·综合研究·　文章编号：1000－7210(2020)05-1102-08

声波时差长趋势脱压实校正

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赖生华，曹鉴华，张翠萍. 声波时差长趋势脱压实校正. 石油地球物理勘探，2020，55(5)：1102-1109.

摘要　延长气田 F 区储层沉积环境为三角洲前缘，压实作用导致储层具有低孔、低渗、非常致密的特征，其声波时差、密度与围岩差异较小，地球物理特征不明显，严重影响地震储层预测的可靠性和精度。为了减小或者部分消除压实作用对声波时差的影响，增大储层与围岩的声波时差(速度)差异，提出了声波时差长趋势脱压实校正方法。采用时频分析方法对原始声波时差曲线分频处理，以标准井的低频组分为标准，对 F 区所有井进行声波低频长趋势校正；然后与原有高频组分分频融合形成新的声波时差数据，完成声波时差长趋势脱压实校正，使储层与围岩的声波时差值重叠区域减小，提高了对储层的辨识精度。基于声波时差长趋势脱压实校正实施神经网络地震速度反演，获得了较高分辨率的声波速度反演剖面，精细预测了储层厚度。

关键词　压实作用　时频分析　声波时差长趋势　脱压实校正　储层预测

中图分类号：P631　**文献标识码**：A　**doi**：10.13810/j.cnki.issn.1000-7210.2020.05.018

0　问题的提出

储层反演是储层定量化分析和评价的关键技术手段[1]，其中地震和声波时差资料是必备的基础数据。声波时差资料常用于识别储层岩性和物性[2]，同时也是连接测井(深度域)与地震资料(时间域)的关键桥梁。一般情况下储层的声波时差特征明显(与围岩速度差异明显)，有助于获得高分辨率的反演剖面，为最终地质解释提供可靠的依据。

延长气田 F 区块二叠系岩性主要为砂、泥岩，储层以三角洲前缘沉积相为主。由于受沉积作用、压实作用、成岩改造等多种复杂地质因素影响，储层表现为低孔、低渗、非常致密的特征[3-5]，其声波时差、密度与围岩差异较小，地球物理特征不明显，严重影响地震储层预测的可靠性和精度(图 1)。如果直接使用声波时差曲线进行反演，反演成果将缺乏可靠的地质解释依据，严重影响储层预测精度。若能减小或者部分消除压实作用对声波时差(声波速度)的影响，将使储层(砂岩)与围岩(泥岩)的声波时差(速度)差异变大，有利于后续的地震反演处理和分析。通常的声波脱压实校正方法根据现今观测到的岩层的孔隙度—深度或密度—深度数据，利用统计方法建立岩层的孔隙度—深度函数，再根据地层骨架体积不变(或地层骨架密度不变)原理进行脱压实校正，恢复岩层的压实埋藏过程[6-8]。这种方法理论较为严谨，应用非常广泛，但操作过程复杂，影响因素多，而且往往无法获得准确的初始孔隙度值、精确的孔隙度—深度函数等。基于 F 区储层地震反演的实际情况，认为以传统地质过程分析为主的声波脱压实校正方法较为复杂，同时受限于该区现有的资料现状，实际可操作性较差。

声波分频重构是解决上述问题的一种方案，其做法是将对岩性敏感的测井曲线(如自然伽马)高频成分与声波原有低频组分融合重构，再利用重构声波曲线进行储层地震反演[9-10]，但该方案缺乏有力的地球物理理论支撑。为此，针对 F 区致密储层预测，本文提出了声波时差长趋势脱压实校正方法。

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本文于 2019 年 11 月 8 日收到，最终修改稿于 2020 年 7 月 2 日收到。

本项研究受国家自然科学基金项目“煤层对砂岩地震反射特征的影响及其地震岩性学意义——以鄂尔多斯盆地山 2 段为例”(41372118)、陕西省国际合作项目“基于极限学习机神经网络方法的储层地震反演预测——以鄂尔多斯盆地延长探区上古生界为例”(2018KW-010)及天津市教委项目“基于深度超限学习的地质目标建模与识别”(2018KJ-106)联合资助。

选用标准井对该区声波低频分量统一校正，然后将其与原有的高频分量融合形成新的声波时差曲线，并参与后续的储层多属性神经网络反演，获得了较好的应用效果[11-13]。

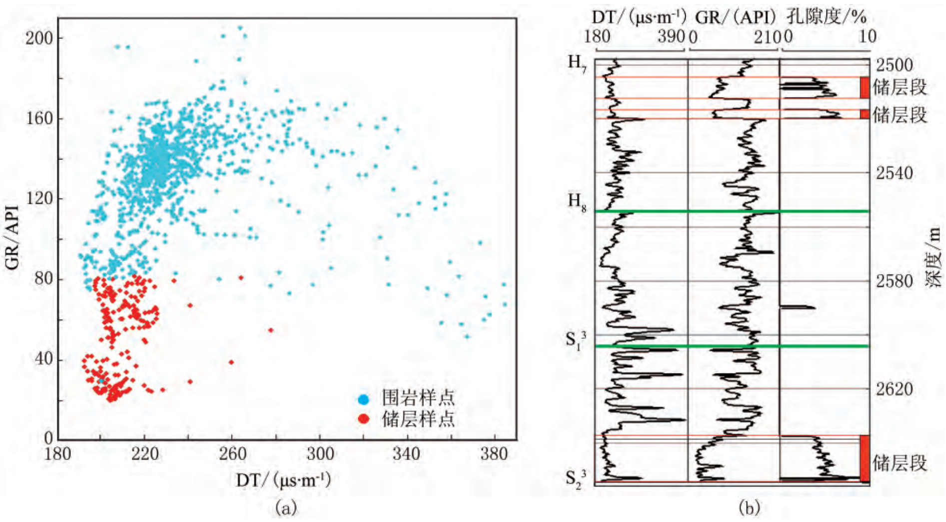

图 1　F 区 AN4 井目标层段储层的地球物理响应特征

(a)声波时差(DT)—自然伽马(GR)交会图；(b)AN4 井测井曲线

主力产层段下石盒子组盒 8 段和山西组的声波时差幅值范围为 180～390μs/m，储层样点具有明显低自然伽马、低声波时差特征，其声波时差幅值范围集中分布在 185～220μs/m，储层与围岩声波时差重叠范围较大。H_7 为中二叠统石盒子组 7 段底界，H_8 为中二叠统石盒子组 8 段底界，$S_1{}^3$ 为下二叠统山西组 1 段 3 亚段底界，$S_2{}^3$ 为下二叠统山西组 2 段 3 亚段底界

1　声波时差长趋势脱压实校正

当声波在地层中由浅入深传播时，传播速度受地层岩性、孔隙度、含流体性质及压实性等诸多因素的影响。在使用声波时差曲线时，除了直接利用其幅值变化特征外，还可将其转换到频率域并分析地层特征。通常声波时差低频组分曲线幅值变化较平缓，且随地层埋深增加而逐步增大，反映了地层的整体结构变化特征。中、高频组分曲线幅值变化相对剧烈，与地层中存在岩性突变、物性变化、含流体等地层因素有关[14-16]。

F 区目标层沉积环境为三角洲前缘，地层厚度变化相对稳定，同时山西组内发育了多套厚层泥岩，目标层整体较为致密。结合该区声波时差变化特征，认为压实作用对本区声波时差低频组分影响较大，适当校正声波时差超低频组分信息可以突显目标层中由于岩性、物性、流体等变化因素引起的高频组分特征，增大储层与围岩的速度差异，进而达到声波脱压实校正的目的。

为提高 F 区声波时差对砂岩储层的辨识精度，文中提出了基于时频分析的声波时差长趋势脱压实校正方法。首先对声波时差曲线进行时频分析。如今常用广义 S 变换、小波变换、匹配追踪等方法进行时频分析，并基于处理结果预测储层[14-16]。声波时差信号具有时间刻度单位(μs/m)，满足时序序列分析数据要求。与地震数据不同，声波时差曲线的时频分析无需过于复杂的变换手段。这里选用短时傅里叶变换方法，其表达式为

$$\mathrm{STFT}(t,f)=\int_{-\infty}^{\infty}\mathrm{e}^{-\mathrm{i}\omega t}f(\tau)g(t-\tau)\mathrm{d}t \qquad (1)$$

式中：$f(t)$为输入信号，t 为时间；$g(t-\tau)$为对称的时间窗函数，τ 为时移；ω 为角频率。

图 2 为 Y140 井声波速度低频分量、高频分量分离曲线。由图可见，低频分量变化平缓，高频分量呈频繁抖动、尖刺特征，这些变化特征反映了地层结构。图 3 为 Y140 井声波速度低频分量特征。由图可见，0～10Hz频段曲线明显反映了中、下部高速岩性段引起的速度变化，0～20Hz、0～30Hz 频段曲线对速度变化的响应更明显。经过对 0～10Hz 频段的低频分量进行扫描，发现 0～3Hz 的低频分量对中、下部高速岩性段引起的速度变化存在较弱响应，因此将0～2Hz 的低频速度作为声波时差长趋势低频分量。在上述声波时差曲线时频分析基础上，通过信号的频谱扫描，参考已有研究成果[17-18]，最终将 2Hz 以下频率成分的信号定义为低频声波时差长趋势分量。

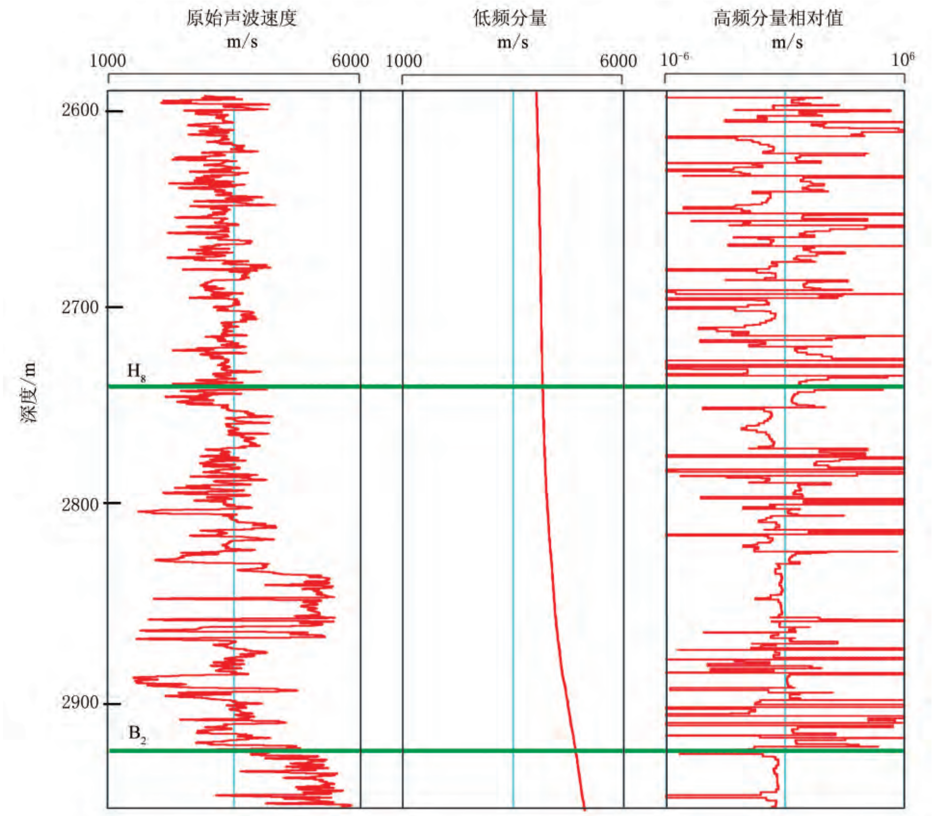

图 2 Y140 井声波速度低频分量、高频分量分离曲线

B_2 为上石炭统本溪组 2 段底界

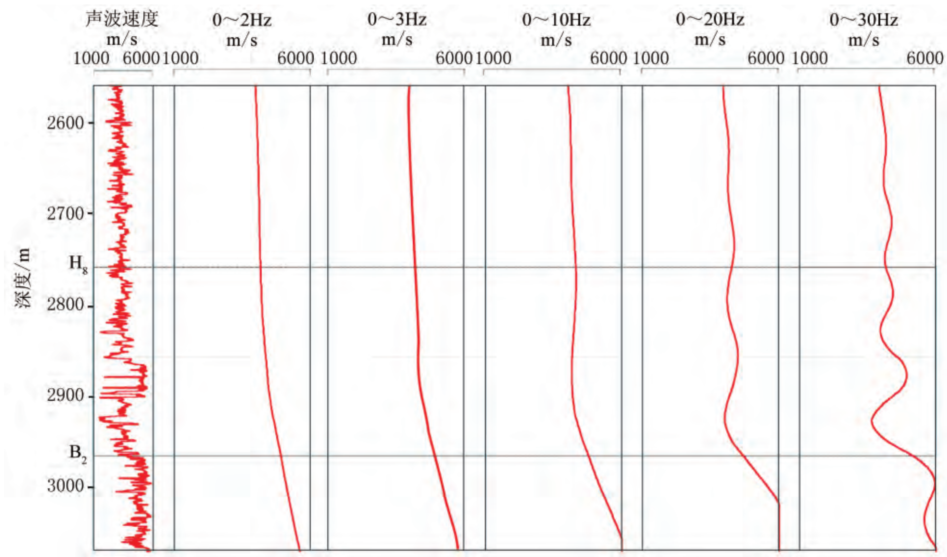

图 3 Y140 井声波速度低频分量特征

选择目标层段对岩性特征区分相对清晰的声波时差曲线作为标准井曲线，然后对所有井的声波时差曲线进行时频分析，分离低频长趋势分量和高频分量。以标准井声波时差低频长趋势分量为参考，对 F 区内其他井的声波时差长趋势低频分量进行标准化处理，使各井的声波时差长趋势低频分量变化趋势一致。标准化处理利用简单、实用的频率分布直方图法，确定标准井低频分量分布概率峰值，利用概率峰值速度差值完成其他井的低频分量校正（图 4）。将校正后的低频分量与原始中、高频分量

在频率域叠加，再通过傅里叶逆变换

$$\tilde{f}(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\mathrm{e}^{\mathrm{i}\omega t}F(\omega)\mathrm{d}\omega \tag{2}$$

及时深转换完成分频重构，获得新的声波时差曲线，完成脱压实校正（图 5）。式中：$F(\omega)$为频谱；$\tilde{f}(t)$为输出信号。

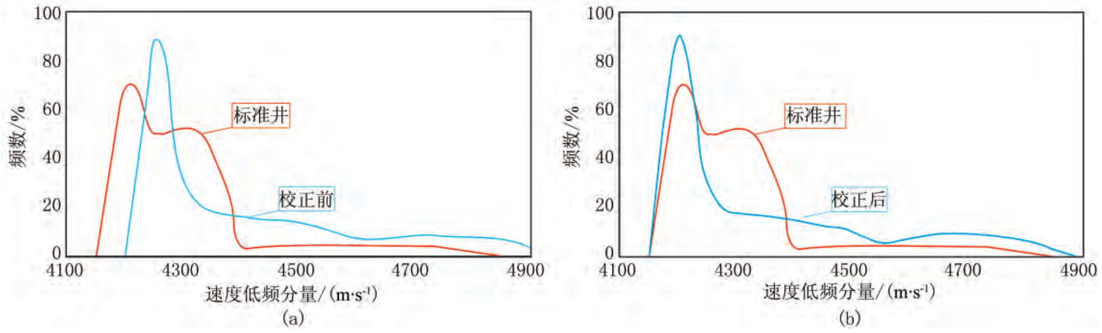

图 4　声波速度低频分量频率分布直方图

（a）标准化处理前；（b）标准化处理后

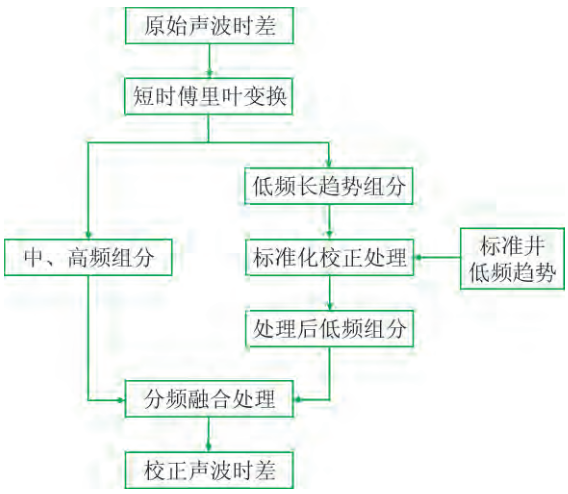

图 5　声波时差长趋势脱压实校正技术流程

2　实际数据应用

图 6 为 Y454 井目标层段声波时差长趋势脱压实校正效果。由图可见，声波时差长趋势脱压实校正后声波时差曲线不仅很好地保留了原始声波时差曲线的高频变化细节，而且较好地突出了储层与非储层的差异，明显改善了对砂岩储层与围岩的辨识效果（图 6c）。为了进一步验证文中方法的合理性，结合地震标定对比声波时差长趋势脱压实校正前、后的合成记录（图 7）。可见，Y454 井目标层段声波时差曲线经长趋势脱压实校正后，合成记录标定更合理，但目标层段的整体地震分辨率还偏低。

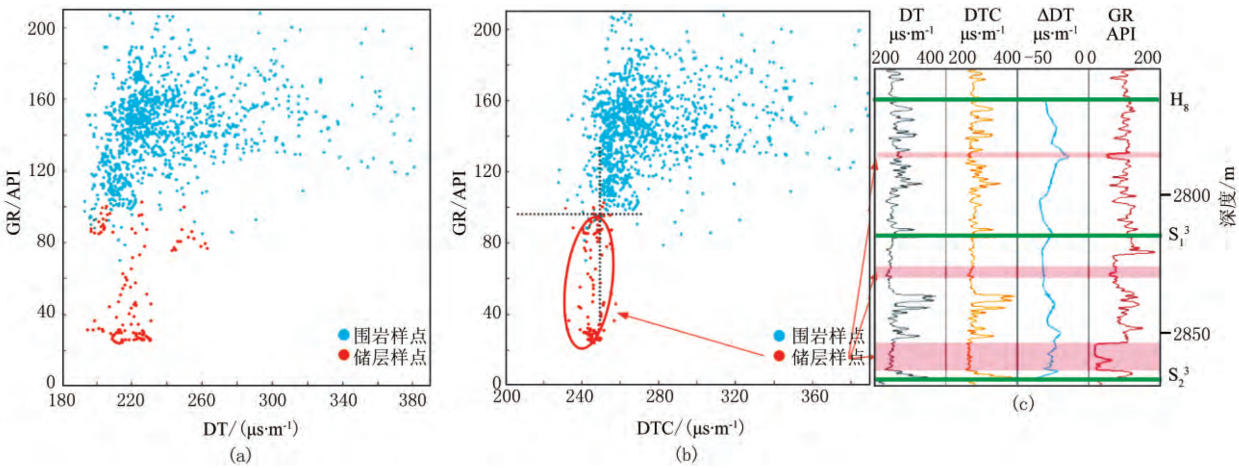

图 6　Y454 井目标层段声波时差长趋势脱压实校正效果

（a）原始声波时差—自然伽马交会图；（b）长趋势脱压实校正后声波时差—自然伽马交会图；（c）测井曲线

图 b 中砂岩储层的声波时差幅值范围为 200～255μs/m，围岩的声波时差明显略高，两者重叠范围较小。GR、DT、DTC 分别为自然伽马、原始声波时差、长趋势脱压实校正后声波时差曲线，ΔDT 为 DT 与 DTC 之差

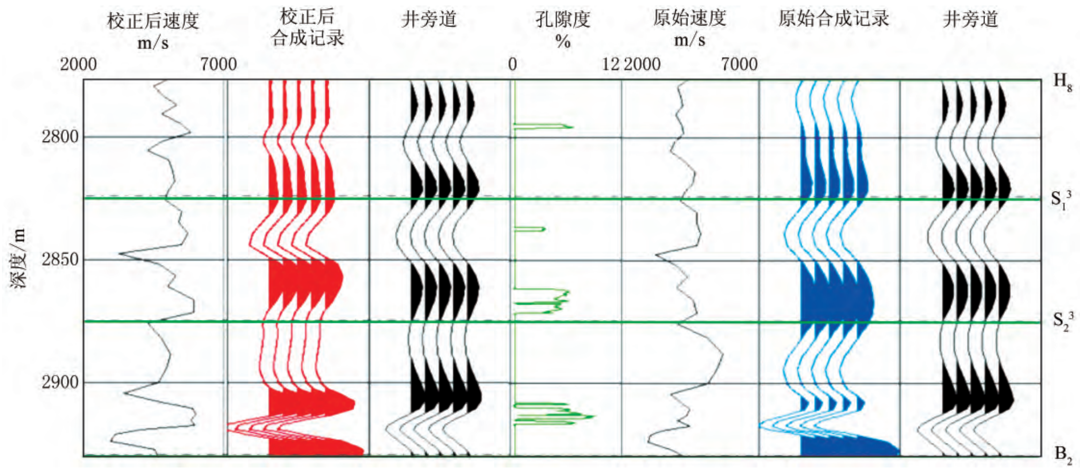

图 7　Y54 井目标层段声波时差长趋势脱压实校正前、后合成记录

F 区目标层单砂体厚度较小，地震资料主频约为 35Hz，采用常规基于模型的地震反演方法识别储层效果有限。为了更好地应用声波时差长趋势脱压实校正资料，在该区开展储层多属性神经网络地震反演，综合利用井震属性数据获得高分辨声波速度反演数据体以解释和预测储层。

储层多属性神经网络地震反演融合地震属性和测井属性预测储层[1,19-20]。基本原理是借助已知井点的硬数据分析井曲线和地震数据，应用非线性逐步回归、人工神经网络技术分析和训练提取的已知井点的地震属性、测井特征，找出地震属性和测井特征之间的关系，然后利用神经网络将这种高相关性的映射关系用于整个地震数据，完成神经网络测井特征反演。

在 F 区对目标层段由声波时差长趋势脱压实校正后的声波速度作为特征曲线参与反演，优选多种地震属性（地震瞬时频率、振幅包络、振幅导数、瞬时相位余弦等）作为神经网络的输入。通过样本训练、测试确定神经网络的拓扑结构和网络参数，然后对所有地震数据反演声波速度。

图 8 为 07YC-EW242 测线二维声波速度反演结果。由图可见：振幅剖面的目标层段视分辨率较低，主频约为 35Hz（图 8a）；声波时差长趋势脱压实校正后反演速度剖面（图 8b）的地层分辨率明显高于声波时差长趋势脱压实校正前反演速度剖面（图 8c），储层纵、横向分布特征清晰（箭头所指处）。影响神经网络反演效果的因素较多，对比声波时差长趋势脱压实校正前、后反演结果可知，后者更合理，与井数据特征更匹配。

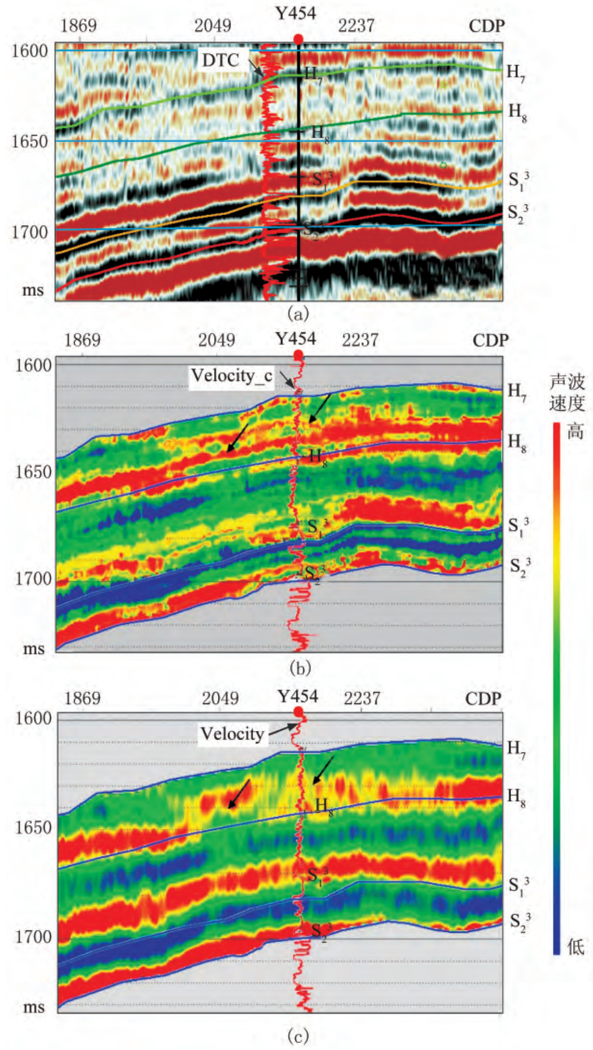

图 8　07YC-EW242 测线二维声波速度反演结果

（a）地震剖面；（b）声波时差长趋势脱压实校正后反演速度剖面；（c）声波时差长趋势脱压实校正前反演速度剖面
DTC 为长趋势脱压实校正后声波时差曲线，Velocity_c 为声波时差长趋势脱压实校正后的声波速度，Velocity 为原始声波速度

利用反演成果解释和预测目标储层的横向展布特征。根据前述地球物理特征分析确定储层的声波时差特征和速度分布范围，取储层速度门槛值为 4000m/s（大于该值的认为是储层样点），然后在反演速度剖面上提取目标层满足条件的样点，经统计转换为分析时窗内的储层厚度。最终获得 F 区二叠系盒 8 段（H_7 与 H_8 之间地层）储层厚度图（图 9）。可见：盒 8 段主要为三角洲前缘沉积亚相，主要沉积微相为水下分流河道、分流间湾及河口砂坝等。平面上整体呈南北向条带或片状分布。较厚储层主要分布在北部、中部 Y140 井以西条带及东南侧，储层厚度一般大于 15m，局部可达 20m。经钻井资料证实，预测的储层厚度与钻井资料和沉积相带平面分布规律吻合良好。

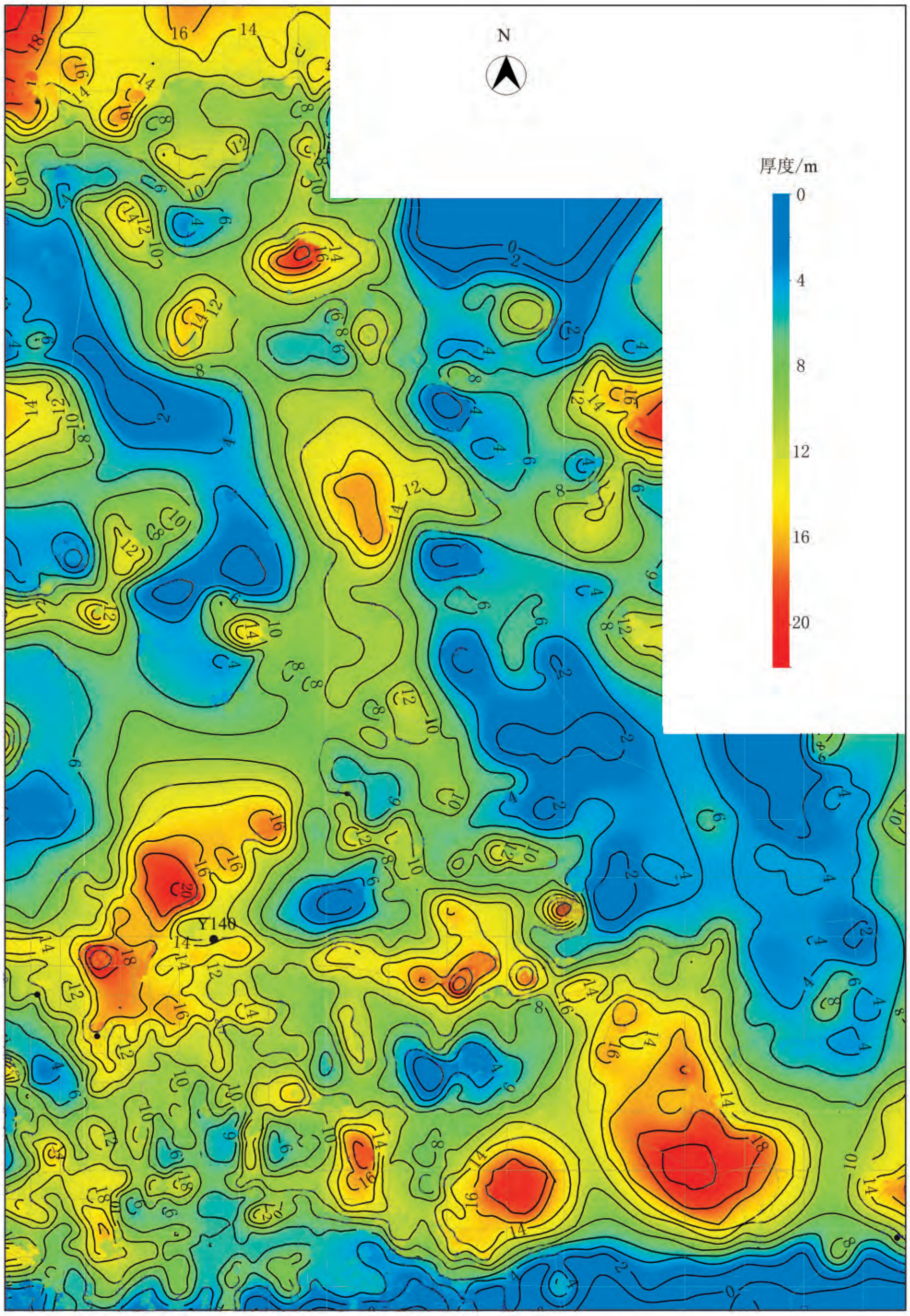

图 9　F 区二叠系盒 8 段储层厚度图

3 结论

(1)压实作用导致延长气田F区块二叠系石盒子组和山西组储层较致密,致使储层与围岩声波时差特征接近,不利于地震反演和储层预测。减小或者消除压实作用对声波时差的影响,可改善对储层与围岩的辨识效果,从而获得较好的地震反演结果。

(2)结合地震反演需求,采用时频分析方法对原始声波时差曲线分频处理,以标准井的低频组分为标准,对F区所有井进行声波低频长趋势校正;然后与原有高频组分分频融合形成新的声波时差数据,完成声波时差长趋势脱压实校正,使储层与围岩的声波时差值重叠区域减小,提高了对储层的辨识精度。

(3)基于声波时差长趋势脱压实校正实施神经网络地震速度反演,获得了较高分辨率的声波速度反演剖面,精细预测了储层厚度。

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本期广告索引

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A joint inversion method using amplitude and velocity anisotropy. ZHOU Xiaoyue[1], GAN Lideng[1], YANG Hao[1], WANG Hao[2], and JIANG Xiaoyu[1]. Oil Geophysical Prospecting, 2020, 55(5): 1084-1091.

The fracture prediction method based on amplitude anisotropy with high resolution is sensitive to the degree of medium anisotropy and easy to realize, but it is poor in dealing with noises and has high requirements on the quality of seismic data. For this reason, a joint inversion method using prestack amplitude and velocity anisotropy is proposed. For each time window, the anisotropic gradient obtained from velocity inversion at the bottom of the time window is taken as a constraint of amplitude inversion at the top of the time window, and then an inversion volume can be obtained by moving the time window. Applications to model and real data show that: ①compared with prestack and poststack amplitude anisotropy inversion, the inversion accuracy of the proposed method is the highest; ② in the GS1 well block, the result of prestack velocity anisotropy inversion coincides with the fracture curve of the well, which can be used as a constraint of amplitude inversion, but the resolution of velocity anisotropy inversion is lower than that of amplitude anisotropy inversion. The joint inversion of prestack amplitude with velocity anisotropy can improve the resolution of velocity inversion.

Keywords: anisotropy, fracture prediction, prestack amplitude, velocity, joint inversion

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Geological modeling of braided river reservoir based on genesis and evolution: a case study on block M in Orinoco Heavy Oil Belt, Venezuela. CHEN Shizhen[1,2], Lin Chengyan[1,2], REN Lihua[1,2], ZHANG Xianguo[1,2], and HUANG Wensong[3]. Oil Geophysical Prospecting, 2020, 55(5): 1092-1101.

The Orinoco Heavy Oil Belt in Venezuela is the largest heavy oil accumulation area in the world. It is rich in geological reserves and has a huge exploitation potential. However, because the primary oil pay zone in the area is almost fluvial deposits of sandy braided river, it is characterized by laterally fast facies change and vertically complex superimposition of sand bodies, resulting in serious heterogeneity inside the reservoir, and restricting the following production and the implementation of the development plan. Taking the lower Oficina formation in block M as a case, according to the cores, well logging and seismic data, four main genetic units were identified and summarized including compound bars, braided channels, abandoned channels and residual floodplain mudstone. Under the guidance of a sedimentary conceptual model, the strata slicing method was used to extract and analyze the evolution process of the genetic units over time. This information extracted was transformed into a probability volume to control the geological modeling process. Taking the identified results of horizontal and vertical wells as hard data, a final geological model controlled by genesis and evolution information was established under the constraint of the probability volume. The drill-in rate by horizontal wells has been increased to more than 95% after the model was applied in field operation, indicating a good application effect.

Keywords: seismic sedimentology, Orinoco Heavy Oil Belt, braided river, geological modeling, genesis and evolutional information

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A method of decompaction correction based on long trend of interval transit time. LAI Shenghua[1], CAO Jianhua[2], and ZHANG Cuiping[3]. Oil Geophysical Prospecting, 2020, 55(5): 1102-1109.

The sedimentary environment of the reservoir in Block F in the Yanchang gas field is a delta front. Due to the formation compaction, the reservoir has features of low porosity and low permeability. The contrast of interval transit time and density between the reservoir and the surrounding rock is small, which seriously affects the reliability and precision of seismic reservoir prediction. In order to reduce or partially eliminate the influence of compaction on interval transit time and increase the interval transit time contrast (velocity) between the reservoir and the surrounding rock, a method of decompaction correction with a long trend of interval transit time is proposed in the paper. Firstly, the interval transit time are transformed after time-frequency analysis, and divided into different components in the frequency field. Taking the low-fre-

quency component of the standard well as criteria, low-frequency long-trend correction to the interval transit time is carried out for all wells in Block F. Then new interval transit time data are formed by integrating the original high-frequency component and the corrected low-frequency part. Geophysical responses are reanalyzed using the new interval transit time. Now the reservoir is obvious with lower interval transit time, and could be distinguished clearly from the surroundings. Finally, neural network seismic velocity inversion is carried out using the corrected new interval transit time, and a high-resolution acoustic velocity inversion profile is obtained. The reservoir thickness has been accurately predicted.

Keywords: compaction, time-frequency analysis, long trend of interval transit time, decompaction correction, reservoir prediction

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Deepened application of horizon-flattening technique in seismic interpretation. GUO Wen[1], LIU Yongtao[2,3,4], ZHAO Junfeng[2,3], WANG Xiuzhen[4], ZHAO Hongge[2,3], and DING Fufeng[5]. Oil Geophysical Prospecting, 2020, 55(5): 1110-1120.

From the perspective of seismic interpretation, horizon-flattening is a paleo-surface reconstruction technique. Due to the limitation of the horizon-flatten technique, it is impossible to recover the thickness of inclined strata, the thickness of compacted strata and the horizontal expansion of the strata. According to the principle of the horizon-flattening technique, first it was compared with other recovery techniques, and then by adding geological constraints or improving the original techniques, the impact of recovering error on results was minimized to let it be better applied for seismic interpretation. The following conclusions have been drawn: ①If the angle between the top and bottom boundaries of a wedge sequence is less than 15°and the thickness of the interval is less than 1000m, thin reservoirs can be approximately predicted with horizontal slices instead of stratal slices; ②When the compaction constrast above and under an unconformity is relatively small, the thickness of the denuded layer can be recovered by horizon-flattening, and then restored to the paleo-geomorphology by the modified residual thickness method; ③In a hydrocarbon generation area with increased temperature, no compaction correction is needed to restore the paleo-structure in the main accumulation stage, therefore, while improving the recovery accuracy, it also enhances the hydrocarbon geological significance of the paleo-structure; ④In a regions with less intense tectonic deformation, the tectonic evolution can be analyzed through seismic horizon-flattening instead of balanced cross-section. These conclusions can further promote the application of seismic horizon-flattening technique in oil and gas exploration.

Keywords: seismic horizon-flattening, stratal slice, horizontal slice, paleo-geomorphology, paleo-structure, tectonic evolution, balanced cross-section, Ordos Basin

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Structure characteristics and genetic mechanism of extensional faults in Cheduba accretionary wedge-slope basin, Myanmar. YANG Songling[1] and XIE Jielai[2]. Oil Geophysical Prospecting, 2020, 55(5): 1121-1130.

In recent years, as a kind of rare oil/gas-bearing basin, accretionary wedge-slope basins have been paid more and more attention to. At present, exploration and research on this kind of basin is relatively less, so its complex structural features, especially the genesis of the complex fault system, have been debating. There are a lot of seismic and geological data about the Cheduba accretionary wedge-slope basin, which provide a basis for studying the tectonic characteristics and fault genesis of the basin. Based on the regional geology and under the guidance of the idea of "vertical (tectonic) layers and lateral (segments) blocks", firstly the fault type is defined in different stages; then the genetic mechanism of the extensional faults that are nearly parallel to the orientation of the accretionary wedge structural belt is discussed. This solves the contradiction between geological understanding and stress. On this basis, a new induced extension model of normal fault development is proposed, and