常用地震反演方法技术特点与适用条件

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摘要： 不同的地震反演方法具有不同的技术特点及适用条件，针对当前石油行业常用的基于地质模型的地震反演、约束稀疏脉冲反演、储层特征属性反演、分频反演和地质统计反演等地震反演方法，从基本原理、技术关键、存在的优缺点等角度进行分析，并结合其在不同的区块、层系、储层特征和油气藏类型的应用实例，分析了各种反演方法的技术特点和适用条件。研究结果表明，针对复杂的地质目标，只有通过优选确定适用的地震反演方法，将获得的反演结果与属性分析结合，才能进一步提高储层描述的精度，达到解决复杂地质问题的目的。

关键词： 地震反演 反射系数 波阻抗 地震属性 变差函数 声波时差
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地震反演是众多储层预测技术中较为有效的方法之一。经过十几年的发展，尽管其本身存在着许多不足，但在实际生产中，无论是进行圈闭评价与探井井位论证还是开展油气藏描述及编制开发方案，都离不开基于地震反演的储层纵、横向预测工作。关于地震反演方法的分类，前人均有研究[1－2]。不同的地震反演方法具有不同的技术特点及适用条件，如何针对研究区具体情况选择最合适的反演方法，除了需要对各种反演方法的基本原理、技术关键充分了解之外，还须经过实际应用，不断积累总结经验，才能恰当地通过它们来解决实际问题。前人对各种反演方法的对比评述大多偏重于理论方面[3－4]。笔者基于多年从事地震反演工作的经验，对当前石油行业常用的基于地质模型的地震反演、约束稀疏脉冲反演、储层特征属性反演、分频反演和地质统计反演等多种地震反演方法，从基本原理、技术特点、存在的优缺点等角度进行分析，结合应用实例，分析各种反演方法的适用条件，以期为地震反演工作提供参考。

1 基于地质模型的地震反演

1.1 技术特点

该方法基于测井资料具有较高的垂向分辨率和地震资料具有较好的横向连续性的特点[1]，先利用井资料中的波阻抗数据建立初始波阻抗模型，通过对其不断修改完善，最终形成与实际地震数据吻合程度最好的正演地震模型。应用过程中需要具备 2 个技术关键：①初始波阻抗模型的建立及其在反演时所占比重。当其所占比重值选取过大时，反演剖面就成了测井曲线的复制品，没有充分利用地震资料较好的横向连续性；取值过小，则相当于无井约束，没有充分利用测井资料较高的垂向分辨率。②建立初始波阻抗模型要与沉积相分析成果结合起来，同时要处理好断层、不整合等特定地质现象与层位的对应关系。

20 世纪 90 年代至今，该方法在勘探井位部署、开发方案编制中得到了广泛使用，并取得了较好的应用效果。埕岛油田主力含油层系东营组为三角洲沉积，储层横向变化较大，含油砂体厚度较薄，多为 3～15 m。统计结果显示，由于测井信息的约束作用，大于 5 m 的砂体均可以反演出来，反演厚度与实钻结果吻合较好。埕岛油田埕北 326 区块实钻资料（图 1）显示东营组发育 5 套油层。当反演模型量取值为 20% 时，在反演剖面上只反演出 3 套砂体；而当反演模型量取值为 30% 时，5 套砂体在反演剖面上都有显示，与井点对应情况较好，横向上与地震反射特征相符；当模型量取值继续增加时，反演结果模型化严重，横向上与地震轴发育情况不符。因此，模型量取值的合理性是将测井资料垂向信息与地震资料的横向信息结合起来的关键。

1.2 适用条件

基于地质模型的地震反演是在初始波阻抗模型基础上进行迭代反演，充分加入了测井信息，反演结

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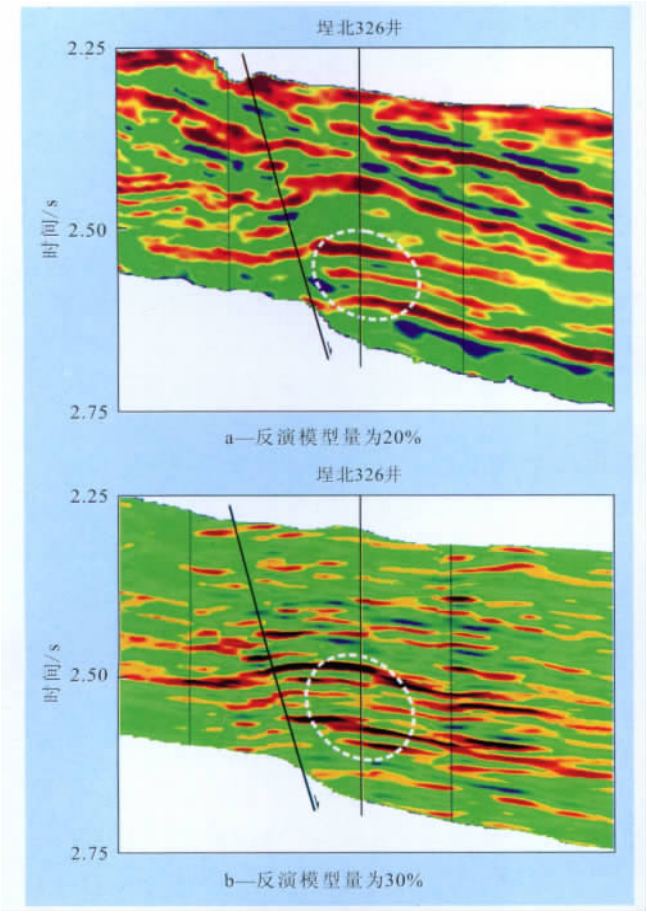

图 1　反演模型量不同取值对应的反演结果对比

果具有相对较高的分辨率，但同时又对初始波阻抗模型存在过重的依赖性。参数取值稍有不当，模型反演会产生多种结果。要建立比较合适的初始波阻抗模型，要求地震资料具有较高品质、较宽的频带、较低的噪音及相对振幅保持；较多的井资料作为约束条件；同时构造要相对简单，以便于迭代收敛。综上所述，基于地质模型的地震反演方法比较适用于井资料丰富、横向非均质性较强、构造相对简单的河流相、(扇) 三角洲等沉积类型。

2　约束稀疏脉冲反演

2.1　技术特点

约束稀疏脉冲反演的基本原理是基于地下的强反射系数界面是稀疏分布的这一认识来实现的[5]。其实质就是在波阻抗趋势的约束下，用最少的层反射系数脉冲实现合成记录与地震道的最佳匹配，进而得到相对波阻抗数据，然后再通过测井信息进行低频补偿，最终得到全频带的绝对波阻抗数据体。其技术关键在于地震匹配系数(λ) 的确定及全区波阻抗变化的趋势、范围的确定[6-7]。过大的 λ 值过分强调了地震残差最小，只考虑使合成记录与原始地震道吻合，结果会导致更多的噪音参与反演；λ 值过小，则强调了稀疏性，反演结果细节少，分辨率低，残差大。因此，在反演中选择应用软件中各质量监控曲线均收敛的相对合理的 λ 值，既能拓宽反演结果的频谱，也能保证一定的分辨率。使用过程中应尽量加密用于控制的地震解释层，保证约束井的趋势线更加精细；如果低频模型做的比较好，也可以从中直接提取全区波阻抗变化的趋势线。

近年来，稀疏脉冲反演作为主要的反演方法之一，在胜利油区多个区块进行了应用。垦东 481 区块主力含油层系为馆陶组上段 2 套储层，垦东沉积相带为曲流河沉积，厚度为 5 ~ 10 m。依据 JASON 软件用于质量监控的 5 条曲线的收敛情况，确定该区块 λ 值为 12。从反演结果(图 2) 来看，横向上与地震资料吻合良好，能够客观反映储层横向变化，但是纵向上砂体厚度吻合较差，分辨率基本等同于原始地震。

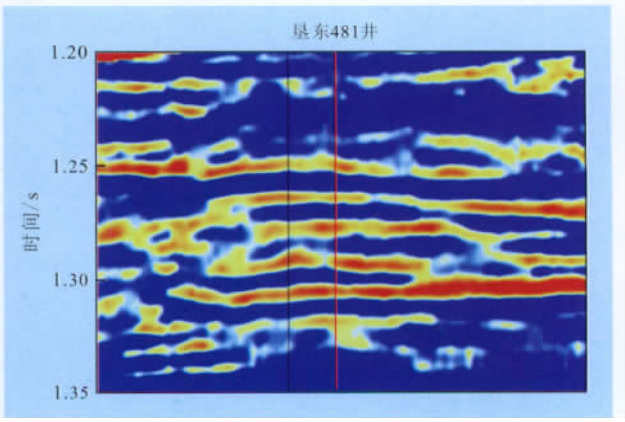

图 2　垦东 481 井区稀疏脉冲反演结果

2.2　适用条件

稀疏脉冲反演过程中，井资料没有直接参与反演，只是起到提供低频信息的作用。同时，这种反演算法是尽量考虑大的反射界面，因此细节部分不能完全反映出来，导致反演分辨率只能达到地震资料最大分辨率。其优势是横向上比较完整地保留了地震反射的基本特征，能反映出岩性、岩相的空间变化。稀疏脉冲反演多用于井资料较少、储层较厚、横向非均质性较强的区块，主要针对河流相、三角洲、浊流沉积等沉积类型。适用于勘探、开发的各个阶段，在勘探初期只有很少钻井资料的条件下，可用来进行岩相分析，寻找有利勘探区带；在勘探中后期，根据钻井揭示的储层特征进行横向预测，确定评价

井位;在开发阶段,为地质建模提供储层厚度的变化,优化方案设计。

3 储层特征属性反演

3.1 技术特点

储层特征属性反演方法是通过建立井点处能反映储层物性变化的特征属性与井旁地震道所提取的一系列地震属性之间的映射关系,将这种对应关系应用于全三维工区,便可得到研究区的储层特征数据体反演结果。其技术关键是储层特征曲线的构建及其与地震属性映射关系的建立。通常是选择对储层反映敏感的测井曲线来构建储层特征曲线。在建立储层特征曲线和多种地震属性之间的映射关系时,在误差趋势控制下选取地震属性。

富台油田车古 201 潜山主要含油层位为下古生界,储层原生孔隙不发育,裂缝为主要储集空间。潜山的储层和非储层声波时差差异较小,波阻抗反演方法无法适用,因此,采用储层特征属性反演技术实现潜山裂缝性储层的定量预测。选取对裂缝储层反应敏感的深浅电阻率和自然伽马来构建特征曲线。应用逐步多元回归的算法来筛选地震属性,当误差下降收敛至最低点后,再发散时,对应的地震属性即为与井点特征曲线相关关系最为密切的地震属性。应用该方法选取了 11 个属性参数,将反演结果按 3 个目的层段进行抽取和定量转换,在平面上编绘等值线图,可以直观地确定各目的层的裂缝发育情况。

3.2 适用条件

储层特征属性反演是通过建立测井属性与地震属性之间的映射关系来实现的反演技术。当储层和非储层声波时差差异非常小,常规波阻抗反演无法应用时,可以考虑应用该技术。其优势是可以得到分辨率较高的反演结果,而且井点处与实际情况吻合较好,缺点是储层特征曲线的构建及其与地震属性映射关系的建立难度较大。储层特征属性反演较多应用于井资料丰富、声波无法区分储层的区块,适用于滩坝砂等储层发育较薄的沉积类型以及潜山裂缝、泥岩裂缝等常规反演较难进行的沉积类型。

4 分频反演

4.1 技术特点

分频反演是目前反演领域中一项比较新的技术,首先对地震数据进行分频,产生不同频带的数据体,计算出振幅与频率的关系,将频率作为独立信息引入反演,建立起测井波阻抗曲线与分频属性之间的映射关系,进而得到反演结果[8]。其技术关键为地震分频属性提取及其与测井资料非线性映射关系的建立。提取地震分频属性的重点是要对地震资料进行频谱分析,掌握地震频带宽度、低频、主频及高截频等信息,为滤波参数设定提供依据。利用支持向量机进行多次学习来建立地震分频属性与测井资料非线性映射关系。

在胜利油区新北油田垦东 70 区块、陈家庄气田陈气 12 区块应用了此项技术。由于在地震有效频带内合理利用了相对低频和相对高频成分,反演结果的分辨率较高,与井的吻合程度比较好。但是此类反演方法的算法稳定性不是很好,有时不易收敛,导致产生的反演结果难以满足需要。

4.2 适用条件

分频反演实际上是一种无子波提取、无初始模型的高分辨率线性反演,理论上可以达到较高的分辨率,可以更真实地反映地层接触关系。但是由于其算法的不稳定性,有时会产生较差的反演结果,在实际应用时应该多加注意。分频反演较多用于储层厚度较薄、横向非均质性较强的区块,适用于河流相、(扇)三角洲、滩坝等沉积类型。

5 地质统计反演

5.1 技术特点

地质统计反演方法以测井、地震、地质资料为基础,将地质统计模拟与地震反演紧密结合,其原理和方法特点较为成熟,很多文献都有报道[9-10]。其技术关键为利用井点直方图及变差函数进行分析,剔除异常的井点数据,使得数据符合正态分布,从而得到研究区储层参数的概率分布特征。变差函数拟合时,要充分了解区块储层空间分布特征,选择合理的参数,以保证得到的变差函数能够准确代表储层参数的空间变化特征。

胜利油区老 168 地区面积为 40 km^2,馆陶组上段为河流相沉积,储层厚度较薄,共有 29 口探井,能够满足反演要求。通过应用地质统计反演来尝试解决薄储层的识别问题。在变差函数分析时,Z 方向井点数据丰富,变程可以通过变差函数拟合来求取。对于 X 和 Y 方向的变程,理论上也可以通过变差函数拟合来求取,但由于平面上样点数(井数)有限,拟合结果不具代表性。结合分频属性分析结果,从

沉积规律入手，来确定 X 和 Y 方向的变程，确保能够如实反映储层空间的变化。最终获得的反演结果分辨率较高，统计反演与实钻结果符合率为 87%（图 3）。

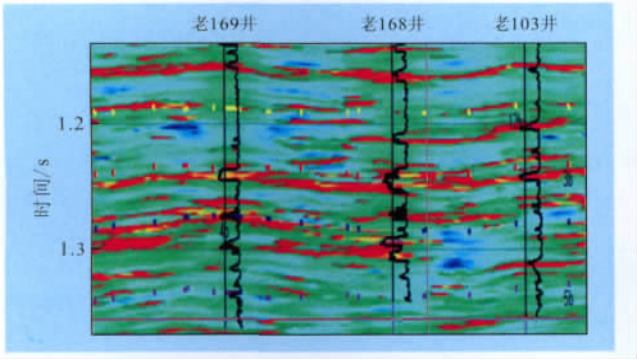

图 3　老 168 井区地质统计反演结果

5.2　适用条件

地质统计反演不仅仅局限于波阻抗反演，也可以得到多种储层物性参数分布特征。其反演结果可以与井达到最佳吻合，分辨能力能同时兼顾不同厚度储层。但这种反演方法也存在诸多不足之处：①只适用于三维工区，运算速度慢，实现的次数多，对多次获得的结果要进行综合分析；②研究区内要有适当数量的井位，而且分布要均匀；③储层参数统计特征要符合正态分布、对数正态分布或者通过转换形成满足上述分布的参数。总之，统计反演多用于勘探后期和开发阶段井资料丰富且分布均匀的区块，在储层厚度上没有限制，适用于河流、三角洲、碳酸盐岩等各种沉积类型，可以为地质建模提供储层参数分布。

6　结束语

不同的地震反演方法具有各自的技术特点及适用条件，应该立足于研究区的实际情况，针对不同的区块、层系、储层发育特征和油气藏类型，通过试验对比，优选出最适合的地震反演方法。在研究区块地质条件日趋复杂的情况下，单一的地震反演方法解决地质问题的能力是有局限性的，只有在熟悉工区地质资料的前提下，利用优选出的地震反演方法与属性分析相结合，才能进一步提高储层描述的精度，达到解决复杂地质问题的目的。

参考文献：

[1] 赵铭海. 常用叠后波阻抗反演技术评析 [J]. 油气地质与采收率，2004，11(1)：36－38.
[2] 石磊，王昌景. 常用的几种反演软件的比较 [J]. 西南石油学院学报，2004，26(3)：16－19.
[3] 吴大奎，唐必锐，覃发兰，等. 地震资料储层预测反演方法应用研究 [J]. 天然气工业，2004，24(10)：38－40.
[4] 刘喜武，年静波，吴海波. 几种地震波阻抗反演方法的比较分析与综合应用 [J]. 世界地质，2005，24(3)：270－275.
[5] 安鸿伟，李正文，李仁甫，等. 稀疏脉冲反演在 YX 油田开发中的应用 [J]. 石油物探，2002，41(1)：56－60.
[6] 杨晓兰，刘小平，刘彦君. 稀疏脉冲反演在东营凹陷坨 163 井区沙三段储层预测中的应用 [J]. 油气地质与采收率，2008，15(1)：53－55.
[7] 李廷辉，岳跃龙，胡永军，等. Jason 反演技术在张东地区储层预测中的应用 [J]. 石油地球物理勘探，2005，40(增刊)：108－113.
[8] 于建国，韩文功，刘力辉，等. 分频反演方法及应用 [J]. 石油地球物理勘探，2006，41(2)：193－197.
[9] 慎国强，孟宪军，王玉梅，等. 统计反演方法及其在埕北 35 井区的应用 [J]. 石油地球物理勘探，2004，39(1)：75－83.
[10] 易平，林桂康. 统计地震反演技术及在文昌 13－1 油田的应用 [J]. 石油地球物理勘探，2005，40(1)：87－93.

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Yang Yanmin, Ao Lide, Liu Jinhua et al. Study on characteristics of connate water in the first member of Dainan Formation, deep concave belt of Gaoyou sag. *PGRE*, 2012, 19(4): 27-30.

Abstract: In recent few years, in the research of the exploration and the exploitation of the oilfield, the research on the paleosalinity, paleoclimate and palaeobathymetry is very limited. In this research, we use the result of the tests, such as the clay mineral, microelement, palaeontology and palynomorph, to infer the information of the paleosalinity, paleoclimate and palaeobathymetry. The characteristic of palaeontology shows that the environment of the deep concave belt of Gaoyou sag in the first member of the Dainan Formation is freshwater lake of continental facies, and by the analysis of the microelement, the paleosalinity of the research area changed from the brackish water to freshwater. And, we use the color of the mud stone to analyze the palaeobathymetry, and in the well, the color of the mud stone changed from the deep grey to brown, grey, and to deep grey again, this shows that the palaeobathymetry is increased in the process.
Key words: paleosalinity; paleoclimate; palaeobathymetry; paleo-water; Gaoyou sag
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Du Zhenjing. Analysis of hydrocarbon accumulation of buried hill in east Chengdao area. *PGRE*, 2012, 19(4): 31-33.

Abstract: In accordance with complicated geological framework and hydrocarbon accumulation rules and insufficient understanding for reservoir characteristic, comprehensive analysis of drilling, borehole logging, structure interpretation and testing data was put forward to study its structure and strata characteristics, petroleum distribution rules and master control factors for hydrocarbon accumulation. Result shows that the strata of research area are distributed irregularly as the result of multiphase tectonic movement and rollover. Strata in different structural zone or different place of the same structural zone have deviation. There is variable degree of petroleum enrichment in Archean, lower Paleozoic, upper Paleozoic, and Mesozoic along the vertical section. Lower Paleozoic has the most enrichment and petroleum mainly accumulates in high part of structure. Along the horizontal section, oil distribution horizon varies from older to newer and oil reservoir styles varies from fault block and residual hill to disconformity crossing the structural main part to the limb. Dissection of typical wells shows that the reservoir-cap relationship and lateral sealing condition are main control factors of hydrocarbon accumulation, and the hydrocarbon accumulation mode is herein constructed.
Key words: weathering crust; fault block and residual hill oil reservoir; oil distribution rule; main control factors of hydrocarbon accumulation; buried hill in east Chengdao area
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Jin Qiang, Wu Aijun, Jin Fengming et al. Estimation of source rocks by seismic attributes in the Damengzhuang sag, Wuqing depression. *PGRE*, 2012, 19(4): 34-37.

Abstract: It is rather difficult to conduct source rock evaluation in low degree of exploration area for shortage of drill-well data. Based on differences in the average amplitudes and energies between the source rocks and non-source rocks, an estimating method for identification of the source rocks is established by research on the sequence and seismic stratigraphy on the seismic profiles, i. e. to remove sandy contents in the source rock interval by seismic velocity spectrum plot, to establish relationship between the seismic attributes and TOC contents measured from the source rocks, and to estimate the source rocks on the seismic profiles. Therefore, source rocks in the upper forth member, lower and middle third member of the Shahejie Formation are estimated by this method. The TOC contents are distributed in the studied area as "west high and east low, and south high and north low", the belt in the southern studied area from well Jing-24 to well Wugu-1 is estimated as favorable place for oil and gas accumulation as high TOC contents in the source rocks.
Key words: source rocks; seismic attributes; quantitative estimate; seismic prediction; Wuqing depression
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Sui Shuling, Tang Jun, Jiang Yubing et al. Technical characteristics and applicable conditions analysis on seismic inversion traditional methods. *PGRE*, 2012, 19(4): 38-41.

Abstract: Different seismic inversion methods have different technical characteristics and applicable conditions. Seismic inversion methods usually applied in petroleum occupation, such as geological based model inversion, constrained sparse spike inversion, reservoir characteristic attributes inversion, frequency-divided inversion and geological statistics inversion, are analyzed in basic principles, technical keys, advantages and disadvantages. Technical characteristics and applicable conditions of these methods are also analyzed combined with some applying cases in different blocks, series of strata, reservoir feature and reservoir types. Researching results indicate that, in view of complicated geological designation, only proper seismic inversion methods are defined by optimizing, and inversion results obtained are combined with attributes analysis, can enhance the precision of reservoir description, and attain the aim of resolving complicated geological problems.
Key words: seismic inversion; reflection coefficient; impedance; seismic attributes; variogram; acoustic time
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Tong Minbo, Gao Fei, Li Chunxia et al. Pre-stack density inversion in reservoir and hydrocarbon prediction application in Yong block, Subei Basin. *PGRE*, 2012,19(4):42-45.

Abstract: Yong block is located in the center of Dongtai depression in north Subei Basin, and its reservoir type is complex and diverse. This paper predicts reservoir and hydrocarbon in study area using pre-stack seismic inversion method which is used to guide the rock-physics analysis. With log data correction and standardization, the log curves perform the real stratigraphic rock characteristics, and then carry out the effective stratigraphic correlation to ensure the accuracy of geological understanding. With different lithology and fluid rock-physics sensibility analysis, we distinguish reservoir sands and hydrocarbon, and then identify the best parameter for pre-stack inversion. According to system analysis of elastic parameters of seismic rock physics, and aimed at the complex reservoir characteristics in study area, we combine the rock-physics analysis with pre-stack seismic inversion technology and using approximate Zeoppritz equation method to predict the reservoir sands and hydrocarbons. Finally, combined the well with seismic correction, the results indicate that: pre-stack inversion results can predict reservoir sands distribution well, because of the limit of reservoir itself complexity, hydrocarbons prediction can't exposit its distribution characteristics completely. The next step of oil and gas exploration should enhance the study of sedimentary facies and sequence stratigraphy.

Key words: petrophysics; sensitivity; pre-stack seismic; density inversion; hydrocarbon prediction

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Wang Jun, Lü Xiaowei, Wang Lixin. Model-based relative-amplitude-preserved estimation methods and application of seismic processing technology. *PGRE*, 2012,19(4):46-49.

Abstract: Now, there are few effective methods in the relative amplitude preserved estimation of seismic processing technology. It is difficult to evaluate the amplitude-preserved feature using real seismic data, which are affected by many factors such as noise, surface condition, and so on. Based on model data, four kinds of amplitude-preserved estimation methods are proposed, including amplitude statistics curve, residual difference, amplitude ratio and AVO attribute-preserved method. In addition, using model data, the amplitude-preserved features of some key processing techniques are estimated by means of methods mentioned above. By the estimation result, processing parameters and flows can be optimized for geometrical spread compensation, predictive deconvolution and surface consistent amplitude compensation techniques. In consequence, the research is very useful for the improvement of amplitude-preserved of seismic processing results.

Key words: forward model data; relative amplitude preserve; residual difference; amplitude curve; deconvolution; amplitude compensation

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Song Xinwang, Li Zhe. Study on seepage characteristics of hydrophobic associated polymer in porous media. *PGRE*, 2012,19(4):50-52.

Abstract: In order to know whether the hydrophobic association polymer can keep high effective viscosity during migration in porous media, different types of hydrophobic association polymer solution character evaluation and physical simulation test are discussed in the paper to give guidance to the field application. The viscosifying performance is tested for different types of polymer solution with different concentration and shear rate. It shows that hydrophobic association polymer has better viscosifying performance than traditional HPAM in high concentration, but shear rate takes great effect on its pseudo-viscosity. It also shows that ultra high molecular weight hydrophobic association polymer with high molecular weight and some degree of association action performs well viscosifying capacity and even pressure transmitting character in porous media by the test of effective apparent viscosity, flow migration characteristic and displacement characteristics. It perhaps has well application feasibility as oil displacement agent. And, the traditional hydrophobic association polymer with its viscosity generation mainly depending on intermolecular association action perhaps should be further improved as oil displacement agent.

Key words: hydrophobic association polymer; viscosity; porous media; filtering flow; injection pressure; displacement performance

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Yuan Shibao, Sun Xiyong, Jiang Haiyan et al. Ignition experimental analysis of in-situ combustion under condition of preheating. *PGRE*, 2012,19(4):53-55.

Abstract: In-situ combustion is an important way of development mode on heavy oil reservoir, and it is increasingly becoming one of the key replacing technologies after steam soaking. Ignition is the first link in the process of in-situ combustion, in order to examine the different impact of reservoir conditions on ignition combustion and improve the thermal efficiency and success rate of ignition, the impacts for crude oil of different preheating temperature (210 ~ 300 ℃), different flow rate and combustion adjuvant with combustion tube experiments are studied. It concluded that, based on a certain air flux, high preheating temperature is beneficial to reservoir fast ignition, and combustion adjuvant can improve the combustion status of crude oil. For in-situ combustion test, preheating, combustion adjuvant technology is a simple and effective combustion ignition technology, so it is worthy of promotion and application.

Key words: laboratory experiment; in-situ combustion; preheating; combustion adjuvant; ignition; thermal recovery

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