 ZEISS Axio Imager. A2 显微镜观察薄片镜下特征。40 个样品研磨至 200 目以上,经酸洗、水洗、烘干后使用 LECO CS 400 碳硫分析仪测定样品总有机碳;使用 Rock-Rval II 分析仪进行热解实验,此部分实验在中国地质大学(武汉)构造与油气资源重点实验室完成。

对 70 个样品开展 XRD 实验,X 射线射入矿物中会发生衍射现象,而不同的矿物因为构造各异会产生

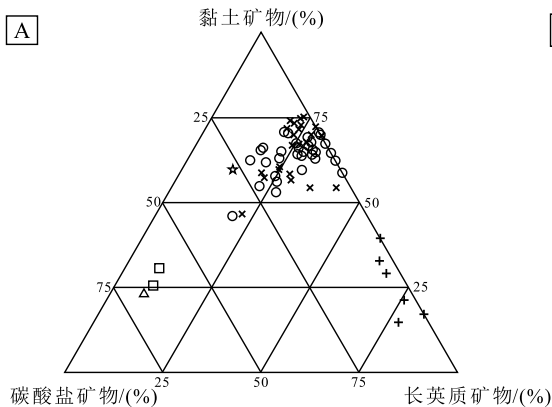
不同的衍射图谱,本次实验使用 PanalyticalX’Pert PRO MPD 仪(检测依据见 SY/T6201 - 2010)进行分析,在中国地质调查局油气资源调查中心完成。

3 岩相划分及特征

笔者综合样品有机质丰度、沉积构造特征和矿物学特征三方面对大煤沟组 7 段进行岩相划分(姜在兴等,2013)。根据有机质丰度划分为富有机质($TOC>2\%$)和贫有机质($TOC<2\%$)2 类;根据沉积构造特征划分为纹层状和块状 2 类。大煤沟组 7 段顶、底粉砂质泥岩长英质矿物含量高(图 3A、图 4A),划为硅质泥岩相;泥岩、碳质泥岩黏土矿物含量高(图 3B、图 3F、图 4A),划为黏土质泥岩相。油页岩较为特殊,出现钙质纹层和藻类体富集段(图

3C)、钙质纹层和黏土质纹层富集段(图 3D)、黏土质纹层和颗石藻富集段(图 3E)3 种不同特征,尽管样品数较少,依然划为 3 种岩相来讨论。综上所述,将大煤沟组七段共划分出 6 种岩相类型,分别为贫

有机质块状硅质泥岩相、贫有机质块状黏土质泥岩相、富有机质块状黏土质泥岩相、富有机质纹层状钙质泥岩、富有机质纹层状富黏土钙质泥岩相及富有机质纹层状黏土质泥岩相(图 4B)。



岩相类型	TOC(%)	沉积构造
+ 贫有机质块状硅质泥岩	<2	块状
x 贫有机质块状黏土质泥岩	>2	块状
o 富有机质块状黏土质泥岩	<2	块状
Δ 富有机质纹层状钙质泥岩	>2	纹层状
□ 富有机质纹层状富黏土钙质泥岩	>2	纹层状
★ 富有机质纹层状黏土质泥岩	>2	纹层状

图 4 (A)大煤沟组七段全岩矿物组成(B)大煤沟组七段岩相划分结果图

Fig. 4 (A)Mineral composition of the whole rock in the 7th member of Dameigou formation and (B)results of lithofacies division in the 7th member of Dameigou formation

3.1 贫有机质块状硅质泥岩相

该岩相分布于大煤沟组七段底部,呈灰色块状,岩心可见波状交错层理和虫迹(图 5A、图 5B),镜下可见晶型明显的石英颗粒,呈次棱角-次圆状,粒径 100 μ m 左右(图 5C)。XRD 结果为该岩相长英质矿物含量为 60.6%~82.9%,平均含量为 71.32%;黏土矿物含量为 14.7%~39.4%,平均含量为 25.73%;碳酸盐矿物含量为 0~7.7%,平均含量 2.95%(表 1)。该岩相 TOC 平均为 0.57%,S1+S2 为 0.33~7.54 mg/g,平均为 3.94 mg/g(图 3),干酪根类型主要为 II 2、III 型(图 6A),整体有机质含量低,生烃潜力弱。

3.2 贫有机质块状黏土质泥岩相

该岩相分布于大煤沟七段顶部与底部,呈灰黑色块状,岩心可见平行层理、交错层理及钙质团块产生的变形构造(图 5E),底部发现植物碳屑(图 5D)。镜下以长英质矿物和黏土矿物混合为特征,其中石英颗粒粒径约 20 μ m,晶形不明显(图 5F)。XRD 结果为该岩相黏土矿物含量为 46.5%~74.8%,平均含量为 65.44%;长英质矿物含量为 20.4%~42%,平均含量为 26.16%;碳酸盐矿物含量为 0~31.6%,平均含量为 8.40%(表 1)。该岩相 TOC 含量为 0.30%~3.28%,平均含量为 1.01%;S1+S2 为 0.02~10.59mg/g,平均为 3.05 mg/g(图 3),干酪根类型为II

2、III 型(图 6A),整体有机质含量低,生烃潜力弱。

3.3 富有机质块状黏土质泥岩相

该岩相分布于大煤沟七段中下部,为一段碳质页岩,岩心可见水平层理(图 5G),镜下以长英质矿物在富黏土基质中随机分布为特征,晶型不明显(图 5I)。XRD 结果为该岩相黏土矿物含量为 46%~70%,平均含量为 63.38%;长英质矿物含量为 46.1%~41.3%,平均含量为 26.94%;碳酸盐矿物含量为 0~34.3%,平均含量 9.68%(表 1)。该岩相 TOC 含量为 2.25%~6.53%,平均为 4.16%;S1+S2 为 1.94~13.92 mg/g,平均为 8.01 mg/g(图 3),干酪根类型为 II 1、II 2 型(图 6A),整体有机质含量高,生烃潜力强(图 7A)。

3.4 富有机质纹层状钙质泥岩

该岩相分布于大煤沟组七段油页岩段底部,镜下可见明显纹层,以隐晶碳酸盐纹层和黏土质纹层为主,界限清晰,有时呈微波状,同时可见大量透镜状藻类体顺层分布,透射光下呈现淡黄色-棕黄色,长轴约 100~500 μ m,方向平行于纹层(图 7C),局部发现磷灰石,具生物形态(图 7H),表明其丰富的生物含量(袁伟等,2016)。XRD 结果为该岩相碳酸盐矿物平均含量为 68.3%;黏土矿物平均含量为 24.6%;长英质矿物平均含量为 7.1%(表 1)。该岩相 TOC 平均为 3.88%;S1+S2 平均为 14.82 mg/g(图 3),干酪根类型

为Ⅱ1 型(图 6A),整体有机质含量高,生烃潜力强。

3.5 富有机质纹层状富黏土钙质泥岩相

该岩相分布于大煤沟组七段油页岩段中部,纹层特征明显,主要为水平纹层,界限清晰。以富有机质纹层、黏土质纹层和隐晶碳酸盐纹层互层为主(图 7D、图 7E)。其中隐晶碳酸盐纹层 5~40 μm 左右,

黏土质纹层和有机质纹层互层为 20~250 μm。XRD 结果为该岩相碳酸盐矿物平均含量为 62.65%;黏土矿物平均含量为 28.05%;长英质矿物平均含量为 9.30%(表 1)。该岩相 TOC 平均为 4.50%;S1+S2 平均为 17.94 mg/g(图 3),干酪根类型为Ⅱ1 型(图 6A),整体有机质含量高,生烃潜力强。

表 1 大煤沟组七段矿物含量变化表
Tab. 1 Change of mineral content in the 7th member of Dameigou formation

岩相(样数/个)	石英(%)	长石(%)	方解石(%)	白云石(%)	文石(%)	菱铁矿(%)	黏土矿物(%)
贫有机质块状 硅质泥岩相(6)	52.30~70.90 (61.9)	6.70~12.00 (9.42)	0~2.90 (0.48)	/	/	0~7.70 (2.47)	14.70~39.40 (25.73)
贫有机质块状 黏土质泥岩相(26)	17.20~40.30 (23.12)	0~7.40 (3.10)	0~12.20 (1.14)	/	/	0~20.50 (6.93)	46.50~74.80 (65.70)
富有机质块状 黏土质泥岩相(34)	16.10~26.70 (21.98)	0~14.60 (4.96)	0~17.30 (0.51)	/	/	0~23.00 (9.16)	46.00~70.70 (63.38)
富有机质纹层 状钙质泥岩(1)	7.10	/	5.40	0.00	57.40	5.50	24.60
富有机质纹层状 黏土质泥岩相(1)	11.30	1.70	27.40	/	/	0.00	59.60

注:最小值—最大值(平均值)。



A. 波状交错层理;B. 虫迹;C. 贫有机质块状硅质泥岩相;D. 植物碳屑;E. 钙质团块、变形构造;
F. 贫有机质块状黏土质泥岩相;G. 水平层理;H. 碳质页岩;I. 富有机质块状黏土质泥岩相

图 5 块状泥岩相岩心及薄片特征图

Fig. 5 Core and thin section characteristics of massive mudstone facies

3.6 富有机质纹层状黏土质泥岩相

该岩相分布于大煤沟组七段油页岩段顶部,纹层构造发育,主要为有机质纹层与黏土质纹层互层。其中,有机质纹层厚度 10 μm 左右,呈现红褐色,黏土质纹层为 20~200 μm,两者界限明显(图 7G)。同时可见大量微生物沿纹层分布(图 7F),从几微米到几十微米不等,呈现同心圆状,半圆状,多数粒径较小且聚

集在一起,少数粒径较大为单体存在,具十字消光现象(图 7G),与颗石藻特征相符(郝诒纯等,1993)。

XRD 结果为该岩相黏土矿物为平均含量为 59.60%;碳酸盐矿物平均含量为 27.40%;长英质矿物平均含量为 13.00%(表 1)。该岩相 TOC 平均为 6.72%;S1+S2 平均为 22.93 mg/g(图 3),干酪根类型为Ⅱ1 型(图 6A),整体有机质含量高,生烃潜力强。

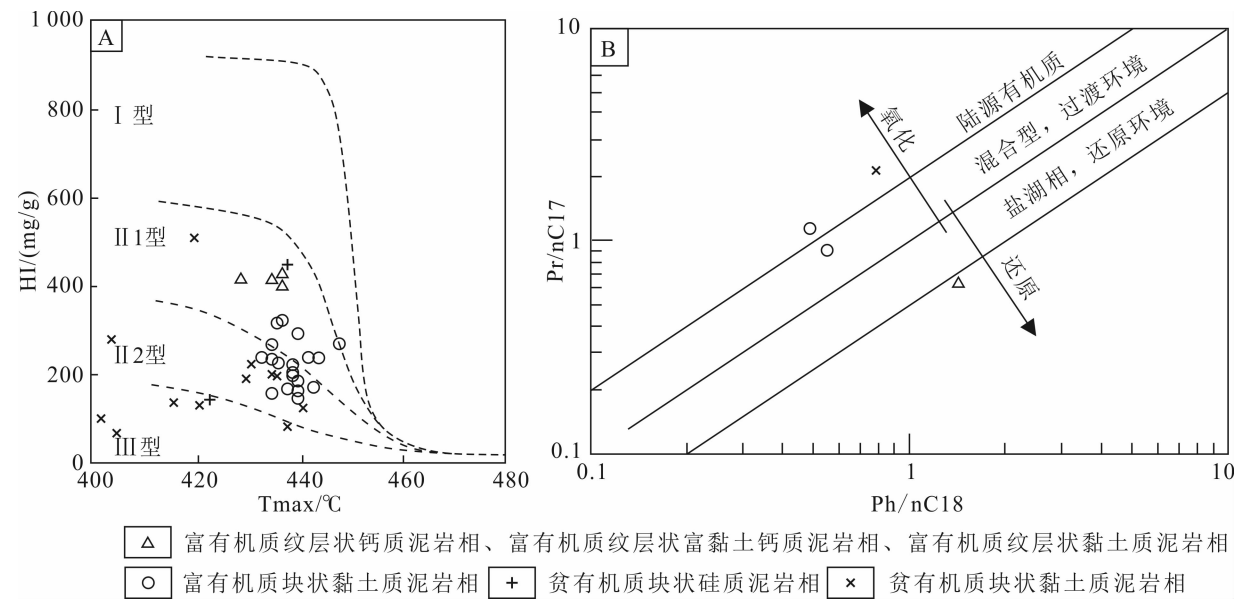


图 6 (A)大煤沟组七段各岩相母质类型图和(B)大煤沟组七段各岩相氧化还原条件图(改自 Qin et al., 2018)

Fig. 6 (A)Parent material types of each lithofacies in the 7th member of Dameigou formation and (B)The redox conditions of each lithofacies in the 7th member of Dameigou formation (Adapted from Qin et al., 2018)

4 讨论

4.1 古气候条件

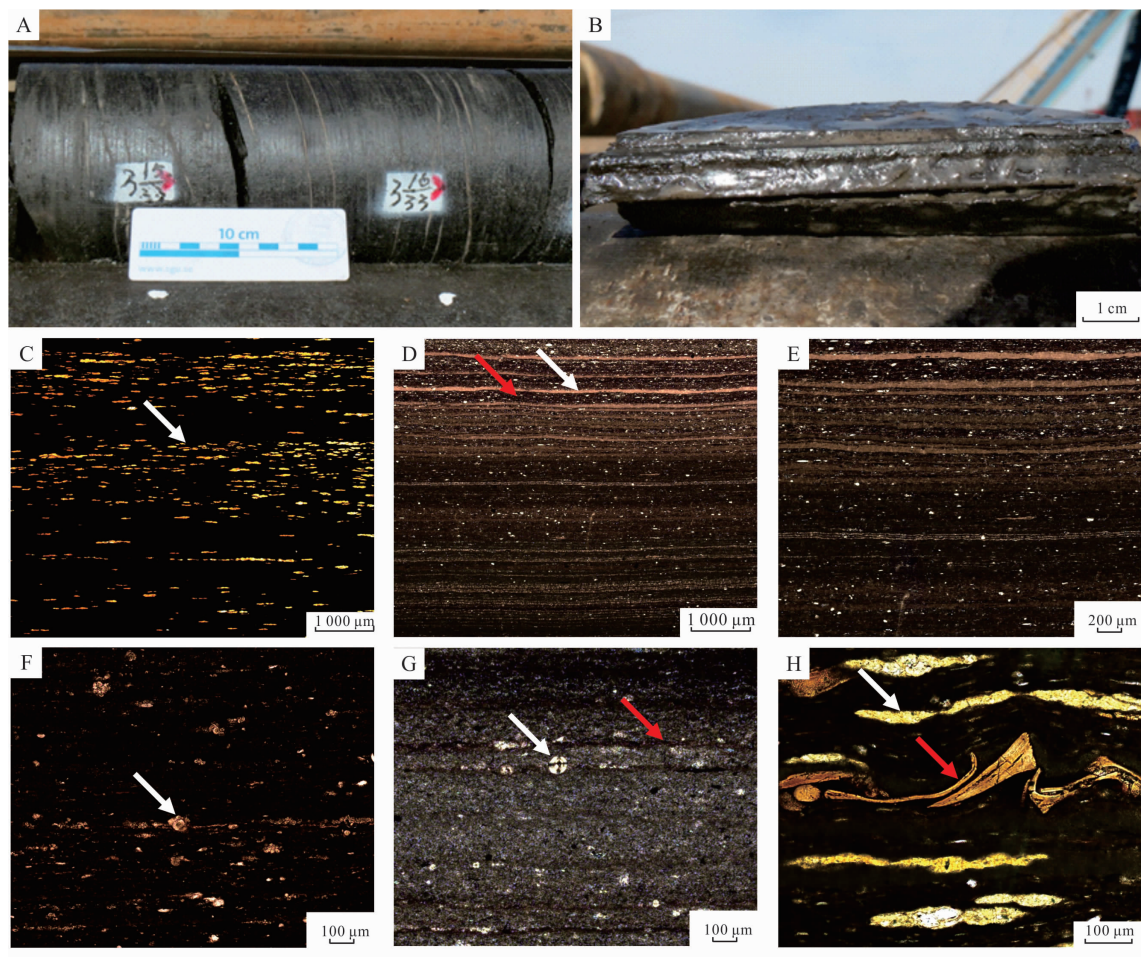
大煤沟组七段页岩厚度可达 56 m,下部主要为富有机质块状黏土质泥岩相(深度 1 930~1 978 m)(图 2),顶部主要为富有机质纹层状钙质、富黏土钙质、黏土质泥岩相(深度 1 922~1 930 m)(图 2)。其中顶部岩相碳酸盐矿物突然大量富集(表 1),纹层构造大量发育(图 7D、图 7E),在以往的陆相盆地研究中,隐晶质碳酸盐纹层对指示干旱气候有一定的意义,其与气候干湿指数相关性强,形成受干旱气候控制明显(王勇等,2017);也有研究者认为隐晶质碳酸盐纹层是夏季高温化学作用的产物(王慧中等,1998),属季节性纹层。另外,孙镇城等(2003)在中国西北和东北 15 处无争议的新生代—现代内陆咸

化湖泊沉积物中发现了 10 属颗石藻化石,均反应了干旱咸化的沉积环境。因此,研究区颗石藻(图 7F、图 7G)的出现也反应了这 3 个岩相沉积时气候条件的突变,即从温湿向干旱的转换。

4.2 沉积演化模式

鄂尔多斯盆地三叠系延长组长 7 段是中国陆相非常规油气代表性层位,现已发现 10×10⁸ t 级源内非常规庆城大油田(付金华等,2020)。长 7 段细粒岩沉积时气候湿润,以淡水还原环境为主,现阶段研究认为其高生产力主要来自火山喷发和热液活动所引起的“肥沃效应”,深湖还原环境则提供了保存条件(蕙克来等,2020)。因此,沉积了一套广泛分布的优质烃源岩。

大煤沟组七段沉积演化不同于此,其经历了从淡水向咸水环境的转换,且在湖水最咸时有机质丰度最高,这说明一定的咸水条件并不会完全促使所



A. 油页岩; B. 油页岩; C. 藻类体(白色箭头); D. 隐晶质碳酸盐纹层(白色箭头)、富有机质黏土纹层(红色箭头);
E. 纹层构造; F. 颗石藻(白色箭头); G. 颗石藻十字消光(白色箭头)、有机质纹层(红色箭头);
H. 藻类体(白色箭头)、磷灰石(红色箭头)

图7 纹层状泥岩相岩心及薄片特征图

Fig. 7 Core and thin section characteristics of laminated mudstone facies

有生物死亡,个别适应性强的物种在获得了更大的生存空间后反而会发生“勃发”现象(江继纲等,2004),而在生产力高的基础上,构造沉降、水体咸化分层又提供了良好的保存条件(金强等,2008),最终形成一套优质烃源岩。现将大煤沟组七段沉积过程划分为3个阶段进行讨论。

阶段A沉积时期,发育贫有机质块状黏土质、硅质泥岩相。Ⅱ2、Ⅲ型干酪根类型指示有机质主要来源于陆源高等植物(图6A),生标参数指示为氧化环境(图6B)。波状交错层理、变形层理、虫迹、植物碳屑等现象(图5A~图5F)表明其沉积时水动力扰动强,水体较浅,以三角洲前缘、浅湖环境为主。该阶段沉积时气候温暖潮湿,陆源输入丰富,河流携带

着丰富的溶解氧一同进入湖泊,通过水体循环使湖水处于富氧环境,有机质被大量氧化,无法保存,因此,TOC含量低,生烃潜力弱(图8)。

阶段B沉积时期,发育富有机质块状黏土质泥岩相,Ⅱ1、Ⅱ2型干酪根类型指示有机质来源既有陆源高等植物又有浮游生物(图6A),生标参数指示为过渡环境(图6B),可见水平层理发育(图5G),指示低能环境下的悬浮沉积。该阶段沉积时气候保持温湿,但在鱼卡地区整体断陷、凹陷的控制下,湖盆沉降,湖水加深,沉积环境向半深湖-深湖环境转换。此时陆源输入减弱,湖底氧气被消耗完且得不到补充,形成静水还原环境,改善了有机质的保存条件。因此,TOC含量高,生烃潜力强(图8)。

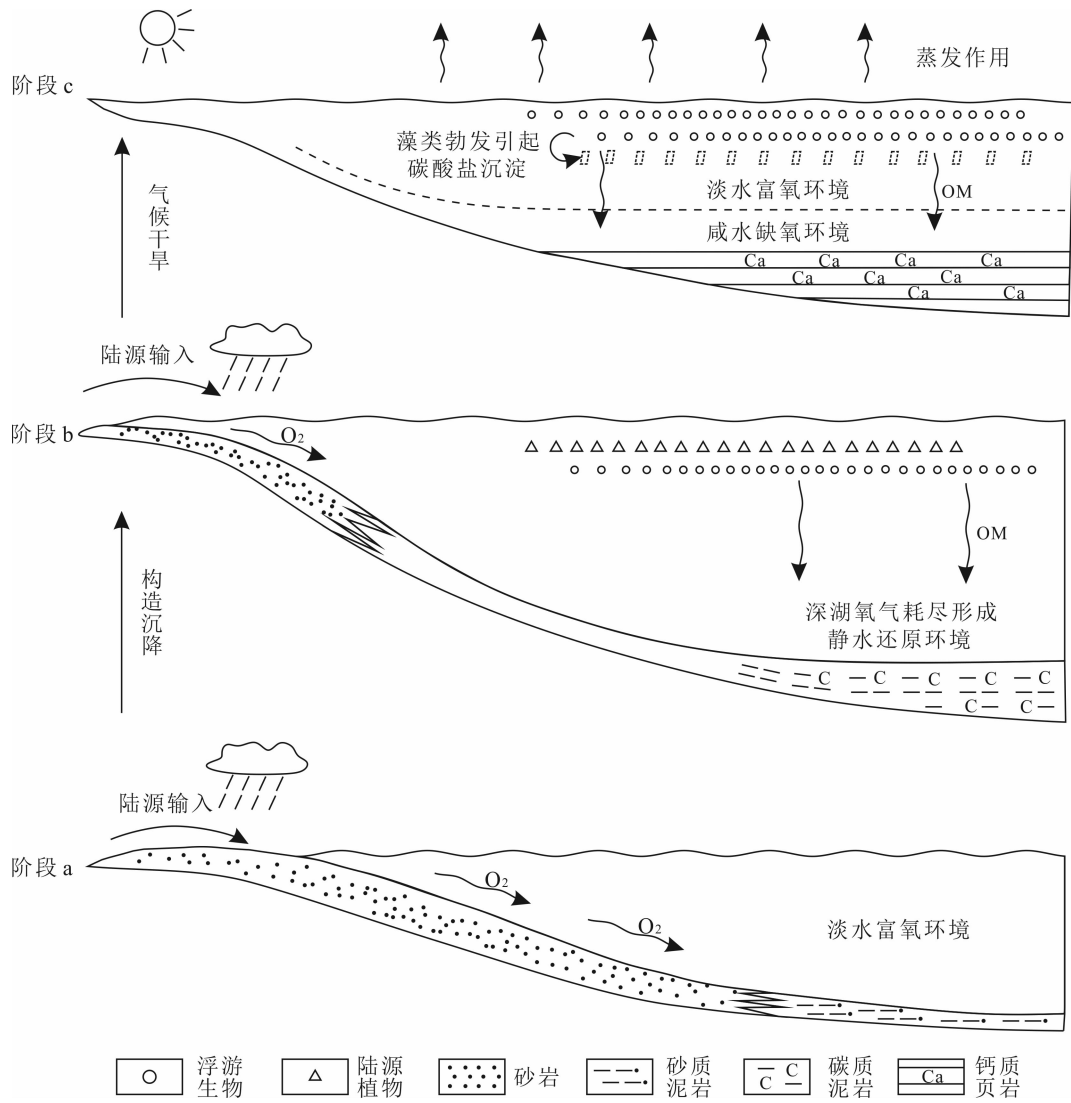


图 8 大煤沟组七段沉积演化模式图

Fig. 8 Sedimentary evolution model of the 7th member of Dameigou formation

阶段 C 沉积时期,发育富有机质纹层状钙质、富黏土钙质、黏土质泥岩相。Ⅱ 1 型干酪根类型指示有机质主要来源于浮游生物(图 6A),生标参数指示为还原环境(图 6B)。该阶段沉积时气候干旱,水体变咸,咸化湖泊会在重力作用下形成上下分层(金强等,2008)。其中,上层为含盐量低、富含藻类、生产力较高的淡水水体(颗石藻、藻类体及生屑磷灰石的发现都说明了此时的高生产力),下层为含盐量高的缺氧还原环境水体,具有良好的保存条件,有机质在上层形成后悬浮沉积到下层且不会被氧气消耗掉,对于烃源岩来说是非常好的保存环境。因此,TOC 含量最高,生烃潜力最强(图 8)。

5 结论

- (1)利用沉积构造特征、总有机碳和矿物组成将大煤沟组七段泥岩划分为 6 种岩相:包括贫有机质块状硅质泥岩相、贫有机质块状黏土质泥岩相、富有机质块状黏土质泥岩相、富有机质纹层状钙质泥岩、富有机质纹层状富黏土钙质泥岩相和富有机质纹层状黏土质泥岩相。
- (2)大煤沟组七段可划分为 3 个沉积阶段,其中阶段 A 沉积于温湿气候,陆源输入稳定,多以粉砂岩和粉砂质泥岩互层为主;阶段 B 沉积时受构造沉降影响,湖水变深,陆源输入逐渐减弱,沉积了一套

碳质泥岩,具有较高的生烃潜力;阶段 C 则沉积于干旱气候,此时湖水咸化分层,沉积了一套油页岩,纹层发育,生烃潜力最高。

(3)不同气候-构造条件形成不同性质的湖盆,进而控制优质烃源岩的发育分布,干旱气候引起的“藻类勃发”可以带来丰富的生产力,而水体咸化分层和构造沉降形成的深水还原环境则为大煤沟组七段有机质保存提供了最有利条件。

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