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地质统计学反演方法及其在薄层砂体预测中的应用

Geostatistical inversion method and its application in the prediction of thin reservoirs

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摘要:地质统计学反演首先应用确定性反演方法得到波阻抗体,以了解储层的大致分布,并用于求取水平变差函数;然后从井点出发,井间遵从原始地震数据,通过随机模拟产生井间波阻抗,再将波阻抗转换成反射系数并与确定性反演方法求得的子波进行褶积产生合成地震道,通过反复迭代直至合成地震道与原始地震道达到一定程度的匹配. 该方法有效地综合了地质、测井和三维地震数据,反演结果是多个等概率的波阻抗数据体实现,符合输入数据的地质统计学特征并受地质模型的约束,具有测井数据的垂向分辨率高和地震数据的横向分辨率高的优势,可用于不确定性评价.

关键词:地质统计学反演;薄层砂体;随机模拟
中图分类号:TE12;P631.4 文献标识码:A

地质统计学反演(Geostatistical Inversion)由 Haas[1](1994)提出,Dubrule[2](1998)和 Rothman[3](1998)加以发展. 它以地震反演为初始模型,从井点出发,井间遵从原始地震数据即以地震数据为硬数据(hard data),建立定量的波阻抗三维地质模型,进行储层横向预测. 其特点在于综合了地震反演与储层随机建模的优势,充分利用地震数据横向密集的特点,精确求取不同方向上的变差函数.

1 地质统计学反演思路

地质统计学反演是一种将随机模拟理论与地震反演相结合的反演方法. 它由 2 部分组成,即随机模拟过程以及对模拟结果进行优化并使之符合地震数据的过程[4]. 反演过程中充分发挥随机模拟技术综合不同尺度数据的能力,如可以综合层序地层研究与地震解释成果建立精细地质模型. 序贯随机模拟沿任一随机路径进行,不同的随机路径得到不同的结果和实现,不同实现的差异反映了地下地质的非均质性和随机性,差异越大,非均质性愈强. 可以通过不同实现的差异评价反演结果的风险,因此,这也是对地震反演多解性的有效反映. 尽管各个实现各不相同,但每次实现都满足:①在井点处与测井数据计算的波阻抗一致;②在井间符合地震数据和已知数据的地质统计学特征. 具体步骤如下:

(1) 建立初始模型;

(2) 随机地选取井间一个网格点;

(3) 估计该网格点的条件概率密度函数;

(4) 从该条件概率分布函数中随机抽取一个值,利用反射系数公式计算反射系数并与子波进行褶积生成合成地震道;

(5) 根据合成地震道与实际地震道匹配程度而决定是否接受该地震道,若接受则计算终止,转向下一个地震道即转向步骤(2),否则重复步骤(4)—(5)[5-6];

(6) 直到完成整个数据体的模拟.

由于测井资料垂向分辨率高,因而,垂向变差函数从测井资料计算;由于地震数据横向上较为密集,例如目前三维地震数据 CDP 一般为 20～25 m,所以水平方向变差函数从地震数据中计算. 这样,不仅可以精确求取任意方向上的变差函数,更能反映储层空

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间结构特性变化. 因此,该方法综合了测井数据的垂向分辨率和地震数据的横向分辨率高的优势[7].

2　技术流程

地质统计学反演的技术流程如图 1 所示.

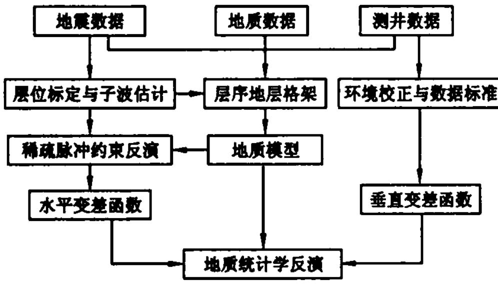


图 1　地质统计学反演流程图

2.1　地层模型

应用钻井取心、测井资料及三维地震资料进行高分辨层序地层学研究和地层对比,建立高精度等时地层格架模型,然后在地层模型约束下进行波阻抗条件模拟.

2.2　确定性反演

为了初步了解波阻抗的大致分布特征,本文采用稀疏脉冲反演方法[8],反演中利用地震数据横向分辨率高的优势,反演波阻抗主要用于求取水平变差函数,在反演过程中求得的地震子波直接用于随后的地质统计学反演.

2.3　地质统计学反演

(1) 测井波阻抗数据的统计分析. 序贯高斯模拟要求数据服从高斯分布,因此模拟前应对数据进行分析,若不服从高斯分布,需要进行数据转换.

(2) 拟合变差函数. 求取空间变差函数是地质统计学反演的关键步骤之一,在常规随机建模中一般使用井点数据,但井点数据只在垂向上数据点密集,求取变差函数精度高,而在水平方向可供用于拟合的数据点稀少,点距大,常常需要给定较大的容错角,拟合出的变差函数不仅精度低,也难以反映井间储层特征的小尺度变化. 如图 2 所示,在滞后距 600 m 以内实验点对很少,缺少统计效应. 地质统计学反演中垂向变差函数从井数据求取,水平方向变差函数从稀疏脉冲约束反演波阻抗数据体中计算. 充分发挥地震波阻抗数据横向上密度的优势,对各个方向进行扫描计算,求取各个方向的变差函数,充分表征储层性质空间分布的各向异性.

变差函数计算在地层模型控制下分层进行,然后分别赋予相应的层. 由于地质模型是在地震资料精细解释和高分辨层序地层学分析的基础上建立的,这有力地保证了层位对比方案的精确性.

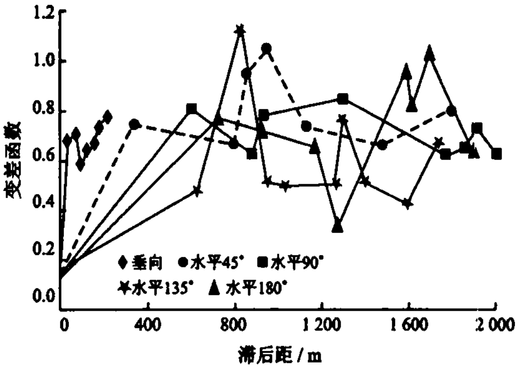


图 2　根据测井数据求取变差函数

3　应用实例

扶余油田 3 号构造于 2004 年新部署了近 300 km^2 的三维地震区域,目的是在油区内部进行挖潜的同时,在油田边部寻找新的有利目标以"增储上产". 本次工作研究区位于扶余油田"二夹五井网"北部. 作为目的层的扶余油层属于白垩系泉头组四段,厚度约 100 m,沉积相研究认为属于三角洲内前缘亚相,岩性组合呈现明显的向上变细的旋回,单砂层厚度 3～5 m,具有厚度薄、横向变化大的特点,常规确定性反演方法受地震频带的限制而难以准确识别,对砂体的不确定性难以进行估计,因此,尝试应用地质统计学反演方法进行反演以提高分辨率和储层预测精度.

3.1　地震资料解释与层序地层格架

地震资料解释是做好反演的基础,而地震剖面上可以在较大范围内追踪的同相轴较少,无法满足反演的需要,进一步的层位解释需要井数据和地震资料的结合. 但在本区,可以在工区内追踪的地震同相轴只有泉四段的顶和底,需要进一步的精细层位解释. 传统上这类工作主要在测井曲线上识别砂体的顶面,并将其顶面标定到地震同相轴上,然后在工区内进行追踪,这种基于岩性地层的解释方法忽略了这样的事实: ①砂体的分布并不是在全区连续的,尤其是在陆相地层中; ②这种对比并不是等时的. 本区通过综合应用钻井取心、测井资料结合三维地震资料进行高分辨层序地层学研究和地层对比,识别出了 4 个短期旋回(SSC1-SSC4) (图 3) ,其中有 3 个较明显的洪泛面(对应泥岩段)在研究区内是相对稳定的,将旋回划分标定到地震剖面上,经反复修改建立了本区等时层序地层格架,这大大增加了地质模型的等时性.

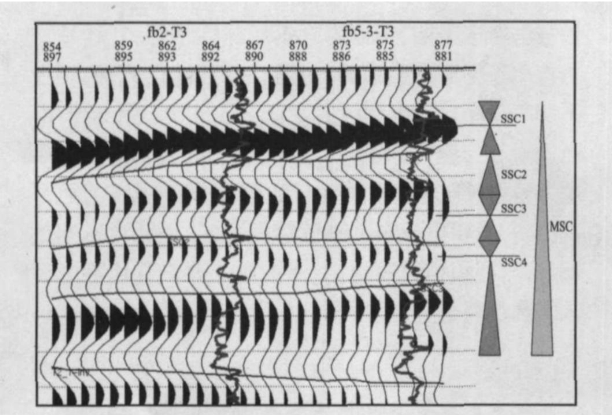


图 3　地质、测井与地震结合建立的高分辨层序地层格架

3.2　稀疏脉冲约束反演

假定地下的强反射系数界面稀疏分布,根据稀疏的原则从地震道中抽取反射系数,与子波褶积生成合成地震道,利用合成地震道与原始地震道的残差修改反射系数,得到新的反射系数序列,再做合成记录.如此迭代,直至得到一个能最佳逼近地震道的反射系数序列.当得到反射系数后,就可以求得相对波阻抗.稀疏脉冲约束反演增加了地质模型和井约束控制波阻抗的趋势和范围,由于地震数据是带限的,因此得到的数据缺少低频信息,必须通过建立地质模型进行低频补偿才能获得一个全频带的绝对波阻抗.

由于该反演是一种基于地震道的反演方法,因此,反演结果更能反映地震数据本身的空间变化,更多地保留了地震数据的原始特征.虽然其垂向分辨率有限,但仍能反映波阻抗的总体变化特征,可用于求取水平变差函数.在反演过程中求得的地震子波可直接用于随后的地质统计学反演.

图 4 为稀疏脉冲约束反演的一条剖面,目的层下部砂体明显发育,厚度大,向上部砂体发育程度减弱,厚度减小.通过与井点扶北 14-7 及扶北 14-2 井旁波阻抗曲线对比可以看出,二者吻合较好,即反演结果基本反映了储层的大致变化规律.但剖面上砂体以块状为主,垂向分辨率有待于进一步提高.

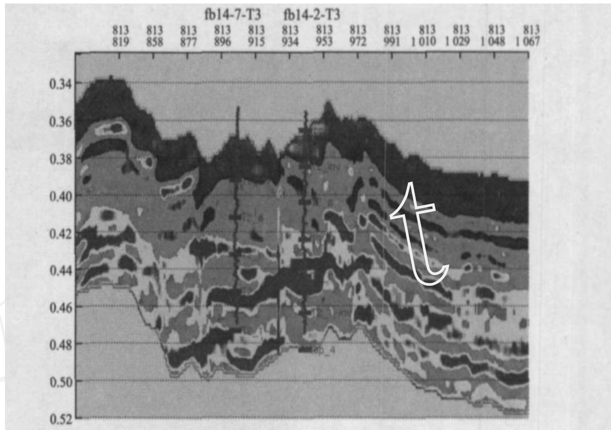
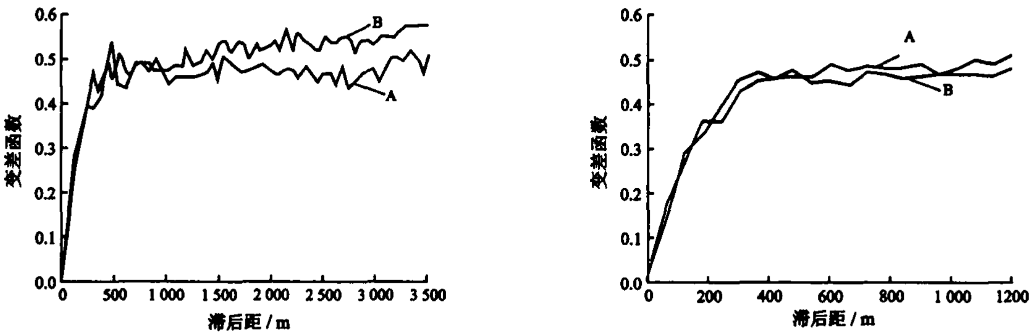


图 4　稀疏脉冲约束反演的波阻抗剖面

3.3　地质统计学反演

由于储层预测关注的重点是井间储层的变化情况,其空间各向异性用变差函数表征.垂向和水平变差函数分别从井数据和稀疏脉冲约束反演波阻抗数据体中计算.在水平方向上,不同方向变差函数变程不同,反映了不同方向数据相关性的差异.根据地震反演波阻抗计算的水平方向变差函数精度明显高于从井数据得到的结果(图 5),这样充分发挥二者在垂向和水平方向的分辨率优势,然后通过实验选取合适的变差函数模型将其拟合成三维变差函数.



(a) 方位角为30°及120°方向　　(b) 方位角为90°及180°方向

图 5　根据地震波阻抗求取变差函数

反演中首先随机选取一个网格点并计算该点的局部概率密度函数(lpdf),从中选取一个波阻抗值,然后将波阻抗转换成反射系数,并用稀疏脉冲反演方法求得的子波与其褶积产生地震道,通过反复迭代直至合成地震道与原始地震数据达到一定程度的匹配.这样,逐个网格点进行模拟和优化.在这里,地震数据和井数据一样作为硬数据得到尊重,由于随机模拟方法包容了噪声,并考虑到数据在一定空间内的相关性,拓宽了地震数据频带,反演结果同时符合测井数据、地震数据和输入数据的地质统计学特征,并受建立的地

层模型的约束,反演结果是多个等概率的波阻抗数据体实现[9-11].

如图6所示是本次地质统计学反演过的扶北4-7、扶北16、扶北12和扶北4井的波阻抗剖面的二次实现,可以看出垂向分辨率较稀疏脉冲约束反演有了很大提高,井点处地震与测井完全吻合,在井间尤其是井距较大时,两次实现之间有一些差异,反映了反演结果的随机性与不确定性.砂体底部的薄层高波阻抗钙质砂岩非常清晰,这种钙质砂岩非常致密,通常被解释成干层,但砂岩含钙后脆性增强,在构造应力作用下易于产生裂缝,是潜在的裂缝发育段,因此了解其分布对研究裂缝的发育与分布具有指导作用.通过岩心与测井标定,利用其速度上的差异,解释了主力砂组(Ⅲ砂组)钙质砂岩的厚度分布(图7),可以看出,它主要位于东部厚砂体发育区,呈北北东向的条形,与沉积相研究规律一致,对应原来分流河道砂体底部最粗部分.

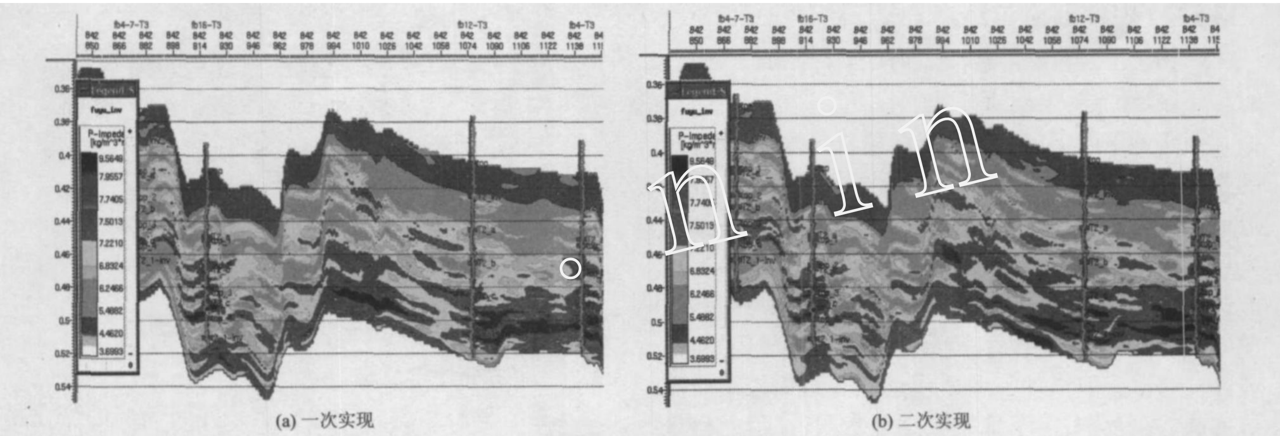


图6　地质统计学反演典型剖面

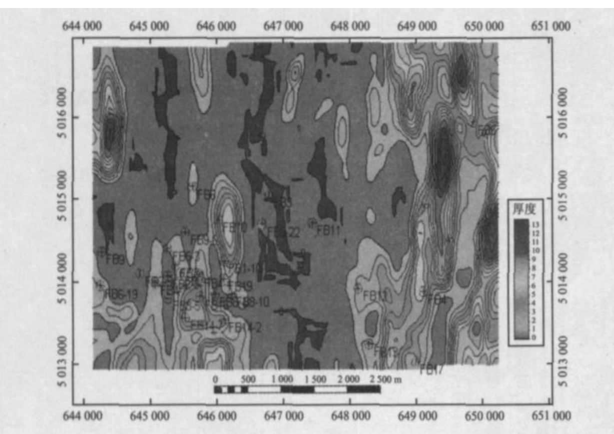


图7　扶余油田"二夹五井网"区北部扶余油层Ⅲ砂组钙质砂层厚度图

4　结　论

在稀疏脉冲约束反演基础上,应用地质统计学反演进行储层表征与预测,不仅可以大大提高地震资料的垂向分辨率,而且可以对反演结果的不确定性进行分析和评价,通过在吉林扶余油田"二夹五井网"区的应用,表明该方法可以有效地综合地质、测井和地震数据进行储层预测,尤其在预测薄砂体方面效果良好.

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5 结 论

鄂尔多斯盆地苏里格庙地区为上古生界盒 8、山 1 储层大面积含气区,天然气资源丰富.然而,对该区盒 8、山 1 储层"甜点"控制因素的分析表明,心滩微相控制了有利砂体的分布,生排烃早—中期(三叠世末至中侏罗世)的古鼻隆构造控制了储层的选择性溶蚀,并控制了有利成岩相分布,最终,生排烃高峰期(晚侏罗—早白垩世)的古鼻隆构造控制了较高产能气井的分布,因此,控制苏里格气田储层"甜点"的关键因素为心滩微相和生排烃期的古鼻隆构造,对它们的精确把握将有助于井位优选和气井产能预测.

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Analysis of the factors of controlling the formation of the lithologic reservoirs in Yangxin subsag

Abstract : The existence of many faults ,the frequent variation of sedimentary facies and sedimentary system and the wide distribution of hydrocarbon rock in the Paleogene of Yangxin subsag all provide favorable geological conditions for the formation of the lithologic reservoirs. The lithologic reservoirs include five types: updip pinch-out sandstone reservoirs ,lens-type sandstone reservoirs , fault-lithologic reservoirs ,igneous reservoirs and structural-lithologic reservoirs. The updip pinch-out sandstone reservoirs mainly distribute in northern steep slope zone and southern slope zone ,the lens-type sandstone reservoirs distribute mainly in central deep subsag zones ,secondly in northern fan-delta front sedimentary facies zones and southern delta front sedimentary facies zones ,and the fault-lithologic reservoirs mainly distribute near fault belts ,the structural-lithologic reservoirs mainly distribute in nose structure belts ,and the igneous lithologic reservoirs mainly distributed in volcanic activity belts. The favorable structural conditions-sedimentary system , the rich oil and gas source conditions ,reservoir property ,the connection or side barriers of fault systems ,the effective cap rocks and the good source-reservoir-caprock assemblage are all the factors of controlling the formation and distribution of the lithologic reservoirs in Yangxin subsag.

Key words : Yangxin subsag ;lithologic reservoir ;controlling factor ;reservoir forming condition ;turbidity sandbody

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Geostatistical inversion method and its application in the prediction of thin reservoirs

Abstract : In geostatistical inversion ,first ,wave impedance is obtained by using deterministic inversion methods in order to understand the general distribution of reservoirs and to get horizontal variogram ;then ,interwell wave impendence is produced by stochastic simulation based on original seismic data ;third ,the interwell wave impendence is transformed into reflection factor ,the compose seismic traces are produced by the convolution of the wave impendence with the wavelets obtained by the deterministic inversion methods , the proper matching of the compose seismic traces with original seismic traces is reached by iterating again and again. The geostatistical inversion method integrates geologic ,logging and 3D seismic data ,and it combines the higher vertical resolution of logging data with the higher horizontal resolution of seismic data. The inversion result accords with the geostatictical characteristics of the input data and is restrained by geologic model. The several implementations of the inversion result are used for the non-deterministic assessment of the reservoirs. The applied result of the inversion method in Fuyu Oilfield in Jilin Province shows that ,the geostatistical inversion method can effectively predict reservoirs ,especially thinner reservoirs by integrating geologic ,logging and 3D seismic data.

Key words : geostatistical inversion ;thin reservoir ;stochastic simulation

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Discussion on the factors of controlling the distribution of the reservoir "sweet spots" of Sulige Gasfield

Abstract : Through the analyses of sedimentary facies ,diageneses and paleostructure inversion during hydrocarbon generation and expulsion period ,it is held that ,the factors of controlling the distribution of the reservoir "sweet spots" of Sulige Gasfield are the distributions of channel bar sedimentary microfacies and the paleo-nose structures during hydrocarbon generation and expulsion period. The channel bar microfacies controls the distribution of effective sandbodies ,the paleo-nose structures in the early--middle stage of hydrocarbon generation and expulsion (from late Triassic to middle Jurassic) control the selective dissolution of the reservoir and the distribution of the favorable diagenetic facies with high--medium porosity ,while the paleo-nose structures in the peak stage of hydrocarbon generation and expulsion (from late Jurassic to early Cretaceous) control the distribution of the gas wells with higher productivity. These points of view offer new thoughts for the exploration and development of Sulige Gasfield ,and are also helpful to effectively and economically exploit the gasfield.

Key words : Sulige Gasfield ;reservoir "sweet spot"; sedimentary facies ;diagenesis ;paleo-nose structure

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Application of inversion techniques to the exploration of the lithologic reservoirs in the regions with low prospecting degree —taking the middle-upper Jurassic in Fudong slope as an example

Abstract : It is a problem commonly faced in the exploration of the central or western basins of China how to explore the lithologic reservoirs in the regions with low prospecting degree. Taking the middle--upper Jurassic of Fudong slope in Zhungeer Basin as a research object ,the lithologic traps in this area are predicted under finite seismic and well-drilling data by synthetically applying inversion techniques ,and the hydrocarbon-bearing potentials of the predicted lithologic traps are analyzed. An inversion course suitable to the prediction of the lithologic traps in the regions with low prospecting degree is put forward :first ,the wave impedance inversion of 2D seismic sections is finished by the inversion method whose core is simulated annealing technique ;then the lithologic traps are identified on wave impedance sections ;finally ,the absorption coefficient inversion to the 2D seismic profiles around a favorable lithologic trap is