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鄂西地区震旦系陡山沱组二段页岩气 储层测井评价初探

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摘要:鄂西地区震旦系陡山沱组是中国页岩气勘查的新层系,其页岩储层矿物成分以白云石为主,测井响应特征与奥陶系五峰组—志留系龙马溪组、寒武系牛蹄塘组硅质页岩明显不同,原有储层“七性”关系测井评价对于陡山沱组页岩储层精细刻画和压裂施工解释评价存在一定的不适用性。本文以鄂阳页 1 井为例,综合利用常规测井、特殊测井和样品测试分析资料,研究发现不同于五峰组—龙马溪组和牛蹄塘组硅质页岩“四高四低”测井响应特征,陡山沱组二段云质页岩具有低伽马、低铀、低声波时差、低中子,高电阻率、高密度“四低两高”测井响应特征,认为元素测井是评价陡山沱组二段页岩地层总有机碳含量最直接和有效的方法,MRIL-P 型核磁测井适用于该地层孔隙度参数评价。通过拟合计算完善了适用于该地层的含气量估算方法,获取了有利页岩储层评价参数,研究成果将为同类型页岩储层测井评价提供参考依据。

关键词:页岩气;测井;储层评价;震旦系陡山沱组;鄂阳页 1 井;油气勘查工程;湖北省

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Discussion on petrophysical evaluation of shale gas reservoir in the second Member of Sinian Doushantuo Formation in Western Hubei Province, South China

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Abstract: Being a new layer of shale gas exploration in China, the Sinian Doushantuo Formation located in western Hubei Province, which shale reservoir mineral composition is dominated by dolomite and therefore its log response characteristics is obviously

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different with the siliceous shale of Ordovician Wufeng Formation, Silurian Longmaxi Formation and the Cambrian Niutitang Formation. The previous “seven parameter relationship” study on Longmaxi and Niutitang Formation is not support effectively for the fine characterization and fracturing construction of the Doushantuo Formation shale reservoir. In this paper, after analyzed the conventional logging, special logging and sample data of Eyangye 1 well, we suggested that the logging response characteristics of second member of Sinian Doushantuo Formation with low gamma, low uranium, low acoustic time difference, low neutron, high resistivity, and high density on the conventional logging curve. Furthermore, we proposed that the elemental logging is the most direct and effective logging method for evaluating the TOC of the second member of Doushantuo Formation shale, and analyzed that MRIL-P type nuclear magnetic survey is suitable for the evaluation of porosity parameters. At last, we evaluated the shale gas content via the new fitting method, and obtained favorable evaluation parameters of shale reservoirs. The research results above mentioned will provide parameter basis for the logging evaluation of the same type shale reservoir.

Key words: shale gas; logging; reservoir evaluation; Sinian Doushantuo Formation; Eyangye 1 well; oil-gas exploration engineering; Hubei Province

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1 引 言

国外学者利用测井资料和岩心数据,对北美 Barnett、Marcellus、Woodford 硅质页岩,建立了密度与总有机碳含量(TOC)、矿物成分与孔隙度、TOC 与含气量的评价模型与参数,并有效评价储层品质(Jacobi et al., 2008; Kale et al., 2010; Glorioso et al., 2012; Gupta et al., 2012)。参照 Barnett 页岩的测井响应特征,有学者根据中国寒武系牛蹄塘组和奥陶系五峰组—志留系龙马溪组富含有机质页岩矿物成分富含硅质的特点,总结提出高自然伽马、高铀、高电阻率、高声波时差、低密度、低中子、低无铀伽马、低光电吸收截面指数的“四高四低”测井响应特征(王金彬等, 2012; 王明飞等, 2015),形成了基于密度曲线、自然伽马能谱、声波时差和补偿中子等多参数线性回归 TOC 的计算方法(黄仁春等, 2014; Zhang et al., 2015; 钟光海等, 2015; 王濡岳等, 2015),提出有机孔隙、黏土孔隙、碎屑孔隙和微裂缝孔隙的定量计算方法(李军等, 2014),拟合了龙马溪组和牛蹄塘组页岩层段 TOC、石英含量、黏土含量与含气量的计算公式,计算结果与岩心测试结果相吻合(聂海宽等, 2012; 张晓明等, 2017; 陈孝红等, 2018),表明上述储层测井评价方法对于龙马溪组和牛蹄塘组具有较好的适用性,为储层优选与资

源潜力评价提供了技术支撑。

2017—2018年,中国地质调查局发现鄂西地区震旦系陡山沱组二段发育厚层暗色页岩,在鄂阳页1井、鄂宜页1井、秭地2井均见到良好页岩气显示,其中鄂阳页1井直井压裂获最高达 5460 m³/d 气量(李浩涵等, 2017; 翟刚毅等, 2017; Bao et al., 2018; Chen et al., 2018),鄂阳页 2HF 井 1410 m 水平井压裂试气获得 5.53 万 m³/d 的稳定高产工业气流,展示良好资源前景。经野外及钻井岩心观察,震旦系陡山沱组二段发育云质页岩,与寒武系牛蹄塘组和奥陶系五峰组—志留系龙马溪组的硅质页岩成分不同,因此前述页岩测井响应特征和储层参数计算经验公式很难适用于陡山沱组云质页岩储层。本文以鄂阳页1井为例,综合利用常规测井、特殊测井和分析化验资料,系统研究了陡山沱组二段云质页岩测井响应特征,分析了矿物组成、烃源岩特性、储层物性和含气性等储层参数,试图为同类型地层页岩储层测井评价提供参数依据。

2 地质特征

鄂西地区包括宜昌市、恩施自治州、襄阳、荆门市和神农架等,大地构造位于扬子板块中段,处于川东褶皱构造带与湘鄂西褶皱带的结合部位。受燕山期以来多期构造活动影响,研究区发育北东向

为主的“隔槽式”褶皱构造,鄂西地区发育利川复向斜、中央复背斜、花果坪复向斜、宜都—鹤峰复背斜以及桑植—石门复向斜等多个构造单元(马力等,2004;刘保林等;2015;李海等,2016)。

鄂阳页1井位于鄂西地区黄陵背斜的西南部,井区附近主要发育2组断裂,其中北北西走向的仙女山断裂形成于晚侏罗世,以走滑运动为主,而后经历了晚白垩世和古近纪末期的伸展作用与挤压逆冲作用(邓铭哲等,2018);北西走向的天阳坪断裂在早燕山期为由北向南的逆冲断层,晚燕山期—早喜山期发生构造反转为正断层(甘家思等,1997)。在黄陵背斜南部地区鄂宜页1井、鄂宜参1井和秭地2井也钻遇陡山沱组页岩(图1)。

岩石组合上,陡山沱组可划分为4段,陡山沱组一段为灰色泥质白云岩,厚度11.46 m;研究层段陡山沱组二段以黑色页岩为主,厚度127.69 m;陡山沱组三段以灰色灰质白云岩、浅灰色白云岩为主,厚度57.72 m;陡山沱组四段为深灰色泥岩,厚度0.65 m(邓胜徽等,2015;陈孝红等,2015)(图2)。陡山沱组二段是在海侵条件下,发育形成的一套面积广、厚度大、层位稳定的烃源岩层系,其页岩层段总有机碳含量普遍大于1%,有机质类型主要为I-II₁型,成熟度平均为3.24%;矿物成分以白云石为主,脆性

矿物含量高,黏土含量低,发育有机质孔、粒内孔、粒缘缝等(单长安等,2015;Zhai et al.,2018)。

为精细评价矿物成分、孔隙度等参数,标定测井评价结果,在鄂阳页1井陡山沱组实施了自然伽马能谱、补偿中子、岩性密度、双侧向电阻率等常规测井和微电阻率扫描成像、核磁共振、正交偶极阵列声波测井、岩性扫描特殊测井。另外,在实验室开展了TOC、X衍射全岩分析、孔隙度、渗透率及等温吸附共101组分析化验。

3 测井响应特征

震旦系陡山沱组二段云质页岩表现为低伽马、低铀、低声波时差、低中子、高电阻率、高密度的测井响应特征。其中,陡山沱组自然伽马值介于13.90~105.20 API,平均值36.93 API;铀值介于 0.75×10^{-6} ~ 3.75×10^{-6} ,平均值 1.80×10^{-6} ;去铀伽马值介于6.92~100.90 API,平均值24.27 API。岩性密度、补偿中子及声波时差受3299.0~3350.2 m和3389.8~3396.5 m扩径影响,曲线失真。剔除受扩径影响的部分,岩性密度数值介于2.53~2.78 g/cm³,平均值2.69 g/cm³;补偿中子数值介于1.46%~19.57%,平均值11.55%;声波时差数值介于47.62~77.92 μs/ft,平均值57.14 μs/ft。光电吸收截面指数值介于

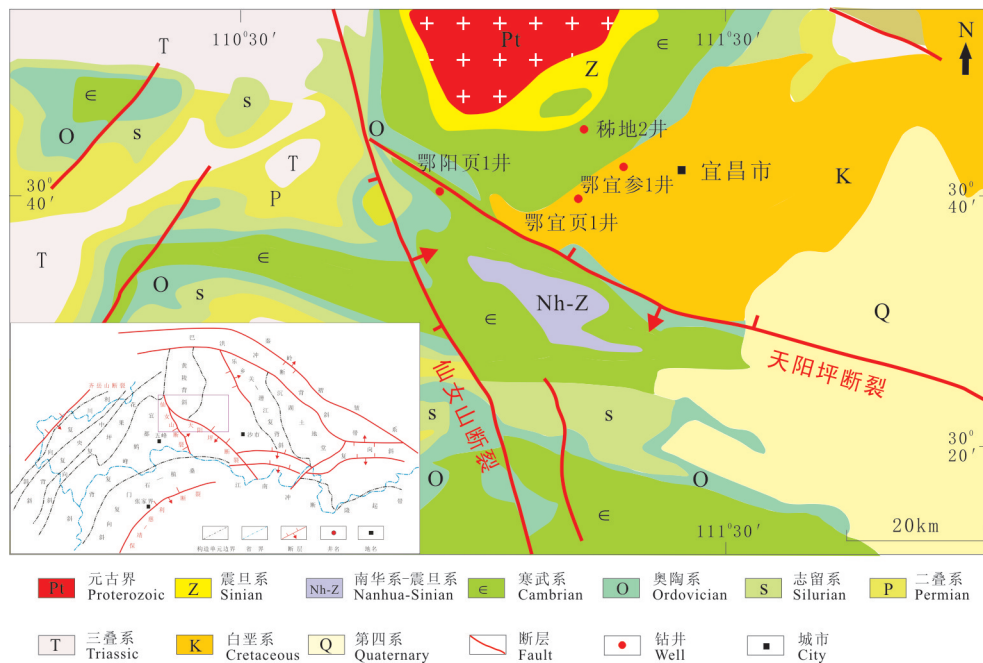


图1 研究区地质图和钻井位置

Fig.1 Geological map of study area and well site



图2 鄂阳页1井震旦系陡山沱组地层柱状图
Fig.2 Stratigraphic column of the Sinian Doushantuo Formation, Eyangye1 Well

3.92~8.84 b/e, 平均值 5.76 b/e。深侧向电阻率数值介于 16.52~1680.49 Ω·m, 平均值 199.33 Ω·m (图 3)。

4 页岩关键参数测井评价

4.1 岩石矿物与地球化学特征

Litho Scanner 测井结果显示,页岩储层矿物成分以白云石为主,平均含量 54%,其次是石英,平均含量 21%,方解石平均含量 5%,长石平均含量 5%,黏土矿物平均含量 13%(图 4)。实验分析数据与测井评价结果一致显示,震旦系陡山沱组二段页岩矿物成分与奥陶系五峰组一志留系龙马溪组和寒武系牛蹄塘组明显不同,脆性矿物(白云石+石英+方解石+长石)达 85%。

利用 Litho Scanner 岩性扫描获得地层中 TOC 的含量(魏国等, 2015; Radtke et al., 2017),结果显示,陡山沱组二段 TOC 介于 0.15%~4.16%,平均值为 1.7%;实验室分析测试 TOC 介于 0.18%~4.05%,平均 2.02%,两者数据吻合度较高(图 4),陡山沱组二段 TOC 大于 2%的优质页岩累计厚度为 56.84 m。

4.2 页岩储层物性

利用 MRIL-P 型核磁测井获取了鄂阳页 1 井地层的精细的孔隙结构和储层孔隙度参数,结果表明,陡山沱组二段以小孔隙为主, T₂ 谱主频小于 10 ms(图 5)。在氩离子抛光扫描电镜上可以看到发育有机质孔、粒内孔、粒缘缝以及莓粒状黄铁矿与黏土颗粒形成大量孔洞,但孔缝较小,有机质孔径约 60 nm(图 6)。

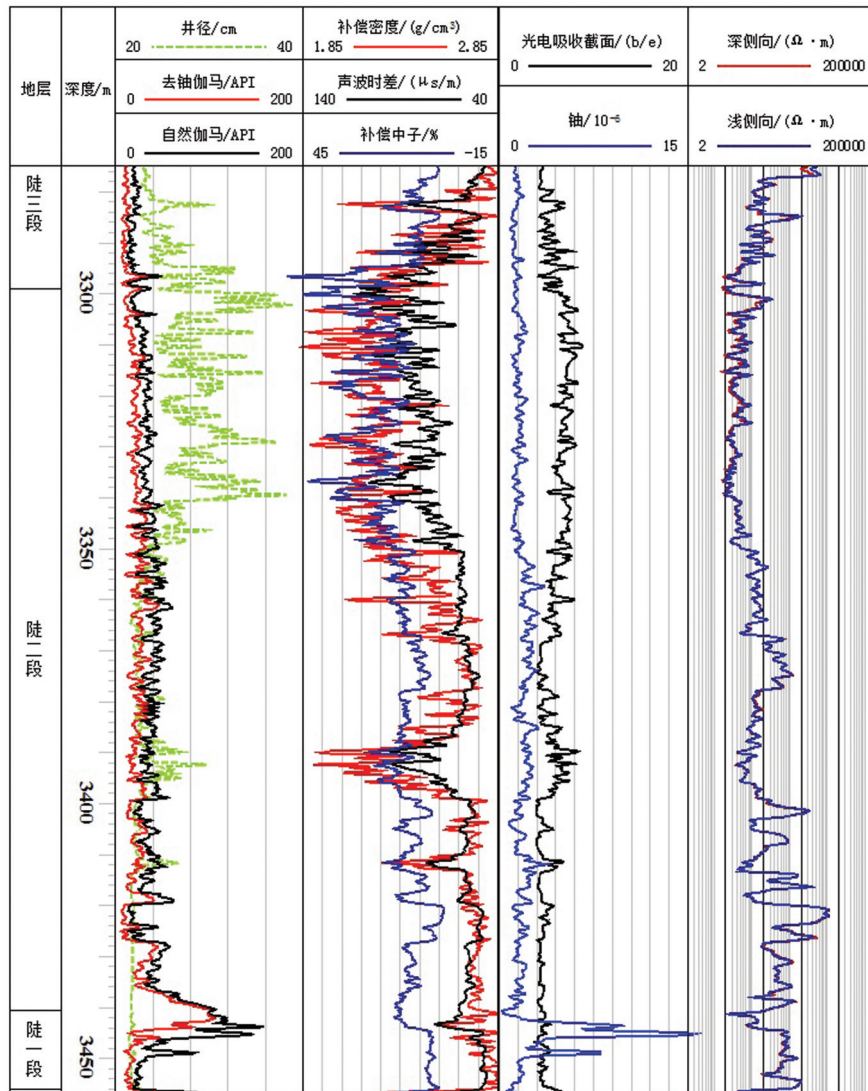


图3 鄂阳页1井震旦系陡山沱组二段测井响应图

Fig.3 Logging response of shale in the second Member of Sinian Doushantuo Formation

虽然 3299.0~3350.2 m 和 3389.8~3396.5 m 扩径较严重,核磁共振测井孔隙度失真偏大,但结合常规曲线以及 Litho Scanner 测井得到的矿物含量进行孔隙度综合评价,并以实验室物性分析资料对计算得到的孔隙度进行标定,保证了扩径层段孔隙度的准确性。井眼条件较好的层段核磁孔隙度介于 0.39%~3.70%,平均值 1.72%;实验室核磁共振分析测试数据显示,孔隙度介于 0.28%~3.47%,平均值 1.69%。结果表明,在井眼条件好的条件下,即使对于低孔页岩储层,核磁共振测井也可以提供较为准确的孔隙度评价结果(图 4)。

页岩储层基质渗透率极低,目前尚无利用常规测井方法求取云质页岩地层基质渗透率的有效方法(金武军,2017)。本文利用实验室核磁共振测试手段,确定渗透率介于 0.007~5.450 md,3384.83 m、3400.04 m 和 3419.08 m 样品存在裂缝,导致渗透率增大(表 1)。

4.3 页岩含气性

测井方法评价页岩地层的含气性主要是通过计算吸附气和游离气含量实现。鄂阳页 1 井陡山沱组为常压地层,计算地层压力约为 34.42 MPa,目的层温度为 57.8℃,陡山沱组 14 个样品等温吸附实验

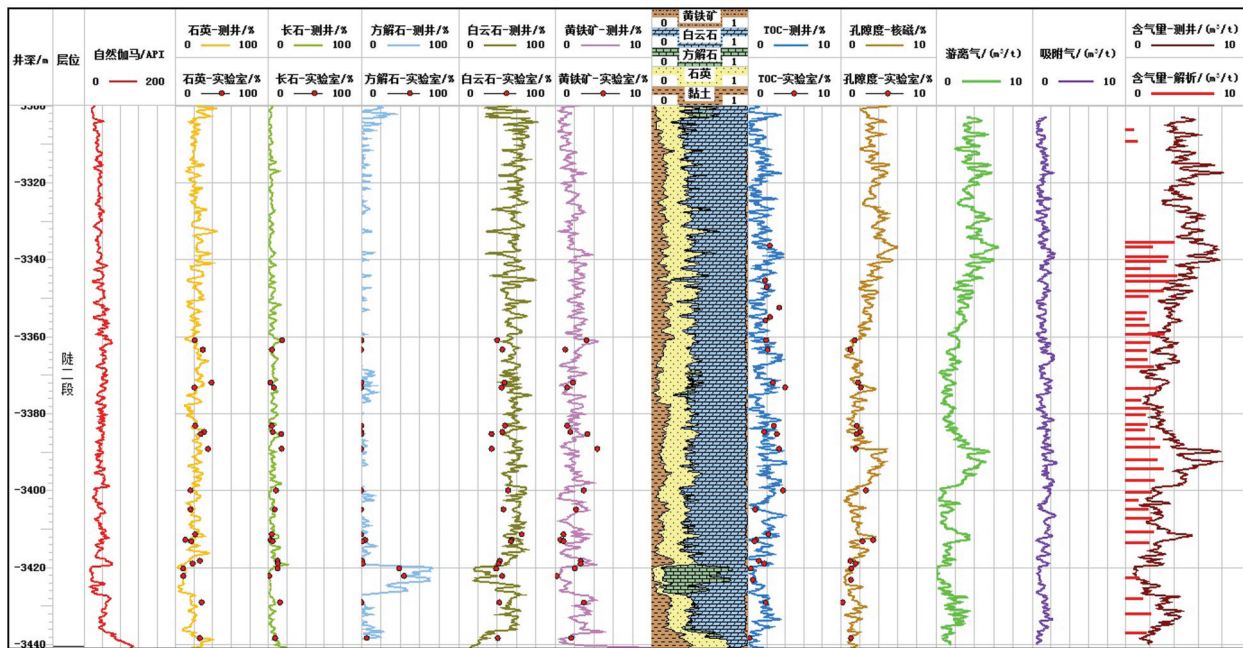


图4 鄂阳页1井震旦系陡山沱组二段测井解释综合图

Fig.4 Petrophysical evaluation of shale in the second Member of Sinian Doushantuo Formation

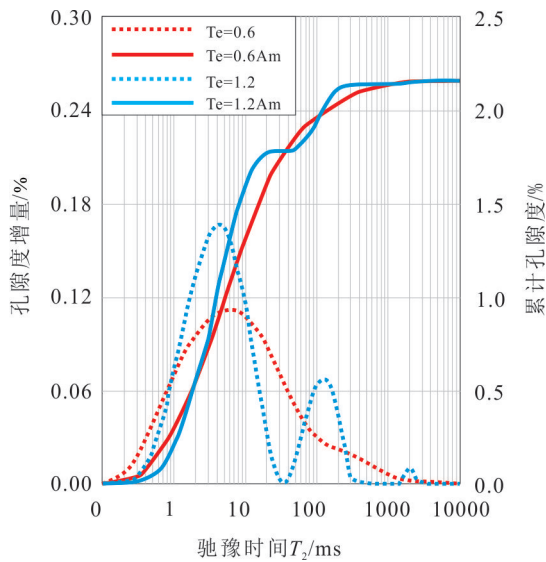


图5 页岩核磁共振 T₂谱分布图

Fig.5 Distributing diagram of NMR T₂ spectrum of shale

的理论吸附值 V_L 为 0.58~6.02 m³/t, 换算到地层压力下的等温吸附量为 0.44~5.26 m³/t。根据实验室实测 TOC 和等温吸附数据拟合了研究区吸附气量与总有机碳之间的关系(图 7)。

游离气含气量主要受储层孔隙度与含气饱和度影响, 游离气的计算公式(Lewis et al., 2004)为:

表 1 云质页岩渗透率实测值

Table 1 Permeability from the laboratory data of dolomitic shale

深度/m	围压/MPa	密度/(g/cm ³)	孔隙度/%	渗透率/10 ⁻³ μm ²
3440.12	3	2.58	2.77	0.902
3360.96	3	2.65	1.52	0.017
3363.45	3	2.68	1.07	0.061
3371.97	3	2.69	1.87	0.588
3373.26	3	2.62	2.16	0.007
3383.19	3	2.63	1.75	0.250
3384.83	3	2.63	2.10	5.450
3385.37	3	2.63	1.74	0.008
3389.21	3	2.61	1.65	0.996
3400.04	3	2.59	2.73	4.830
3412.89	3	2.67	3.47	0.013
3413.18	3	2.68	2.35	0.009
3418.31	3	2.65	1.07	0.194
3419.08	3	2.63	1.62	1.380
3420.35	3	2.69	1.18	0.010
3423.29	3	2.79	1.13	0.012
3429.11	3	2.72	0.28	0.035
3438.39	3	2.70	1.13	0.015

$$G_{cfm} = \frac{1}{B_g} \cdot (\phi_{eff}(1 - S_w)) \cdot \frac{\psi}{\rho_b}$$

式中: G_{cfm} = 游离气含量, scf/ton;

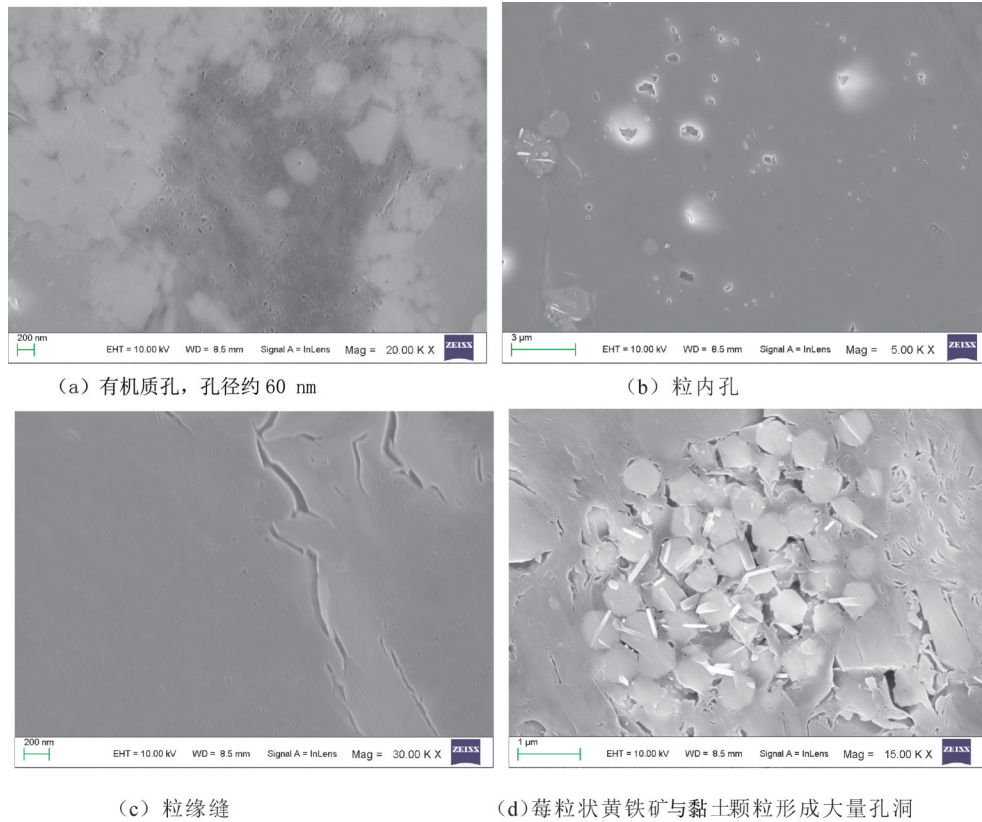


图6 页岩孔隙结构特征

Fig.6 Pore structure characteristics of shale

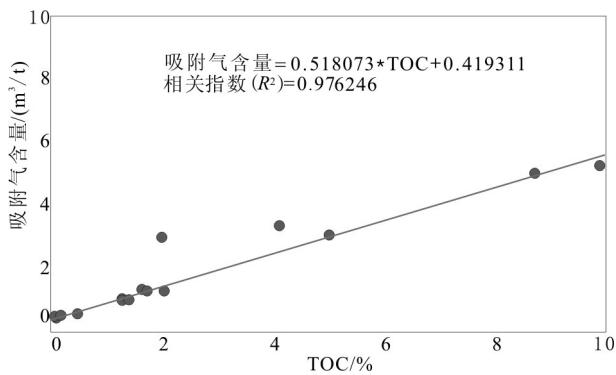


图7 陡山沱组页岩吸附气含量与TOC拟合关系

Fig.7 The relationship between absorbed gas content and total organic carbon content of shale in Doushantuo Formation

B_g = 气层体积系数, cg/sf;

Φ_{eff} = 有效孔隙度, %;

S_w = 含水饱和度, %;

ρ_b = 体积密度, g/cm³;

Ψ = 转换常数 (32.1052)

吸附气和游离气计算结果显示, 陡山沱组二段总含气量介于 0.67~7.91 m³/t, 其中, 吸附气含量介

于 0.42~2.57 m³/t, 平均 1.25 m³/t; 游离气含量介于 0.08~6.43 m³/t, 平均 2.52 m³/t。现场解析的总含气量介于 0.12~4.80 m³/t, 平均 2.01 m³/t (图4)。

5 讨论

5.1 测井响应特征对比分析

中国南方地区奥陶系五峰组—志留系龙马溪组、寒武系牛蹄塘组页岩气有利储层自然伽马值均大于 150 API, 铀含量平均大于 10×10⁻⁶, 声波时差值平均为 77.84 μs/ft 和 78.49 μs/ft, 密度曲线值平均分别为 2.53 g/cm³ 和 2.57 g/cm³, 光电吸收截面指数平均分别为 3.38 b/e 和 4.71 b/e。奥陶系五峰组—志留系龙马溪组有利页岩层段电阻率小于 100 Ω·m, 寒武系牛蹄塘组有利页岩段电阻率变化幅度较大, 整体偏高, 平均 480.03 Ω·m。上述两套页岩在常规测井曲线均表现为高伽马、高铀、高电阻率、高声波时差、低密度、低中子、低去铀伽马、低光电吸收截面指数的“四高四低”响应特征 (严伟等, 2014; 郭旭升, 2014; Han et al., 2016)。

震旦系陡山沱组二段 3299.0~3350.2 m、3389.9~3396.5 m 扩径较严重,对常规测井的中子、密度等曲线产生影响,对比上述两套层系,未扩径层段富有机质页岩在常规测井曲线上表现为低伽马、低铀、低声波时差、低中子、高电阻率、高密度的测井响应特征(表2)。

矿物成分的不同造成陡山沱组页岩与五峰组—龙马溪组和牛蹄塘组页岩测井响应差异大。五峰组—龙马溪组和牛蹄塘组优质页岩位于深水陆棚沉积环境,页岩矿物成分以石英为主(王明飞等, 2015;王濡岳等, 2015;高莉等, 2019),平均含量分别为 56.8%和 37.0%,黏土含量均大于 25%;陡山沱组以台地相的白云石为主,平均含量为 54.0%,黏土含量为 13%(图 8)。沉积岩中放射性的强弱与泥岩含量紧密相关(黄隆基, 2000),陡山沱组黏土含量低,放射性物质吸附能力较弱,造成铀含量较低。高成分的白云石含量使地层电阻率增高,也使储层更加致密,导致储层测井密度值增加,中子值变小,声波时差值较低。

5.2 陡山沱组 TOC 计算方法评价

元素测井是评价陡山沱组二段页岩地层 TOC 最直接和有效的测井方法。相对于普通硅质页岩来说,有机碳的存在会导致密度偏低、声波时差变大、中子变高、电阻率增大,往往又伴随着铀含量的增大,所以体积密度法、自然伽马、铀曲线法、声波—电阻率曲线法等基于常规测井的 TOC 评价手段较为适用(Schmoker, 1981; Autric et al., 1985; Passey et al., 1990; 王胜建等, 2016)。特别是四川涪陵地区

奥陶系五峰组—志留系龙马溪组海相页岩, TOC 与测井密度之间具有极强的相关性(李军等, 2014),通过岩心数据的标定,由密度曲线可回归得到计算 TOC 的经验公式。

由于陡山沱组二段为云质页岩,测井曲线的响应更多是白云石等矿物的响应,储层中有机碳的电性特征基本被掩盖,本文尝试利用常规测井的自然伽马、铀、电阻率、声波时差及密度与实验室 TOC 结果进行交会,建立回归公式,但相关性均较差,无法建立仅依靠常规测井曲线评价云质页岩储层 TOC 的计算模型。Litho Scanner 元素测井受井眼和泥浆类型的影响较小,直接测量地层中总碳含量,通过减去方解石、白云石等中的无机碳,获取 TOC,与岩心实测 TOC 高度吻合,表明利用元素测井可有效评价陡山沱组二段地层的 TOC。

因鄂阳页 1 井部分井段井眼条件较差,常规测井受到影响,很难通过常规测井曲线构建泥岩、砂岩及云岩计算模型求取不同层段矿物成分。通过 Litho Scanner 元素扫描测井在裸眼段和套管中进行元素测量,测量结果与岩心分析结果一致,但 Litho Scanner 矿物含量与常规曲线间的关系,尚需在合适的井况下进一步测量和研究建立。

5.3 储层评价参数分析

页岩含气量受埋藏深度、压力、有机地化参数、矿物成分等影响,其中 TOC 与孔隙度是控制页岩含气量计算的两个关键参数(聂海宽等, 2012; 王金彬, 2015)。在游离气计算过程中,由于受 3299.0~3350.2 m、3389.9~3396.5 m 井段扩径影响,使得核

表 2 不同层系页岩气储层常规测井响应特征

Table 2 Logging response of shale gas reservoir in different Formations

层系	震旦系陡山沱组 (以鄂西地区为例)	寒武系牛蹄塘组 (以贵州岑巩地区为例)	奥陶系五峰组—志留系龙马溪组 (以重庆焦石坝为例)
自然伽马/API	13.90~105.20/36.93	194.80~871.10/459.37	141.51~307.42/182.37
去铀伽马/API	6.92~100.90/24.27	14.29~100.42/54.31	45.54~122.70/85.50
铀/ 10^6	0.75~3.75/1.80	22.36~105.37/54.62	4.82~30.39/12.92
井径	扩径严重	井径质量好	井径质量好
声波时差/(μ s/ft)	47.62~77.92/57.14	57.95~101.90/78.49	72.37~87.76/77.84
中子/%	1.46~19.57/11.55	7.95~16.86/12.18	10.67~19.92/13.89
密度 g/cm^3	2.53~2.78/2.69	2.43~2.76/2.57	2.42~2.72/2.53
光电吸收截面指数/(b/e)	3.92~8.84/5.76	3.11~7.56/4.71	2.88~4.54/3.38
电阻率/($\Omega \cdot m$)	16.52~1680.49/ 199.33	28.20~1754.22/480.03	10.06~71.02/42.08

注:表格中数字表示方式为最小值~最大值/平均值。

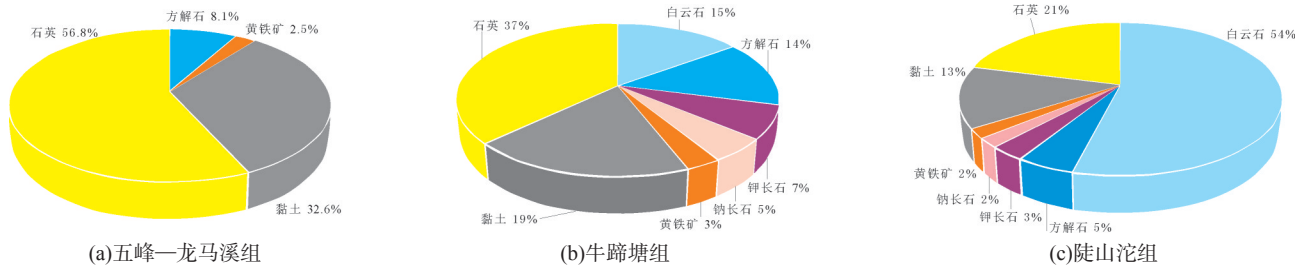


图8 不同层系页岩矿物成分组成

Fig.8 Mineral compositions in different shale formation

磁测井计算的有效孔隙度数值偏大,因此要针对扩径层段加密采样,进行核磁共振等实验室分析化验求取孔隙度,与元素测井获取的地层骨架密度建立关系,实现地层孔隙度的准确计算,进行获取更精准的地层含气量。在非扩径层段,测井计算含气量介于 $0.67\sim 5.79\text{ m}^3/\text{t}$,平均 $2.91\text{ m}^3/\text{t}$,与现场解析总含气量基本一致,其中游离气与吸附气占比为1:1。但裂缝发育的页岩,特别是开启缝的发育,给渗透率评价带来很大挑战,要加强实验室渗透率测试分析。另外,云质页岩的岩石力学参数也不同于硅质页岩,有待结合偶极子声波测井定量评价。

6 结论

(1)陡山沱组二段有利层段页岩矿物成分以白云岩为主,与奥陶系五峰组—志留系龙马溪组、寒武系牛蹄塘组硅质页岩典型“四高四低”测井响应特征相比,具有低伽马、低铀、低声波时差、低中子、高电阻率、高密度的“四低两高”测井响应特征,以往基于常规测井资料针对硅质页岩的评价手段,难以准确计算云质页岩TOC和含气量。

(2)常规测井、核磁测井、元素扫描测井的综合可有效评价陡山沱组页岩气储层的岩性、孔隙性、烃源岩特性及含气性。孔隙度、TOC、含气量及储层厚度综合分析,表明研究区陡山沱组二段优质页岩储层发育,具有较好的勘查前景。

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