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渝西大足地区下志留统龙马溪组深层页岩气储层 差异性成因

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摘要:渝西大足地区龙马溪组富有机质深层页岩气储层非均质性强,制约了该区龙马溪组页岩气的高效勘探开发。利用三维地震恢复大足地区早志留世龙马溪期古地貌格局,结合岩相学与矿物学资料、有机及无机地球化学资料、井震资料及储层表征成果,研究不同古地貌单元下龙马溪组沉积环境、物质组成与储层差异性,并探讨其成因机制。结果表明:①研究区龙马溪组沉积期古地貌呈北高南低阶梯状格局,自北向南依次发育陆棚高地、陆棚斜坡和陆棚洼地,沉积水体还原性与古盐度向南逐渐增高;②页岩储层物质组成与次级古地貌单元具有明显协变关系,生物成因石英含量与总有机碳(TOC)含量向南递增,黏土矿物与陆源碎屑含量向南递减,陆棚洼地高生产力与良好保存条件利于有机质富集,长石蚀变等成岩作用控制矿物组成空间分布;③矿物组成与有机质含量的空间差异进一步控制储层特征,陆棚斜坡孔隙度最高,以晶间孔与有机质孔为主;陆棚高地孔隙度次之,以粒间孔与粒内孔为主;陆棚洼地孔隙度最低,与有机质孔径较小、生物成因石英充填粒间孔有关;④经定量反演与实测数据约束,I类页岩气储层厚度自陆棚高地至陆棚洼地逐渐增大,与沉积环境变化具有明显成因联系。古地貌控制的沉积环境差异是造成页岩气储层强烈非均质性的根本原因,研究成果可为非均质页岩气储层高效勘探开发提供依据。

关键词:大足区块;龙马溪组;深层页岩气;储层差异;储层成因;古地貌格局

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Genesis of heterogeneity in deep shale gas reservoirs of Lower Silurian Longmaxi Formation, Dazu block, western Chongqing

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Abstract: The organic-rich deep shale gas reservoirs of the Longmaxi Formation in the Dazu area of western Chongqing exhibit pronounced heterogeneity, which constrains the efficient exploration and development of the Longmaxi Formation shale gas in this region. Three-dimensional seismic data were used to reconstruct the paleogeomorphic pattern of the Early Silurian Longmaxi period in the Dazu area. Combined with lithological and mineralogical data, organic and inorganic geochemical data, well logging-seismic data, and reservoir characterization results, the sedimentary environment, material composition, and reservoir heterogeneity of the Longmaxi Formation under different paleogeomorphic units were investigated, and their genetic mechanisms were explored. The results indicated that: (1) The paleogeomorphology during the deposition of the Longmaxi Formation in the study area showed a step-like pattern, with higher elevations in the north and lower in the south. From north to south, shelf highlands, shelf slopes, and shelf depressions were developed sequentially, and

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the redox conditions and paleosalinity of the sedimentary water body gradually increased southward. (2) The material composition of shale reservoirs showed a clear co-variation relationship with the secondary paleogeomorphic units. The biogenic quartz content and total organic carbon (TOC) content increased southward, while the clay mineral and terrigenous clastic contents decreased southward. High productivity and good preservation conditions in the shelf depressions favored organic matter enrichment, and diagenetic processes such as feldspar alteration controlled the spatial distribution of mineral composition. (3) The spatial variations in mineral composition and organic matter content further controlled the reservoir characteristics. The porosity of the continental shelf slope was the highest, dominated by intercrystalline pores and organic pores. The porosity of the continental shelf highlands was the second highest, primarily consisting of intergranular and intragranular pores. The porosity of the continental shelf depression was the lowest, which was associated with the small size of organic pores and the filling of intergranular pores by biogenic quartz. (4) Constrained by quantitative inversion and measured data, the thickness of type I shale gas reservoirs gradually increased from the continental shelf highlands to the continental shelf depressions, showing a significant genetic connection with the changes in the sedimentary environment. The differences in sedimentary environment controlled by paleogeomorphology are the fundamental cause of the strong heterogeneity of shale gas reservoirs. The research findings can provide a basis for the efficient exploration and development of heterogeneous shale gas reservoirs.

Keywords: Dazu block; Longmaxi Formation; deep shale gas; reservoir heterogeneity; reservoir genesis; paleogeomorphic pattern

随着世界能源格局的不断变化,加大非常规油气资源的勘探开发有利于保障中国能源安全^[1]。页岩气作为非常规油气资源之一,近年来勘探重点不断向深层(埋深3 500~4 500 m)一超深层(埋深>4 500 m)领域拓展^[2]。目前,对于深层一超深层页岩气的研究主要集中在沉积环境^[3]、储层特征^[4-6]、微裂隙展布^[7-10]、成藏富集规律^[11-13]等方面,深化了对页岩气富集机制及有利区发育主控因素的认识^[14]。然而,深层一超深层页岩气储层经历了漫长且复杂的埋藏历史,其储层特征受控于沉积环境、成岩演化和后期构造作用等因素共同影响,导致其具有强烈的非均质性,显著降低了页岩气勘探开发效率^[15]。因此,深入理解深层一超深层页岩气储层差异性成因,有助于准确刻画高效储层分布规律,大幅度提升深层一超深层页岩气开发效率。

四川盆地及其周缘发育上奥陶统五峰组一下志留统龙马溪组,具有含气量高、产出周期短、勘探成本低的特点,已成为页岩气勘探开发的主要层位^[3]。位于五峰组一龙马溪组沉积中心的川南长宁、威远、泸州等地,因其沉积厚度大、有机质含量高、有机质类型好、有机质成熟度高,以及页岩储层孔喉结构有利等因素,早已实现规模性商业开发^[16]。然而,长宁、威远等区域的龙马溪组深层页岩储层仍存在显著非均质性。研究表明,川南龙马溪组页岩储层差异主要受古地貌格局控制,古地貌格局与龙马溪组页岩岩相存在成因耦合^[17-18],古地貌单元控制着优质黑色页岩厚度^[19],其中发育于古地貌低洼区的页岩储层品质最优^[20]。渝西大足区块作为四川盆地深层页岩气勘探的重点区域,龙马溪组优质页岩埋深介于4 050~4 400 m,厚度达40~70 m,总有机碳(TOC)含量介于1.3%~5.6%,孔隙度介于2.7%~6.9%,含气量介于2.5~8.0 m³/t,脆性指数介于40.9%~98.6%^[21-23],具备良好的页岩气资源前景。但该区龙马溪组页岩储层差异性成因认识不足,制约了高效开发,导致不同地区、深度探井

产量差异显著^[24]。本研究利用三维地震恢复渝西大足地区龙马溪组古地貌格局,结合井震资料反演优质页岩储层厚度展布特征,通过X射线衍射、有机及无机地球化学分析,明确沉积环境、矿物学特征及有机质类型对古地貌格局的响应;借助扫描电镜与核磁共振技术,揭示不同古地貌单元下页岩储层孔隙结构差异,阐明龙马溪组深层页岩气储层非均质性成因,以期为该区页岩气高效勘探开发提供地质依据。

1 区域地质背景

渝西地区位于川中平缓褶皱带、川东高陡褶皱带与川南低陡褶皱带交叉区块(图1a)。晚奥陶世时期,川中、黔中、雪峰古隆起和康滇古陆受构造抬升露出海平面,导致扬子地台发生大规模海退事件。在此背景下,四川盆地由原本开放的海洋环境转变为半封闭的局限陆棚环境^[25-27]。这种特殊的古地理格局造就了水体垂向分层显著,形成大范围的贫氧还原环境^[28-29]。伴随着全球性海退事件,五峰组顶部观音桥段广泛发育灰质泥页岩和泥质灰岩^[26]。至早志留世初期,受晚奥陶世赫南特冰期消融驱动,全球海平面快速上升,引发扬子地区大规模海侵。该时期龙马溪组底部沉积环境发生显著转变,形成深水陆棚相富笔石泥页岩,发育水平层理^[30]。之后,海平面波动式下降,沉积环境由深水陆棚过渡至半深水-浅水陆棚环境^[31]。在此期间,四川盆地周缘发生多期次的强烈火山活动,沉积了大量的斑脱岩^[32]。

大足区块作为渝西深层页岩气主力勘探目标,自东向西依次发育西温泉背斜、蒲吕场向斜、西山背斜和弥陀场向斜构造。其中,西山背斜相对较陡,西温泉背斜狭窄,蒲吕场向斜地层平缓(图1a)。五峰组上覆于临湘组泥质灰岩,主要岩性为碳质页岩及碳质硅质页岩;其上覆

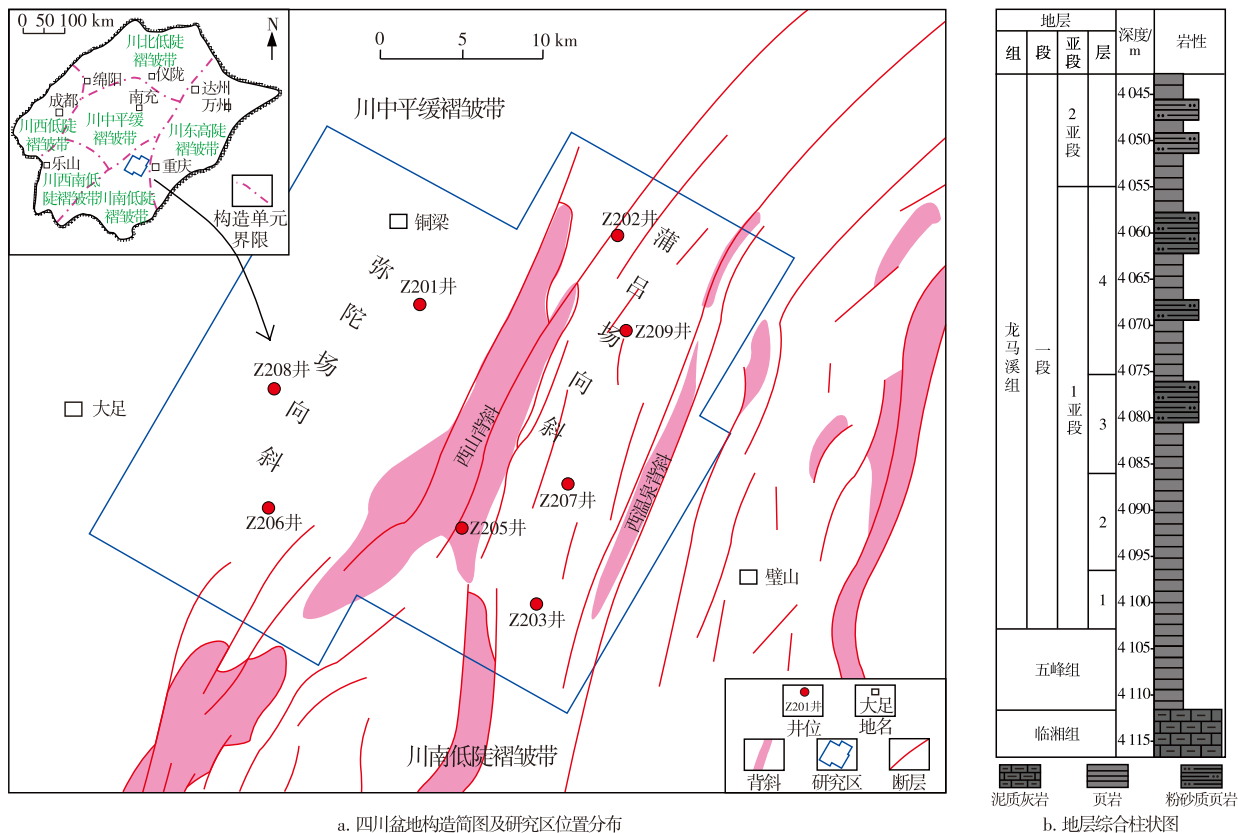


图1 研究区构造位置及地层柱状图(据文献[33-34]修改)

Fig. 1 Structural location and stratigraphic column of study area (modified from references [33-34])

龙马溪组厚度介于200~530 m,岩性自下而上呈现粉砂质含量递增趋势,主要发育碳质硅质页岩、碳质黏土质页岩及黏土质硅质页岩(图1b)^[15, 34]。龙马溪组可划分为两段,下部龙一段依据高精度层序地层学可进一步划分为两个亚段^[11-15, 35-36]。其中,底部龙一₁亚段依据古生物等特征可进一步细分为龙一₁¹至龙一₁⁴共4个小层(简称为1小层、2小层、3小层、4小层)(图1b)^[37-38]。1—3小层为研究区页岩气开发的核心层系,具有显著沉积与储集优势,岩性以黑灰色、黑色薄层状页岩或粉砂质页岩为主,纹层发育,厚度介于6~12 m;4小层厚度最大,达38~55 m(图1b)。龙一₁亚段是大足地区深层页岩气勘探开发的主力层段,各小层岩相特征差异显著。1小层黄铁矿发育,硅质含量高(图2a);1—3小层均发育笔石,碳质含量高(图2b、图2c),而4小层常见泥砾,碎屑含量高(图2d)。高碳硅质页岩发育泥纹层(图2e);中碳硅质页岩粉砂纹层和泥纹层均发育(图2f、图2g),石英或碳酸盐矿物是组成粉砂纹层的主要成分;低碳-特低碳黏土质页岩偶见不连续纹层或泥质条带(图2h)。扫描电镜下可见草莓状黄铁矿分布(图2i)。

2 样品采集与分析方法

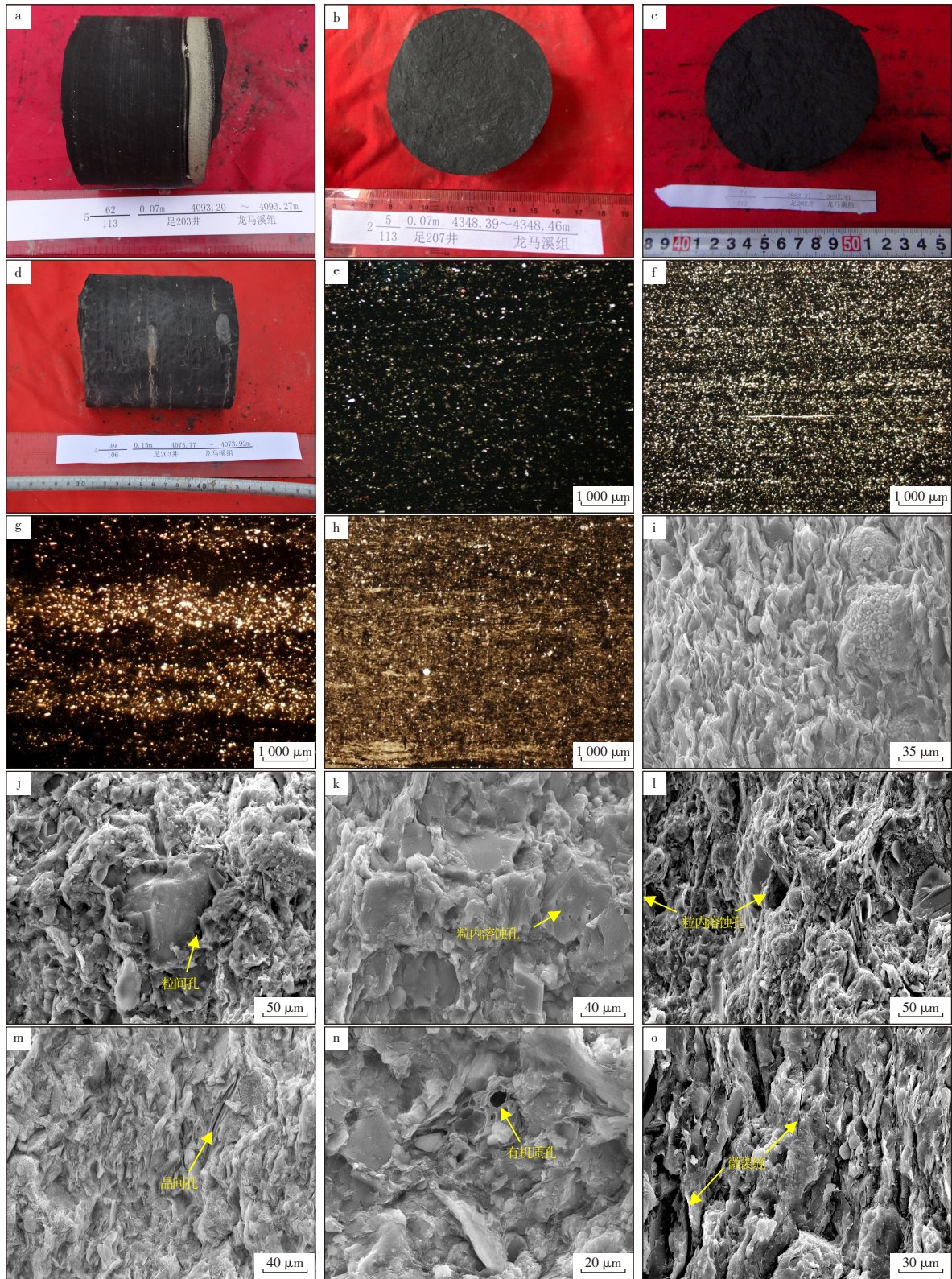
本研究采集渝西大足区7口钻井的龙马溪组黑色页

岩样品(钻井分布见图1a),开展总有机碳(TOC)含量、孔隙度、微量元素、全岩矿物X衍射(XRD)、扫描电镜(SEM)观察等实验分析。所有实验均在中国石油西南油气田公司勘探开发研究院分析实验中心完成。其中,TOC测试采用CS-230型碳硫测定仪,孔隙度测定使用全径柱塞岩心孔隙度测定仪,微量元素分析利用Nex ION 350X电感耦合等离子体质谱仪,XRD分析采用PhillipsXpert-MPD型X-射线衍射仪。样品经研磨至200目、干燥并压片后,使用FEI Quanta250 FEG场发射扫描电镜观察。

3 古地貌格局

3.1 古地貌恢复方法

整合大足区块900 km²三维地震及7口关键井数据,通过精细合成记录标定,开展龙马溪组沉积期的古地貌恢复。基于陈维铭等^[15]报道的大足区块基本地质特征,选取龙马溪组顶部界面作为等时基准面,采用去压实校正与印模法相结合的技术手段,对该地区龙马溪组沉积初期的古地貌形态进行恢复。针对钻井井资料,发现7口井的龙马溪组现今埋藏深度与压实率具有正相关性,即埋藏深度越大,压实率越高^[10]。印模法以沉积补偿原



注:a为黑色碳质页岩,含黄铁矿,硅质含量高,Z203井,4 101.87~4 102.18 m,龙一₁¹;b为黑色碳质页岩,碎屑含量高,见笔石化石,Z207井,4 348.39~4 348.46 m,龙一₁²;c为黑色碳质页岩,碳质含量高,发育笔石化石,Z202井,3 882.31~3 882.41 m,龙一₁³;d为含泥砾灰黑色页岩,Z203井,4 073.77~4 073.92 m,龙一₁⁴;e为黑色粉砂质页岩,Z202井,3 891.94 m,龙一₁¹;f为黑色富有有机质钙质页岩,Z207井,4 386.41 m,龙一₁²;g为灰黑色粉砂质页岩,Z203井,4 088.45 m,龙一₁²;h为灰黑色黏土质页岩,Z207井,4 352.99 m,龙一₁⁴;i为泥质呈片状、纹层状分布,见莓状黄铁矿,Z203井,4 058.60 m,龙一₁⁴;j为粒间孔,Z206井,4 243.48 m,龙一₁³;k为粒内溶蚀孔,Z207井,4 267.80 m,龙一₁³;l为溶蚀孔,Z202井,3 887.50 m,龙一₁²;m为晶间孔,Z205井,3 330.21 m,龙一₁³;n为有机质孔,足208井,4 352.85 m,龙一₁³;o为微裂缝,Z202井,3 881.29 m,龙一₁²。

图2 渝西大足区块龙一₁亚段岩相学特征

Fig. 2 Lithofacies characteristics of Long 1₁ sub-member in Dazu block, western Chongqing

理为基础,通过分析等时基准面与上覆标志层间的厚度空间分布特征,间接反演古地貌形态^[39]。结合上述方法,恢复出龙马溪组沉积期古地貌整体呈现北高、南低(图3a),其地貌形态与波形聚类属性平面展布具有显著空间耦合性(图3b),有效验证了恢复结果可靠性。此外,渝西大足地区具有东西向两隆两凹的构造特征。鉴于构造隆起区反射能量弱、同相轴不连续及层位追踪困难,在平面图中剔除了该区域。

3.2 古地貌恢复及古环境变化

晚奥陶世至早志留世过渡期,川南地区五峰组—龙马溪组形成于乐山—龙女寺古隆起的东南斜坡,由北向南地势逐渐变低^[40]。在过 Z201—Z208—Z206 井二

维地震测线上(图3c),发育三级阶梯式地形坡折。自 Z206 井以北,地震反射同相轴具有上超尖灭的特征,表明该斜坡在形成过程中具有同沉积隆起的性质。上超点之下,地层表现为平行整合接触,未见任何削截现象。渝西大足区块龙马溪组沉积期整体处于深水陆棚环境^[41],其古地貌格局呈现明显的南北分带特征,由北至南可划分为陆棚高地、陆棚斜坡、陆棚洼地(图3a)。

渝西大足区块古地貌呈北高南低的特征,古水深向南逐渐递增,导致沉积环境还原性不断增强,与氧化还原指标 U/Th 和 Ni/Co 值变化一致(图4a)。此外,古盐度在不同古地貌单元也不一致。Sr/Ba 含量自陆棚高地向陆棚洼地逐渐增高,指示古盐度由北向南递增(图4b),可

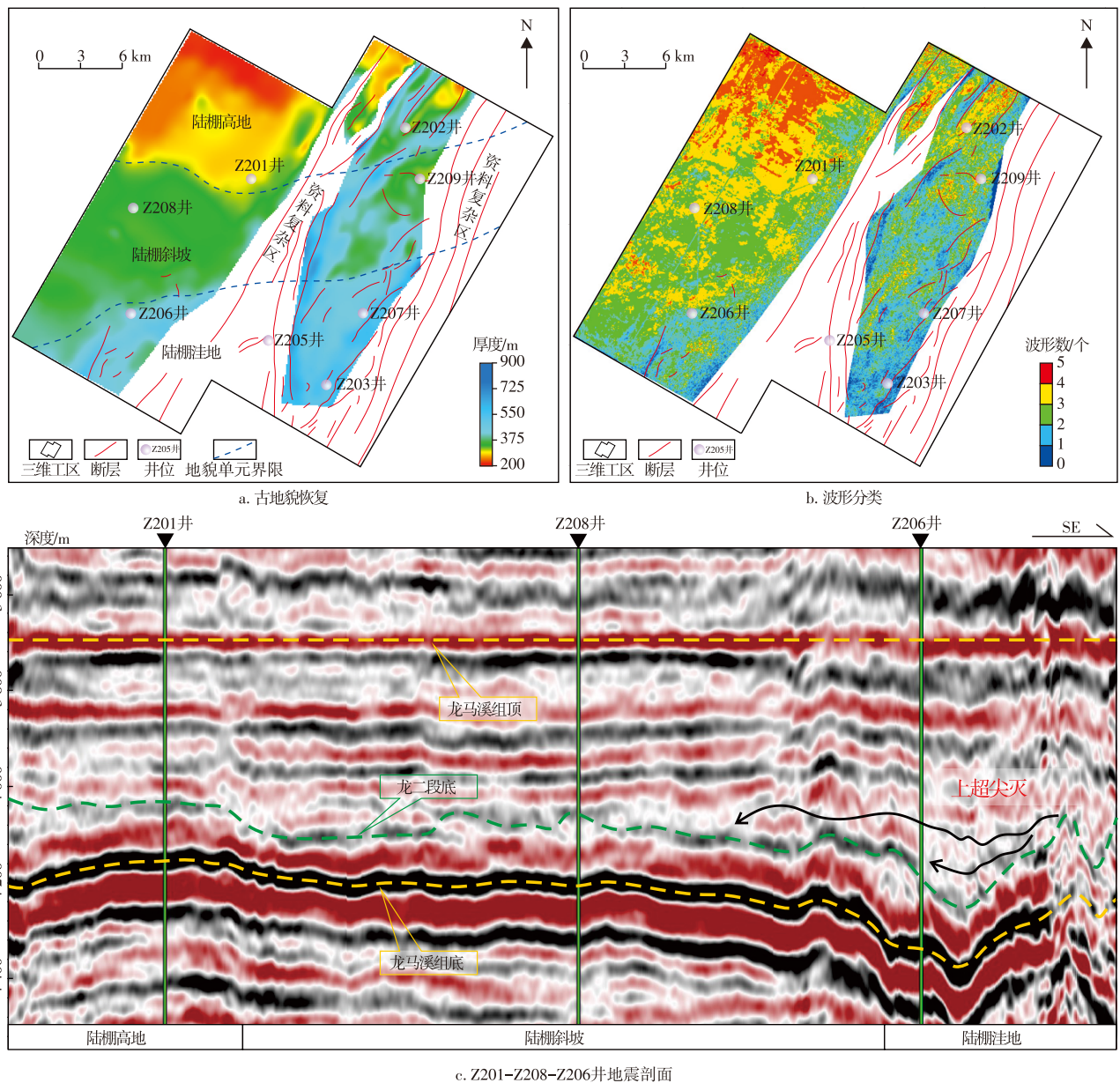
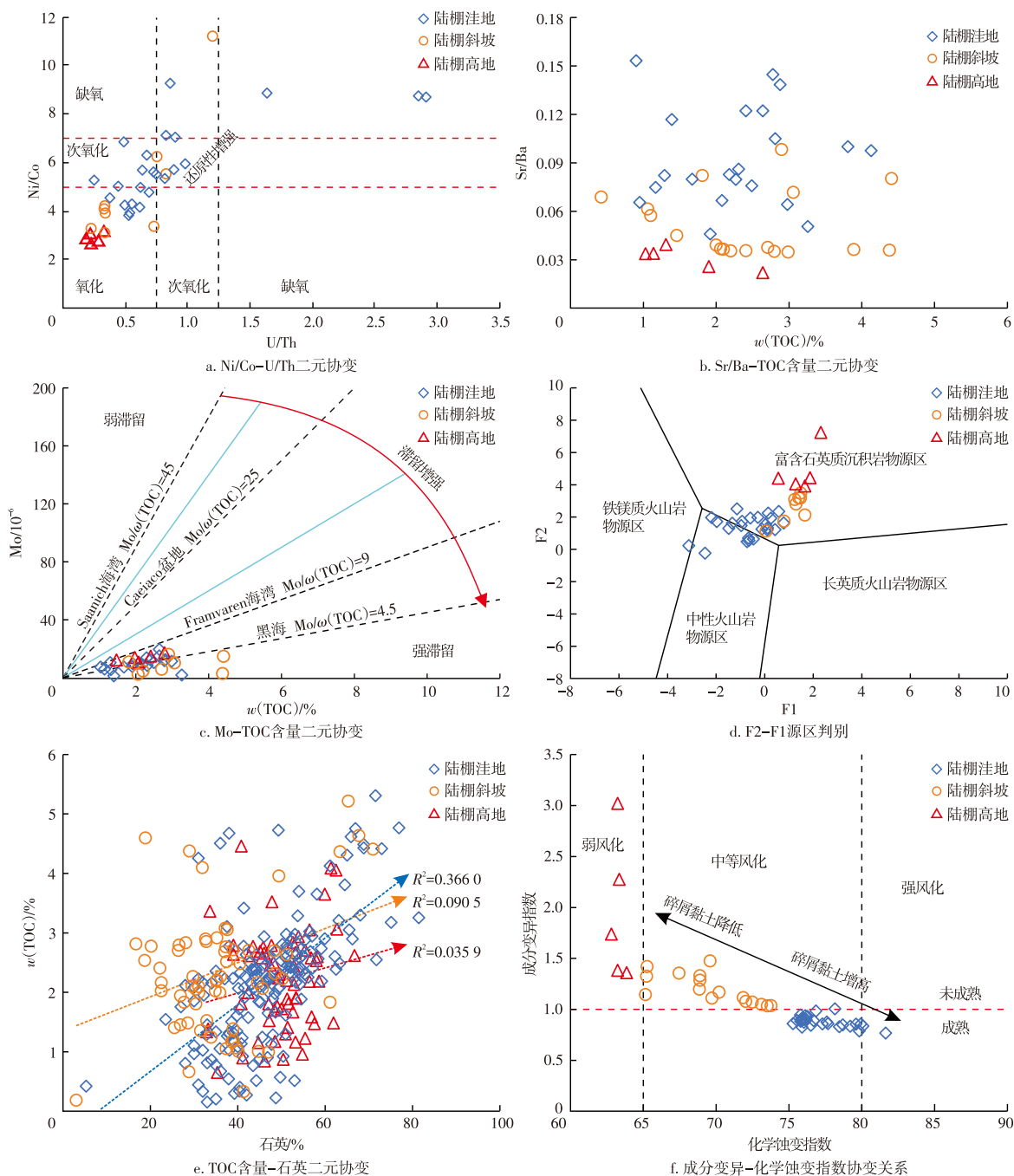


图3 渝西大足区块龙马溪组沉积早期古地貌恢复图、波形分类图及地震剖面

Fig. 3 Early sedimentary paleogeomorphic restoration map, waveform classification map, and seismic profile of Longmaxi Formation in Dazhu block, western Chongqing

能与沉积环境的滞留程度或岩浆热液作用相关。基于 Mo-TOC 图解显示研究区整体处于强滞留沉积环境(图 4c),三者并没有表现出明显的差异性,故沉积环境滞留程度导致古盐度高的机制可被排除。物源分析表明,研究区龙马溪组物源主要集中于北部川中古隆起,火山碎屑物质含量应具有由北向南递减特征。然而,仅陆棚洼地显示火山碎屑来源(图 4d),且矿物成分中出现方沸石(表 1)。方沸石通常是由火山碎屑物质在成岩过程中蚀变形[42],表明陆棚洼地沉积环境可能受微弱的岩浆热

液影响。早志留世,在华南板块南部陆内造山运动与扬子板块北缘商丹洋俯冲运动的共同作用下,发生广泛火山活动[32,43],构造薄弱区域容易产生构造裂缝,利于岩浆热液流动并带来大量 Mg^{2+} 、 Fe^{2+} 、 Fe^{3+} 、 Ca^{2+} 、 Na^{+} 、 S^{2-} 等离子,改变了沉积环境的水介质条件。强滞留沉积环境和大量热液流体注入,不仅增高陆棚洼地沉积水体的古盐度,且增强沉积水体的还原条件。因此,渝西大足地区龙马溪期沉积环境由北向南还原条件和古盐度逐渐增强,明显受古地貌格局控制。



注:ω(ToC)为ToC含量,%。

图4 渝西大足区块龙₁亚段地球化学参数对比(据文献[44-46]修改)

Fig. 4 Comparative analysis of geochemical parameters in Long 1₁ sub-member, Dazu block, western Chongqing (modified from references [44-46])

表1 渝西大足区不同古地貌龙一₁亚段页岩矿物特征

Table 1 Characteristics of shale minerals in Long 1₁ sub-member under different paleogeomorphic units of Dazu block, western Chongqing

古地貌	区间	黏土/ %	方沸石/ %	石英/ %	斜长石/ %	方解石/ %	白云石/ %	黄铁矿/ %	伊利石/ %	伊/蒙混层/ %	蒙皂石/ %	高岭石/ %	绿泥石/ %
陆棚 高地 (N=61)	最小值	17.2	—	40.4	4.95	0.30	0.58	2.03	65.3	—	—	—	16.00
	最大值	50.5	—	61.2	19.40	15.40	9.65	5.93	84.0	—	—	—	34.80
	平均值	30.6	—	49.8	12.20	5.19	3.39	3.83	74.3	—	—	—	25.30
陆棚 斜坡 (N=66)	最小值	17.9	—	20.5	3.94	0.45	0.00	0.80	61.5	0.33	0.33	1.50	4.33
	最大值	57.1	—	59.8	11.30	15.00	17.50	4.90	86.3	13.30	4.20	8.00	32.00
	平均值	41.0	—	34.5	7.69	5.49	7.65	3.12	73.1	7.19	1.45	4.78	18.70
陆棚 洼地 (N=92)	最小值	13.4	0.28	38.5	3.25	1.00	0.66	1.33	62.4	0.47	—	—	22.90
	最大值	47.2	1.64	69.7	8.72	16.60	9.28	4.80	75.9	6.69	—	—	33.90
	平均值	28.6	0.75	50.6	6.81	6.06	4.28	3.27	71.2	2.16	—	—	27.60

4 不同古地貌单元储层差异及成因

4.1 沉积环境控制有机质来源

龙马溪组页岩储层有机质显微组分呈现显著的分异特征(表2),以腐泥组为主,含少量壳质组与惰质组。地球化学分析表明,该储层TOC整体大于1%,主体层段普遍高于2%。晚奥陶世全球冰期结束之后,气候逐渐转暖使微体生物空前繁荣,为TOC增高提供了有利条件^[30]。渝西大足区块龙马溪组物源来自于北部川中古隆起,随着古地貌变化,陆源有机质含量由北向南逐渐降低^[34]。有机质显微组分表现出腐泥组含量向南递增、壳质组和

惰质组含量向南递减的特征(表2)。腐泥组分主要由海相/湖相环境中藻类贡献;壳质组主要由高等植物繁殖器官或组织贡献;惰质组主要由高等植物残骸经丝炭化作用转化而来。富氢程度表现为腐泥组>壳质组>惰质组^[47]。因此,古地貌格局导致龙马溪组有机质组成差异性。与此同时,TOC含量呈现由北至南逐渐增高的特征(图5a)。除沉积环境还原性向南增强有利于有机质保存外^[48],陆棚洼地发生的热液作用同样具有重要影响。热液流体注入会带来大量营养元素,促进微生物生存繁衍。陆棚洼地Sr/Ba含量相对较高(图4b),适当盐度有利于藻类发育,提高古生产力条件。因此,较好的初级生产力和有利的保存条件是陆棚斜坡和陆棚洼地龙一₁亚段的TOC含量高于陆棚高地的主要原因。

表2 渝西大足区块龙马溪组富有机质页岩干酪根显微组分及类型

Table 2 Maceral composition and kerogen types of organic-rich shale in Longmaxi Formation, Dazu block, western Chongqing

古地貌 单元	腐泥组/%	壳质组/%	镜质组/%	类型
陆棚高地	72~89(平均值83,N=26)	0~15(平均值13,N=26)	0~4(平均值2.83,N=26)	I-II ₁
陆棚斜坡	93~98(平均值95,N=13)	—	1~7(平均值5,N=13)	I
陆棚洼地	90~97(平均值93,N=10)	—	3~10(平均值7,N=10)	I

4.2 沉积环境控制物质组成

龙马溪组页岩储层以黏土矿物(28.6%~41.0%)和石英(34.5%~50.6%)为主。黏土矿物以绿泥石和伊利石为主体,并发育伊/蒙混层和绿/蒙混层;次要矿物中斜长石、碳酸盐矿物和黄铁矿含量较低(表1),部分层段出现方沸石和高岭石(表1)。随着古地貌地势由北至南逐渐降低,沉积区与物源区距离增大,碎屑长石石英含量应逐渐降低,黏土矿物含量理论上应增加^[49]。然而,不同地貌单元龙马溪组页岩储层的石英含量未呈由

北向南降低的趋势(图5b),而长石含量显示由北向南逐渐降低的特征(图5c),黏土矿物含量未呈由北向南逐渐增高的趋势(图5d)。陆棚斜坡显示高长石和黏土矿物含量但低石英含量,陆棚洼地则相反(图5c、图5d)。陆棚高地和陆棚斜坡的石英含量与TOC相关性不明显(图4e),说明主要为陆源碎屑石英;陆棚洼地石英与TOC含量有较好的正相关性,说明石英主要是生物成因来源(图4e)。前人通过蛋白石演化和Al-Si质量分数交汇图的研究也提出渝西区块龙马溪组底部存在很高生物成因石英含量^[22,34]。

长石作为典型的陆源碎屑矿物,其含量由北向南逐渐降低(图5c),主要反映研究区北部古隆起持续供给碎屑物质,且古地貌格局控制沉积物搬运路径^[50](图3)。然而,黏土矿物含量变化未遵循由高地貌向低地貌增高的规律(图5d)。在扣除成岩作用对化学蚀变指数(CIA)和成分变异指数(ICV)的影响后,陆棚斜坡具有低CIA值和高ICV值,而陆棚洼地则相反(图4f)。CIA值越高指示化学风化越强^[51];ICV值表征碎屑岩的成分成熟度,若ICV>1,表明碎屑岩含很少黏土物质,成分成熟度较低;若ICV<1,则表明碎屑岩含较多黏土物质,成分成熟度较高^[52]。因此,陆棚高地和陆棚斜坡的低CIA值和高ICV值指示相较于陆棚洼地更低的黏土矿物含量,与X-射线衍射分析(XRD)结果相矛盾。

陆棚斜坡黏土矿物中出现高岭石,而陆棚高地和陆棚洼地未见高岭石(表1),表明该高岭石由成岩作用形成。随着页岩储层埋藏深度增加及有机质热演化程度提升,当有机质热演化达到生烃门限时,生烃过程中所释放的酸性流体侵入页岩储层系统,碎屑长石在酸性环境中易蚀变成高岭石^[53-55]。同时,长石、碳酸盐矿物等易溶矿物蚀变溶解不断消耗有机酸^[56],导致成岩流体逐渐向碱性转变,高岭石在碱性成岩环境中会转化成绿泥石或伊

利石。尽管如此,充足的烃类侵位会形成局部惰性成岩环境,使部分高岭石得以有效保存^[53]。因此,碎屑长石蚀变成黏土矿物的程度受有机酸充注强度的影响。陆棚高地的黏土矿物含量低于陆棚斜坡(图5d),表明有机酸充注强度较低,碎屑长石蚀变相对较弱,但明显强于陆棚洼地。陆棚洼地具有低长石含量与低黏土矿物含量(图5c、图5d),表明陆棚高地和陆棚斜坡碎屑长石在成岩蚀变过程中修按住增加了黏土矿物含量。脆性指数与脆性矿物质量分数相关,可利用脆性指数计算公式求得^[57]。脆性指数在空间上呈现南北高、中间低的特征(图5e),与石英含量变化相似,而与黏土矿物含量变化相反,表明脆性指数主要受石英和黏土矿物含量控制。含有高生物成因石英或高碎屑石英含量的区域将具有更强的可压裂性。

4.3 沉积环境控制储层特征

通过场发射扫描电镜观察,渝西大足区块龙马溪组页岩储层识别出粒间孔、粒内孔、晶间孔、有机质孔和微裂缝等储集空间类型(表3)。粒间孔主要为方解石和长石等矿物边缘因溶蚀产生,呈不规则形状或长条状(图2j);粒内孔主要为方解石和石英颗粒内溶蚀形成,呈圆

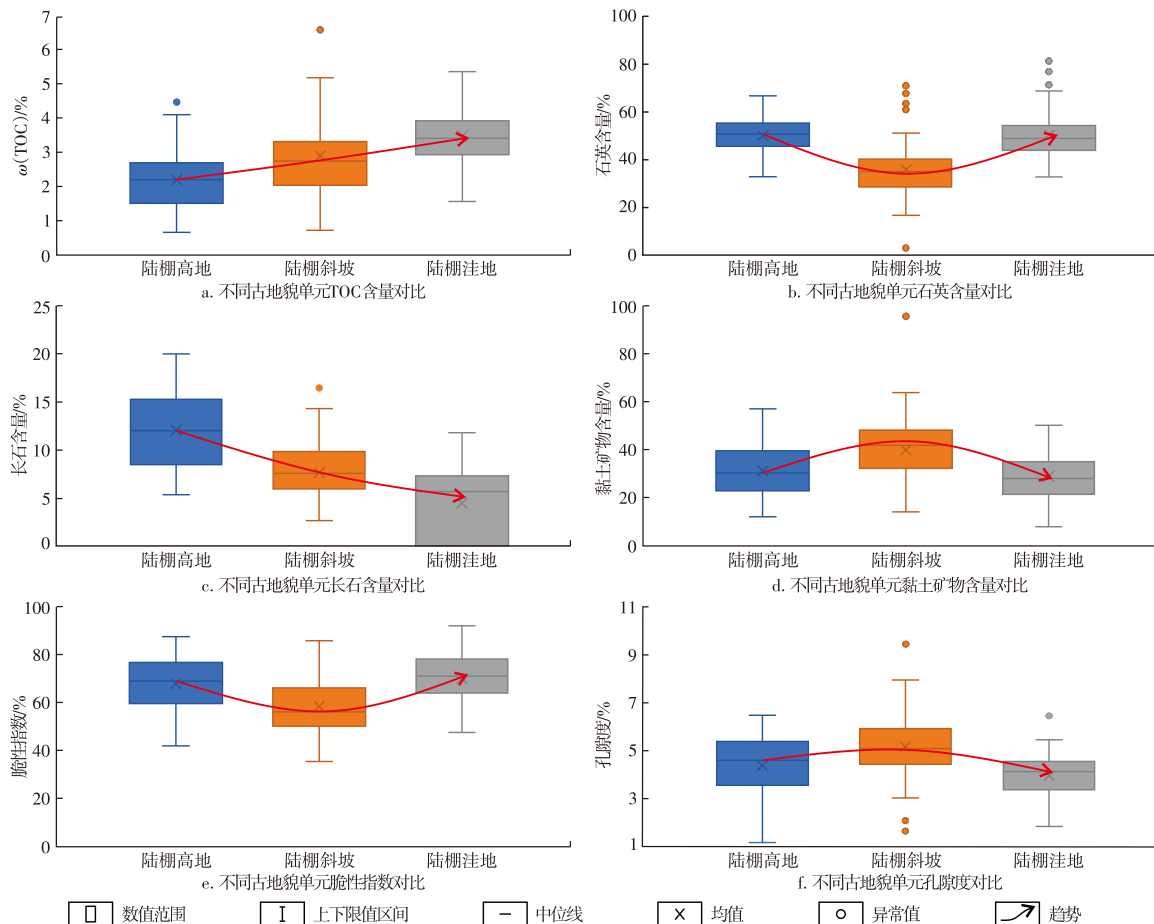


图5 渝西大足区块龙₁亚段不同古地貌单元对比

Fig. 5 Comparison of different paleogeomorphic units in Long 1₁ sub-member, Dazu block, western Chongqing

形、三角形或不规则状(图2k);伊利石内部包裹的长石和方解石等易溶矿物溶解也会形成圆形溶蚀孔(图2l)。黏土矿物作为层状铝硅酸盐矿物,易形成晶间孔,多呈长条状(图2m)。有机质孔发育在有机质内部,由有机质热演化形成,以圆形和椭圆形为主,孔径较小(图2n)。微裂隙主要包括黏土矿物片间缝和脆性矿物颗粒边缘缝(图2o),如沥青收缩缝、有机质微裂缝、石英和长石刚性矿物开裂缝等成岩收缩缝。

表3 渝西大足区块龙一₁亚段页岩储层特征
Table 3 Shale reservoir characteristics of Long 1₁ sub-member, Dazu block, western Chongqing

古地貌单元	储集空间类型	孔隙结构	孔隙度/%
陆棚高地	粒间孔、粒内孔	中孔为主,分布较均匀	1.17~6.48
陆棚斜坡	晶间孔、有机质孔	大孔为主,分布均匀	1.64~9.46
陆棚洼地	有机质孔、微裂缝	中一大孔径,非均质性强	1.84~6.46

粒间孔和粒内孔占比与矿物组成密切相关。石英、长石及碳酸盐矿物等刚性矿物在成岩过程中易被溶蚀产生次生粒间孔,且高含量的刚性矿物可增强页岩储层抗压实能力,从而保留原生粒间孔^[58]。粒内孔同样由长石、方解石和石英等易溶矿物在成岩过程中溶解形成(图2k)。有机质作为有机质孔发育的载体,其TOC越高,有机质孔越发育;同时,TOC升高可促进生物成因石英形成,生物成因石英的支撑作用有利于有机质孔的保存^[59]。如前所述,矿物组成和TOC的变化明显受到古地貌格局的控制。陆棚高地靠近物源区,碎屑石英与长石含量最高(图5b、图5c),有利于粒间孔和粒内孔形成,但TOC较低导致有机质孔比例较低。陆棚洼地生物成因石英与TOC最高(图5a、图5b),而碎屑石英长石含量较低,因此有机质孔是陆棚洼地主要的孔隙类型。陆棚斜坡碎屑长石含量介于两者之间(图5c),但黏土矿物含量较高(图5d),故发育黏土矿物晶间孔(图2m)。此外,陆棚斜坡有机质孔较陆棚洼地更发育,原因在于构造高部位页岩储层微裂缝发育,导致有机质内部天然气发生不同程度运移,最终形成孔径细小、形态不规则的特征性有机孔^[60]。研究区陆棚洼地页岩储层主要集中于现今构造相对高部位,其有机质孔隙的发育程度较陆棚斜坡有所减弱^[34]。微裂缝发育程度同样与矿物组成相关。龙一₁亚段微裂缝较发育,尤其是1小层脆性指数高,微裂缝极其发育。陆棚高地碎屑矿物含量高,发育高角度微裂缝;陆棚洼地碎屑黏土矿物和TOC含量高,则发育水平微裂缝^[38]。

基于5口井龙一₁亚段岩心核磁共振分析(图6),陆棚高地和陆棚斜坡样品的弛豫时间(T_2)谱主要表现为窄

峰特征,且高孔隙度分量,而陆棚洼地则呈现宽 T_2 谱峰与低孔隙度分量。核磁共振 T_2 时间与孔隙大小呈正相关,李维等^[61]通过不同含水条件下甲烷吸附实验标定出大足区块龙一₁亚段页岩储层孔隙类型:小孔(<5 nm)、中孔(5 nm~10 nm)、大孔(<10 nm~110 nm)及微裂缝(>110 nm),主体孔径范围为5.35 nm~25.38 nm。有机孔孔径主要分布于1.72~400 nm,占比19.58%~54.32%;无机孔孔径主要分布于2~320 nm,占比39.11%~67.92%;微裂缝占比4.14%~14.6%^[62]。陆棚高地页岩以中孔为主,孔径分布相对均匀;陆棚斜坡页岩以大孔为主,孔径分布均匀且优于陆棚高地;陆棚洼地则呈现中-大孔共存特征, T_2 谱峰较宽(表3),表明其储层非均质性较强。陆棚高地页岩储层碎屑石英与长石含量较高(图5b、图5c),易形成粒间孔与粒内孔,但黏土矿物常包裹碎屑矿物颗粒并充填粒间空间,导致孔径缩小甚至堵塞^[63]。陆棚斜坡不仅发育晶间孔与有机质孔,且微裂缝较发育,这与高黏土矿物含量及TOC含量密切相关:高黏土矿物含量易形成泥纹层,后期挤压构造作用下易形成微裂缝^[21]。陆棚洼地TOC与生物成因石英含量较高,有利于有机质孔形成与保存,但强烈石英胶结作用导致储层致密,后期挤压构造作用下高脆性特征易形成构造裂缝,从而加剧储层非均质性。

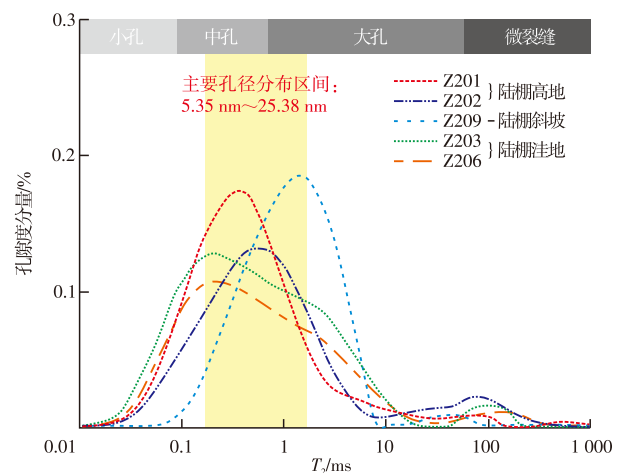


图6 渝西大足区块龙一₁亚段页岩孔隙度分量与孔径分布
Fig. 6 Porosity components and pore size distribution of shale in Long 1₁ sub-member, Dazu block, western Chongqing

龙一₁亚段页岩储层孔隙度呈现陆棚斜坡最高、陆棚高地次之、陆棚洼地最低的特征(图5f)。陆棚斜坡TOC和黏土矿物含量与孔隙度呈一定相关(图7a、图7b),而石英和长石含量与孔隙度呈负相关趋势(图7c、图7d),表明其高孔隙度由晶间孔与有机质孔共同贡献。陆棚高地孔隙度与TOC及黏土矿物含量相关性较弱(图7a、图7b),但与石英及长石含量呈显著负相关(图7c、图7d),

表明碎屑石英和长石的刚性特征既保护原生孔隙又占据孔隙空间,对储层具有破坏性,其保护的粒间孔和粒内孔是孔隙度的主要贡献者。陆棚洼地生物成因石英含量较高,TOC与孔隙度呈显著正相关(图7a),但石英与孔隙度呈负相关(图7c),黏土矿物及长石与孔隙度相关性较弱

(图7b、图7d),表明有机质孔为其主要孔隙类型,但有机质孔孔径较小,对孔隙度贡献较低;而高含量生物成因石英属成岩自生矿物^[64],形态以微晶石英为主,不仅占据原生粒间孔,且胶结碎屑颗粒使页岩更致密,从而导致陆棚洼地孔隙度急剧降低。

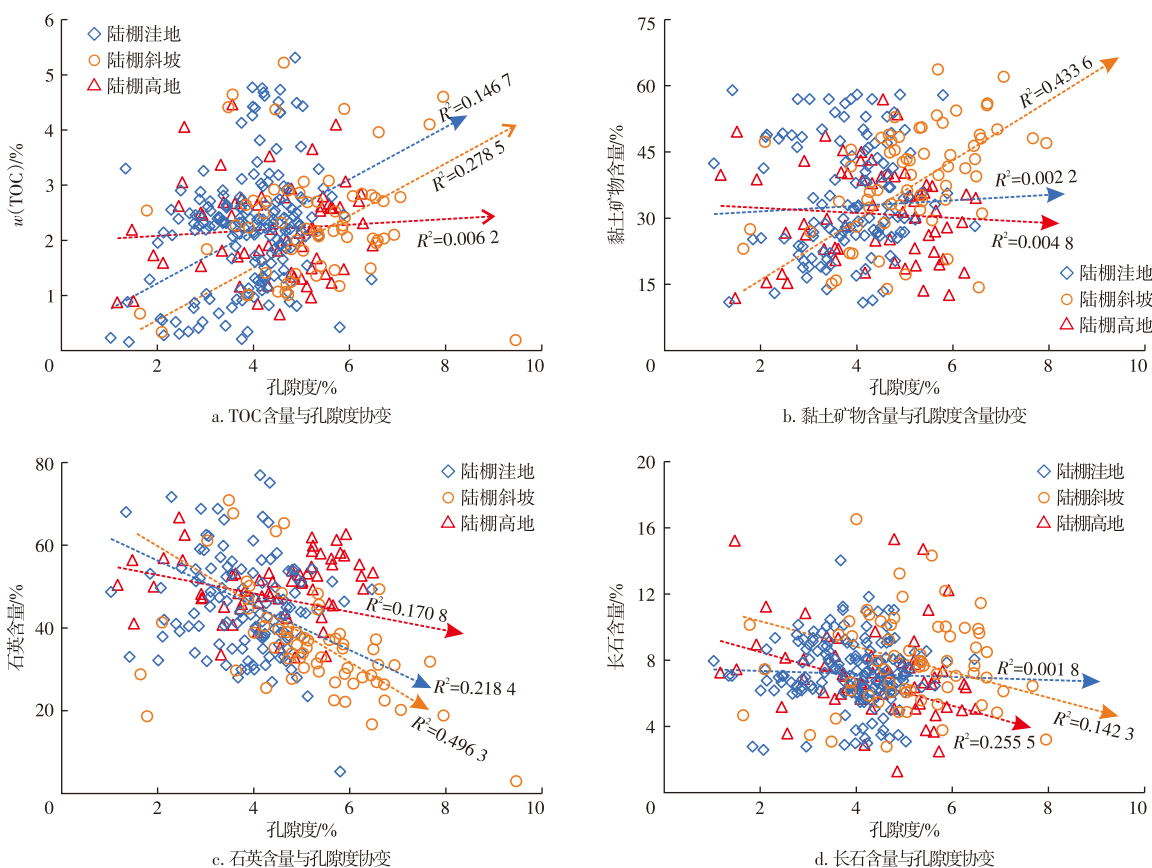


图7 孔隙度与矿物和TOC含量相关性

Fig. 7 Correlation between porosity and mineral/TOC content

4.4 古地貌格局控制优质页岩储层厚度空间展布

研究区龙一₁亚段的含气量、孔隙度、脆性指数及TOC等参数平均值在空间上具有明显的变化。通过西部Z201-Z208-Z206连井实测数据对比分析(图8a),含气量平均值介于1.33~2.08 m³/t,呈现由北向南逐渐递增趋势;孔隙度平均值介于3.76%~6.16%,其中Z208井最高,Z206井最低,呈现中部高、南北低特征;脆性指数平均值介于49%~71%,呈现中部低、南北高特征;TOC含量平均值介于2.13%~2.81%,同样呈现由北向南逐渐递增趋势。通过东部Z202-Z209-Z207-Z203连井实测数据对比分析(图8b),除Z209井孔隙度和TOC含量平均值略高外,含气量、孔隙度及TOC含量平均值均呈现由北向南逐渐递增趋势,分别介于1.42~2.87 m³/t、3.30%~4.19%、2.31%~2.87%;脆性指数平均值变化较小,介于62%~68%。综上,大足区块龙一₁亚段储层参数呈现规律性空

间分异:含气量与TOC向陆棚洼地逐渐增高,孔隙度在陆棚斜坡高而陆棚高地和陆棚洼地低,脆性指数在陆棚斜坡较低但陆棚高地和陆棚洼地高(图8a、图8b)。

基于勘探开发中采用的优质页岩储层分类评价标准(表4),将龙马溪组页岩储层划分为3类。通过测井曲线和实测数据对单井进行评价,统计显示I类页岩储层厚度呈现由北向南逐渐增厚特征(图8c),其中陆棚洼地最厚达4.40~5.90 m,陆棚高地最薄为1.54~2.71 m;位于陆棚斜坡带的Z209井因处于坡内局部洼地(图3a),其I类页岩储层厚度达6.36 m。本研究采用叠前地震反演与地震岩石物理分析方法,重点开展优质页岩储层参数定量预测。在明确密度与TOC含量、脆性指数及含气量均呈显著负相关的基础上,利用三维地震数据反演获得敏感参数体,并通过经验公式转换得到TOC含量、孔隙度、脆性指数及含气量等参数数据体^[15]。最后,对比分析4个数据体的反演结果,按储层评价权重系数

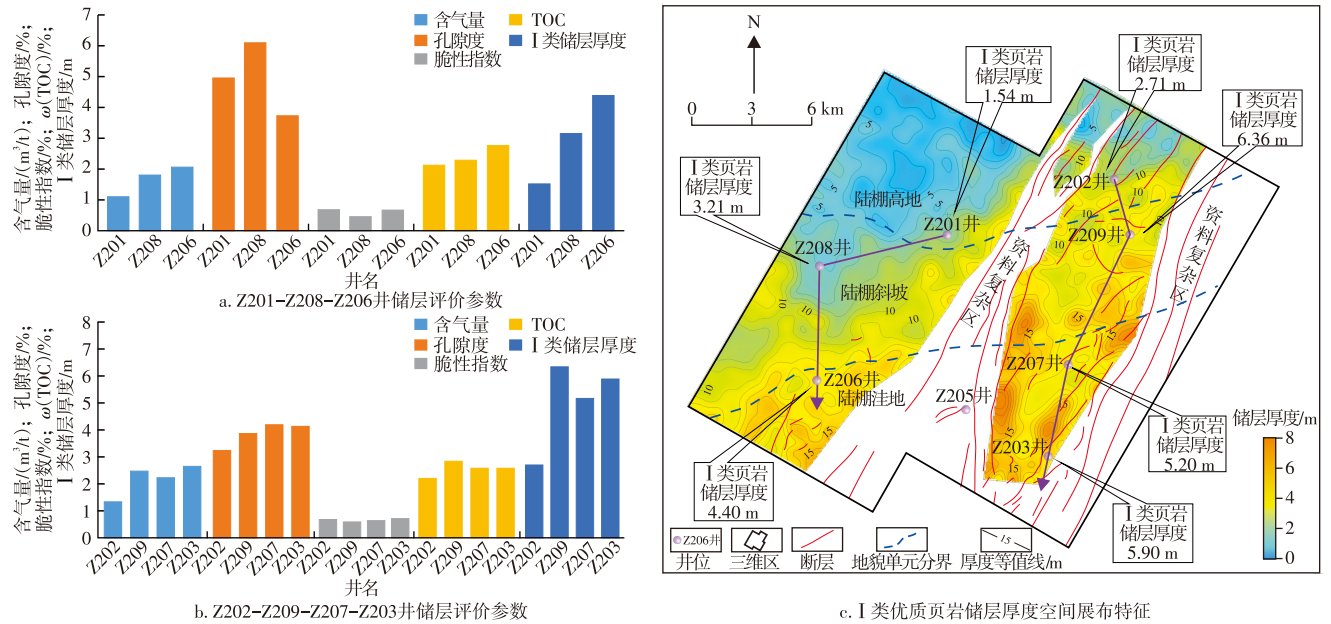


图8 储层评价参数连井对比及I类优质页岩储层厚度空间展布

Fig. 8 Well-to-well comparison of reservoir evaluation parameters and spatial distribution of type I high-quality shale reservoir thickness

表4 研究区龙马溪组页岩综合品质分类评价标准

Table 4 Comprehensive quality classification and evaluation criteria for shale of Longmaxi Formation in study area

评价参数	分类			综合评价		
	I类	II类	III类	I类	II类	III类
w(TOC)/%	>3	2~3	<2	四项单项指标均为I类	四项单项指标至少有一项为II类	四项单项指标至少有一项为III类
孔隙度/%	>4	3~4	<3			
含气量/(m ³ /t)	>3	2~3	<2			
脆性指数/%	>55	35~55	<35			

3:2:3:2进行重新分配计算,最终获得研究区储层预测反演结果。

龙一₁亚段I类优质页岩储层厚度分布显示北部薄、南部厚,自陆棚高地至陆棚洼地逐渐增厚,与单井实测数据分布相吻合(图8c)。结合区域北高南低的古地貌特征分析,揭示由北向南水深递增的沉积环境下营养物质与有机质含量增加,并形成有利有机质保存条件,为优质页岩储层发育奠定物质基础。因此,龙一₁亚段优质页岩储层厚度分布指示陆棚洼地为有利区。实际生产数据显示,2017年至2024年初,陆棚洼地(Z203、Z206井)累计产气量(2 482~6 120)×10⁴ m³显著高于陆棚斜坡(Z208井,2 266×10⁴ m³)与陆棚高地(Z202井,437×10⁴ m³),实际生产情况与定量预测一致,均表明陆棚洼地为优质页岩气储层有利区。此外,陆棚斜坡Z209井作为新井,月产气量达79.2×10⁴ m³,且I类页岩储层厚度达6.36 m,均高于陆棚洼地,与前文推测Z209井位于坡内局部洼地的认识相符。综上,研究区龙马溪组优质储层分布受物质组成、TOC及孔隙结构控制,三者与沉积环境存在强烈内在联系。

5 结论

1) 大足区龙马溪期古地貌格局自北向南划分为陆棚高地、陆棚斜坡及陆棚洼地。在该方向上,呈现出还原条件和古盐度逐渐增强的特征,陆源有机质逐渐减少,水生有机质逐渐增多。陆棚洼地的强还原环境和丰富的营养物质,为有机质的繁盛和保存提供了有利条件,这是陆棚洼地具有高TOC含量的主要原因。

2) 陆棚高地和陆棚斜坡区的石英主要以陆源碎屑为主,黏土矿物含量较高且由碎屑长石蚀变形成。其中,仅陆棚斜坡出现的高岭石,指示长石在被有机质包裹形成的局部惰性成岩环境中发生高岭石化并得以保存。而陆棚洼地的高石英含量主要为生物成因。

3) 龙马溪组页岩储层发育有机质孔、粒间孔、粒内孔和微裂隙等储集空间类型。陆棚斜坡的孔隙度最高,由晶间孔和有机质孔共同贡献;陆棚高地的孔隙度次之,由粒间孔和粒内孔贡献;陆棚洼地的孔隙度最低,这是由于有机质孔径小以及生物成因石英占据粒间孔所致。

4) 龙一₁亚段含气量、TOC、孔隙度和脆性指数具有

明显的空间变化特征。通过储层反演定量预测, I类页岩气储层厚度分布具有从陆棚高地至陆棚洼地逐渐增高的特征,受古地貌格局控制显著。

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