引用格式：彭浩天，何青林，陈康，等．“双高”处理技术在薄储层识别中的应用：以川中蓬莱地区深层二叠系茅口组为例[J]. 油气藏评价与开发，2025，15(3)：417-424.

PENG Haotian, HE Qinglin, CHEN Kang, et al. Application of “high-fidelity and high-resolution” processing technology in thin reservoir identification: A case study of the deep Permian Maokou Formation in Penglai area, central Sichuan[J]. Petroleum Reservoir Evaluation and Development, 2025, 15(3): 417-424.

DOI: 10.13809/j.cnki.cn32-1825/te.2025.03.008

“双高”处理技术在薄储层识别中的应用

——以川中蓬莱地区深层二叠系茅口组为例

彭浩天，何青林，陈　康，曾　鸣，何宗强，屠志慧，孔令霞，屈伯章

（中国石油西南油气田公司勘探开发研究院，四川 成都 61000）

摘要：川中蓬莱地区深层二叠系茅口组位于四川盆地，是一套以碳酸盐岩为主的沉积地层，其主要岩性为白云岩，储集物性较好，是四川盆地重要的油气储层之一。然而，由于茅口组储层具有埋藏深、储层薄、非均质强、围岩阻抗差异小、反射信号弱等特点，造成地震预测困难。常规的提频处理要么是不能识别薄储层，要么是处理成一大片同相轴，从而导致该区薄储层地震难以预测。因此，研究了“双高”处理技术在茅口组薄储层识别中的应用。针对茅口组埋藏深、信号弱、储层薄、储层围岩波阻抗小等不利因素，开展了碳酸岩深层弱信号处理技术攻关研究。另外，提出了全过程“保护低频、拓宽高频”的“双高”处理技术思路，并且研究了叠前保真去噪、高频端剩余静校正、多次波压制、共偏移距矢量片域叠前时间偏移、各向异性校正、基于压缩感知拓频处理等突出二叠系白云岩储层弱反射信号的方法，研究结果有效识别出茅口组有利储层为不连续中强振幅反射，井震标定吻合率为100%，从而实现了对茅口组深层白云岩薄储层的有效识别和非均质性的精确刻画。依据新成果，钻探的PY001-H1井成功钻遇优质储层。因此，证明了研究的“双高”处理技术在提高地震资料分辨率、保幅处理、非均质性分析和弱信号恢复等方面有利于深层储层预测。

关键词：二叠系茅口组；白云岩；高保真；高分辨率；多次波；共偏移距矢量片域；压缩感知

中图分类号：TE122　　　　**文献标识码：**A

Application of “high-fidelity and high-resolution” processing technology in thin reservoir identification: A case study of the deep Permian Maokou Formation in Penglai area, central Sichuan

PENG Haotian, HE Qinglin, CHEN Kang, ZENG Ming, HE Zongqiang, TU Zhihui, KONG Lingxia, QU Bozhang

(Research Institute of Exploration and Development, PetroChina Southwest Oil & Gasfield Company, Chengdu, Sichuan 610051, China)

Abstract: The deep Permian Maokou Formation in the Penglai area, central Sichuan, is located in the Sichuan Basin. It is a sedimentary formation primarily composed of carbonate rocks, with dolomite being the main lithology. With good reservoir properties, it represents an important oil and gas reservoir in the Sichuan Basin. However, due to characteristics such as deep burial, thin reservoirs, strong heterogeneity, minimal impedance contrast with surrounding rocks, and weak reflection signals, seismic prediction becomes challenging. Conventional frequency enhancement processing either fails to identify thin reservoirs or results in a large area of coherent seismic events, making seismic prediction of thin reservoirs in this region difficult. Therefore, the application of “high-fidelity and high-resolution” processing technology for identifying thin reservoirs in the Maokou Formation was investigated. In response to the adverse factors such as deep burial, weak signals, thin reservoirs, and small impedance contrast with surrounding rocks in the Maokou Formation, research on weak-signal processing techniques for deep carbonate formations was conducted. In addition, the “high-fidelity and high-resolution” processing technology involving the concept of “protecting low frequencies and enhancing high frequencies” throughout the processing workflow was proposed. Methods such as pre-stack fidelity denoising, high-frequency residual static correction, multiple-wave suppression, pre-stack time migration in the Offset Vector Tile (OVT) domain, anisotropic correction, and frequency enhancement based on compressed sensing were studied to highlight the weak reflection signals of the Permian dolomite reservoirs. The research results effectively identified favorable reservoirs in the Maokou Formation as discontinuous, medium-to-strong amplitude reflections, with a well-seismic calibration match rate of 100%, thereby achieving effective identification and precise characterization of heterogeneity of thin dolomite reservoirs in the Maokou

---

收稿日期：2024-06-11。

第一作者简介：彭浩天（1993—），男，硕士，工程师，从事地震资料处理方面的研究。地址：四川省成都市高新区天府大道北段12号，邮政编码：610000。E-mail：penghaotian@petrochina.com.cn

Formation. Based on the new findings, the drilled well PY001-H1 successfully reached high-quality reservoirs. Therefore, the results demonstrate that the studied "high-fidelity and high-resolution" processing technology is beneficial for deep reservoir prediction by improving seismic data resolution, amplitude preservation, heterogeneity analysis, and weak signal recovery.

Key Technical Descriptions

1. Pre-stack Fidelity Denoising Technology

Fidelity processing aims to preserve both amplitude and phase integrity. The current approach primarily employs the "six-step method" for denoising in the F-X, F-K, and Tau-P domains, which involves classification and segmentation by time, frequency, domain, step, and region. The principle of fidelity ensures that the chosen modules protect effective signals while maintaining relative amplitude relationships, particularly preserving low-frequency signals and improving the signal-to-noise ratio of weak high-frequency signals.

The data in this area is primarily affected by impulsive noise, surface waves, and linear noise. While methods for suppressing impulsive and surface waves are well-established, this study used frequency-domain suppression and localized surface wave suppression to maintain the original data's frequency range. Due to wide-azimuth acquisition, residual surface waves and linear noise often remain at non-vertical offsets. In these cases, cross-spread domain suppression was applied post-static correction. This method considers interference wave frequency, apparent velocity, and non-vertical offsets for effective suppression.

2. Multiple-Wave Suppression Technology

A combination of Radon transforms and curvelet transform achieved effective suppression of interlayer multiples. Specifically, high-precision Radon transform was used to obtain multiple models, enhancing signal identification during curvelet transform. The curvelet transform better differentiates energy by frequency, dip, and position. By controlling the strength of simulated multiples through thresholds and applying adaptive subtraction, this approach improves multiple-wave suppression and enhances data quality for low signal-to-noise ratio datasets.

3. Compressed Sensing Frequency-Expansion Technology

Compressed sensing is a novel signal sampling theory. The method used here employs a robust compressed sensing spectral inversion algorithm. It determines initial reflection coefficients using a thin-layer matching pursuit algorithm and then performs post-stack sparse inversion based on the L0-norm compressed sensing theory. The final reflection coefficient model is obtained by applying regularization. Subsequently, wavelet decomposition and high-frequency wavelet replacement are conducted to expand the high-frequency spectrum while maintaining amplitude and fidelity, significantly improving seismic data resolution.

Application Results

The test area spans 200 km^2, using an observation system with 24 lines, 7 sources, 270 receivers, and 180-fold coverage. The bin size is 20 × 20 meters, with a maximum offset of 6 332.46 meters and an aspect ratio of 0.62, representing typical high-density and wide-azimuth acquisition. The raw data exhibits high noise levels, low dominant frequencies in deep layers, and narrow frequency bandwidths. Interferences include surface waves, impulsive noise, interlayer multiples, and anisotropy effects. After applying "Double-High Processing," multiple-wave interferences were eliminated, and the quality of gathers significantly improved. Well-to-seismic profiles achieved good alignment, yielding favorable results.

For example, well PY1, with a burial depth of 6 040 meters and a reservoir thickness of 7 meters, showed a weak reflective base on synthetic seismograms and seismic profiles, with consistent matching between synthetic records and seismic waveforms. Clear reservoir characteristics were identified. Following these advancements, a new development well was drilled to a depth of 6 103 meters. In the second member of the Maokou Formation, a dolomite reservoir was encountered with a slanted thickness of 23.1 meters, a vertical thickness of 8.5 meters, and an average porosity of 3.8%. This high-quality dolomite reservoir achieved excellent drilling results.

Keywords: Permian Maokou Formation; dolomite; high-fidelity; high-resolution; multiple wave; OVT domain; compressed sensing

川中蓬莱地区深层二叠系茅口组位于四川盆地，是一套以碳酸盐岩为主的沉积地层，堪称四川盆地重要的油气储层之一。茅口组发育形成于茅口组茅二期台缘带，其台缘滩体自南向北呈进积式迁移，埋藏深度约为6 000 m，具备延展长度长（延展长度达290 km）、分布面积广（台缘带宽度介于15～80 km）、滩体连片叠置的显著特征。近期茅口组多井测试显示高产，明确揭示茅二期发育环裂陷边缘带的茅口组地层岩性主要由白云岩、灰岩和少量泥灰岩构成，其中，白云岩作为主要储集岩尤为突出。

茅口组储层在纵向上展现出明显的分层性，可细分为多个小层，不同小层的储集物性差异显著，非均质性较强。储集空间主要表现为粒间溶孔和晶间溶孔，呈现出孔隙型特征，平均孔隙度介于3.5%～6.0%。茅口组蕴藏着良好的勘探潜力[1-3]，对其储层特征的深入研究对油气勘探与开发具有至关重要的意义。

白云岩储层厚度通常较薄，介于2～30 m，但储集物性良好。该储层具有埋藏深、储层薄、非均质性强、与围岩阻抗差异小、反射信号弱等特点，导致地震预测难度较大。常规的提频处理方法要么无法识别薄储层，要么将

其处理成一大片同相轴,造成该区域薄储层地震预测困难,且与实际钻井结果不符[4–8]。何昌兴悦、龙隆等[9–10]采用叠后积分方法识别白云岩储层,何宗强等[11]通过突出弱信号处理识别薄储层,均取得了一定的成效。

新近钻探的PS16井,尽管预测存在较厚的储层,但实际并未钻遇储层,这使得储层研究变得更为复杂。为了精准识别此类特殊储层,必须对处理流程、参数和技术进行再次优化,构建面向储层成像的处理技术流程,从而为储层预测提供坚实的数据支撑。

针对川中蓬莱地区深层茅口组这种非均质储层,通过高分辨率地震资料的保真处理,识别白云岩储层,实现对薄储层的高效识别和非均质性的精细刻画。这些研究成果不仅为蓬莱地区的油气勘探提供了关键的技术支持,也为类似复杂地质条件下的储层预测和地震资料处理提供了宝贵的参考和借鉴。

1　地震资料应用问题分析

近年来,中国积极推广“两高一宽”勘探技术[12–15],使得“双高”处理技术逐渐受到重视。杨广广等[16]应用“双高”地震资料处理技术,对四川盆地射洪区块浅层沙溪庙组河道砂储层成像进行了深入研究,取得了显著成果。然而,在深层薄储层应用方面,“双高”处理技术的研究尚显不足。

前期的基础研究表明:影响茅口组储层成像的关键因素包括信号的保真性、地震分辨率、高精度成像方法等[8,16]。同时,常规地震资料在储层研究中面临以下问题:

1)弱有效信号恢复难题。深层海相白云岩储层薄且埋藏深,反射信号振幅弱、分辨率低、保真度差。新近钻探的JT1井、PS2井、PY1井、PY3井虽钻遇白云岩储层,但地震资料储层响应不明显,薄储层弱信号恢复难度较大。

2)高保真压制多次波问题。多次波与一次反射波混叠,难以区分,导致真假储层识别困难。如何高保真压制多次波并增强道集弱信号能量成为一大挑战。

3)储层准确成像难题。受碳酸盐岩储层内部沉积层序结构复杂和储层非均质性影响,储层方位各向异性增强,造成井震不匹配,薄储层高精度成像难度大。例如,PY1井储层厚度为7 m,合成地震道储层表现为弱波峰,但剖面无响应。

4)高保真提频处理问题。常规提频方法噪音大、波组特征变化显著,提频后储层特征反而不清晰,严重影响对茅口组储层的识别。

综上所述,亟须在弱信号保真恢复、精确成像、保真拓频等方面开展流程和方法的攻关研究。

2　“双高”地震资料处理技术思路和流程

针对深层储层存在的储层薄、横向变化迅速、地层吸收衰减严重、地震响应特征不明显、分辨率低等问题,构建了针对性的处理流程(图1)。与常规处理流程相比,研究采用了变网格胖射线初至波层析静校正,十字排列法高保真叠前去噪,地表一致性稳健反褶积,精细速度分析,低、中、高分频剩余静校正,曲波变换多次波压制,四维去噪等技术,以提升高频信号的信噪比。在此基础上,进一步运用OVT(共偏移距矢量片)域共孔径面非对称走时叠前时间偏移成像技术,结合各向异性校正和高保真压缩感知拓频处理技术,有效提高储层分辨率,从而实现对深层薄储层的精准识别。

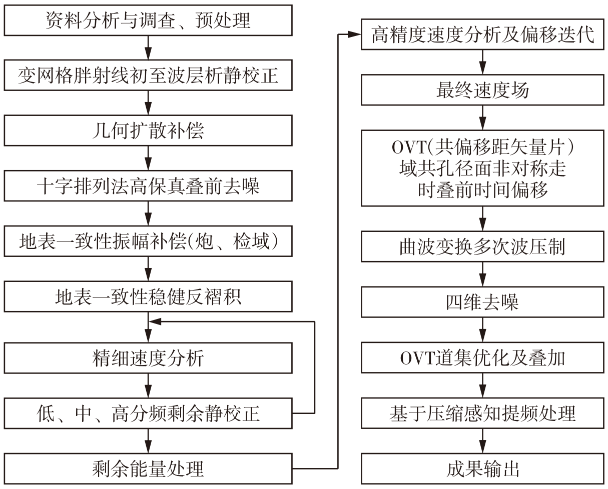


图1　“双高”处理技术流程

Fig. 1　Flow chart of “high-fidelity and high-resolution” processing technology

3　关键处理技术

3.1　叠前保真去噪

保真处理技术原理主要涵盖振幅保真和相位保真2个关键方面。目前,业界普遍遵循在F-X域、F-K域、Tau-P域实施“六分法”去噪的策略,即通过“分类、分时、分频、分域、分步、分区”方法联合逐级去噪的思路[17]。在保真原则指导下,模块选择着重保护有效信号不受损害,同时维持相对振幅关系不变,尤其要确保低频信号不受损失,并提升高频端等弱信号的信噪比,以便地震资料的振幅信息能够真实反映地下反射界面的强度。

相位保真技术则专注于信号的相位信息,通过各向

异性校正，保持地震波的波形特征，确保地震道和合成记录的振幅强弱及波形井震吻合，从而满足后期储层预测的需求，实际应用中已显现出显著效果。

保真去噪处理的关键在于去除噪音的同时确保原始数据的有效低频和高频部分不受影响，这也是弱信号恢复的核心要点。川中蓬莱地区的资料主要受到噪音脉冲干扰、面波和线性干扰的影响。针对脉冲和面波的去噪方法和手段多样且较为成熟。此次研究选择了频域压制脉冲和局部面波压制的方法，能够较好地保持原始数据的频带范围不受干扰[16-17]。然而，由于川中蓬莱地区采用宽方位采集，面波和线性干扰在非纵距较大时往往仍存在残余。为此，在静校正后需采用十字排列域压制方法，该方法不仅考虑了干扰波的频率和视速度，还兼顾了非纵距的影响[18-19]，从而取得了较好的压制效果。图2、图3展示了单炮十字域面波及线性干扰压制效果的对比，低频面波和线性干扰的能量得到有效压制，振幅信息保持良好，频带影响较小，深层弱信号能量得以恢复。图4显示了采用十字排列域线性噪音衰减后的效果，在提高资料信噪比的同时，深层目的层（红色方框）的弱信号得到增强（红色箭头）。

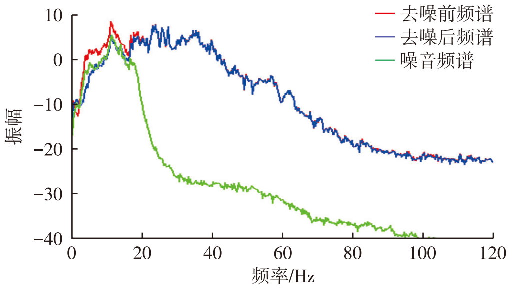


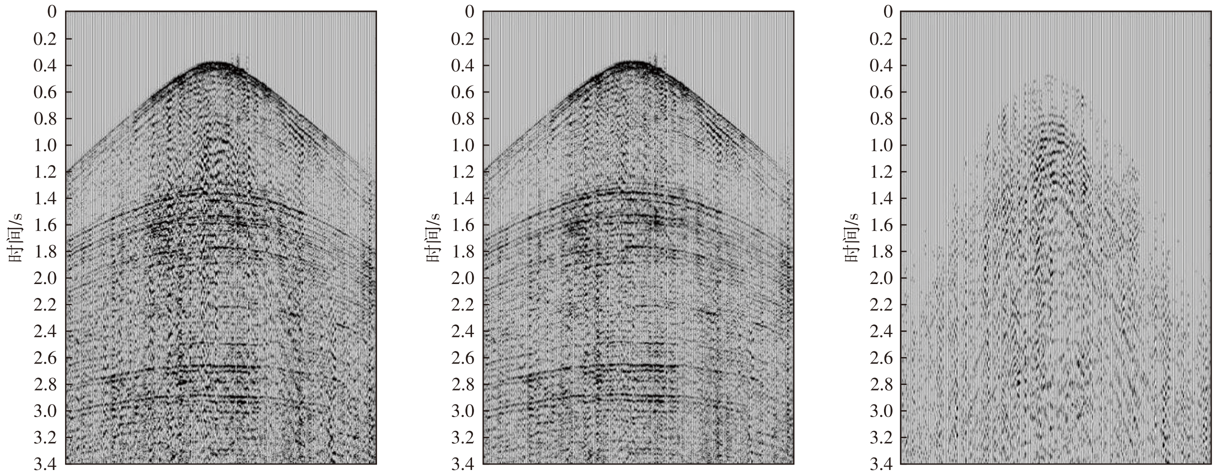
图2　典型单炮去噪效果对应频谱

Fig. 2　Frequency spectra showing denoising effects of typical single shots

3.2　多次波压制

以茅口组为目标，蓬莱工区西南部新钻探井PS16，但未在茅口组钻遇储层，井震数据严重不符。通过VSP（垂直地震剖面）测井分析，发现剖面上茅口组的中强反射实为多次波，误导了解释人员（图5a）。进一步对该井测井曲线进行分析，确认从雷口坡组到二叠系茅口组存在多个低速层，这些地层均为低速至高速的速度转换面[8]。通过单程波正演模拟，证实了多次波的存在。图5b展示了PS16井的单程波正演记录，从中可以观察到PS16井茅口组存在多次波现象。此前被误认为是茅二段上层储层的部分，实际是由多次波所引起。然而，这类层间多次波在速度谱上的能量与一次波能量相当，时差较小且频率较高，难以有效区分。常规的时差类多次波压制方法对此类现象无效。图5c、图5d对比了过PS16井多次波压制前后的偏移叠加合成记录标定结果，展示了干扰储层的多次波压制后有效波更加突出，井震吻合度较高。

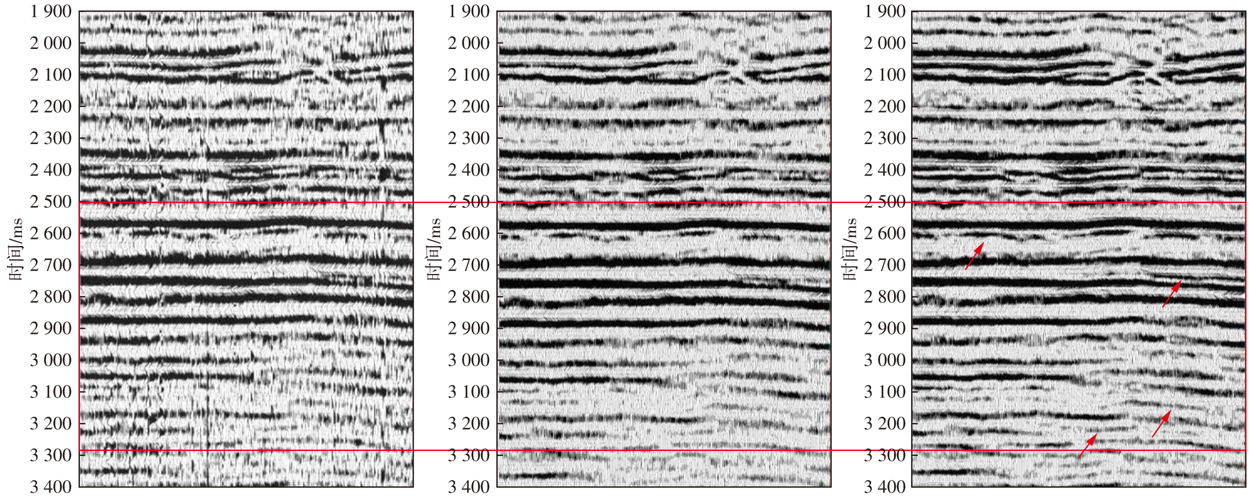
本次研究通过多种方法的测试，最终选定“Radon（拉东）变换+曲波变换”的联合技术来压制层间多次波，取得了显著效果。该方法具体为：通过高精度的“Radon变换+曲波变换”双向预测多次波。曲波域具有多尺度、多方向性的特点，针对多次波的压制更具针对性，从而有效避免了对有效信号的损失[20-22]。具体操作步骤如下：首先，利用高精度Radon变换获取多次波模型，进一步提升曲波变换对信号的识别能力，提高多次波识别的精度；其次，曲波变换能够更清晰地分辨不同频率、倾角和位置的能量，并通过阈值控制模拟多次波的强度；最后，通过与自适应相减方式实现多次波的压制，从多次波预测和



a. 原始单炮　b. 去噪后单炮　c. 去除的噪音

图3　典型单炮去噪效果对比

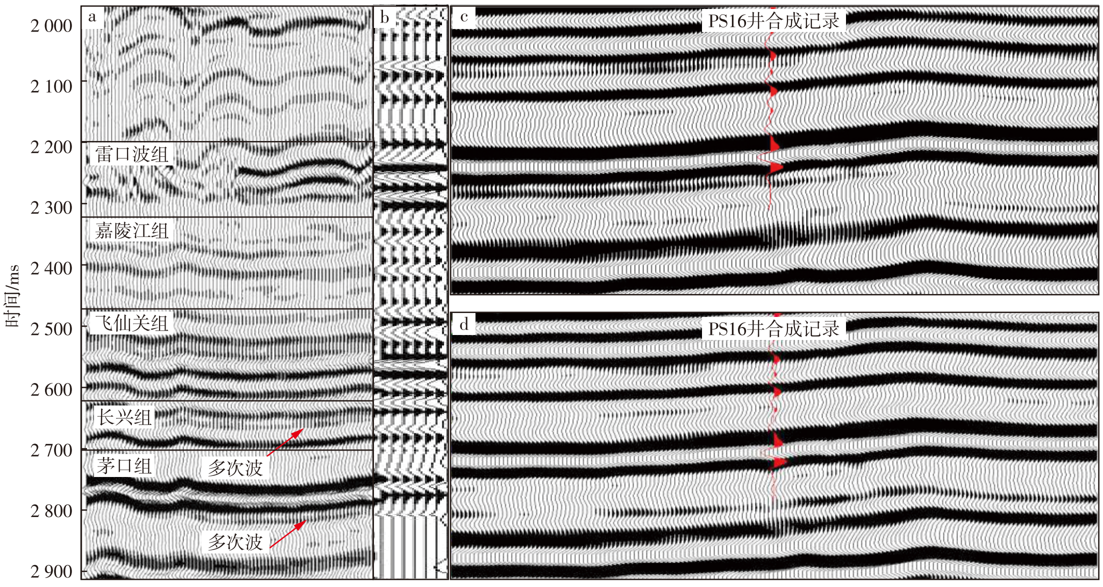
Fig. 3　Comparison of denoising effects on typical single shots



a. 未去噪的叠加剖面　　b. 常规去噪叠加剖面　　c. 十字排列域去噪叠加剖面

图4　去噪叠加剖面效果对比（局部）

Fig. 4　Comparison of denoising effects on stacked sections (partial)



注：a. 叠前时间偏移剖面；b. PS16井单程波正演记录；c. 过PS16井多次波压制前叠前时间偏移剖面；d. 过PS16井多次波压制后叠前时间偏移剖面。

图5　川中蓬莱地区PS16井区多次波压制前后剖面效果对比

Fig. 5　Comparison of stacked section effects before and after multiple-wave suppression in well PS16, Penglai area, central Sichuan

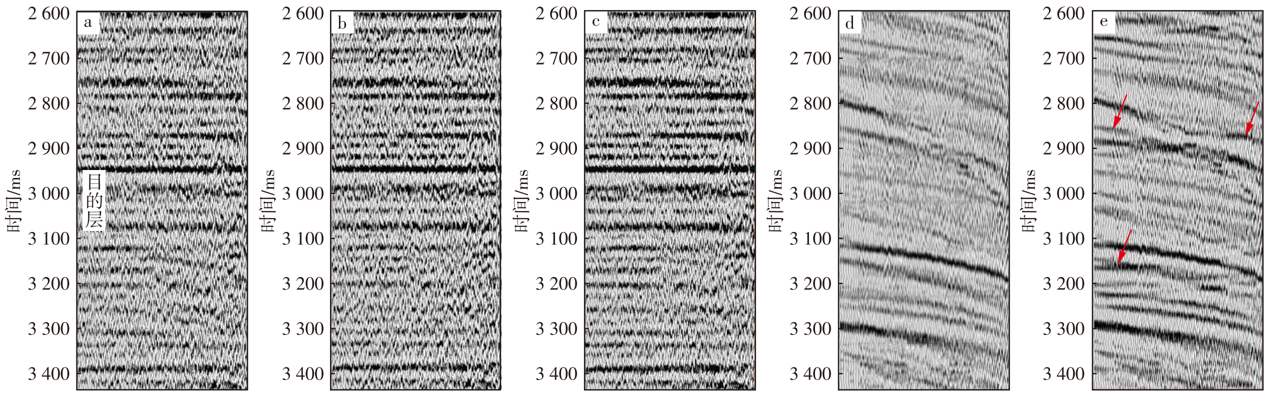
去除两方面提升精度，尤其在低信噪比资料处理中效果显著。

图6a展示了PY1井井旁OVT道集，目的层段存在明显的多次波；图6b为采用Radon法压制多次波后的OVT道集，尽管多次波得到压制，但有效信号也有所削弱；图6c展示了“Radon变换+曲波域”方法压制多次波后的OVT道集，多次波被有效压制，一次反射波得以恢复，道集信噪比明显提高；图6d为该方法压后多次波噪音的情况，近道和远道多次波均得到良好压制，且保真度较高；图6e显示了常规Radon压制方法导致的近、远道多次波压制过度，有效信号（红色箭头）同时被压制，保真性稍差。

3.3　压缩感知拓频处理

在地震波传播过程中，高频成分逐渐衰减，尤其是该区域深层的地震资料分辨率较低。传统的处理方法包括Q值（地层吸收系数）补偿和地表一致性反褶积。然而，川中地区较少采用Q值补偿，因为该地区低频损失较为严重。鉴于此，此次技术攻关在经过多种方法测试后，最终选择了稳健反褶积和基于压缩感知的拓频技术。该方法在压缩子波的同时，有效拓宽了频谱范围。

压缩感知拓频方法：压缩感知是一种创新的信号采样理论，具备稳健性的压缩感知谱反演算法。该方法首先利用薄层匹配追踪算法求取初始反射系数；在此基础



注:a. PY1井井旁道的OVT道集;b. Radon法多次波压制后的OVT道集;c. "Radon变换+曲波域"多次波压制后的OVT道集;d. "Radon变换+曲波域"压后的多次波噪音;e. 常规Radon变换压制后的多次波噪音。

图6 川中蓬莱地区PY1井井旁道OVT域道集多次波压制效果对比

Fig. 6 Comparison of multiple-wave suppression effects in OVT domain gather near well PY1, Penglai area, central Sichuan

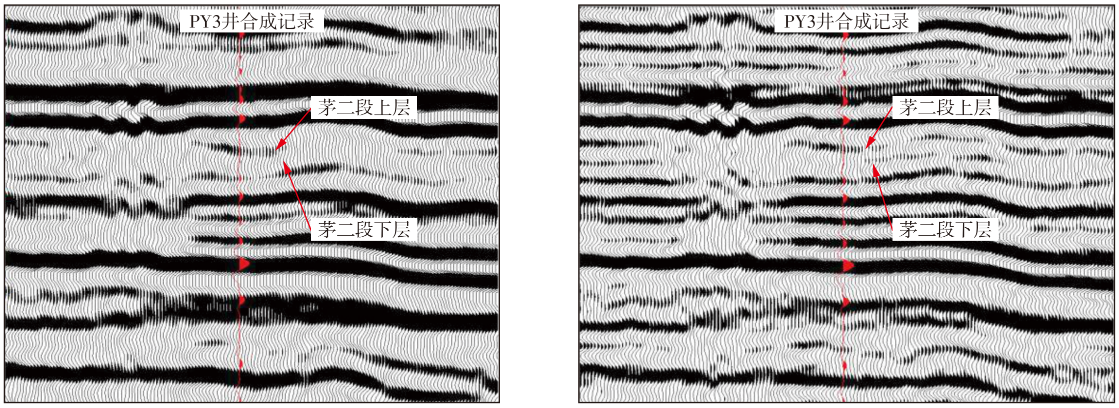
上采用基于L0范数(向量中非零元素的个数)的压缩感知理论进行叠后稀疏反演,以获得最终反射系数模型;最后通过整形正则化进行子波提取,并结合小波分解和高频子波替换,实现保幅、保真的高频拓展,以及显著提升地震数据分辨率的目标。

该过程通过以下三步完成提频处理[23]:①利用薄层匹配追踪算法求取地震数据的初始反射系数;②在步骤①所得初始反射系数的基础上,进行基于压缩感知L0范数的谱反演计算,从而求得最终反射系数;③通过子波整形正则化提取子波,并进行小波分解和高频子波替换,最终达到提高分辨率的目的。

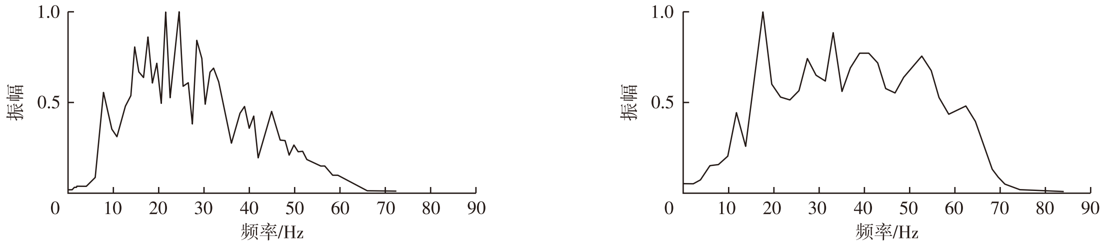
图7为PY3井高分辨率处理前后的剖面效果对比,高分辨率处理的剖面波组特征与合成记录特征(红色曲线)一致、波形强弱吻合较好,目的层层间反射更加清晰,可以明显分辨出目的层茅二段上层和茅二段下层(图7b),频谱能量明显拓宽。

3.4 方位各向异性校正

由于蓬莱地区三维采集的纵横比达到了0.62,且方位角相对较宽,因此存在方位各向异性问题。在OVT域叠前时间偏移处理后,方位各向异性依然显著[24-26]。图8a展示了OVT域偏移道集,受方位因素影响,无法实现同



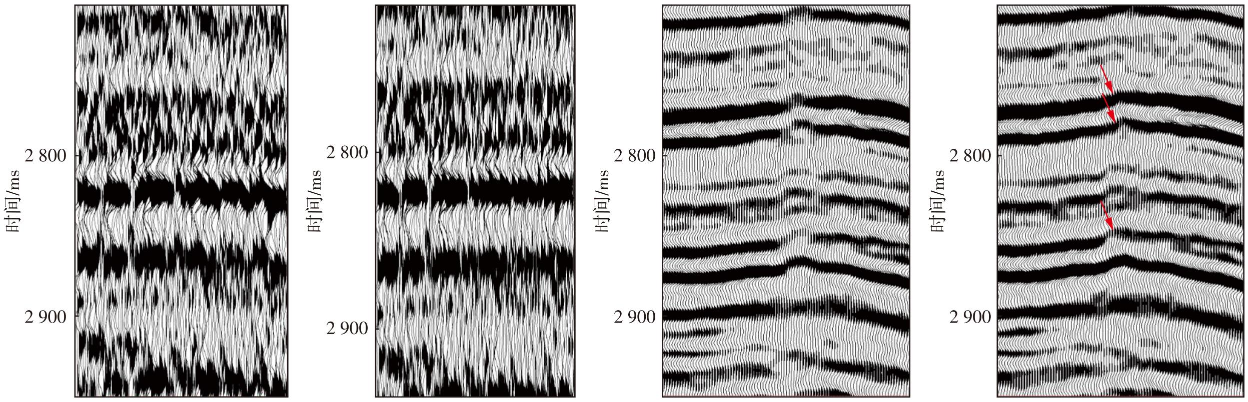
a. 压缩感知提频前剖面　b. 压缩感知提频后剖面



c. 压缩感知提频前频谱　d. 压缩感知提频后频谱

图7 川中蓬莱地区过PY3井测线叠前时间偏移剖面压缩感知提频处理前后效果对比

Fig. 7 Comparison of pre-stack time migration sections before and after frequency enhancement using compressed sensing along well PY3 line in Penglai area, central Sichuan



a. 各向异性校正前OVT道集　b. 各向异性校正后OVT道集　c. 各向异性校正前叠前时间偏移剖面(局部)　d. 各向异性校正后叠前时间偏移剖面(局部)

图8　各向异性叠前时间偏移前后效果对比

Fig.8　Comparison of pre-stack time migration sections before and after anisotropic correction

相叠加；图8b显示了经过各向异性校正后的道集，成功消除了方位各向异性，实现了同相叠加；图8c为未进行各向异性校正的偏移剖面，构造形变处能量分散，不够聚焦；图8d为经过各向异性校正的剖面，不仅增强了深层弱信号，而且断层也更加清晰可见（红色箭头处）。

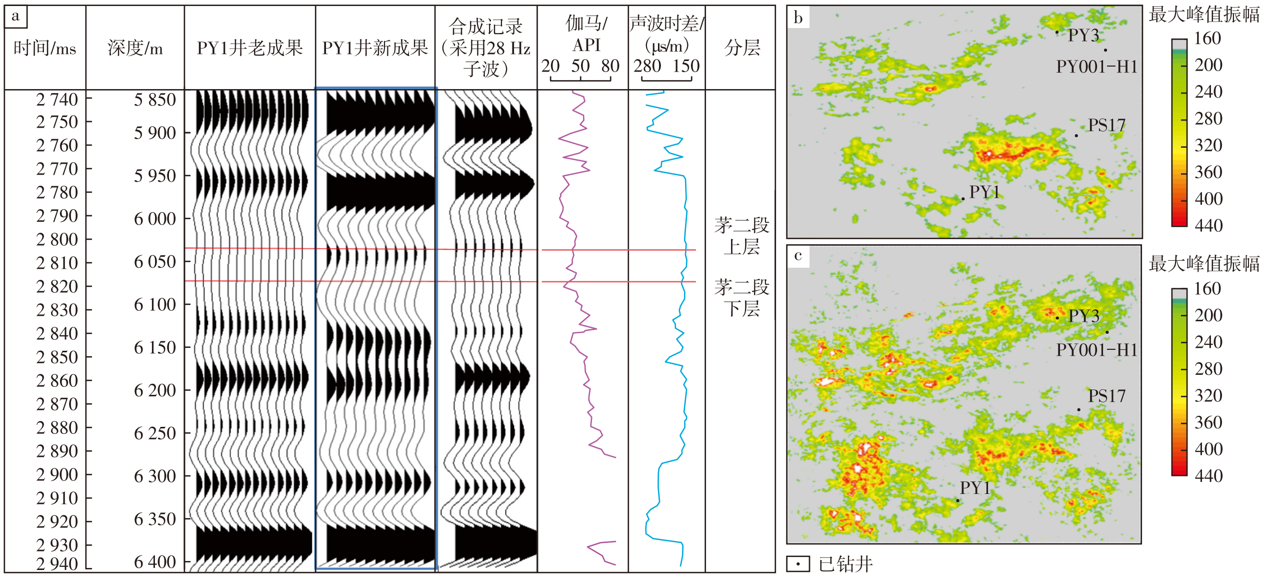
4　应用实例

本次试验区位于西充三维区，面积为200 km²。数据采集于2019年，采用24线7炮270道的观测方式，覆盖次数达180次。面元为20 m×20 m，最大偏移距为6 332.46 m，纵横比为0.62，属于典型的高密度、宽方位采集。原始资料信噪比高，但深层主频较低、频带较窄。主要干扰因素包括面波、脉冲干扰、层间多次波干扰及各向异性等。经过“双高”处理后，干扰储层的多次波得以消除，道集质量显著提升，井震剖面吻合度较高，取得了良好的效果。

该区储层主要为茅二段上层。前期研究表明：茅二段上层具有中等强度振幅且横向不连续，通常采用茅二段上层最大峰值振幅来表征储层[10-12]。PY1井的埋深为6 040 m，储层厚度为7 m。图9a展示了PY1井合成记录的储层标定结果，合成地震道显示储层底界呈现弱反射，剖面同样表现为弱反射，合成记录与地震波形的强弱吻合度较高，储层特征清晰可见。

图9b和图9c分别展示了攻关前后茅二段上层新、老处理的最大峰值振幅平面图。攻关处理后的结果显示：井震平面吻合度良好，储层区域表现为弱振幅。具体而言，PY1井储层厚度为7 m，PY3井储层厚度为14 m，PS17井储层厚度为3 m。

根据最新的攻关成果，新钻开发井PY001-H1，井深达6 103 m，在茅二段成功钻遇优质白云岩储层，储层斜



注：a. PY1井攻关前后成果和合成记录标定；b. 研究区攻关前茅二段上层最大峰值振幅；c. 研究区攻关后茅二段上层最大峰值振幅。

图9　川中蓬莱地区深层二叠系茅口组茅二段上层储层预测平面图

Fig.9　Planar prediction graphs of upper reservoir of Mao-2 member of Maokou Formation, deep Permian in Penglai area, central Sichuan

厚为23.1 m，垂厚为8.5 m，平均孔度为3.8%，展现出显著的钻探成效。同时，这一成果也验证了此次"双高"处理技术在提高地震资料分辨率、保幅处理、非均质性分析、弱信号恢复等多个方面，对深层储层预测具有显著的促进作用。

5 结论

1）针对蓬莱地区深层薄储层弱反射信号问题，采用"保护低频、拓宽高频"的处理思路，优选处理流程和模块，对解决茅口组、龙王庙组储层薄、埋藏深、信号弱等难题具有一定效果。获得的新成果使二叠系茅口组和龙王庙组储层特征更加清晰，可识别性显著提高，提升了目标层段的井震匹配度，值得推广应用。

2）深层薄储层的目标处理是一项系统工程，高频段有效信号的信噪比是后期提频处理的关键因素。因此，在每个处理阶段都应重视提高高频端弱信号的信噪比，以确保实现后续的高保真拓频处理。

参考文献

[1] 陈宗清. 四川盆地中二叠统茅口组天然气勘探[J]. 中国石油勘探, 2007, 12(5): 1-11.
CHEN Zongqing. Exploration for natural gas in middle Permian Maokou Formation of Sichuan Basin[J]. China Petroleum Exploration, 2007, 12(5): 1-11.

[2] 张宇, 曹清古, 罗开平, 等. 四川盆地二叠系茅口组油气藏勘探发现与启示[J]. 石油与天然气地质, 2022, 43(3): 610-620.
ZHANG Yu, CAO Qinggu, LUO Kaiping, et al. Reservoir exploration of the Permian Maokou Formation in the Sichuan Basin and enlightenment obtained[J]. Oil & Gas Geology, 2022, 43(3): 610-620.

[3] 胡东风. 四川盆地元坝地区茅口组台缘浅滩天然气勘探的突破与启示[J]. 天然气工业, 2019, 39(3): 1-10.
HU Dongfeng. Breakthrough in natural gas exploration in the platform margin shoal at the Maokou Fm in the Yuanba area, Sichuan Basin, and its implications[J]. Natural Gas Industry, 2019, 39(3): 1-10.

[4] 常少英, 李昌, 陈娅娜, 等. 海相碳酸盐岩储层地震预测技术进展及应用实效[J]. 海相油气地质, 2020, 25(1): 22-34.
CHANG Shaoying, LI Chang, CHEN Ya'na, et al. Progress and application of seismic prediction technology for marine carbonate reservoir[J].Marine Origin Petroleum Geology, 2020, 25(1): 22-34.

[5] 李素华, 胡昊, 朱兰, 等. 川北元坝地区茅口组生屑滩岩溶储层识别及预测[J]. 石油物探,2021, 60(4): 589-594.
LI Suhua, HU Hao, ZHU Lan, et al. Identification of bioclastic beach reservoir in the Maokou formation, Yuanba area, north Sichuan Basin[J]. Geophysical Prospecting for Petroleum, 2021, 60(4): 589-594.

[6] 蒋晓迪, 朱仕军, 张光荣, 等. 四川盆地蜀南地区茅口组储层预测研究[J]. 天然气勘探与开发, 2014, 37(1): 37-40.
JIANG Xiaodi, ZHU Shijun, ZHANG Guangrong, et al. Reservoir prediction of Maokou Formation, southern Sichuan Basin[J]. Natural Gas Exploration and Development, 2014, 37(1): 37-40.

[7] 徐姣, 孙庆莉, 段杰, 等. 四川盆地东部涪陵—巴南地区茅口组储层特征及预测[J]. 天然气勘探与开发, 2019, 42(3): 86-94.
XU Jiao, SUN Qingli, DUAN Jie, et al. Predicting reservoir characteristics of Maokou Formation, Fuling-Ba'nan area, eastern Sichuan Basin[J]. Natural Gas Exploration and Development, 2019, 42(3): 86-94.

[8] 赵容容, 张宇, 周星合, 等. 基于褶积地震正演技术在碳酸盐岩储层预测中的应用: 以川中高磨地区灯影组为例[J]. 物探化探计算技术, 2022, 44(4): 442-451.
ZHAO Rongrong, ZHANG Yu, ZHOU Xinghe, et al. The seismic modeling method based convolution using in the reservoir predicting of carbonate rock: Using the Gao-Mo block Dengying formation as example[J]. Computing Techniques for Geophysical and Geochemical Exploration, 2022, 44(4): 442-451.

[9] 何昌兴悦, 陈康, 李承泽, 等. 四川盆地东部卧龙河地区茅口组白云岩储层地震响应特征[J]. 天然气勘探与开发, 2023, 46(4): 107-115.
HE CHANG Xingyue, CHEN Kang, LI Chengze, et al. Seismic-response characteristics on dolomite reservoirs of Maokou Formation, Wolonghe area, eastern Sichuan Basin[J]. Natural Gas Exploration and Development, 2023, 46(4): 107-115.

[10] 龙隆, 何青林, 张艺华, 等. 川中龙女寺地区茅口组储层地震预测方法[J]. 天然气勘探与开发, 2022, 45(4): 40-48.
LONG Long, HE Qinglin, ZHANG Yihua, et al. Seismic prediction methods for reservoirs of Maokou Formation, Longnvsi area, central Sichuan Basin[J]. Natural Gas Exploration and Development, 2022, 45(4): 40-48.

[11] 何宗强, 何青林, 韩嵩, 等. 川中地区北斜坡二叠系碳酸盐岩储层弱反射信号处理技术[J]. 天然气勘探与开发,2023, 46(4): 99-106.
HE Zongqiang, HE Qinglin, HAN Song, et al. Weak reflected-signal processing technologies for Permian carbonate reservoirs, north slope of technologies for central Sichuan Basin[J]. Natural Gas Exploration and Development, 2023, 46(4): 99-106.

[12] 席彬, 任达, 王金刚, 等. 高密度三维地震勘探技术在川中地区的运用[J]. 天然气勘探与开发, 2013, 36(4): 39-43.
XI Bin, REN Da, WANG Jin'gang, et al. Application of high-density 3D seismic technology to central Sichuan Basin[J]. Natural Gas Exploration and Development, 2013, 36(4): 39-43.

[13] 谢格云, 胡欣, 王旭丽, 等. 龙门山北段推覆构造带—山前带构造解析及油气勘探前景[J]. 天然气勘探与开发, 2023, 46(1): 11-18.
XIE Geyun, HU Xin, WANG Xuli, et al. Structural analysis and exploration prospects of nappe-piedmont structural belt in northern Longmenshan area, Sichuan Basin[J]. Natural Gas Exploration and Development, 2023, 46(1): 11-18.

[14] 李亚, 钟佳倚, 汪华, 等. 川东地区茅一段储层地质特征及勘探潜力分析: 以XT1井为例[J]. 天然气勘探与开发, 2023, 46(4): 57-68.
LI Ya, ZHONG Jiayi, WANG Hua, et al. Geological characteristics and exploration prospects of the first member of Maokou Formation in eastern Sichuan Basin: An example from XT1 well[J]. Natural Gas Exploration and Development, 2023, 46(4): 57-68.

[15] 孙丹. 基于叠加速度谱建立速度模型方法在X开发区的应用[J]. 非常规油气, 2023, 10(5): 30-37.
SUN Dan. Application of velocity model based on superimposed velocity spectrum in X development zone[J]. Unconventional Oil & Gas, 2023, 10(5): 30-37.

[16] 杨广广, 吕襲, 韩嵩, 等. "双高"地震资料处理技术与应用: 以四川盆地射洪区块沙溪庙组河道砂储层成像为例[J]. 天然气勘探与开发, 2020, 43(2): 1-8.
YANG Guangguang, LYU Yan, HAN Song, et al. "Double-high" seismic-data processing technology and its application: An example from imaging of channel sandbody reservoirs of Shaximiao Formation, Shehong block, Sichuan Basin[J]. Natural Gas Exploration and Development, 2020, 43(2): 1-8.

（下转第433页）