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西湖凹陷K气田薄煤系地层声波测井曲线拟合及应用

王瑞, 刘舒, 郝伟航, 严曙梅, 徐晨, 吕鹏

(中国石化上海海洋油气分公司 上海 200120)

摘要: 东海陆架盆地西湖凹陷是一个规模较大的中—新生代含油气凹陷, 蕴藏着丰富的油气资源。但该地区含煤地层普遍发育, 平北斜坡带含油气地层平湖组发育受潮汐影响三角洲沉积, 以砂、泥、煤薄互层沉积为特征。其中, 煤层伴随砂体发育且厚度薄, 岩性以砂泥岩互层夹煤为主, 具有单层厚度较薄、层数多、横向变化快等特征。薄煤层在煤层段测井曲线呈现出异常的低速、低密度、高中子测井值、高电阻率等特征, 常规声波测井曲线参与反演时, 会降低砂体预测准确性。因此, 如何消除煤层影响, 精确识别砂体是亟须解决的问题。基于对煤层段测井曲线特征分析, 提出了一种针对煤系地层的声波拟合测井曲线方法。该方法依据钻井资料、录井认识和岩心分析数据, 将地层划分为煤层段和非煤层段。非煤层段采用常规碎屑岩岩石物理建模方法测井曲线拟合方法; 煤层段运用经验公式统计回归方法进行曲线拟合。随后, 将煤层段和非煤层段拟合结果进行整合与匹配。拟合后的声波纵波速度曲线校正了因煤层井径坍塌导致的异常值, 原始曲线与拟合的声波纵波速度曲线相关系数为0.82, 应用拟合校正后的声波纵波速度曲线参与反演, 可精细刻画砂体。该气田应用结果表明: 基于该方法拟合校正的声波纵波速度曲线参与反演, 能有效预测砂体, 预测结果与钻井吻合度高, 有助落实岩性—构造圈闭。本研究为薄煤系地层储层预测提供了一种有效方法, 通过对声波测井曲线煤层段与非煤层段分别拟合, 排除煤层干扰, 从而达到高精度砂体预测的目的。

关键词: 声波测井曲线拟合; 薄煤系地层; 煤层段; 统计回归; 反演

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Acoustic logging curve fitting and its application in thin coal measure strata of K gasfield in Xihu Sag

WANG Rui, LIU Shu, HAO Weihang, YAN Shumei, XU Chen, LYU Peng

(Sinopec Shanghai Offshore Oil & Gas Company, Shanghai 200120, China)

Abstract: The Xihu Sag in the East China Sea Shelf Basin is a large Mesozoic–Cenozoic oil and gas-bearing sag with abundant oil and gas resources. However, coal-bearing strata are widely developed in this area. In the Pingbei slope zone, the oil and gas-bearing Pinghu Formation strata develop tide-influenced deltaic deposits, characterized by thin interbedded layers of sandstone, mudstone, and coal. The coal seams are thin and develop along with sand bodies. The lithology is mainly dominated by sandstone–mudstone interlayers interbedded with coal, featuring thin single layers, multiple layers, and rapid lateral changes. The thin coal layers in the coal seam section show abnormal features in logging curves, including low velocity, low density, high neutron values, and high resistivity. When conventional acoustic logging curves are used for inversion, the accuracy of sand body prediction is reduced. Therefore, eliminating the influence of coal seams and accurately identifying sand bodies has become an urgent issue. Based on an analysis of the logging curve characteristics of coal-bearing sections, a fitting method for acoustic logging curves in coal measure strata was proposed. Using drilling data, logging observations, and core analysis, the strata were divided into coal-bearing sections and non-coal sections. For non-coal sections, a petrophysical model was constructed for logging curve fitting, which was commonly applied in conventional clastic rock analysis. For coal-bearing sections, fitting was carried out using statistical regression techniques based on empirical formula methods. Subsequently, the results for coal-bearing and non-coal sections were matched and combined. The fitted acoustic primary wave velocity curve corrected the abnormal values caused by borehole collapse in coal seams. The correlation coefficient between the original curve and the fitted curve was 0.82. The fitted and corrected velocity curve was then used for inversion to delineate sand bodies. Application in a gasfield showed that the fitted and corrected acoustic primary wave velocity curve based on this method effectively

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第一作者简介: 王瑞(1984—), 女, 硕士, 副研究员, 主要从事油气地球物理与油气勘探开发综合研究。地址: 上海市浦东新区商城路1225号, 邮政编码: 200120。E-mail: wangr.shhy@sinopec.com

通信作者简介: 刘舒(1988—), 女, 硕士, 副研究员, 从事海洋油气开发地质研究。地址: 上海市浦东新区商城路1225号, 邮政编码: 200120。E-mail: liushu.shhy@sinopec.com

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predicted sand bodies in inversion, and the prediction results were consistent with drilling data, proving useful for identifying lithologic structural traps. This study provides an effective method for reservoir prediction in thin coal measure strata. By separately fitting the acoustic logging curves of coal-bearing and non-coal sections, the interference from coal seams is eliminated, and high-precision sand body prediction is achieved.

Keywords: acoustic logging curve fitting; thin coal measure strata; coal seam section; statistical regression; inversion

东海陆架盆地西湖凹陷是规模较大的中—新生代含油气凹陷^[1-4],蕴藏着丰富的油气资源。该地区含煤地层普遍发育,平湖组为一套海陆过渡相的薄煤系地层,岩性主要为砂岩、泥岩互层夹煤^[5-6],煤层具有单层厚度薄、层数多、横向变化快等特征^[7]。沈玉林等^[8]基于岩心、地球化学、地震、测井等数据,认为同沉积断层活动是该区煤层薄、层数多的主要原因。谢国梁^[9]利用测井数据、地球化学等资料进行平湖组含煤地层旋回划分的研究,认为成煤泥炭沼泽不稳定性导致煤层分布范围小和厚度薄。张功成等^[10]认为中国近海新生代叠合断陷煤层主要形成于古新世—渐新世,其识别方法主要有测井资料多方法综合识别和地震多属性线性回归等技术系列。蒲仁海等^[11]分析储层、泥岩和煤层测井参数,对比取心和测井曲线,对测井岩性识别统计,地震岩性反演恢复沉积相和古坡度等手段,表明平湖组围岩存在煤层、暗色泥岩和碳质泥岩。杜玉山等^[12]基于匹配追踪去除煤层强反射。王红岩等^[13]在沉积认识的基础上,进行岩石物理分析,利用波形指示反演和模拟技术剔除储层中薄煤层干扰,进行含油气储层预测,结果表明平湖组煤层厚度约为1 m,煤层间隔约为5 m。袁悦等^[14]通过地球物理半定量解释定位煤层、地震高幅滤波过滤煤层、多子波分解重构置换煤层等方法,在尽可能保留有效地震反射信息的基础上,去除煤层强反射对地震信号的影响。以上识别煤层再剔除煤层的方法在煤系地层储层预测流程体系中较为常用,然而,当煤层厚度小于1 m时,受限于常规地震分辨率,剔除煤层的过程可能干扰储层的识别。

目前,测井曲线拟合常用的方法有经验公式法和岩石物理曲线拟合法^[15-16]。GREENBERG等^[17]提出了基于经验公式的纵横波关系式,根据岩石样品纵波速度和横波速度测量数据和测井数据,应用统计方法建立了横波速度预测方法。已有的经典经验公式有Castagna公式^[18]、Han公式^[19]等,经验公式法针对性较强,不同地区、不同岩性的经验公式各异,相比于理论建模的岩石物理方法,经验关系式能更简单地描述岩石速度曲线与其他参数间的数学关系,计算岩石速度曲线也更直接。岩石物理建模方法是针对某种岩石物理特征提出的模型,再推广到具有类似岩石物理特征的储层,因此,构建岩石物理模型的测井速度曲线拟合方法在应用中更具针对性,主要应用于碎屑岩或者碳酸盐岩等常规储层的研究。在岩石物理建模方面,前人针对矿物岩性、孔隙结构、流体性质等做了大量研究^[20-22],目前对煤系地层进行岩石物理建模方面的研究还比较少见,对于含煤储层,已有学者

进行岩石物理建模,周琦等^[23]利用自洽模型耦合煤的影响,将煤层以包含物的形式加入背景介质中,利用模拟退火全局寻优算法实现煤系地层中横波速度预测。汤红伟^[24]通过测井解释获得煤层顶板岩性的体积模型,再应用Xu-White方法建立岩石物理模型,模拟出岩石的纵波速度测井曲线。上述2种曲线拟合方法都较为直观,但对数据的要求较高,花费的时间较长。将测井曲线分为煤层段与非煤层段分别拟合:煤层段基于已有的研究区井数据,采用经验公式法的统计回归技术进行拟合。非煤层段应用Xu-White方法建立岩石物理模型进行声波测井曲线拟合。这样可以在有限的基础数据条件下,声波测井曲线能够准确地反映研究区的地层特性。

1 地质背景

西湖凹陷(图1)经历了早期断陷、中期拗陷和晚期整体沉降3个阶段^[25-27],呈现出东西分带,南北分块的构造特征。新生代碎屑岩沉积为主,自下而上发育宝石组、平湖组、渐新统花港组,中新统龙井组、玉泉组。

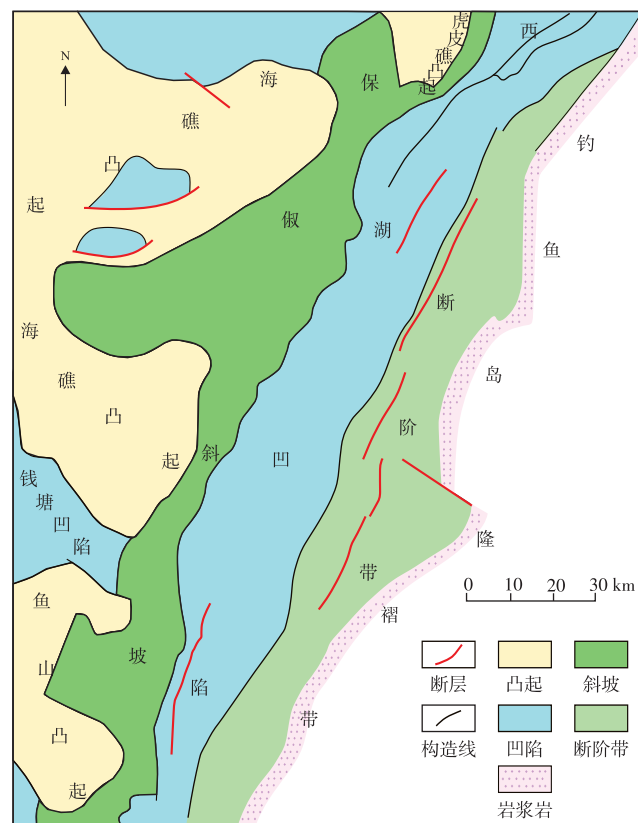


图1 东海陆架盆地西湖凹陷区带划分

Fig. 1 Zoning division of Xihu Sag, East China Sea Shelf Basin

研究区K气田构造位于西湖凹陷平湖斜坡带中北部的1个鼻状隆起上,面积约为300 km²。平湖组为一套发育于潮控三角洲-潮坪环境的薄互层煤系地层^[28],围岩岩性有泥岩、碳质泥岩和煤。测井解释(图2)表明,煤层普遍伴随砂层发育,具有厚度薄,数量多的分布特征。目前,仅有6口探井地层揭示较全,基础参数有限。

2 薄煤层特征分析

基于张尚虎等^[29]、刘道燕^[30]、蒋一鸣等^[31]的研究成果,总结如下:平湖组下段(以下简称平下段)以受潮汐作用控制的三角洲沉积体系为主,岩心观察显示砂岩发育典型的潮汐层理(图3a),煤层形成于受潮汐影响的三角洲泥炭坪环境,岩性组合以灰色泥岩、粉砂质泥岩为主,夹多套薄煤层,煤层空间上常与砂体伴生,发育于砂体顶部或底部(图2);平湖组中—上段(以下简称平中—上段)沉积体系以河控三角洲为主,煤层多发育于河控三角洲平原环境中的泥炭沼泽沉积环境。岩心可见砂岩粒度变粗,部分层段发育

浅灰色含砾中—粗砂岩,长轴向排列,见冲刷面(图3b)。

统计研究区每百米煤层数量和厚度:平湖组下段(以下简称平下段)每百米发育8套煤层,累计厚度为6.3 m,即平均单煤层厚度为0.79 m;平湖组中段(以下简称平中段)每百米发育6套煤层,累计厚度为4.5 m,即平均单煤层厚度为0.75 m。统计结果表明,研究区煤层呈现出数量多、厚度薄的特征。

在煤层段,井径曲线表现出异常值,即煤层段存在一定程度的井径垮塌。该垮塌导致煤层在1 m厚度内出现测井曲线异常,即异常的声波速度。结果显示:砂岩储层的声波速度平均为4 300 m/s,而煤层段的声波速度均值为2 800 m/s,显著低于砂岩段。此外,该储层段还表现出低密度、异常高中子测井值和高电阻率等特征。该声波测井的异常导致基础数据的不可信,使用未校正声波测井曲线进行井震标定,相关系数约为0.73。因此,若直接利用这种未经校正的声波测井曲线构建低频模型参与反演,将导致后续储层参数预测精度降低。

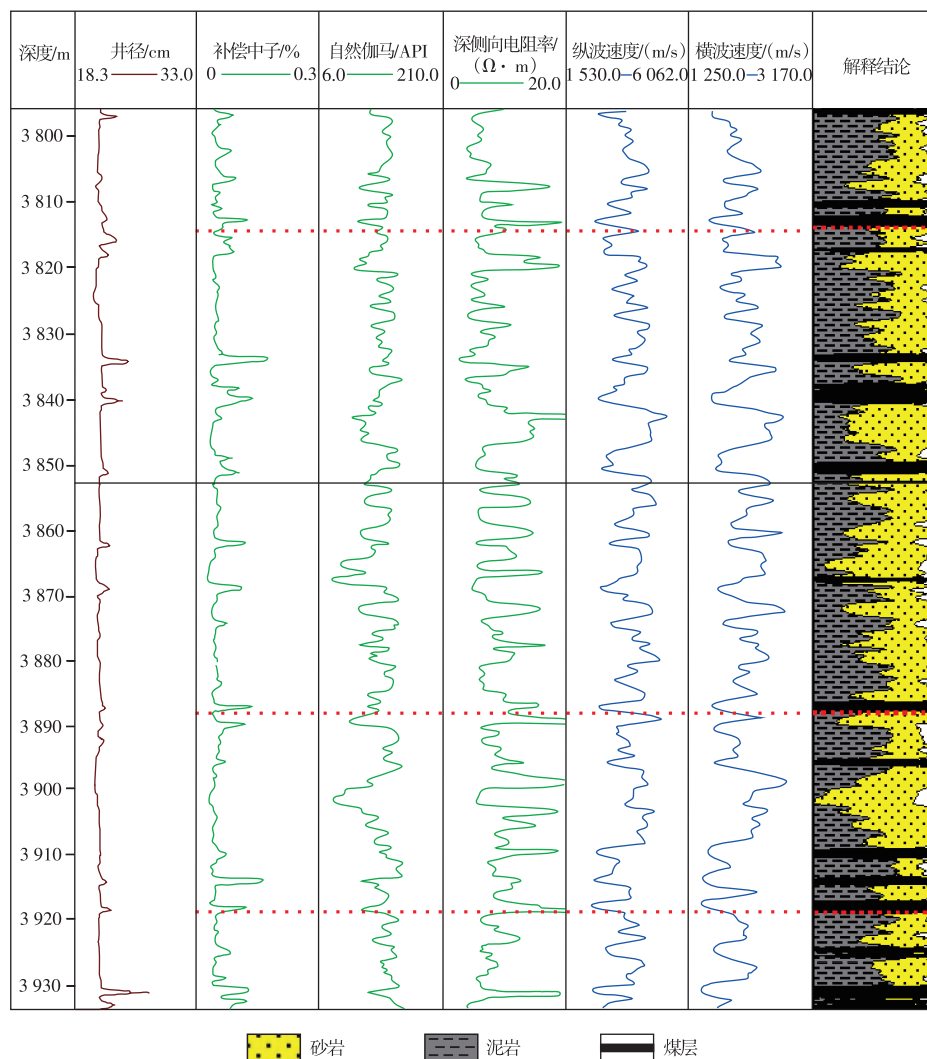


图2 东海陆架盆地西湖凹陷K气田煤层测井曲线特征

Fig. 2 Characteristics of coal seam logging curves of K gasfield, Xihu Sag, East China Sea Shelf Basin

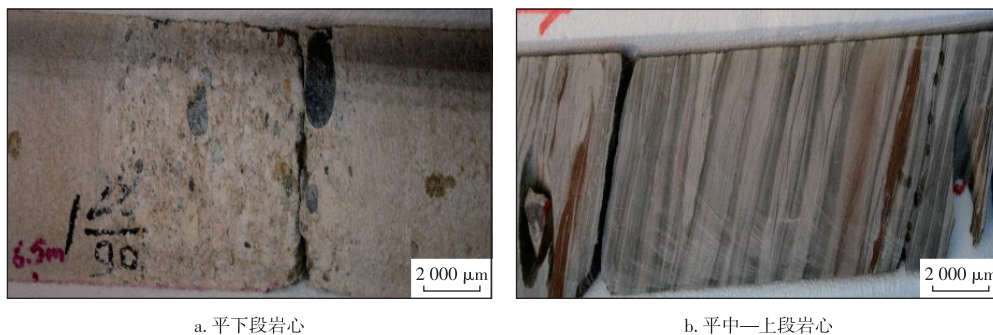


图3 东海陆架盆地西湖凹陷K气田研究区主要目的层岩心特征

Fig. 3 Core characteristics of main target seams in study area of K gasfield, Xihu Sag, East China Sea Shelf Basin

3 针对薄煤系地层的声波测井曲线拟合方法

根据煤层段的异常测井曲线,如低速、低密度、高中子测井值和高电阻率等,提出了一种针对煤系地层的声波测井曲线拟合方法,通过该方法拟合校正声波测井曲线。依据钻井资料、录井认识、岩心分析数据将地层分为煤层段和非煤层段(图4)。其中,非煤层段为砂泥岩地层段,煤层段为煤层发育地层段,平均厚度为1 m。非煤层段和煤层段分别采用岩石物理法和经验公式法进行拟合。

非煤层段是碎屑岩地层主体,以碎屑岩储层为研究对象,运用经典Xu-White模型,使用等效介质岩石物理模型进行构建。Xu-White模型基于Kuster-Toksoz理论,Gassmann方程和有效差分介质理论基础上,采用孔隙度与泥质含量来进行纵波速度预测的砂-泥混合介质模型,其应用依据是考虑岩石总孔隙包括砂岩颗粒和泥岩颗粒有关孔隙。

对于煤层段而言,常规经典Xu-White模型将石英和黏土作为碎屑岩的背景矿物,未考虑地层含煤对参数的影响,在煤层段,存在因井径垮塌引起的曲线异常,Xu-White模型并不适用煤层段声波测井曲线拟合。因此,基于标准井的其他测井曲线和速度测井曲线的相关性,采

用经验公式统计回归算法,拟合声波测井曲线。

标准井、标准地层段的确定,对比录井和测井数据,筛选井径垮塌较小段作为标准地层段。通过标准地层段内声波测井曲线和其他测井曲线的交汇分析得到二者相关系数,研究区内煤层的声波速度与补偿中子、自然伽马、自然电位、深侧向电阻率均呈现出一定的相关性,相关系数分别为83.90%、59.48%、32.40%、23.59%。经过多次试验,结果表明:采用三项式对原始曲线进行拟合,相较于二项式拟合,具有更高的相关性。因此,选取相关系数排名前三位的曲线进行公式拟合,基于补偿中子、自然伽马、自然电位这3条曲线,运用经验公式统计回归方法,构建煤层段声波纵波速度曲线。

根据统计回归法确定煤层段声波测井曲线回归关系式,得到煤层段的声波纵波速度曲线计算公式:

$$v_p = 4855.28 - 3789.6A_{\text{CNL}} - 1.72579B_{\text{GR}} - 3.58648C_{\text{SP}} \quad (1)$$

式中: v_p 为声波纵波速度,单位m/s; A_{CNL} 为补偿中子,%; B_{GR} 为自然伽马,单位API; C_{SP} 为自然电位,单位mV。

基于上述关系式计算获得煤层段校正后的纵波声波速度曲线,通过分段匹配整合煤层段与非煤系地层的速度曲线,最终构建适用于煤系地层的校正后纵波声波速度模型(图5)。通过标准井验证该方法,原始曲线和拟合声波纵波速度曲线在非煤层段相关系数为0.80,煤层

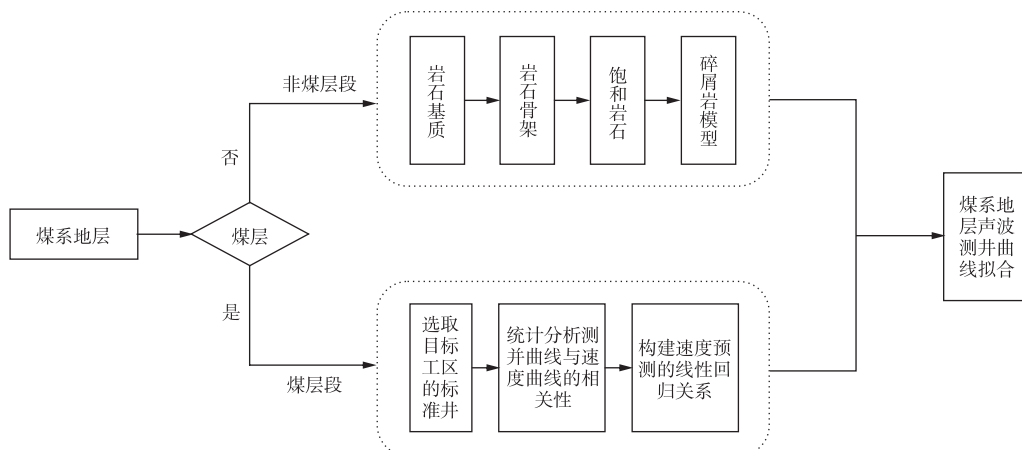


图4 东海陆架盆地西湖凹陷K气田煤系地层声波测井曲线拟合方法

Fig. 4 Acoustic logging curve fitting method for coal measure strata of K gasfield, Xihu Sag, East China Sea Shelf Basin

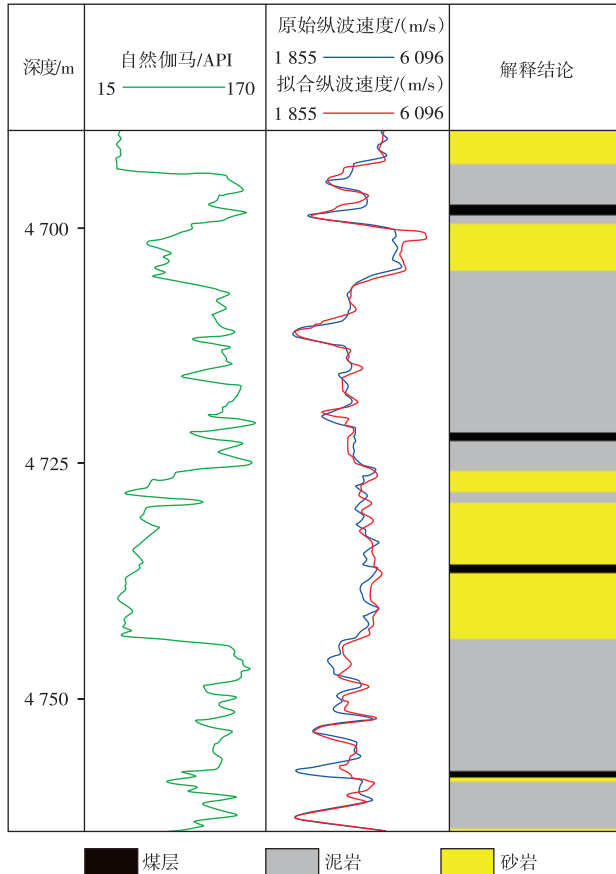


图5 东海陆架盆地西湖凹陷K气田煤系地层声波测井曲线拟合

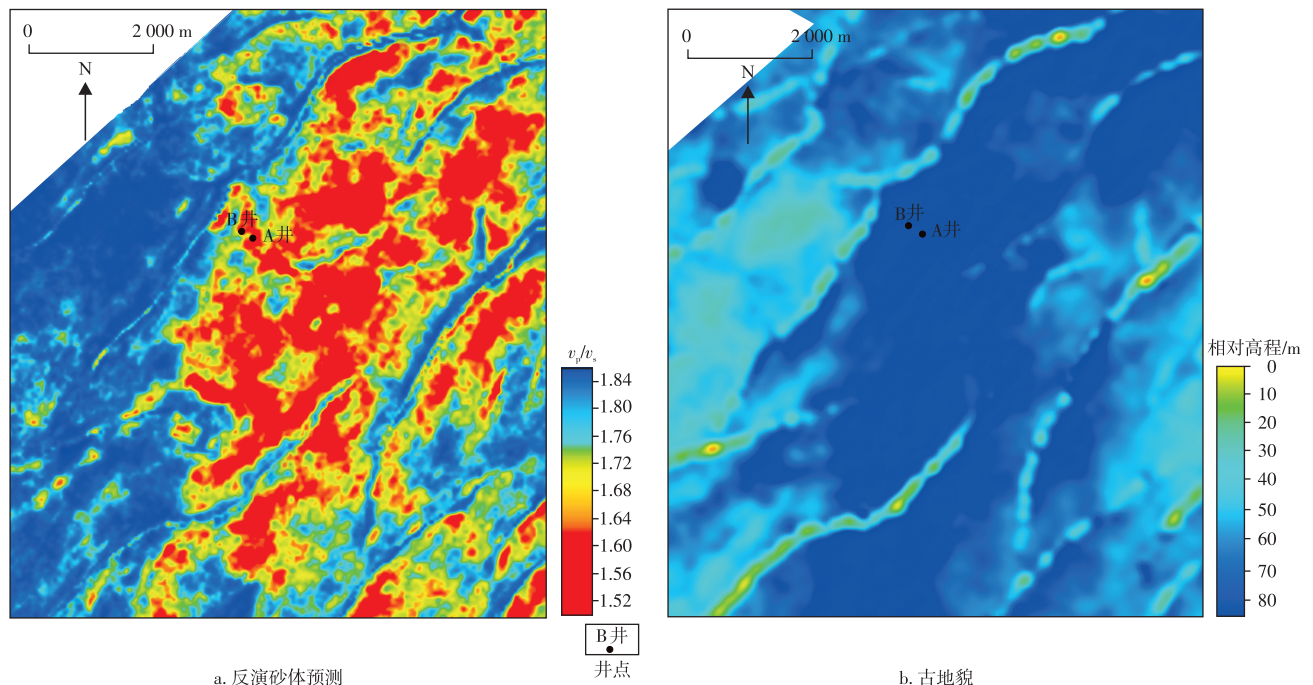
Fig. 5 Acoustic logging curve fitting for coal measure strata of K gasfield, Xihu Sag, East China Sea Shelf Basin

段相关系数为0.90,全井段相关系数为0.82。相较于未考虑煤层效应的常规岩石物理模型,全井段相关系数提升0.03,有效消除了煤层段因有机质富集和裂隙发育导致的声波速度异常。选取研究区合成记录标定较好的井的声波测井曲线进行拟合误差分析,平均绝对误差(MAE)在0.040~0.065 km/s之间,平均相对误差(MRE)约为1.67%,均低于行业标准容许阈值(平均绝对误差小于0.1 km/s,平均相对误差小于3%),验证了此方法的可靠性。

平湖组围岩岩性包括煤层、暗色泥岩和碳质泥岩,不同岩性在校正程度上也存在差异。较纯煤层声波速度偏低,低至2 800 m/s,校正程度较大,碳质泥岩本身低速异常较弱(速度为3 225 m/s),校正幅度较小。上述方法拟合声波纵波速度曲线,去除了煤层引起的声波速度异常,井-震标定相关系数从0.73上升至0.76,将拟合的声波纵波速度曲线用于常规反演进行应用验证。

4 应用效果

西湖凹陷K气田已证实为具有一定规模的岩性圈闭群,已部署4口开发井,平中段均钻遇单层20 m以上厚气层,单井日产天然气量超 $50 \times 10^4 \text{ m}^3$ 。采用拟合方法校正后的声波测井曲线参与常规叠前确定性反演。反演砂体预测(图6a)在古地貌低洼区(图6b),清晰见水下分流河道。其中,A井和B井位于一级卸载区,砂体规模较小,具一定展布规模,发育三角洲前缘(水下)分流河道,易发



注: v_p/v_s 为纵波速度与横波速度之比。

图6 东海陆架盆地西湖凹陷K气田基于煤系地层测井曲线拟合数据的砂体预测

Fig. 6 Sand body prediction based on fitted data of coal measure strata logging curves of K gasfield, Xihu Sag, East China Sea Shelf Basin

育规模构造-岩性气藏。A井钻遇16 m厚砂岩储层,间隔10 m发育1 m煤层; B井钻遇砂岩储层与干层互层20 m,其中,砂岩储层厚10 m,整体物性较差,间隔4 m发育1 m煤层。二者在地震剖面上都为强反射特征,不同

的砂煤组合在地震响应特征上没有明显的不同,与实际钻遇砂体厚度不吻合。反演结果显示:A井钻遇较好储层,为反演亮点; B井钻遇物性较差,砂体为较弱亮点响应,与实际钻遇吻合(图7)。

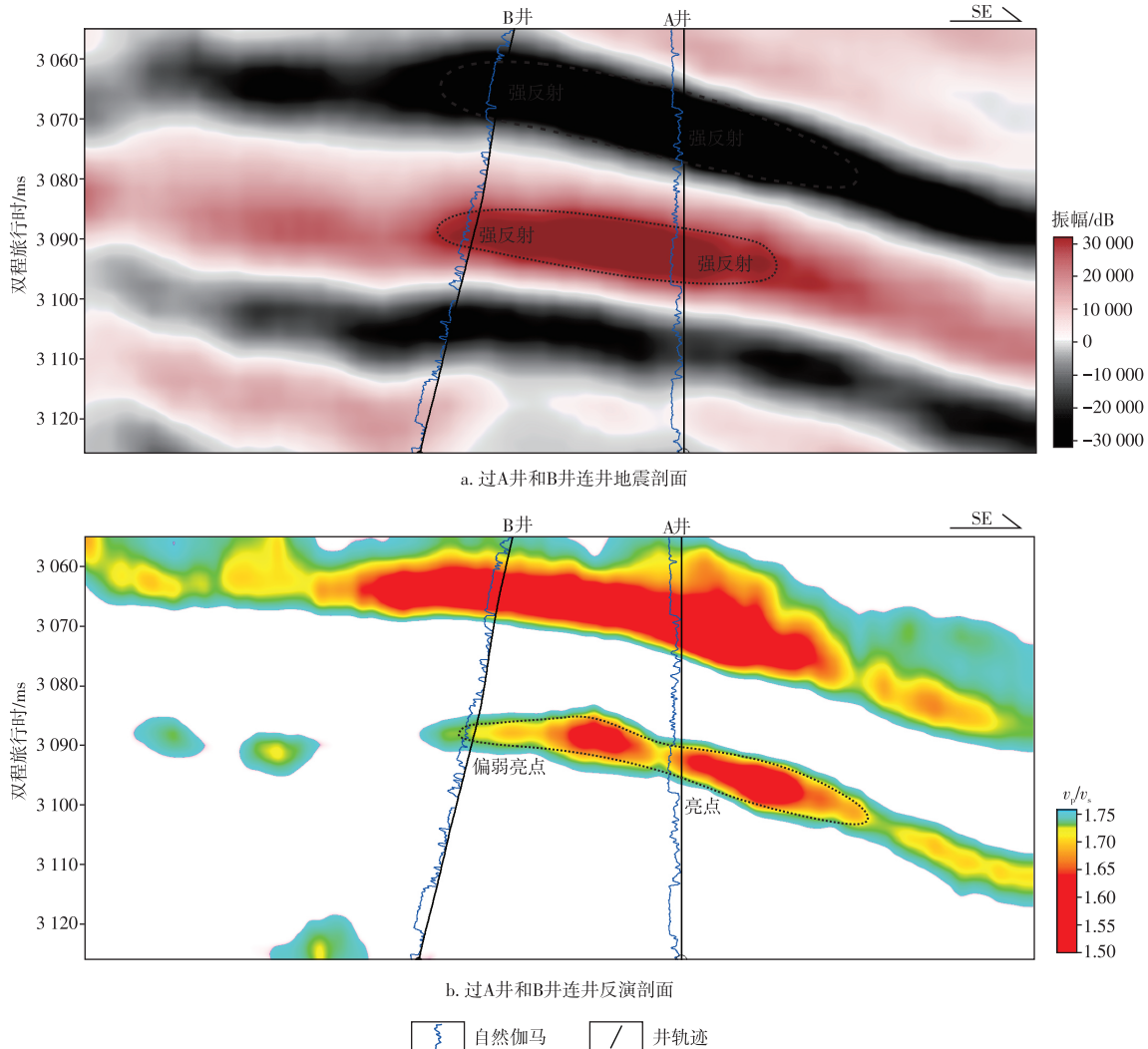


图7 东海陆架盆地西湖凹陷K气田地震和反演剖面特征

Fig. 7 Seismic and inversion profile characteristics of K gasfield, Xihu Sag, East China Sea Shelf Basin

5 结论

1) 研究区平湖组为受潮汐影响三角洲及潮坪沉积的一套薄煤系地层,通过井上分析认为煤层普遍发育,且厚度薄,小于1 m。煤层段声波测井曲线表现为井径垮塌导致的测井曲线异常,需要校正。

2) 基于薄煤层分析提出一种针对薄煤系地层的声波测井曲线拟合方法。该方法将测井曲线分为非煤层段和煤层段:非煤层段采用常规碎屑岩岩石物理建模测井曲线拟合方法;煤层段采用经验公式统计回归方法进行曲线拟合。将拟合后的煤层段和非煤层段匹配结合,最终获得声波纵波速度曲线校正了煤层由于井径垮塌引起

的异常值,提高数据可靠性。

3) 利用基于薄煤系地层的声波测井曲线拟合方法校正后的测井曲线建立低频模型参与反演,反演结果有效去除了储层预测时煤层的影响,精准刻画了不同岩性组合储层砂体。

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