

# 改进的断层封闭性计算参数的获取方法及应用

——以辽西凸起中南段为例

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**摘要:**上覆岩层压力、断层倾角和断裂带泥质含量是断层封闭性计算的重要参数,对这3个参数的准确量化,决定计算结果的可靠性。在辽西凸起中南段断层封闭性研究中,发现上覆岩层密度随压实作用增加而增大,通过密度测井与深度回归获得上覆岩层密度变化函数,并对其积分,求取上覆岩层压力;断层倾角会随岩性、应力发生变化,利用精细三维地震解释成果,并运用空间立体几何计算断层倾角;根据地震资料判断泥质含量整体趋势,并结合自然伽马测井计算值进行井点校正,以获得更为精确的断裂带泥质含量;准确求取研究区辽西1号及其分支断裂的这3个参数,并以其乘积作为断层封闭指数。分析油气分布差异发现,研究区北段断层封闭性最好,南段次之,中段最差;断层封闭性下限与油气性质有关,天然气、正常油、稠油聚集的断层封闭指数下限分别为9.34、8.31和6.12。

**关键词:**上覆岩层密度 断层倾角 泥质含量 断层封闭指数 油气性质

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## An improved method for extracting parameters and its application to calculating fault sealing capacity: A case study of the central-southern section of the Liaoxi Uplift

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**Abstract:** Overlying formation pressure, fault dip angle and shale content are the significant parameters for fault sealing capacity evaluation, and the reliability of evaluation results depends on the accuracy quantification of these 3 parameters. In the research of fault sealing of the central-southern Liaoxi Uplift, it is found that the actual overburden density increases with the increase of compaction. Overburden density function was obtained by density logging and depth regression, and then it was integrated to calculate the overburden pressure. The fault dip angle changes with lithology and stress, and it was calculated by 3D seismic interpretation results and spatial stereo method. The overall trend of mud content was determined according to the seismic data, and then it was corrected by well logging gamma value to obtain the more accurate shale content in fault zone. The 3 parameters of No.1 Liaoxi Fault and its branched faults in the research area uplift were calculated accurately, and then their products were used as the fault sealing indexes. Combined with the analysis of differences in oil and gas distribution, it is found that the sealing capacity of the northern section of the study area is the best, followed by the southern section, and the central part is the worst. The lower limit values of fault sealing index are related to the physical properties of oil and gas, and the lower limit values of natural gas, normal oil and heavy oil are 9.34, 8.31 and 6.12, respectively.

**Key words:** overburden density; fault dip angle; shale content; fault sealing index; properties of oil and gas

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断陷盆地中的断层封闭性对油气的运聚起着至关重要的作用,并决定了油气分布<sup>[1-4]</sup>。中外众多学者针对断层封闭性开展了大量研究,提出了多种断层封闭性的评价方法及应用,其中有断裂带泥岩涂抹评价法<sup>[5-7]</sup>、地应力参数评价法<sup>[8-9]</sup>、断裂带与储层排替压力差评价法<sup>[10-12]</sup>及断层连通概率法<sup>[13]</sup>等综合评价方法<sup>[14-16]</sup>。但是,目前对断层封闭性的评价,还存在两方面的问题:一是计算参数求取精度不够,比如在确定断层倾角时,经常忽略断裂产状的空间变化;求取上覆地层压力时,缺乏考虑上覆岩层密度的变化;利用粗略的砂泥岩层段厚度比值厘定断裂带泥质含量。二是在确定断层封闭性下限时,较少考虑油气物性的差异。笔者在前人研究的基础上,提出了断层封闭性计算参数的求取方法,即利用上覆岩层密度与深度的回归函数积分得到上覆岩层压力,以三维地震解释为基础,运用空间立体几何确定倾角,选取自然伽马测井计算值,结合地震预测计算断裂带泥质含量,以这3个参数的乘积作为断层封闭指数。以辽西凸起中南段为例,计算辽西1号及其分支断裂的封闭指数,确定了天然气、正常油和稠油的断层封闭指数下限值,不同物性油气分布与断裂封闭能力的相关性研究对辽西凸起下步的油气勘探具有重要的指导意义。

## 1 区域地质概况

辽西凸起为发育在辽东湾拗陷西部的一个NNE向长条形凸起,断裂活动对凸起的形成演化起着主导作用,凸起中南段为一受辽西1号断裂控制的单面山,西侧紧邻辽西凹陷,东侧以缓坡带向辽中凹陷过渡(图1)。研究区新生代构造活动整体呈北弱南强的特点<sup>[17]</sup>,构造上可划分为北部A构造、中部B构造和南部C构造。北部A构造沉积较为连续,发育辫状河三角洲和扇三角洲储层,油气主要聚集在沙二段的断块圈闭、断背斜圈闭及中生界潜山,以正常油与天然气为主。中部B构造为A到C构造的过渡区,缺失沙河街组下部地层,发育辫状河三角洲储层,有少量油聚集在沙一段的背斜圈闭。南部C构造由于抬升剥蚀较为严重,基本缺失沙河街组,油气聚集在东二段辫状河三角洲储层,且以断块、复杂背斜的稠油油藏为主<sup>[18-20]</sup>。辽西1号断层断穿层位多,长期继承性活动,是连接西侧辽西凹陷沙三段烃源岩与凸起油气藏的重要通道,而断层及其分支断裂的封闭性是凸起油气聚集的重要控制因素<sup>[21]</sup>。

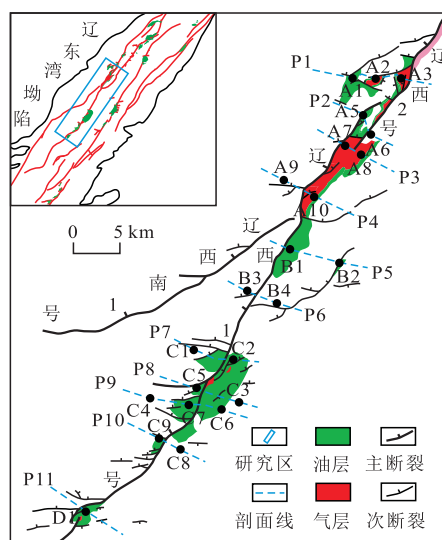


图1 辽西凸起中南段构造纲要

Fig.1 Structural outline of the central-southern section of the Liaoxi Uplift

## 2 断层封闭性评价参数的精细求取

断层封闭性是断裂带内充填物对油气遮挡能力的反映,其与影响成岩作用的断裂带压实程度、断裂带充填物有关<sup>[22]</sup>。对于砂泥岩地层,断层封闭性主要取决于断面正压力与断层岩泥质含量<sup>[23]</sup>。断面正压力越大,断裂带封闭程度越高,断层岩的成岩程度越高;泥质含量越大,其孔渗性越差,断层封闭性越好<sup>[7,24]</sup>。因此,可以利用断层封闭指数,即断面正压力与断裂带泥质含量的乘积作为断层封闭性的定量评价参数<sup>[25]</sup>,其表达式为

$$F_{vs} = p_{\text{断面}} \times V_{sh} \quad (1)$$

断面正压力可以利用上覆岩层压力与断层倾角来求取<sup>[26]</sup>,其表达式为

$$p_{\text{断面}} = p_H \times \cos \theta = H(\rho_r - \rho_w)g \cos \theta \quad (2)$$

由式(1)、式(2)得

$$F_{vs} = H(\rho_r - \rho_w)g \cos \theta \times V_{sh} \quad (3)$$

由式(3)可知,上覆岩层密度、断层倾角和断裂带泥质含量是断层封闭性求取的关键参数,提高断层封闭性评价精度,需要准确获取这3个参数。

### 2.1 上覆岩层压力

在求取上覆岩层压力的过程中,前人往往用平均密度来代替上覆岩层密度<sup>[27]</sup>,而实际上覆岩层密度随压实作用增加而增大,是与地层埋深相关的函数。该函数可以通过密度测井与深度回归获得。以A5井为例(图2),通过密度测井回归得到该井区地层密度与深度的函数为

$$\rho(h) = a \ln h + b \quad (4)$$

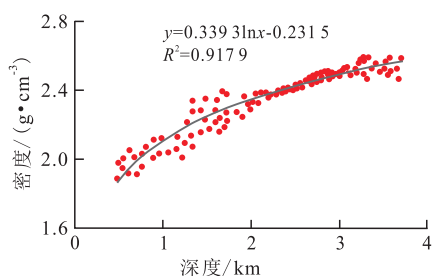


图2 A5井地层密度随深度的变化

Fig.2 Variation of formation density with depth drilled by Well A5

断面埋深  $H$  点上覆岩层压力的计算公式为

$$p_H = Hg\rho_r - \rho_w gH = \int_0^H \rho(h)gdh - \rho_w gH = gH(0.3393 \ln H - 0.1078 - \rho_w) \quad (5)$$

### 2.2 断层倾角

前人在计算断面正压力时,往往选取一个定值来代替研究层段的断层倾角,而实际上各位置断层由于岩性、应力变化,其倾角也不断变化。为准确计算断层的封闭指数,在求取断层倾角时应考虑其变化趋势。断层倾角可以利用精细三维地震解释成果,并运用空间立体几何计算求取(图3),其中,水平面法线向量  $OS=(0,0,1)$ ,断层面法线向量  $OR=MN \times MP$ ,则倾角求取公式为

$$\angle\theta = \angle 1 = \angle 2 = \arccos \frac{OS \cdot OR}{|OS| \cdot |OR|} \quad (6)$$

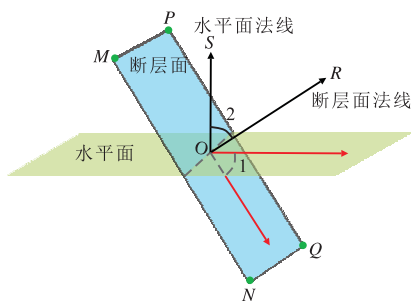


图3 断层倾角计算示意

Fig.3 Schematic diagram of calculation of fault dip

### 2.3 断裂带泥质含量

前人在获取断裂带泥质含量时,常用研究层段的泥地比值来代替<sup>[28]</sup>,而实际地层中并无纯砂岩、纯泥岩,泥地比值难以反映断裂带内充填物的泥质含量。利用钻井取心分析,能够得到精确的断裂带泥质含量,但是受钻井位置和取心数量的限制,利用岩心来确定泥质含量难以实现。对于有井钻穿或紧邻井的断层,利用其自然伽马测井值可直接准确计算出某一点的泥质含量<sup>[29]</sup>。对于离井较远的断层,假定断裂带内的充填物来自于断层两盘,可以利用地震层速度计算地层砂岩含量<sup>[30-31]</sup>,进而求取泥质含量。在实际应用中,通常采用地震与井数

据相结合的方法,首先利用地震资料求取整体趋势,然后利用单井资料进行井点校正,这样得到的泥质含量更接近真实情况,即

$$V_{sh} = \frac{2^{GCUR(GR-GR_{min})/(GR_{max}-GR_{min})} - 1}{2^{GCUR} - 1} \quad (7)$$

将式(5)一式(7)代入式(3),得到改进的断层封闭指数计算公式为

$$F_{vs} = p_H \times \cos \theta \times V_{sh} = (0.3393 \ln H - 0.1078 - \rho_w) Hg \frac{OS \cdot OR}{|OS| \cdot |OR|} V_{sh} \quad (8)$$

## 3 辽西凸起中南段断层封闭性评价

### 3.1 断层封闭指数求取

利用改进的断层封闭指数计算公式,对辽西凸起中南段横切辽西1号断层的11条油藏剖面进行分析(剖面位置见图1),以P2剖面为例(图4)。断层的封闭往往阻止下盘油气的侧向、垂向运移,以断块、断背斜圈闭中起反向断层遮挡作用的①—⑤砂层组为研究对象,砂层组的中心深度作为断面埋深,利用式(5)得到各点的断层压力,并通过井-震结合得到断裂带各点的泥质含量,进而由式(8)计算出相应的断层封闭指数。利用相同的方法,计算其他10条剖面的52个点的断层封闭指数。根据计算结果,可以确定不同位置断层封闭性的差异;结合油气物性,还可确定不同性质油气的断层封闭指数下限。

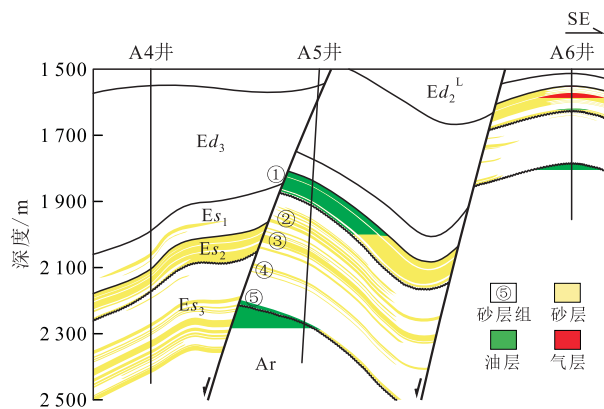


图4 P2油藏剖面

Fig.4 Profile for P2 reservoir

### 3.2 断层封闭性分析

根据计算的断层封闭指数,可以将研究区的断层分为南段、中段和北段,其中北段的P1—P5剖面断层封闭能力最好,  $F_{vs}$  值为8.31~12.19,平均值为9.82;南段的P7—P11剖面次之,  $F_{vs}$  值为5.08~7.82,平均值为6.54;中段的P6剖面断层封闭能力最

差,  $F_{vs}$  值均小于6.1。从研究区含油气情况来看, 南段和北段油气富集, 中段油气较少, 说明断层封闭性对油气聚集具有控制作用。

### 3.3 不同性质油气断层封闭指数下限

研究区存在天然气、正常油和稠油3种不同性质的油气, 其中天然气、正常油分布在研究区北部的A油田, 具有下油上气分布特征; 稠油分布在研究区南部的C油田, 埋藏较浅。利用天然气、正常油和稠油对应的断层封闭指数, 可以确定其断层封闭指数下限。由A油田各储层段断层封闭指数分布(图5)可以得到正常油和天然气断层封闭指数下限分别为8.31和9.34。由C油田各储层段断层封闭指数分布(图6)可以得到稠油的断层封闭指数下限为6.12, 这与稠油本身高密度、高粘度的特性一致。由此可知, 油气的物性越好, 对断层封闭性要求越高。

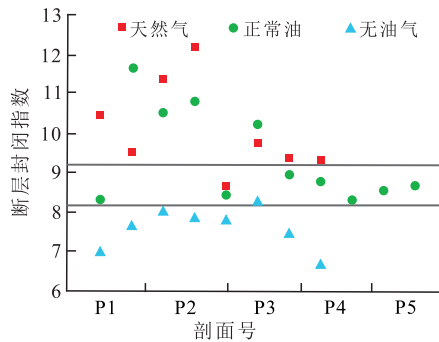


图5 A油田各储层段断层封闭指数分布

Fig.5 Distribution map of fault sealing indexes in each reservoir section of A Oilfield

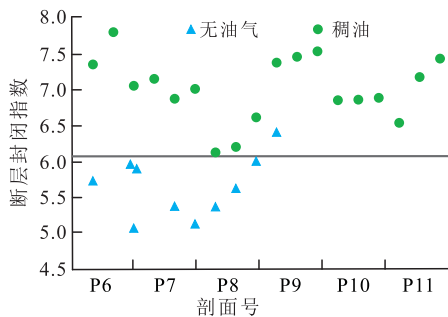


图6 C油田各储层段断层封闭指数分布

Fig.6 Distribution map of fault sealing indexes in each reservoir section of C Oilfield

## 4 结论

上覆岩层压力、断层倾角和断裂带泥质含量是断层封闭性计算的重要参数, 针对这些参数求取过程中量化程度差的问题, 提出利用上覆岩层密度变化函数求取上覆岩层压力, 根据断层产状空间变化确定倾角, 利用测井响应计算断裂带泥质含量, 实现关键参数的精确确定与断层封闭指数计算。辽

西凸起中南段断裂封闭能力与油气分布规律具有很好的相关性, 不同性质油气的断层封闭指数下限不同, 其中天然气的断层封闭指数为9.34, 正常油为8.31, 稠油为6.12。

### 符号解释:

$F_{vs}$  —— 断层封闭指数;  $p_{\text{断面}}$  —— 断面正压力, MPa;  $V_{sh}$  —— 断裂带泥质含量, %;  $p_H$  —— 断面H点处的上覆岩层压力, MPa;  $\theta$  —— 断层倾角, ( $^\circ$ );  $H$  —— 断面埋深, m;  $\rho_r$  —— 上覆岩层密度,  $g/cm^3$ ;  $\rho_w$  —— 地层水密度,  $g/cm^3$ ;  $g$  —— 重力加速度,  $m/s^2$ ;  $h$  —— 地层埋深, m;  $a, b$  —— 系数, A5井  $a$  取值为0.339 3,  $b$  取值为0.231 5;  $GR, GR_{\min}, GR_{\max}$  —— 目的层、理论纯砂岩层、理论纯泥岩层的自然伽马测井值;  $GCUR$  —— 希尔奇指数, 与地层时代有关的常量。

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