·油气地质·

断层输导能力定量评价及其在油气勘探中的应用
——以济阳坳陷青西地区为例

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摘要：为了对断层输导能力进行定量评价，将其表征为与油气资源量成线性正相关关系的、单位时间内断层输导的油气资源量，其影响因素包括烃源岩排烃强度、主要成藏期断层古落差、成熟烃源岩内部断层平面延伸长度和断层停止活动时间。采用断层输导能力定量评价公式对济阳坳陷青西地区的油气勘探潜力进行了研究。结果表明，当断层输导能力与油气资源量拟合的常数取值为210时，断层输导能力之和与邻区辛镇油田东部和研究区永安镇油田对应的探明石油地质储量具有良好的线性正相关关系。拟合结果表明，永101、永106和永116井区位于油源断层附近，圈闭发育，能量半衰时梯度异常，为有利勘探目标；预测新立村油田沙四段上亚段、沙三段约有1 800×10⁴ t的石油地质储量有待发现。

关键词：断层输导能力 定量评价 烃源岩排烃强度 断层活动性 青西地区

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断层与油气运移关系密切，特别是对于缺乏有效烃源岩、被区域性盖层与下伏烃源岩分隔的源上油气藏的形成至关重要[1-4]，因此，断层的输导作用成为目前中外学者研究的热点和难点[5-8]。目前主要通过计算油源断层的生长指数、断层落差、断层活动强度、主要成藏期断层活动时间和断层停止活动时间表征断层的输导作用[9-10]，这些要素主要体现断层活动的特征，尚不能定量对比不同断层输导能力的差异。基于断层输导原理，笔者提出了断层输导能力的定量评价方法，并在济阳坳陷青西地区的油气勘探中取得了较好的应用效果。

1　断层输导能力定量评价方法

根据断层输导原理，油气通过切割成熟烃源岩的油源断层垂向输导，沿断层面及断层面两侧砂体向构造高部位运移，断层输导油气的能力受控于烃源岩排烃强度、主要成藏期断层的活动强度（断层古落差）、成熟烃源岩内部断层平面延伸长度和断层停止活动时间。断层停止活动时间越晚，断层输导的时间越长，其输导能力也相对越强。因此，将

断层输导能力表征为与油气资源量成线性正相关关系的、单位时间内断层输导的油气资源量，其计算式为

$$F = \frac{\xi LE}{n} \times \sum_{i=1}^{n} \frac{T_i}{A_i} \qquad (1)$$

式中：F 为断层输导能力，10^4 t/Ma；ξ 为断层输导能力与油气资源量拟合的常数；L 为成熟烃源岩内部断层平面延伸长度，km；E 为断层切割的成熟烃源岩排烃强度之和，10^4 t/km²；n 为断层计算节点总数；i 为断层计算节点数；T_i 为成藏期同一断层不同部位的断层古落差，km；A_i 为成藏期同一断层不同部位的断层停止活动时间（距今），Ma。

在实际应用中，首先需要明确油源断层的数量、分布、在成熟烃源岩内部的平面延伸长度及其切割成熟烃源岩的排烃强度之和，计算主要成藏期断层的古落差、断层停止活动时间，得出各条油源断层的输导能力；然后需要明确油气来源及油气运移路径，建立烃源岩—油源断层—油气田之间的对应关系，得出各油气田对应的断层输导能力之和；最后通过拟合各油气田探明地质储量（同一地区油气聚集系数取一定值）与断层输导能力之和的关系，得到 ξ 值，明确有利勘探区及其勘探潜力，结合

构造、地震属性分析等研究成果,提出具体的勘探目标。

2　应用实例

2.1　区域概况

青西地区位于东营凹陷东北部陡坡带和中央隆起带的结合部,西部与民丰洼陷相邻,西南部靠近牛庄洼陷,北部为陈家庄凸起,东部与青坨子凸起相邻,勘探面积约为550 km²,已发现永安镇油气田和新立村油田。青西地区为东营凹陷陆相断陷湖盆沉积的一部分,古近纪沙四段上亚段至沙三段沉积时期,靠近民丰、牛庄洼陷中心发育深灰色泥岩、油页岩、灰质泥岩,为烃源岩发育层系,靠近陈家庄凸起和青坨子凸起地区发育近岸水下扇—冲积扇沉积,为研究区主要储层发育层系之一[11-12];沙二段沉积时期是研究区三角洲形成、演化的重要时期,沙二段也是最为重要的储层发育层系;沙一段沉积时期,研究区以泥质沉积为主,夹薄层碳酸盐岩,为区域盖层发育层系。

截至2011年底,研究区共探明含油面积为24.5 km²,石油地质储量为8 139×10⁴ t,其中永安镇油气田为5 862×10⁴ t,新立村油田为2 277×10⁴ t。在永安镇构造带探明天然气含油面积为2.8 km²,天然气地质储量为16.44×10⁸ m³,以气顶气藏为主。永安镇构造带已发现油气藏富集层系主要为沙二段,占71.3%,其次为沙四段和沙三段(图1),分别占23.4%和5.3%,以断块、断鼻油气藏为主。新立村构造带已发现的油藏所在层系为沙二段,其油藏类型与永安镇油田一致。
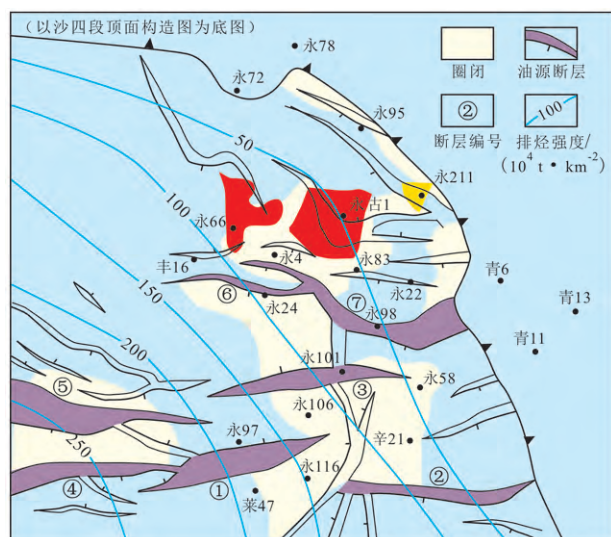

图1　青西地区烃源岩排烃强度平面分布

2.2　断层输导能力评价参数

2.2.1　烃源岩的排烃强度

研究区主要发育沙四段上亚段和沙三段下亚段2套成熟烃源岩,沙四段上亚段烃源岩现今镜质组反射率(R_o)为0.5%~0.85%,沙三段下亚段烃源岩现今镜质组反射率为0.4%~0.75%,烃源岩热演化程度相对较低[13-14],根据最新一次油气资源评价结果,研究区2套烃源岩排烃强度之和为50×10⁴ ~ 250×10⁴ t/km²。

2.2.2　油源断层及其活动特征

研究区油气成藏期主要为新近纪馆陶组—明化镇组沉积时期[15-16],具有晚期成藏的特点。通过对地震剖面分析,明确了研究区切割沙四段上亚段和沙三段下亚段2套成熟烃源岩、且在新近纪活动的油源断层总计有7条,断层编号为①—⑦(图1),目前勘探上发现的油气主要位于这7条油源断层附近,断层控藏作用明显。

研究区油源断层走向以近东西向为主,因此在计算断层活动特征时主要根据主测线(垂直断层走向),以1 km为节点,对7条油源断层馆陶组底部断距和断层停止活动时间进行了计算。计算断层停止活动时间时采用的地层年代为:馆陶组沉积时期为距今14 ~ 6 Ma,即A_2=8 Ma;明化镇组沉积时期为距今6 ~ 2 Ma,即A_1=4 Ma;平原组沉积时期为距今2 ~ 0 Ma,即A_0=2 Ma。

根据油源断层活动强度(馆陶组底部断距)计算结果,⑤号断层西部和①号断层在新近纪活动性最强,③号、⑦号和②号断层次之,④号断层、⑤号断层东部和⑥号断层活动性较弱(图2a)。从油源断层停止活动时间上看,④号断层和⑤号断层东部在馆陶组沉积中期停止活动,⑤号断层西部在馆陶组沉积末期停止活动,其余5条断层在明化镇组沉积中期停止活动(图2b)。

2.2.3　烃源岩—油源断层—油气田间的对应关系

利用伽马蜡烷/C₃₀藿烷值来分析研究区原油与烃源岩之间的亲缘关系。新立村油田沙二段原油伽马蜡烷/C₃₀藿烷值极高,与牛庄洼陷沙四段烃源岩具有亲缘关系,来自②号和③号2条油源断层的输导。永安镇油气田沙四段上亚段原油伽马蜡烷/C₃₀藿烷值较高,与民丰洼陷沙四段上亚段烃源岩具有亲缘关系,来自⑥号和⑦号2条油源断层的输导。永安镇油气田沙二段原油伽马蜡烷/C₃₀藿烷值中等,为民丰洼陷沙四段上亚段和沙三段下亚段烃源岩生成的混源原油,除了来自⑥号和⑦号2条油
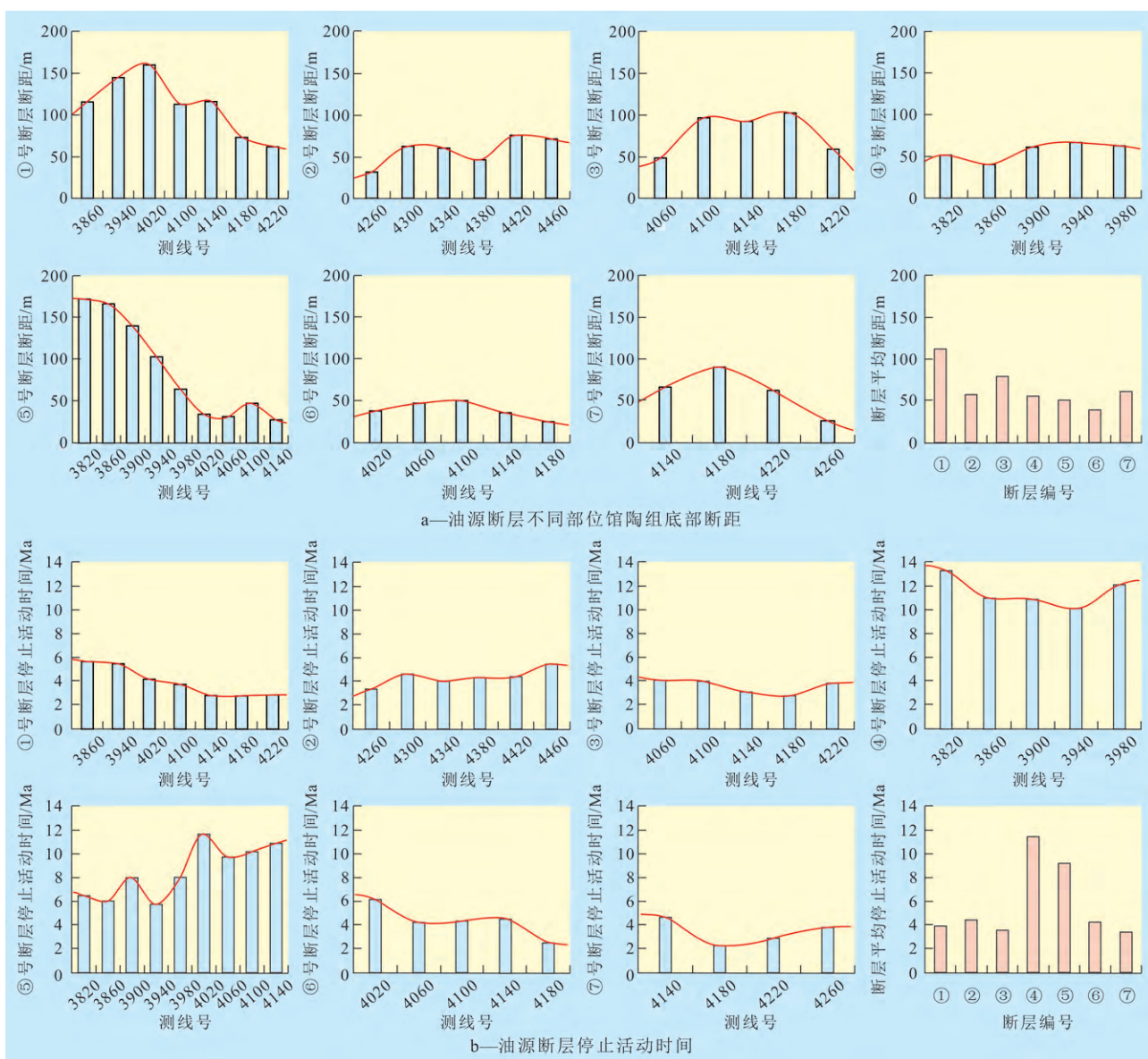
a—油源断层不同部位馆陶组底部断距

b—油源断层停止活动时间

图2 青西地区油源断层不同部位活动强度与停止活动时间

源断层的输导以外,还与⑤号断层的输导有关,该断层靠近民丰洼陷中心,为反向屋脊断层(图1),切割沙四段上亚段和沙三段下亚段2套成熟烃源岩,具有向永安镇油气田和辛镇油田双向供烃的特征。因此,在计算过程中将⑤号断层的输导能力(烃源岩排烃强度)平分给上述2个油气田。

2.2.4 定量评价及勘探潜力

成熟烃源岩内部断层平面延伸长度从图1中得出,将所有参数代入式(1)中计算得出7条油源断层输导能力之和为100ξ(表1),其中①号油源断层输导能力最强,占32.2%;⑤号油源断层输导能力之和次之,占27.6%;③号和⑦号油源断层输导能力分别占14.0%和9.7%;④号、②号和⑥号油源断层输导能力较弱,分别占6.6%,5.6%和4.3%。

为了更加准确地反映各油气田探明地质储量

表1 青西地区油源断层输导能力定量计算结果

地区	断层编号	$E/$ (10^4 t·km^{-2})	$L/$ km	$(T_i/A_i)/$ (km·Ma^{-1})	$F/$ (10^4 t·Ma^{-1})
永安镇油气田	⑤	115	6.1	0.019 7	13.8ξ
	⑥	100	4.4	0.009 7	4.3ξ
	⑦	60	7.8	0.020 8	9.7ξ
新立村油田	②	70	6.1	0.013 0	5.6ξ
	③	100	6.0	0.023 4	14.0ξ
辛镇油田东部	①	180	6.1	0.029 3	32.2ξ
	④	250	5.3	0.005 0	6.6ξ
	⑤	115	6.1	0.019 7	13.8ξ

与断层输导能力之和的关系,求出ξ值,将研究区相邻的辛镇油田东部纳入到对比行列,该地区主要来自①号、④号和⑤号油源断层的输导,探明石油地质储量为10 875×10⁴ t,油气富集层位为沙二段[17]。

从不同油气田对应的油源断层输导能力之和上看,辛镇油田东部的①号、④号和⑤号油源断层输导能力之和最大,占 52.6%;永安镇油气田的⑤号、⑥号和⑦号油源断层输导能力之和次之,占 27.8%;新立村油田的②号、③号油源断层输导能力之和最小,占 19.6%(表1)。

目前辛镇油田东部和永安镇油田勘探程度相对新立村油田较高,当 ξ 取值为 210 时,断层输导能力之和对应的探明石油地质储量具有很好的线性正相关关系(图3)。新立村油田与永安镇油田成藏条件相似,目前以开发沙二段油藏为主,沙四段上亚段、沙三段的油气勘探尚未展开,拟合结果表明,相对前 2 个油田目前的勘探程度,新立村油田至少约有 $1\,800×10^4$ t 的石油地质储量有待探明。
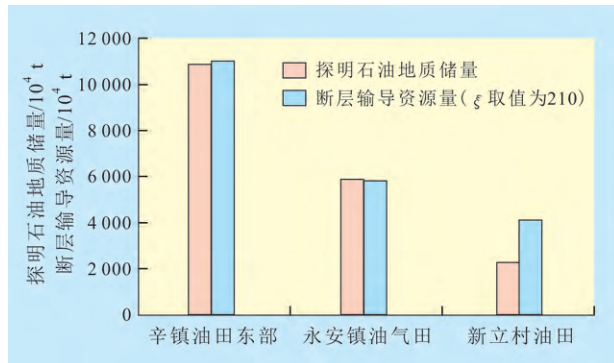

图 3　青西地区断层输导能力与探明石油
地质储量拟合结果

2.2.5　有利勘探目标

能量半衰时地震属性是度量反射波通过地层后能量衰减程度的指标,一般情况下油气分布区能量半衰时梯度明显高于周围值[18]。通过提取各类地震属性,发现能量半衰时地震属性与研究区油气平面分布具有较好的对应关系(图4)。

永安镇油气田永古 1 井区沙三段能量半衰时梯度异常,该井区位于⑦号油源断层附近,圈闭发育(图1),沙三段探明含油面积为 $1.9\ km^2$,石油地质储量为 $311×10^4$ t,在新立村油田永 101、永 106 井区有 2 个类似的能量半衰时梯度异常带(图4a),位于②号和③号油源断层附近,圈闭发育,为沙三段有利勘探目标。永安镇油气田永 552、永古 1 和永 211 井区沙四段上亚段能量半衰时梯度异常,上述 3 个井区均位于⑦号油源断层附近,圈闭发育;永 552 和永古 1 井区为沙四段油藏主要探明区,合计探明含油面积为 $3.9\ km^2$,石油地质储量为 $1\,370×10^4$ t;在永 211 井区发现了天然气藏,探明含气面积为 $0.8\ km^2$,天然气地质储量为 $3.17×10^8\ m^3$。由于圈闭不发育,

永安镇油气田永 98 井区尽管出现了能量半衰时梯度异常,但未形成油气聚集(图1,图4b)。在新立村油田永 101 和永 116 井区有 2 个类似的能量半衰时梯度异常带(图4b),位于②号和③号油源断层附近,圈闭发育,为沙四段上亚段有利勘探目标。
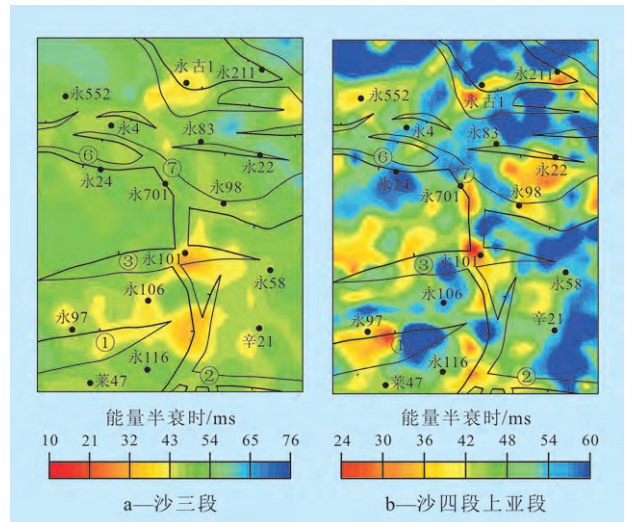

图 4　青西地区能量半衰时地震属性与断层叠合结果

新立村油田和永安镇油田具有相似的成藏条件,在圈闭面积、储层埋深、能量半衰时梯度异常带范围等方面极其相似。与永安镇油田的⑥号、⑦号油源断层输导能力相比(该油田沙三段、沙四段上亚段油气藏的输导断层),新立村油田的②号、③号油源断层的输导能力相对较强(表1),因此新立村油田沙四段上亚段、沙三段具有较大的勘探潜力,其储量规模应该不低于永安镇油气田对应层系探明的 $1\,681×10^4$ t 石油地质储量。这与断层输导能力定量评价公式预测的石油地质储量规模(约 $1\,800×10^4$ t)基本一致。

3　结论

将断层输导能力表征为与油气资源量成线性正相关关系的、单位时间内断层输导的油气资源量。影响断层输导能力的因素包括烃源岩排烃强度、主要成藏期断层古落差、成熟烃源岩内部断层平面延伸长度和断层停止活动时间,据此可对断层输导能力进行定量评价。

青西地区不同油气田对应的油源断层输导能力之和具有明显差异,勘探程度较大的油田,断层输导能力之和与对应的探明石油地质储量具有很好的线性正相关关系。根据拟合结果,要达到永安镇油田的勘探程度,新立村油田沙四段上亚段、沙

三段约有1 800×10⁴ t的石油地质储量有待发现。

研究区永安镇油田沙四段、沙三段油气藏主要分布于油源断层附近、圈闭发育、能量半衰时梯度异常地区。新立村油田与永安镇油田成藏条件相似，且油源断层输导能力较强，通过能量半衰时地震属性预测，认为永101、永106和永116井区沙四段上亚段、沙三段为有利勘探目标区。

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Cao Zhongxiang, Li Youqiang. Drilling result of exploration wells and analysis on measures for Jiyang depression during the "11th Five-Year". *PGRE*, 2013, 20(6): 1-5

Abstract：During the "11th Five-Year", the Jiyang depression has integrally entered into the concealment reservoir exploration stage. Under the conditions of more complex and more concealed exploration targets, and facing more and more difficult exploration situation, the Jiyang depression always maintained a good exploration development situation，and consolidated the resource base for the development of Shengli oilfield. It has important referential significance for further exploration of Shengli oilfield by summarizing exploration features and exploration experience of Jiyang depression in the "11th Five-Year" period. Therefore, through the summary of the distributing characteristics of well types, drilling purposes strata, drilled depth, reservoir types and types of traps that drilled by wells in Jiyang depression in the "11th Five-Year" period，the results showed that the breakthrough from pre-exploration and risk exploration is important to realize the sustainable development; the upper section of Es_4 and the strata above it are still the main exploration target strata system, the Ek and the lower Es_4 deep layer have become the reserves focus; the conglomerate reservoir in steep slope, turbidite sand reservoir in the sag slope, beach bar sandstones of gentle slope and the Neogene fluvial sand body such as a lithologic reservoir have upgraded to be the major exploration targets, moreover, the proportion of deep buried hill reservoir also increased significantly as exploration targets. The detailed exploration is the key for a high matured area to obtain progress, and new crucial district to obtain breakthrough. The evaluation of the reservoir and transporting conditions are the main exploration risks for Jiyang depression at present and in the future.

Key words：distribution characteristics of exploratory wells; drilling result; failure reason; analysis of measures; Jiyang depression

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Yu Baohua. Analysis on several dialectical relationship of petroleum exploration work. *PGRE*, 2013, 20(6): 6-9

Abstract：The eastern exploration area of Shengli oilfield has fully entered the subtle reservoir exploration stage. We should think strategically and discuss on several dialectical relationship of exploration work. Firstly, we deal with the relationship between the subjective and the objective correctly. That is, we handle correctly the relationship between geological researchers as the subject and the geological body being studied and described as the object. Secondly, we handle relationship between the known and the unknown. We should not stress "absolute" concept, and draw artificially absolute limits, exploration work should follow "cycle, spiral" awareness rules. Thirdly, we handle relationship between technical progress and practical application, and determine that the researchers are the decisive factor, it is the basic principle that we combine with advanced technology and practical application. To think these relationships dialectically, it is conducive to ensure the exploration key of "improving quality and efficiency". We make positive contribution for oilfield to achieve sustainable development and the successful completion of the task granted by history.

Key words：petroleum exploration; dialectical relationship; progress of theory; progress of technology; eastern exploration area of Shengli oilfield

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Sun Bo, Zhang Shanwen, Wang Yongshi. Quantitative evaluation of fault transporting capacity and its application in hydrocarbon exploration-case study of west Qingtuozi uplift of Jiyang depression. *PGRE*, 2013, 20(6): 10-14

Abstract：The quantitative capacity evaluation of the fault transporting, defined as hydrocarbon resources transported by faults in unit period, has a linear direct ratio relationship with the hydrocarbon resources. The influence factors are expulsion intensity of hydrocarbon, ancient fault throw in reservoir forming period, plane extension length of faults in matured source rock and inactive period of faults. The hydrocarbon exploration potential in west Qingtuozi uplift of Jiyang depression was evaluated by the equation of fault transporting ability. The results show that when the ξ value at 210, there is a very good linear related relationship between total fault transporting capacity and local oil geological reserves in east Xinzhen oilfield (near the research area) and Yonganzhen oil and gas field. According to the fitting results, 18 billion tons of potential oil reserve in Xinlicun oilfield are existed in the Es_3 member and Es_4 upper section, and need to be located. The Yong101, Yong106, and Yong116 well district in Xinlicun oilfield are the favorable exploration targets, which have favorable hydrocarbon accumulation condition such as adjacent to the source faults, developed trap and abnormal energy-half-time.

Key words：fault transporting ability; expulsion intensity of hydrocarbon; activity of fault; exploration potential; west Qingtuozi uplift

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Qiu Longwei, Zhou Yongyi, Gao Qingsong et al. Study of porosity structure and its influences on Carboniferous and Permian tight sand reservoir rock in Danniudi gasfield, Ordos basin. *PGRE*, **2013, 20(6): 15−18**

Abstract：The porosity structure and its influences on Carboniferous and Permian tight sand reservoir rock are studied through observation on the casting thin section and analysis on mercury data in Danniudi gasfield, Ordos basin. And, we made a conclusion that, the secondly porosity, such as intergranular pore and innergranular pore are the dominant reservoir space in the study area. There exists similar change trend between the average value of displacement pressure and that of maximum pore throat in different formations. While the average value of p_{c50} tends to be smaller with the increment of depth, changes reversely with that of displacement pressure. The low pore−throat sorting, scattered distribution, with micro pore and fine throat, micro throat combination are the dominant pore throat combination type. The pore structure in the area is influenced by buried depth and detrital particular materials. The displacement pressure increases, and the pore and throat decrease along with the increment of the burial depth. Higher content of feldspar and rock fragments is more beneficial to the reservation of pore and throat for the influence of selective pressure dissolution and secondly growth under the detrital components and diagenetic environment in the study area.
Key words：tight sand; reservoir characteristics; pore structure; expulsion pressure; Daniudi gasfield

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Ge Zhongwei, Fan Li. Some notable problems about shale gas in the scientific research. *PGRE*, **2013, 20(6): 19−22**

Abstract：China's shale gas exploration and research is still in the primary stage, and facing many complicated geological and engineering problems. Although it has obtained a large number of precious experiences through the analogy of matured shale gas in the United States, it has its unique characteristics. Therefore, it is necessary to establish a set of effective resources evaluation system. Based on the exploration target of shale gas, this paper provides some questions about the different reservoir characteristics at home and abroad, such as the "formation water" storage and percolation mechanism in shale reservoir, the relationship between fracturing effect and genetic types of natural gas, then suggesting the shale reservoir classification evaluation in different depositional system so as to look for the shale gas "dessert", and realize the reasonable and maintainable development of shale gas in China.
Key words：shale gas exploration target; reservoir classification evaluation; pressure coefficient; fracturing; natural gas origin; throat diameter

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Liu Jie, Cao Yingchang, Fan Tailiang et al. Sequence stratigraphy and modeling of sandbodies distribution in Yonganzhen delta, Dongying depression. *PGRE*, **2013, 20(6): 23−28**

Abstract：The Yonganzhen delta is developed in Minfeng sag and its peripheral area are important oil and gas accumulation belts in Dongying depression, Bohaiwan Basin, China. Based on the principles of seismic sequence, combined with logging and drilling, the target strata of Yonganzhen delta, the middle and the lower submember of third member of Shahejie formation (Es_3z−Es_3x) are divided into a third−order sequence separately. In the sedimentary stage of Es_3z, three fourth−order sequences (MSC1−MSC3) and eight fifth−order sequences (Z1−Z8) are developed; in the sedimentary stage of Es_3x, two fourth−order sequences (MSC4−MSC5) and two fifth−order sequences (X1−X2) are developed. Meanwhile, the scales of Yonganzhen deltaic deposition was small in the periods of MSC5−MSC3; in the period of MSC2, the strength of source supply increased from the Qingtuozi salient, the Yonganzhen delta prograded massively, and reached the downthrown block of Shengtuo fault with the depositions of mixed sources; in the period of MSC1, the Yonganzhen delta migrated to the north is affected by the deposition of the Dongying delta. Moreover, the Yonganzhen delta has the characteristic of self−similarities for development of sandbody controlled by sequence. The self−similarities illustrate that the delta sandbody is developed within the dropping semi−cycle in each grade of base level cycle, with the sand content higher than that of the rising semi−cycle.
Key words：Yonganzhen delta; sequence stratigraphy; sedimentary system; sequence stratigraphy controlled sandbody; Dongying depression

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Zhang Daiyan, Peng Yongcan, Xiao Fangwei et al. Pore structure and influence factors of conglomerate reservoir−case study of lower Karamay formation in mid and east of 7th block, Karamay oilfield. *PGRE*, **2013, 20(6): 29−34**

Abstract：The conglomerate reservoir pore structure of the lower Karamay formation in mid and east of 7th block, Karamay oilfield, is fully studied by means of casting thin sections, SEM and petrophysical and mercury injection data. There are three main types of microscopic pore distribution in the conglomerate reservoir of the lower Karamay formation in the study area, the pore diameter distribution is monomodal, bimodal and complex modal. According to nine parameters screened out (porosity, permeability, mean, skewness, the sat-