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断层输导差异性定量评价及其在致密油气藏勘探中的应用

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摘要:沟通烃源岩与储层的通源断层在活动期会产生诱导裂缝、碎裂岩或断层岩,对油气运移起输导作用。受断层活动强度、两侧岩性、断层岩泥质含量等因素的影响,断层不同部位(断片区)对流体的输导能力存在差异。断层输导差异性定量评价有助于断控致密油气成藏有利区预测。基于断层生长指数、断生裂缝系数和岩石破裂压力等参数,提出断层输导指数计算方法,明确了断控致密油气成藏机理与成藏模式。根据烃源岩厚度、成熟度及类型等参数,计算烃源岩系数,综合分析济阳坳陷渤南洼陷渤深4断层各断片区的输导指数、烃源岩系数、源储压差、有利储集相带等,建立断控致密油气成藏有利区分类标准,预测的成藏有利区得到了勘探实践证实。结果表明:按断片区计算断层输导指数,可以定量评价断层输导能力的差异性;高源储压差、通源断层差异输导和断层岩侧向封堵是断控致密油气成藏的主控因素。

关键词:断层输导差异性;断片区;定量评价;致密油气藏;成藏有利区预测;济阳坳陷

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Quantitative evaluation of fault transport difference and its application in tight oil and gas reservoir exploration

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Abstract:Induced fractures,cataclastic rocks,or fault rocks will be formed during the active periods of faults connecting the source rocks and reservoirs,which play a transporting role in oil and gas migration. Affected by factors such as fault activity intensity,lithologies on both fault walls,and shale contents of fault rocks,different parts of faults(fault sections)have different transport capacities for fluids. Quantitative evaluation of fault transport differences is helpful for predicting favorable areas of fault-controlled tight oil and gas reservoirs. In this paper,parameters including the growth index of faults,fracturing ratios of faults,and rock fracturing pressure were used to develop a calculation method for the fault transport index,and the fault-controlled tight oil and gas accumulation mechanism and pattern were explicated. The source rock coefficient was calculated according to the thickness,maturity,and type of the source rock. In addition,a comprehensive analysis was performed on the transport index,source rock coefficient,pressure differences between source rock and reservoirs,and favorable reservoir facies belt for each section of Fault Boshen4 of Bonan Sag in Jiyang Depression. Then,a classification standard for favorable accumulation areas of fault-controlled tight oil and gas was constructed. The predicted favorable accumulation areas of fault-controlled tight oil and gas are consistent with the actual exploration results. The results reveal

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that the calculated fault transport indexes by section can quantitatively assess the differences in fault transport capacity and that the large pressure difference between source rock and reservoirs, fault transport difference, and lateral sealing of fault rocks are the main factors in the fault-controlled tight oil and gas accumulation.

Key words: difference in fault transport; fault section; quantitative evaluation; tight oil and gas reservoirs; favorable accumulation area prediction; Jiyang Depression

济阳坳陷是渤海湾盆地的主要含油气坳陷之一,其82%的油气藏为与断层相关的油气藏[1-2]。断层作为油气向上运移的单向阀,对油气运移及成藏起重要的控制作用[3]。鄂尔多斯盆地中生界及古生界[4]、柴达木盆地英雄岭构造带[5]、渤海湾盆地济阳坳陷渤南地区和林樊家地区[6]以及中国其他地区[7-8]的致密油气藏勘探实践表明,断层在活动期产生的诱导裂缝(断生裂缝),对油气从烃源岩运移到致密储层起输导作用。常规油气藏的输导体系包括骨架砂、断层和不整合面[9-11],而致密油气藏的输导体系则是由烃源岩/砂岩的裂缝、断层和连续性砂体构成[12-14]。因次,无论是常规油气藏还是致密油气藏,断层始终是输导体系的重要组成。

断层整体的活动强度、输导能力和封闭性是目前研究重点[15-16]。断层泥比率(SGR)可以定量评价断层的整体封闭性[17-18],或其横向封闭性[19-21]。根据断面产状和现今地应力[22],可以评价断层的垂向封闭性[23]。将断层垂向与横向封闭性相互结合,建立断层输导模式[24-28],可以指导油气藏勘探。但受断面体两侧岩性及泥质含量空间变化的影响,沟通烃源岩与储层的通源断层在不同地质时期、不同空间位置(断片区)的输导能力会有一定差异[29-31]。对于受通源断层控制的致密油气藏,不但需要考虑烃源岩品质、生排烃压力、断层输导能力差异,还要分析生排烃期-成储期-断层活动期-成藏期-断层静止期等各时期的耦合关系。

现阶段致密油气藏输导体系研究存在的主要问题为:①烃源岩及砂岩的裂缝成因还不够清楚;②尚未明确裂缝-断层耦合输导机制;③尚未建立断层差异输导定量评价方法,这会直接影响断控致密油气藏勘探的成效。为此,首先根据断层的活动强度及两侧岩石的力学性质等因素,提出断层输导指数的计算方法,为精细评价各断片区输导能力的差异性奠定基础;然后应用成藏动力学理论,分析烃源岩生排烃期、断层活动期、成圈期、致密油气成藏期以及源储配置等因素的时空耦合关系,阐明断控致密油气成藏机理,建立成藏模式;以济阳坳陷渤南洼陷为例,结合地震、测井、岩心、薄片等资料,精细描述通源断层各断片区的活动强度,定量评价输导能力;综合考虑断层输导指数、源储压差及储层类型等因素,建立断控致密油气成藏有利区分类标准,进而预测渤南洼陷沙三段上亚段断控致密油气藏的有利区分布,以期为致密油气藏精细勘探提供依据。

1　断层输导差异性定量评价

断层幕式活动期和静止期分别对油气运移起输导作用和封闭作用。在断层活动期,断生裂缝、未固结的断层岩是油气运移的优势路径[32],对油气成藏起输导作用[33]。断层的活动强度越大、活动时间越长,断生裂缝的密度就越大、输导能力就越强。由于断层活动强度及其附近岩性存在空间变化,各断片区的输导能力也会有一定的差异。在断层静止期,断层岩将经历压实、胶结等减孔成岩作用,断生裂缝因次生矿物充填而闭合。如果成岩后断层岩的排驱压力大于储层的排驱压力,则断层具有封闭性,其封堵能力与断层岩喉道半径的大小有关[34]。

1.1　断层累积生长指数

评价断层活动强度的方法主要有生长指数法[35]、位移-长度法[36]、古落差法[37]、断距-埋深法[38]、活动速率法[39]、古滑距法[40]等。其中生长指数法应用较广,用于评价断层在特定时期的活动强度。当生长指数接近于1时,该时期为断层静止期;当生长指数大于1时,该时期为断层活动期[35]。

为了精细表征断层不同区域的特性,可将一条断层的断面划分为若干"断片区"。首先沿断层走向将断层均分为若干段;然后从纵向上将断面划分为烃源岩上覆浅层(A段)、烃源岩上覆深层(B段)和烃源岩层系(C段)等3个部分,从而把断层面划分成若干断片区(图1)。

考虑到断层活动的时间跨度对其输导能力的影响,提出利用断层累积生长指数来表征断层的活动强度。断片区的断层累积生长指数的计算式为:

$$L = \frac{\sum_{i=1}^{n} \left| Q_i - 1 \right| T_i}{T_z} \tag{1}$$

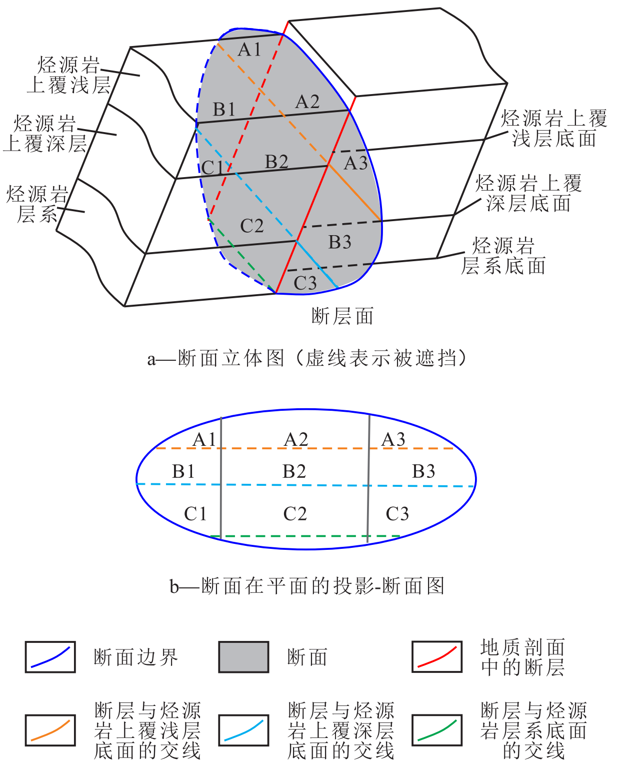

图1　断片区划分示意

Fig.1　Fault section division

在L值较大的断片区，具有较长的活动时间或较大的活动强度，易产生更广泛的断生裂缝网络，其输导能力也较强。

1.2　断生裂缝系数

在断层活动期，断片区两侧岩层出现的断生裂缝会提高断片区的输导能力[41-42]。在断片区活动强度一定的情况下，岩性不同产生裂缝后的渗流能力也有所不同。断生裂缝系数表征断片区两侧因断生裂缝而提高输导能力的幅度。其表达式为：

$$a = \lg\Delta K/\sigma \tag{2}$$

显然，被错断岩层产生裂缝后渗透率增加幅度越大，岩石的破裂压力越小，则断生裂缝系数越大，断层的输导能力越强。

1.3　断层输导指数

断层在某一地质时期的输导指数是断层累积生长指数与断生裂缝系数的综合反映，定量表征了断层及其两侧岩层在断层活动期的输导能力，其表达式为：

$$S = aL = \frac{\lg\Delta K \sum_{i=1}^{n} |Q_i - 1| T_i}{\sigma T_z} \tag{3}$$

2　断控致密油气成藏机理

济阳坳陷致密油气藏具有烃源岩持续供烃、相势控藏、大面积分布的特点[43]，孔隙和断生裂缝组成大面积连通的微裂缝-孔隙网络，是致密油气成藏的重要输导体系[44-46]。致密油气成藏受驱动力和毛管阻力协同控制[47-52]，烃源岩生烃形成的异常高压是油气充注致密储层的主要驱动力[53-55]。

赋存于烃源岩的干酪根经过热演化而转变为油气（生烃）。受烃源岩封闭环境和欠压实的影响，生烃导致烃源岩内部压力升高，出现生烃增压。当烃源岩内部压力超过其破裂压力时，将产生微裂缝，甚至触发通源断层活化；烃源岩生成的高压油气流沿微裂缝运移到烃源岩附近储层或沿通源断层裂缝网络运移到其他储层；之后烃源岩内部压力降低，微裂缝封闭。随着烃源岩热演化的持续进行，将再次重复生烃增压—微裂缝开启—烃源岩排烃的过程，即烃源岩的幕式生排烃[56]。

在断层静止期，断生裂缝与断层岩因压实、胶结作用而形成非渗透段，与断层对接盘的泥岩等非渗透岩石共同形成通源断层的侧向封堵。这些非渗透层段与致密储集体之间存在排驱压力差[57]。烃源岩幕式生排烃期、断层活动期、致密储层成储期、油气成藏期、断层静止期等各时期之间相互耦合，实现断控致密油气成藏和有效保存。

断控致密油气藏是烃源岩生烃增压形成的高压油气流，在通源断层活化、烃源岩幕式排烃和源储压差等因素的共同影响下，沿通源断层运移至与烃源岩近邻的致密储层而形成的油气藏[58]。综合考虑烃源岩-通源断层-储层的空间配置关系、生烃增压、断层输导差异性、断生裂缝网络等因素，建立了断控致密油气成藏模式（图2）。

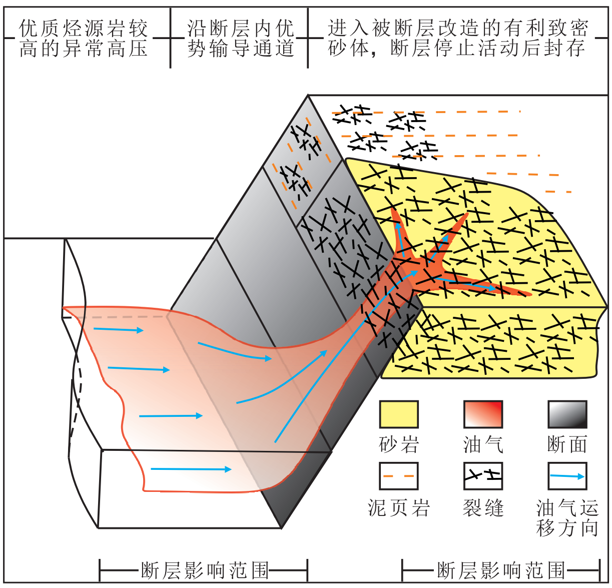

图2　断控致密油气成藏模式

Fig.2　Fault-controlled tight oil and gas accumulation pattern

3 应用实例

3.1 区域地质背景

济阳坳陷分为车镇、沾化、惠民、东营等凹陷[59-62],渤深4断层位于沾化凹陷北部的渤南洼陷,其东侧、南侧、西北侧分别为孤岛凸起、陈家庄凸起、义和庄凸起(图3)。该洼陷主力烃源岩为沙三段中亚段、下亚段深灰色页岩,暗色泥岩平均厚度约为350 m,以Ⅰ型干酪根为主,平均总有机碳含量为1.84%。在东营组沉积末期,烃源岩进入生油门限[63-64]。

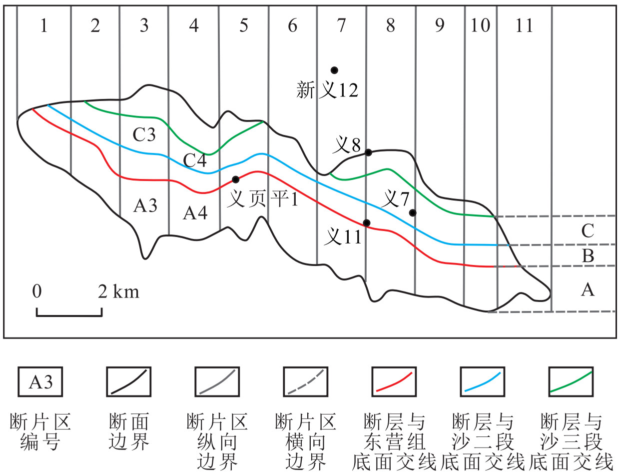

图3 渤深4断层断片区划分

Fig.3 Sections of Fault Boshen4

该区烃源岩生烃增压能够提供足够的排烃动力[65]。主力烃源岩的镜质组反射率小于0.9%,受生烃母质的影响,生成的原油密度大多超过0.85 g/cm^3[66]。笔者研究的目的层段为渤深4断层上升盘沙三段上亚段致密砂岩储层[66]。

3.2 断层输导指数

地震及测井信息显示,渤深4断层面呈纺锤形(图3)。依据地震解释成果,分别将地表至东营组底、东营组底至沙二段底、沙二段底至沙三段底分别划分为烃源岩上覆浅层(A段)、上覆深层(B段)和烃源岩层系(C段)等3个部分;再从横向将断层划分为11个基本等宽的片段,即渤深4断层可划分为33个断片区。利用(1)式计算出渤深4断层各断片区在活动末期的断层累积生长指数(表1)。

渤深4断层两侧砂岩及泥页岩16组岩心及薄片资料显示,该区裂缝发育,裂缝的荧光显示较好,是有效的油气运移通道[67]。该断层两侧砂岩和泥页岩的破裂压力分别为88.3和118.3 MPa,岩石破裂后,渗透率大幅增加,砂岩和泥页岩的渗透率平均增大791.4和38.0倍(表2)。

表1 渤深4断层各断片区生长指数及烃源岩层系累积生长指数

Table1 Growth index and cumulative growth index of source rock strata at each section of Fault Boshen4

断片区	生长指数			累积生长指数
	A段	B段	C段	C段
1	1.01	1.02	1.01	0.478
2	1.02	1.01	1.02	0.776
3	1.07	0.87	1.04	2.332
4	1.07	0.95	1.13	4.714
5	1.1	0.9	1.08	3.544
6	1.05	1.11	1.28	9.764
7	1.1	1.32	1.15	7.09
8	1.06	1.13	1.1	4.2
9	1.03	1.23	1.1	4.68
10	1.02	1.17	1.05	2.69
11	1.03	1.04	1.01	0.678

表2 岩石破裂前后渗透率对比

Table2 Permeability before and after rock fracturing

样品编号	破裂前渗透率/mD	破裂后渗透率/mD	渗透率比值
砂岩-1	0.007	0.44	62.85
砂岩-2	0.004 2	1.52	361.90
砂岩-3	0.018	0.491	27.27
砂岩-4	0.014	37.99	2 713.57
泥质岩-1	0.031	3.91	126.12
泥质岩-2	0.003 1	0.005 1	1.64
泥质岩-3	0.054	0.674	12.48
泥质岩-4	0.068	0.787	11.57

根据(2)式计算,该区砂岩和泥页岩的断生裂缝系数分别为2.90和1.58 MPa^{-1}。结合断层两侧砂地比展布数据,计算出各断片区两侧岩层在沙三段的断生裂缝系数和断层输导指数(表3)。

分析渤南洼陷断层活动情况、封闭性与油气成藏的关系[67],明确断层开启与封闭所对应的输导指数为5。如果输导指数大于5,则该断片区在断层活动期可以起到输导作用;如果输导指数小于5,则该断片区主要起封堵作用。

3.3 烃源岩系数

为精细评价烃源岩的质量和生烃潜力,利用烃源岩系数来反映烃源岩的厚度、总有机碳含量和有机质类型等。其计算式为:

$$t = h \times C \times E \tag{4}$$

表3　渤深4断层各断片区沙三段油气成藏评价指标

Table3　Consistent oil and gas accumulation indices for Third Member of Eocene Shahejie Formation at each section of Fault Boshen4

断片区	断层输导指数			烃源岩系数		源储压差/MPa
	上亚段	中亚段	下亚段	中亚段	下亚段	上亚段
C1	0.88	0.88	0.82	0.22	0.91	4.17
C2	1.43	1.43	1.33	0.45	2.18	8.17
C3	4.30	4.30	3.99	0.68	5.00	16.17
C4	8.69	8.69	8.07	0.68	5.50	14.17
C5	6.77	6.54	6.07	0.68	5.50	12.17
C6	18.65	18.00	16.72	0.68	4.50	12.17
C7	13.54	13.07	12.14	0.57	3.50	16.17
C8	8.02	7.74	7.74	0.45	3.00	12.17
C9	8.63	8.63	8.63	0.45	3.75	16.17
C10	5.32	4.96	4.96	0.41	5.00	18.17
C11	1.34	1.16	1.25	0.41	5.00	15.17

根据(4)式计算渤深4断层各断片区的烃源岩系数(表3)。渤南洼陷构造/地层油气藏与岩性油气藏的烃源岩系数界限为0.25[66]。如果烃源岩系数大于0.25,该烃源岩可以为致密油气藏供烃;如果烃源岩系数小于0.25,该烃源岩只能为构造/地层油气藏供烃。

3.4　油气成藏事件

渤深4断层附近已发现油气藏的油气来源为沙三段中亚段和下亚段烃源岩[66]。生排烃期历经东营组沉积时期至明化镇组沉积时期,其中馆陶组沉积时期烃源岩开始排烃,并逐渐达到生排烃高峰。东营组沉积时期—馆陶组沉积时期,断层具有一定活动性,馆陶组沉积时期为致密油气运移成藏关键期。明化镇组沉积时期及第四纪,渤深4断层停止活动,油气难以沿断层继续向上运移,为致密油气藏的主要保存期(图4)。

3.5　油气成藏有利区

致密油气成藏需考虑油气输导体系、运移动力以及有利储层分布等因素。断层输导指数计算结果表明,渤深4断层C4—C9断片区的输导能力较强,其中C6断片区输导能力最强。渤深4断层沙三段中亚段和下亚段烃源岩排烃后的剩余压力为6~28 MPa,而目的层沙三段上亚段致密砂岩储层的中值毛管压力平均为1.83 MPa,源储压差为4~16 MPa(表3),该区烃源岩的原油充注动力远大于储层的毛管阻力。

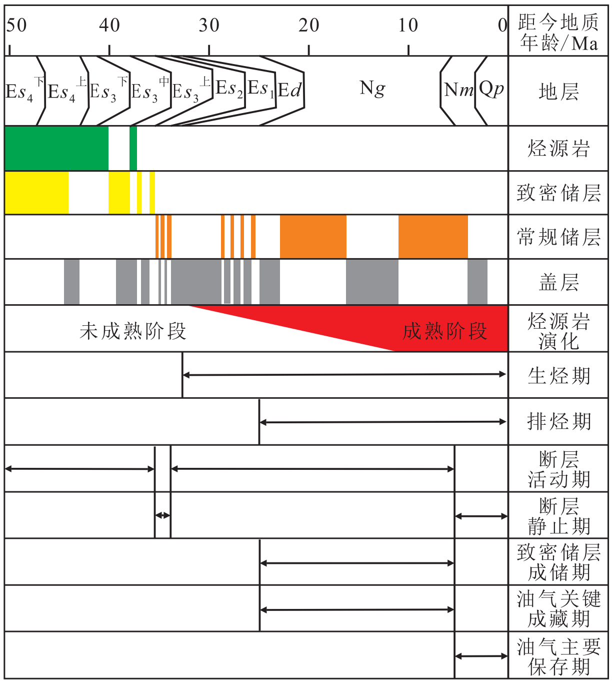

图4　渤深4断层沙三段上亚段断控致密油气成藏事件

Fig.4　Tight oil and gas accumulation events in Upper Third Member of Eocene Shahejie Formation of Fault Boshen4

渤深4断层上升盘发育沙三段上亚段浊积扇沉积的致密储层,与其对接的下降盘是沙二段深湖亚相泥质岩[33],封堵性能好,在断层静止期能有效封堵上升盘沙三段上亚段的致密油气。

根据致密砂岩油气成藏及分布特点[43-46],建立致密砂岩油气成藏有利区分类标准。在断层影响区域内,断片区输导指数大于5、烃源岩系数大于3、源储压差大于10 MPa、发育中厚层砂体的区域为一类有利区;断片区输导指数小于5、烃源岩系数为0.25~3、源储压差为5~10 MPa、发育薄层砂体的区域为二类有利区。在断层影响之外的区域,发育厚层砂体的区域属于一类有利区,发育薄层砂体的区域属于二类有利区。

依据上述划分标准,预测渤深4断层上升盘与孤北断层之间为沙三段上亚段致密油气成藏有利区。C5—C10断片区沙三段上亚段烃源岩系数为3.0~5.5、源储压差为12~16 MPa、发育浊积扇砂体,断片区输导指数大于5,断层活动期输导能力强,为一类致密油气成藏有利区(图5)。

在一类致密油气成藏有利区完钻义11探井,于沙三段上亚段钻遇致密油层8 m;义77探井钻遇沙三段上亚段致密油层9 m。预测的致密油气成藏有利区得到了实际勘探的证实,今后可对一类致密油气成藏有利区的其他区域进一步开展致密油滚动勘探。

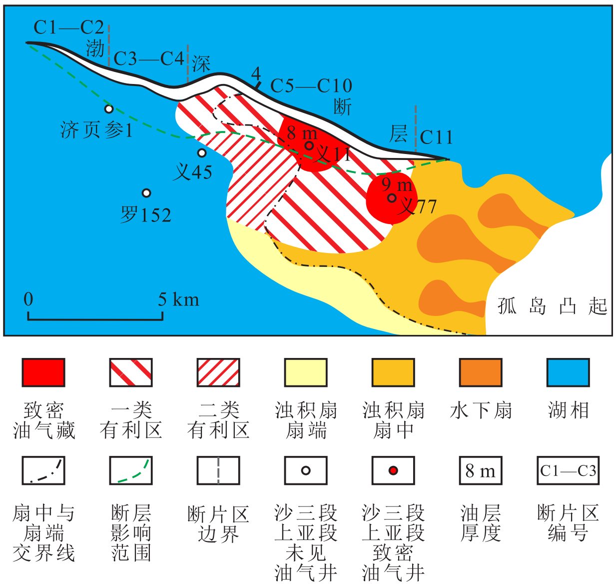

图5　渤南洼陷沙三段上亚段致密油气成藏有利区预测

Fig.5　Favorable area prediction for tight oil and gas reservoirs in Upper Third Member of Eocene Shahejie Formation in Bonan Sag

4　结论

断层输导能力可通过断层累积生长指数和断生裂缝系数来表征。由于断层不同部位的活动强度、活动时间、断面两侧岩性等在空间上具有一定的变化，因此，按断片区评价断层的输导能力可以揭示断层输导的差异性，对断控致密油气藏精细勘探具有重要意义。断控致密油气成藏机理揭示，高源储压差、通源断层差异输导和断层岩侧向封堵是断控致密油气成藏的主控因素。生烃期、排烃期、断层活动期、成圈期、成藏期、断层静止期等各时期有机耦合，是断控油气成藏和有效保存的关键。综合断层输导差异性定量评价、烃源岩系数及储集体特征，建立断控致密油气成藏有利区分类标准。经勘探实践证实，致密油气成藏有利区预测范围与实际勘探结果基本一致。

符号解释

a——断片区断生裂缝系数，MPa^{-1}；

C——断片区总有机碳含量，%；

E——有机质类型赋值；

h——断片区烃源岩厚度与研究区最大烃源岩厚度的比值；

i——沉积时期的编号；

L——断片区的断层累积生长指数；

n——断层活动时期的数量；

Q_i——断层某一活动时期的生长指数；

S——断层输导指数，MPa^{-1}；

t——烃源岩系数；

T_i——断层某一活动时期的时间跨度，Ma；

T_z——被断开地层的沉积时间跨度，Ma；

ΔK——岩石破裂后与破裂前渗透率的比值；

σ——岩石破裂压力，MPa。

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