石油与天然气地质
第43卷 第2期 OIL & GAS GEOLOGY 2022年4月

文章编号:0253-9985(2022)02-0467-10 doi:10.11743/ogg20220218

海相富有机质页岩储层压力预测方法
——以涪陵页岩气田上奥陶统五峰组-下志留统龙马溪组页岩为例

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摘要:页岩储层压力预测是评价页岩储层质量、认识页岩气富集机理、识别页岩含气性及寻找页岩气勘探有利区的基础。高-过成熟的海相富有机质页岩中发育大量纳米级有机质孔隙,且页岩储层普遍存在由生气造成的异常高压。目前页岩储层压力预测多建立在无机孔隙发育演化规律基础之上,没有考虑纳米级有机孔隙发育演化,从而导致“压力异常”的假象或者储层压力预测结果不准确。本文提出了一种适用于海相富有机质页岩的储层压力预测方法:假设页岩储层有机孔隙和异常压力共存,计算有机孔隙的声波测井响应,并校正声波测井曲线,建立新的压力预测模型。以涪陵页岩气田五峰组-龙马溪组页岩为例探讨了该方法的可靠性和实用性。结果表明,相校于原始Eaton法,该方法计算结果与实测压力数据吻合程度更高(R^2=0.81),预测误差相对较小且符合正态分布。因此该压力预测方法能够有效、可靠地预测研究区海相页岩储层压力。据预测,焦石坝一期产建区地层压力总体具有背斜中间高、周缘低、东南侧局部具有高值的特征,该结果与无阻流量具有良好的相关性,进一步说明该方法的可靠性。该方法对于完善非常规页岩储层压力预测方法、推动超压页岩气勘探具有重要的现实意义。

关键词:有机质孔隙;储层压力预测;海相页岩;五峰组-龙马溪组;涪陵页岩气田;西川盆地
中图分类号:TE122.2 **文献标识码**:A

Reservoir pressure prediction for marine organic-rich shale: A case study of the Upper Ordovician Wufeng-Lower Silurian Longmaxi shale in Fuling shale gas field, NE Sichuan Basin

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Abstract: The pressure prediction for shale reservoirs is essential for evaluating shale reservoir quality, understanding shale gas accumulation mechanism, identifying gas-bearing property and seeking favorable shale gas exploration areas. High-to-over-mature marine shale reservoirs rich in organic matters are commonly characterized by considerable nano-scale organic pores and abnormally high pressure caused by gas generation. At present, shale reservoir pressure prediction is practically based on the development and evolution of inorganic pores while ignoring the nano-scale organic pore growth, resulting in an illusion of “pressure anomaly” or inaccurate prediction of reservoir pressure. This study proposes a reservoir pressure prediction method for marine organic-rich shale. With the assumption that organic pores coexist with abnormal pressure in shale reservoirs, this method serves to calculate the acoustic logging responses of organic pores, correct the acoustic logging curve, and establish a new pressure prediction model. The new method is verified with Wufeng-Longmaxi shale reservoir in Fuling gas field as an example. Compared with the Eaton method, an original calculation method, the results of the revised method match well with the measured data (R^2=0.81). Also, the prediction error of the revised method is relatively small and in normal distribution, indicating that this method is

收稿日期:2021-06-10;**修订日期**:2022-01-04。
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基金项目:国家自然科学基金项目(41872124,42130803);中国石化科技部项目(P20046-1)。

suitable for the pressure prediction in the marine shale reservoir. The predicted pressure in Phase I Production Zone in Jiaoshiba area is generally characterized by high value in the center, low value in the surroundings, and locally high value in the southeast. These are well correlated with open flow capacity, further indicating the reliability of the method. It is of great practical significance to improving the unconventional shale reservoir pressure prediction and promoting the exploration in overpressured shale gas.

Key words: organic pore, reservoir pressure prediction, marine shale, Wufeng-Longmaxi Formations, Fuling shale gas field, Sichuan Basin

引用格式:王鹏威,陈筱,刘忠宝,等. 海相富有机质页岩储层压力预测方法——以涪陵页岩气田上奥陶统五峰组-下志留统龙马溪组页岩为例[J]. 石油与天然气地质,2022,43(2):467-476. DOI:10. 11743/ogg20220218.

Wang Pengwei, Chen Xiao, Liu Zhongbao, et al. Reservoir pressure prediction for marine organic-rich shale: A case study of the Upper Ordovician Wufeng-Lower Silurian Longmaxi shale in Fuling shale gas field, NE Sichuan Basin[J]. Oil & Gas Geology, 2022, 43(2): 467-476. DOI: 10. 11743/ogg20220218.

页岩储层压力与页岩气富集、产能及钻井过程中地质灾害等诸多环节息息相关,目前已引起国内外学者和油气勘探工作者的广泛关注[1-5]。勘探实践表明,国内外典型页岩产气区普遍发育异常高压,而且异常高压对页岩气产能具有明显的控制作用[6-8],如四川盆地内斜坡和向斜区五峰组-龙马溪组页岩主要表现为异常高压,页岩气产能相对较高,但盆地边缘的常压区,页岩气产能较低[3-4]。目前,页岩储层异常对页岩气富集控制作用的研究已取得了重要进展。异常高压对页岩储层储集空间的改善和保存具有积极的作用:四川盆地及周缘五峰组-龙马溪组页岩异常高压储层压力系数从川东南向川中递增,但页岩压实程度依次减弱,即异常高压可以通过支撑部分上覆岩体荷重保存原生孔隙,此外异常高压有利于烃源岩释放有机酸,促进储层次生孔隙的发育[9-13]。四川盆地龙马溪组页岩气的勘探开发实践可以证实储层异常高压通常意味着良好的保存条件,在超压条件下五峰组-龙马溪组页岩有机质孔隙以球形为主,孔径大、连通性好;常压条件下主要为定向分布的扁平状中孔,孔径较小[1-2,14-16]。此外,异常压力对页岩气赋存状态及页岩含气性具有积极贡献,在一定范围内,吸附气含量随地层压力升高而增大;游离气含量也随压力增大而呈线性增加,有利于页岩气富集和高产[17-19]。

Eaton法是目前最基本的超压预测和判别方法之一,其主要是在无机孔隙压实原理的基础上运用声波测井计算地层压力[20]。目前该方法不考虑页岩储层有机孔隙发育与演化,可导致“异常压力”的假象或异常压力偏大等问题,从而严重制约了页岩气富集规律等理论研究及页岩气勘探实践。因此,加强页岩储层压力预测方法的研究对深入认识页岩气富集机理和加快页岩气勘探开发尤为关键。本文在前人研究的基础上提出了一种适用于海相富有机质页岩的压力评价方法,并以四川盆地涪陵页岩气田焦石坝地区五峰组-龙马溪组页岩为例,验证了该方法的可靠性,以期为海相页岩气理论研究和超压及常压页岩气勘探实践提供支撑。

1 评价方法

1.1 评价原理

前人研究表明,页岩有机孔隙发育主要受干酪根类型、有机质丰度、热演化程度、有机质物理化学结构、成岩作用和构造作用等的控制[21-25]。尽管页岩有机孔孔隙大小、几何形态、数量,以及不同大小孔隙的比例等在不同的热演化阶段会有所差异[26-29],但是,总体而言,有机孔孔隙度随热演化成熟度具有先增大(镜质体反射率 R_o=1. 3 %~2. 0 %)、再快速减小的趋势(R_o>2. 0 %)[27,29]。在不考虑胶结作用、粘土矿物转化、溶蚀作用等成岩作用的前提下,页岩储层无机孔孔隙度主要在压实作用控制下随埋深增加而逐渐降低,页岩总孔隙度(有机孔+无机孔)在埋深过程中也会发生相应的变化(图1)。因此,既存在异常高压也存在有机孔隙发育的富有机质页岩声波时差响应可认为由两部分组成:一部分是有机孔隙发育;一部分是异常压力。因此,为了准确获取异常压力的声波时差响应,有必要对有机孔隙发育造成的声波时差进行校正。

1.2 岩石物理模型

前人对全球海相页岩矿物组成分析表明,由于不同区域内沉积环境不同,页岩的物质组成存在差异[30],但总体而言,页岩储层的物质组成可归纳为无

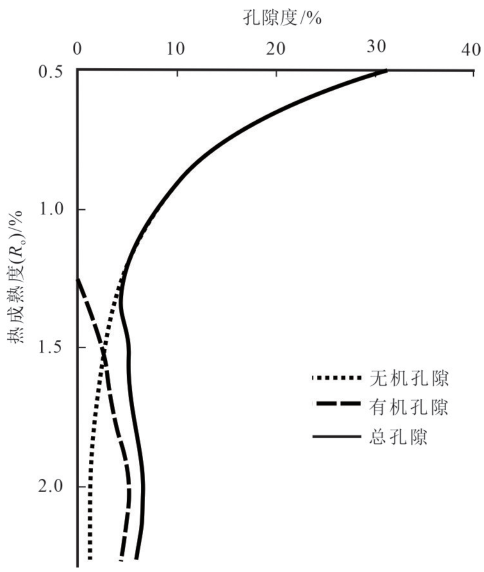

图1　富有机质页岩孔隙演化理论模型[27,29]

Fig. 1　Conceptual model of pore evolution in organic-rich shale[27,29]

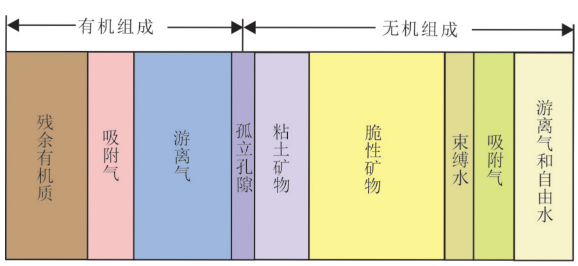

图2　页岩储层岩石物理模型(据文献[31]修改)

Fig. 2　Petrophysical model of organic-rich shale reservoirs (modified from reference [31])

机部分和有机部分(图2)。无机矿物主要包含脆性矿物和粘土矿物。常见脆性矿物颗粒表面多为水润湿,所以脆性矿物孔主要为水和游离气的富集空间;粘土矿物表面显现亲水性特征,优先吸附和储集水分子,所以粘土矿物孔是束缚水的主要赋存空间[31]。粘土矿物对气体的吸附能力受粘土表面水膜的影响较大,前人通过对比干燥条件和湿润条件下粘土矿物吸附能力发现,粘土的吸附能力随含水饱和度的增大而急剧降低[31-32]。因此无机部分的流体组成主要为束缚水、自由水、游离气及部分吸附气。有学者提出有机质润湿性与其热成熟度有关[31],即不同热演化阶段有机质中干酪根的润湿性存在一定差异:低成熟度有机质主要表现为亲水,中等热演化则为混合润湿,高热演化干酪根颗粒表面为亲油,因此,高-过成熟有机孔隙是气态烃类的主要储集空间。

1.3　方法推导

假设页岩储层孔隙主要由无机孔隙和有机孔隙构成,则储层总孔隙度可表达为:

$$\Phi = \Phi_m + \Phi_o \tag{1}$$

式中:Φ,Φ_m和Φ_o分别为总孔隙度、无机孔孔隙度和有机孔孔隙度,%。

根据孔隙模型可建立页岩声波时差体积模型:

$$\Delta t = \Delta t_m(1 - \Phi) + \Delta t_f \Phi \tag{2}$$

式中:Δt,Δt_m和Δt_f分别为实测声波时差、岩石骨架的声波时差和孔隙流体的声波时差,μs/ft。

公式(2)右边第二项流体的声波时差响应可进一步拆分为常压孔隙流体部分和超压孔隙流体部分。后者即为异常压力的测井响应,则公式(2)可变为:

$$\Delta t = \Delta t_m(1 - \Phi) + \Delta t_{nf}\Phi + \Delta t(p) \tag{3}$$

式中:Δt_{nf}为常压流体的声波时差,μs/ft;$\Delta t(p)$为异常压力的声波时差响应,μs/ft。

将公式(1)代入公式(3)可得:

$$\Delta t = \Delta t_m(1 - \Phi_m - \Phi_o) + \Delta t_{nf}\left(\Phi_m + \Phi_o\right) + \Delta t(p) \tag{4}$$

整理公式(4)可得:

$$\Delta t = \Delta t_m\left(1 - \Phi_m\right) + \Delta t_{nfm}\Phi_m + (\Delta t_{nfo} - \Delta t_m)\Phi_o + \Delta t(p) \tag{5}$$

式中:Δt_{nfm}和Δt_{nfo}分别为无机孔隙内流体和有机孔隙内流体的声波时差,μs/ft。

公式(5)等式右侧的第三项为有机孔发育造成的声波时差响应,为了消除该项对异常压力计算的影响,需要将该项从原始声波测井曲线中剔除,获得校正后的声波时差曲线:

$$\Delta t' = \Delta t_m(1 - \Phi_m) + \Delta t(p) + \Delta t_{nf}\Phi_m = \Delta t - (\Delta t_{nfo} - \Delta t_m)\Phi_o \tag{6}$$

将校正后的曲线代入Eaton模型,可获得适用于海相富有机质页岩的压力预测模型:

$$p = S - \left(S - p_n\right)\left(\frac{\Delta t_n}{\Delta t'}\right)^3 \tag{7}$$

式中:p,S和p_n分别为流体压力,上覆地层压力和静水压力,MPa;Δt_n为正常压实的声波时差,μs/ft;3为Eaton指数。

2　实例应用

2.1　地质背景

涪陵页岩气田位于四川盆地齐岳山断裂以西,构造位置上是石柱复向斜、方斗山复背斜和万县复向斜等多个构造单元的结合部位(图3)。该构造单元整体

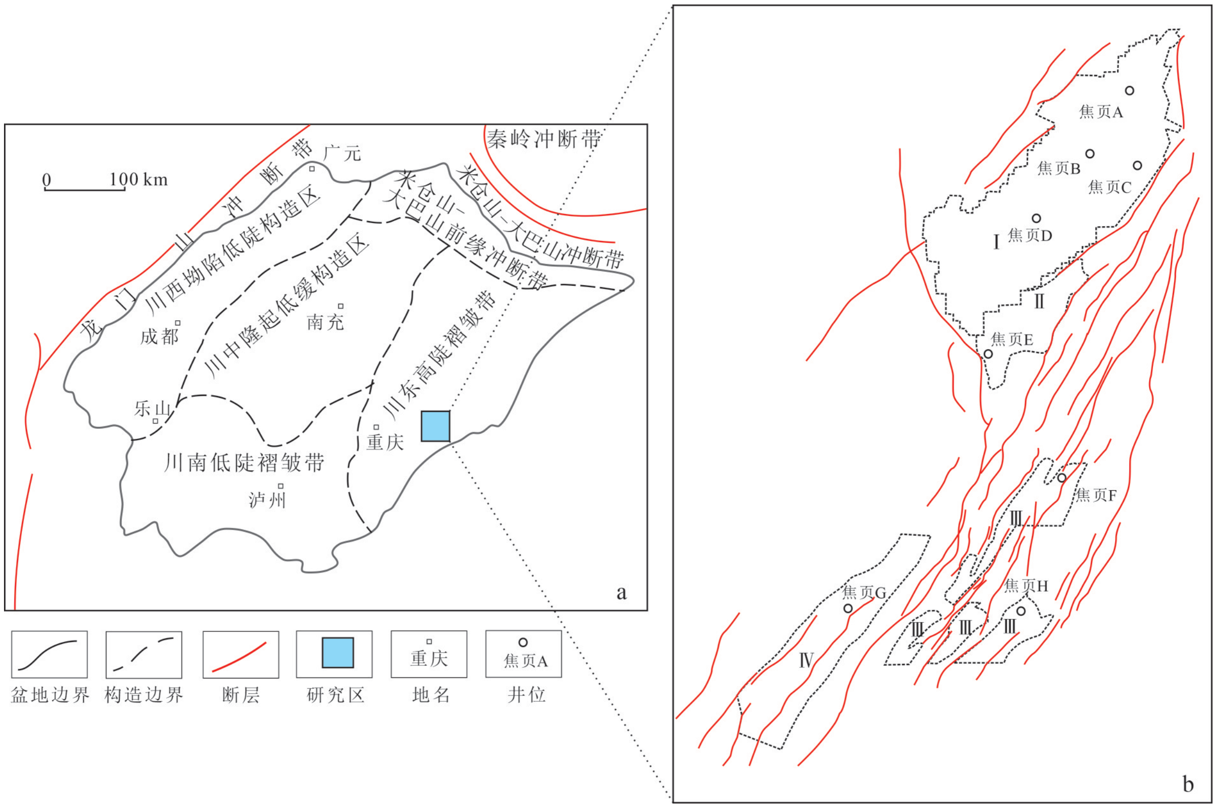

图3　四川盆地涪陵页岩气田构造位置(a)和五峰组底部构造图(b)

Fig. 3　Structural location (a) and diagram showing the bottom structure of the Wufeng Formation (b) of Fuling shale gas field, Sichuan Basin

Ⅰ. 一期产建区；Ⅱ. 白涛区块；Ⅲ. 白马区块；Ⅳ. 平桥区块

呈北东向展布，发育了北东向断裂系统，包括大耳山、石门-金坪、吊水岩、天台场等断裂，及北西向断裂系统，如乌江断层。以石门-金坪断裂为界，该区块构造上可划分为南北两带，北带可进一步划分为焦石坝断背斜、江东斜坡及乌江断背斜等，南带可进一步划分为石门-金坪断背斜及白马向斜等多个次级构造单元。涪陵页岩气田上奥陶统五峰组-下志留统龙马溪组主要为深水陆棚相黑色页岩，横向上岩性变化小，分布稳定，连续厚度介于80～120 m。五峰组-龙马溪组一段下部为优质页岩段，以灰黑色硅质页岩和炭质页岩为主，厚度介于38～45 m。五峰组-龙马溪组一段下部页岩总有机碳含量(*TOC*)介于3.0 %～6.0 %，处于高-过成熟阶段(R_o=2.5 %～3.0 %)，孔隙度介于2.8 %～7.1 %，脆性矿物含量高[33]。

有机质孔隙在五峰组-龙马溪组一段下部富有机质页岩中广泛发育，是重要的储集空间类型[15,34-36]。主要发育在藻类体、固体沥青以及生物碎屑中(图4)。藻类体内部的有机质孔隙多呈现局部发育且发育密度较高，孔隙多为不规则状(图4a)。固体沥青内的有机质孔隙主要发育在中心部位，孔隙形态受控于固体沥青形态，主要为椭球形或近圆形(图4b,c)，其面孔率可达30 %～40 %。

涪陵页岩气田五峰组-龙马溪组页岩气产层既有为超压气层，也存在常压气层，气层压力系数介于1.00～1.55，异常高压主要来源于页岩生气作用所造成的流体膨胀[17-18,29,37-41]，且与不同构造单元的构造活动和保存条件有关[1-2,33]。焦石坝背斜区构造稳定，气藏保存条件较好，实测五峰组-龙马溪组地层压力系数高达1.55。平桥北和平桥东钻井揭示的地层压力系数较高，其中焦页187-2HF井测试压力系数1.59。江东区块构造较为稳定，五峰组-龙马溪组地层压力系数可大于1.30，属超压地层。白马区块白马向斜五峰组-龙马溪组实测地层压力系数高，其中焦页7HF井压力系数为1.39，焦页107-2HF压力系数为1.44。白涛区块构造变形强烈、断裂发育，页岩气保存条件差，多口评价井表现为常压特征，压力系数在0.99～1.25。

2.2　孔隙压力预测

2.2.1　孔隙压力计算参数

本次共采用6口井(焦页A、焦页B、焦页C、焦页D、焦页E和焦页F)的现场测试压力数据对模型进行验

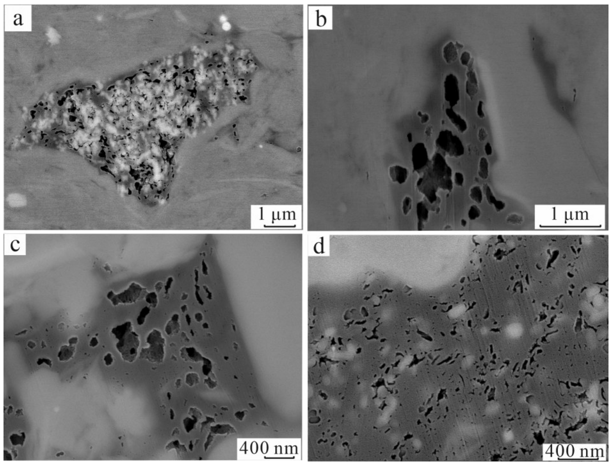

图4　四川盆地焦页A井龙马溪组页岩有机质孔隙SEM照片

Fig. 4　SEM images of the Wufeng-Longmaxi shale in Well Jiaoye A, Sichuan Basin

a，b. 埋深2 346.50 m，黑色炭质页岩；c. 埋深2 385.42 m，灰黑色粉砂质泥岩；d. 埋深2 402.55 m，灰黑色炭质泥岩

证。五峰组-龙马溪组页岩处于高-过成熟阶段且天然气化学组分以甲烷为主（97.22%～98.47%）[42]，结合1.2节的前提条件假设五峰组-龙马溪组页岩有机孔隙被甲烷饱和，所以流体声波时差值为249.326 μs/ft。由于粘土矿物成分复杂，粘土矿物声波时差较难确定，龙马溪组顶部⑧小层泥岩段粘土含量高、有机质含量低（可忽略），据此本文借用该段页岩声波时差作为五峰组-龙马溪组粘土矿物声波时差（约为73.152 μs/ft）。硅质矿物的声波时差值采用理论值55.474 μs/ft。五峰组-龙马溪组页岩有机质含量、有机孔孔隙度、粘土矿物含量和石英含量的计算均参考文献[43]，其中有机质含量、粘土矿物含量和石英含量的计算结果均利用实测值进行校正。上覆地层压力根据单井密度测井值确定（表1）。焦石坝地区8口井的6 114个声波时差数据用于建立五峰组-龙马溪组页岩正常压实曲线（图5），其中每口井采用不同的GR阈值以去除砂岩及碳酸盐岩层段的影响（表1）。由于五峰组-龙马溪组页岩经历过不同程度的抬升[36]，本次研究采用外包络线代表五峰组-龙马溪组页岩正常压实曲线（公式8），由此可计算不同深度正常压实的声波时差值。

焦石坝背斜五峰组-龙马溪组页岩正常压实趋势与深度的拟合公式：

$$\Delta t_n = \left[\ln(D/295\,708)\right]/(-0.085) \qquad (8)$$

式中：D为埋藏深度，m。

2.2.2　压力计算结果及验证

涪陵页岩气田五峰组-龙马溪组富有机质页岩孔

表1　四川盆地涪陵页岩气田五峰组-龙马溪组富有机质页岩相关参数

Table 1　Parameters of the Wufeng-Longmaxi organic-rich shale in Fuling shale gas field, Sichuan Basin

井名	上覆地层密度/(g·cm^{-3})	GR阈值/API	地层压力/MPa	总孔隙度/%	有机孔孔隙度/%
焦页A井	2.67	105	36.62	5.08	2.83
焦页B井	2.68	105	40.79	4.00	1.30
焦页C井	2.69	90	34.91	4.23	2.43
焦页D井	2.65	80	38.47	3.66	1.85
焦页E井	2.71	75	30.46	1.18	1.09
焦页F井	2.71	80	39.17	2.68	0.77

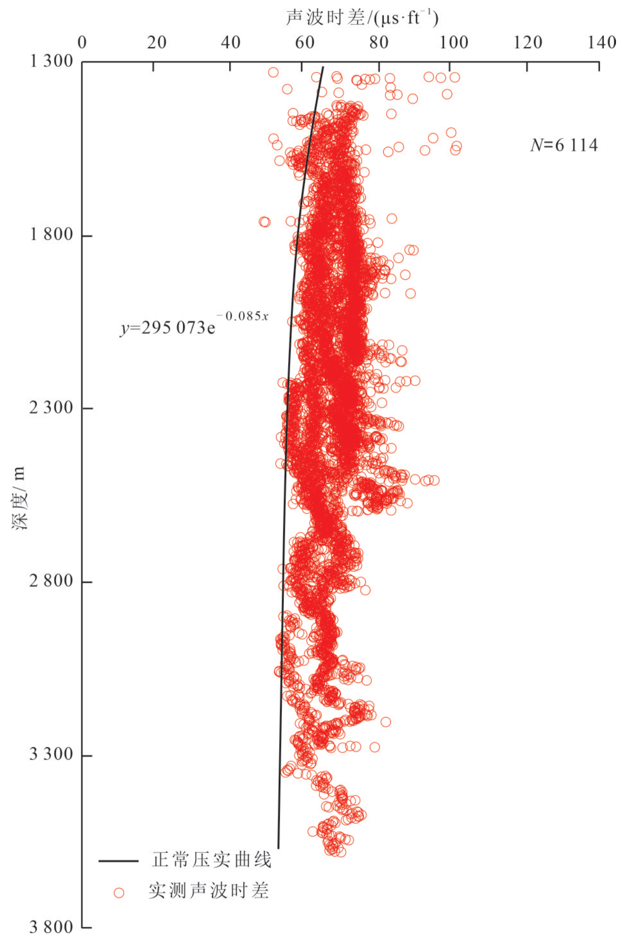

图5　四川盆地涪陵页岩气田五峰组-龙马溪组页岩压实趋势

Fig. 5　Compaction trend of the Wufeng-Longmaxi shale in Fuling shale gas field, Sichuan Basin

隙压力计算结果表明，本文所提出方法的计算结果与实测压力相关性较好（R^2=0.81）且变化趋势一致（拟合曲线斜率更接近1）（图6a），而原始方法计算结果与实测值拟合程度较差（R^2=0.55）且二者的变化趋势存在差异（图6b）。此外，进一步对比两种计算结果的误差可知，新方法的计算误差相对较小且符合正态分布的

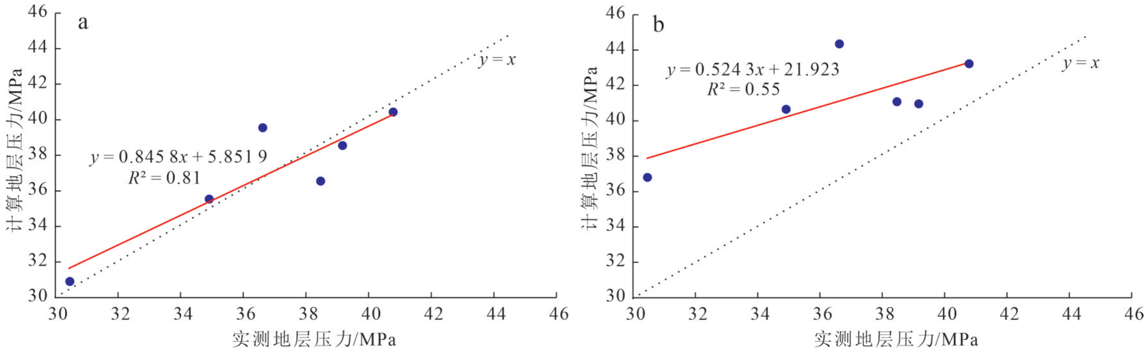

图6　新方法(a)和传统方法(b)计算的四川盆地涪陵页岩气田五峰组-龙马溪组储层压力与实测结果对比

Fig. 6　Comparison between the calculated and measured reservoir pressure in the Wufeng-Longmaxi shale in Fuling shale gas field, Sichuan Basin

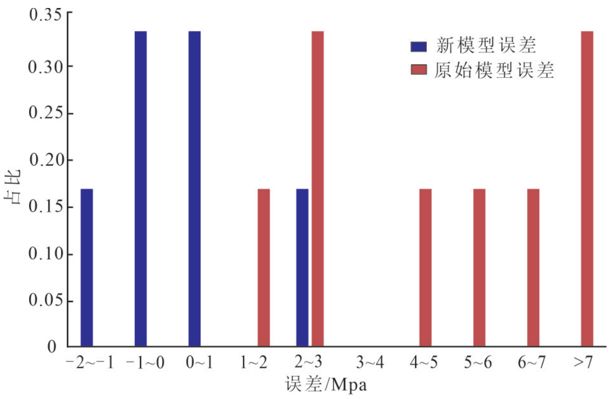

图7　新模型和原始模型计算结果误差对比

Fig. 7　Error comparison of calculated results between the new and original models

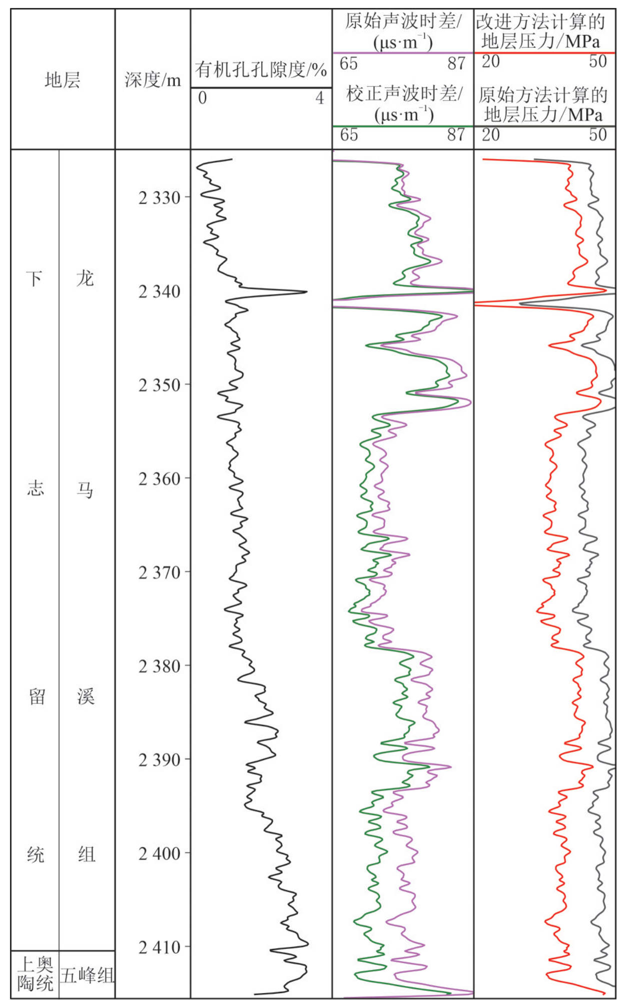

图8　四川盆地焦页A井五峰组-龙马溪组孔隙压力计算结果

Fig. 8　Results of calculated pressure of the Wufeng-Longmaxi shale reservoirs in Well Jiaoye A, Sichuan Basin

特征(图7)。由此证实,本文所提出的方法可以用于评价和预测海相富有机质页岩储层压力。

图8对比了新模型与原始Eaton模型计算的焦页A井五峰组-龙马溪组页岩储层压力特征:有机孔隙发育程度越高,原始声波时差和校正之后的声波时差差异越大,从而导致储层压力差异越大。以五峰组-龙马溪组底部页岩(埋深2 395~2 415 m)为例,计算结果的差值介于1.76~6.37 MPa,平均值为4.54 MPa。由此说明,对于有机孔隙发育程度较高的海相页岩,有必要考虑有机孔隙发育对压力预测的影响。

利用该方法计算了焦石坝一期产建区30口井五峰组-龙马溪组①—③小层页岩储层压力,并据此预测了该地区压力分布规律(图9)。整体而言,五峰组-龙马溪组地层压力在研究区中部相对较高,靠近南部乌江断裂、东南部大耳山西断裂、西部吊水岩-天台场断裂等区域相对较低,这与前人研究认为该地区五峰组-龙马溪组页岩气保存条件相关[1-2]。

为了进一步验证预测压力的可靠性,本文采用一点法计算单井页岩气无阻流量(代表单井产能)[44],并对比了预测地层压力与无阻流量的相关关系(图10)。结果表明,单井无阻流量随地层压力的增大而增加,二者具有良好的正相关关系,由此推测本文所提出的页岩储层压力预测方法具有较高的可靠性。

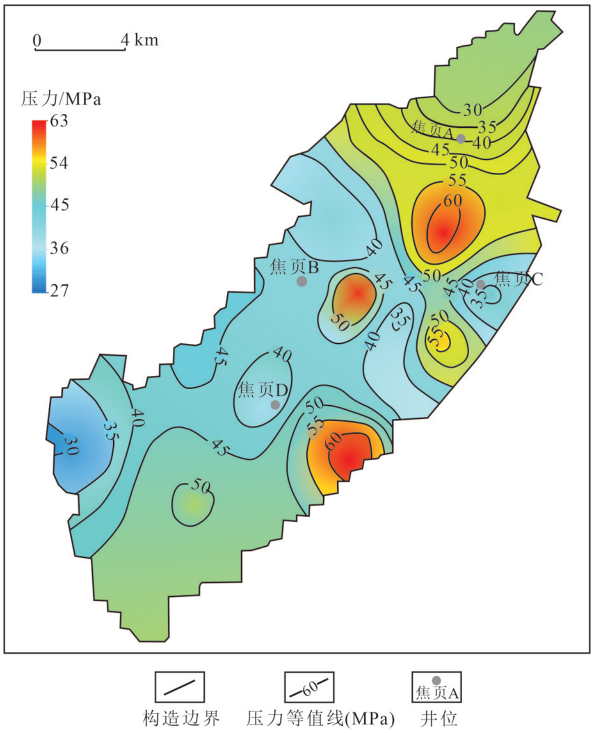

图9　四川盆地焦石坝一期产建区五峰组-龙马溪组①—③小层富有机质页岩压力预测结果

Fig. 9　Pressure prediction of ①-③ intervals in the Wufeng-Longmaxi organic-rich shale in Phase I Production Zone in Jiaoshiba area, Sichuan Basin

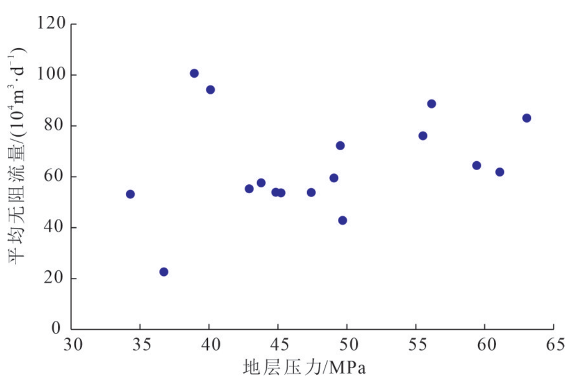

图10　四川盆地焦石坝一期产建区五峰组-龙马溪组①—③小层预测孔隙压力与页岩气产能对比

Fig. 10　Predicted pressure vs. production capacity of ①-③ intervals in the Wufeng-Longmaxi organic-rich shale in Phase I Production Zone in Jiaoshiba area, Sichuan Basin

3　讨论

本文在前人研究基础上考虑富有机质页岩有机孔隙发育对储层压力预测的影响,并提出了海相页岩储层压力评价方法。运用该方法评价了涪陵页岩气田五峰组-龙马溪组页岩储层压力,并证实了评价方法的必要性和可靠性。国内外学者已经对异常压力成因机制展开了大量研究,并进行了全面总结,将超压成因机制分为三大类:压应力增加(压实不均衡和构造挤压)、孔隙或者岩石骨架体积改变(生烃作用和烃类裂解成气、粘土矿物脱水、水热增压等)、流体流动或者浮力作用[45-56]。该方法是以页岩储层中有机孔隙和异常压力共存为假设条件建立的页岩储层压力预测方法,主要针对生烃增压所造成的异常高压。目前关于异常压力研究主要集中于成因机制的判断,而定量表征不同成因机制的异常压力的方法相对较少,Eaton方法以有效应力概念为依据,主要用于计算与孔隙度异常相关的压力成因机制(如欠压实),因此利用该方法计算生烃增压造成的异常压力会存在一定的误差[54]。但目前由于测试数据有限,该方法需要更多数据进行验证。

富有机质页岩的声波测井是对多种地质因素的综合响应,如异常高压、有机质富集和含油气性等因素都可能造成声波时差异常[55-56],其中有机质含量是影响页岩中声波速度的重要因素,因此有必要考虑有机质所造成的声波时差异常。但本文所提出的模型没有单独计算有机质造成的声波时差异常[公式(2)和(3)],这是因为本文主要考虑有机孔隙发育对异常压力评价的影响,因此将有机质视为特殊“矿物”,将其对声波时差的影响考虑在正常压实曲线当中。此外,富有机质页岩中有机质的赋存状态比较复杂,多与粘土矿物共生且紧密结合,形成有机质-粘土矿物复合体[57]。声波在其中传播具有一定的复杂性,目前尚无明确报道[58]。因此该方法没有考虑有机质的声波响应,由此可能造成一定的计算误差。

4　结论

1) 在前人研究的基础上提出了一种适用于海相富有机质页岩的储层压力预测方法,该方法以有机孔隙和异常压力共存为前提,计算了有机孔隙的声波测井响应,并对声波测井曲线进行了校正,建立了新的压力预测模型。

2) 以涪陵页岩气田为例对新方法进行了验证。计算结果表明,相对于原始计算方法,该方法的计算结果与实测压力数据拟合程度更高,计算误差相对较小且符合正态分布,由此说明该方法适用于海相页岩储层压力预测。预测的焦石坝一期产建区地层压力总体具有背斜中间高、周缘低、东南侧局部具有高值的特征,该结果与无阻流量具有良好的相关性,进一步证实了该方法的可靠性。

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(编辑 张 晟)