

济阳拗陷滩海地区断裂网络体系的拓扑结构及分形特征同油气分布的关系



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内容提要:滩海地区位于济阳拗陷东部,发育复杂的断裂网络,通过分形及拓扑方法可以定量表征其复杂程度及连通性。为明确该区古近系断裂网络体系与油气分布的关系,笔者等在地震数据精细解释的基础上,对其分形特征与拓扑结构进行了定量表征。结果表明, T_0 界面,分维值与拓扑值南高北低,高值区北西向展布; T_2 界面,分维值与拓扑值东高西低,高值区北北东向展布; T_1 界面,分维值与拓扑值东高西低,高值区北东向展布。由深至浅,分维值及拓扑值在东部逐渐增加,在西部逐渐减小。分形特征与拓扑结构受先存断裂及局部应力的影响,沿先存断裂,特别是在多向断层交汇区及走滑断层叠覆区表现为高值。结合勘探成果发现,高分维高拓扑部位油藏发育,是油气勘探的有利区域。

关键词:断裂网络体系;拓扑结构;分形特征;断裂网络连通性;油气分布;济阳拗陷;滩海地区

受应力背景、先存断裂及岩石力学性质等因素影响(Deng Chao et al., 2017; Wang Di et al., 2021),含油气盆地形成复杂的断裂网络体系,对油气生成、运移、聚集成藏及保存有重要的影响(Karlsen and Skeie, 2006; 于英华等, 2021)。前人对断裂体系的研究大都停留在定性描述上,缺乏定量表征。笔者等将拓扑(Valentini, 2007; Morley and Nixon, 2016; 王迪等, 2023)与分形(Hirata, 1989; 曾联波等, 2001)的方法应用于对断裂网络的研究,实现了对断裂网络中断层的分布、复杂程度及连通性的定量表征(Sanderson et al., 2019)。

滩海地区油气资源丰富,紧靠庐庐断裂,在多期应力以及深大断裂的影响下形成了复杂的断裂网络,影响油气资源的分布。前人就该区断层对油气分布的影响进行了大量定性研究,包括断层控制储层及圈闭的形成(刘一鸣等, 2019; 张晓庆, 2019)、烃源岩的演化以及油气的运移与逸散(徐长贵, 2016; 吴智平等, 2022)等。然而,以断裂网络体系整体为研究对象定量描述断层展布特征和油气分布影

响的工作鲜有报道。笔者等在地震资料构造解释的基础上对该区断裂网络的发育特征进行定性描述,进一步将分形与拓扑的方法应用于断裂体系,定量表征其复杂性和连通性(马赛婷等, 2024)。最后,将分形维数及拓扑参数的平面展布状况同区域油气分布相结合,建立分形特征及拓扑结构同油气分布间的联系,为含油气盆地勘探提供指导。

1 区域地质概况

渤海湾盆地是位于中国东部的叠合盆地(Qi Jiafu and Yang Qiao, 2010),在多期构造运动作用下形成了复杂的断裂网络(图1)。早侏罗世,受印支运动与燕山运动影响,该区北西向逆冲断层发育;白垩纪,随区域应力拉伸为主,北西向逆断层发生反转作用(Zhu Rixiang et al., 2017; Su Jinbao et al., 2009)。孔店组(E_k)沉积时期(65 Ma),太平洋板块北北西向俯冲,该区受北北西向拉伸作用(任建业等, 2009),近东西向正断层开始发育。沙三段(E_s^3)沉积时期(43.5 Ma),太平洋板块俯冲方向转

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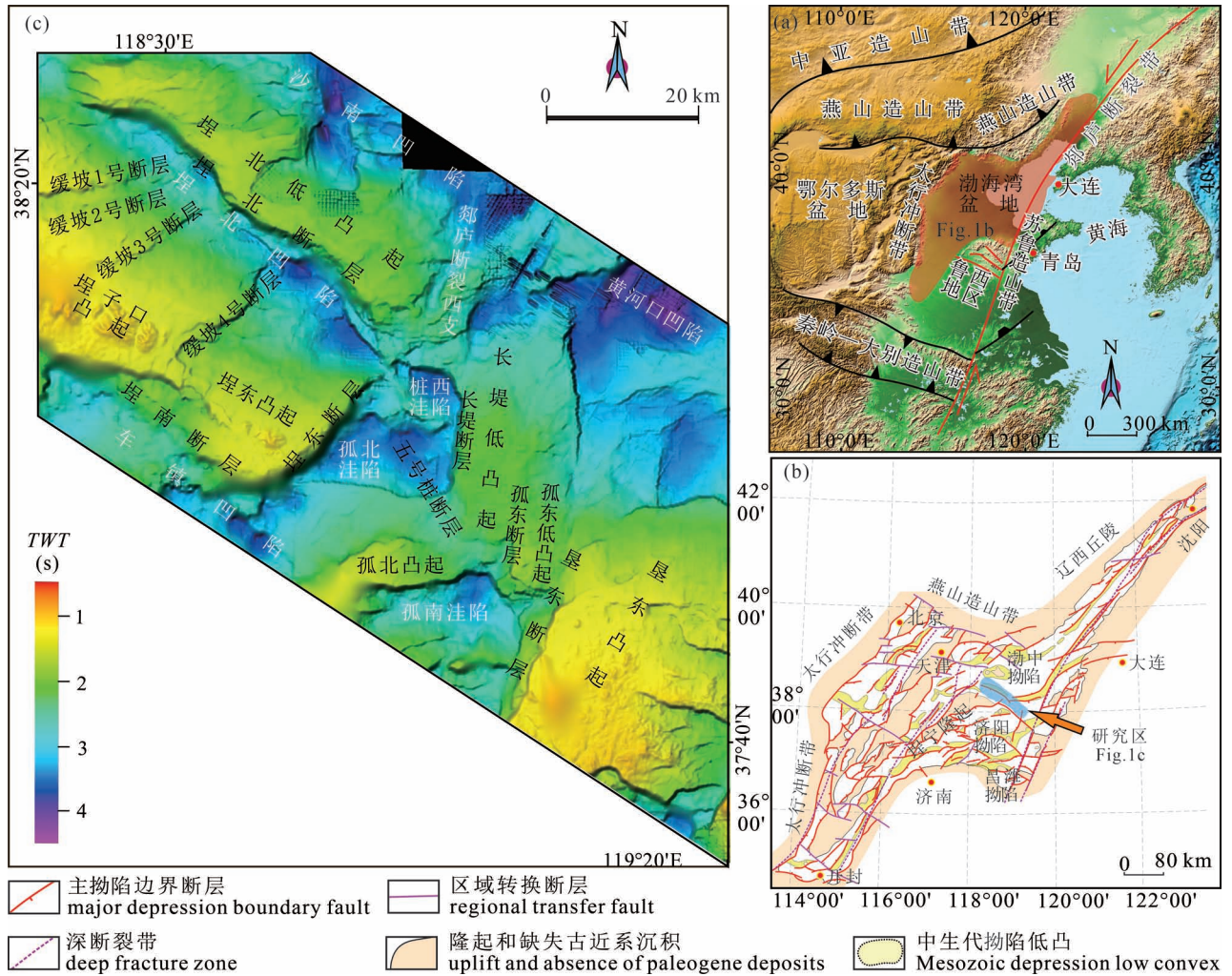


图1 渤海湾盆地济阳拗陷滩海地区构造纲要图(据 Wang Di et al., 2022)

Fig. 1 Structural outline map of Tanhai area, the Jiyang Depression, Bohai Bay Basin (from Wang Di et al., 2022)

为北西西向,伴随板片回撤及俯冲角度的增加(Li Sanzhong et al., 2013),该区地幔上涌与岩石圈拆沉作用明显(Dong Yuexia et al., 2010),区域受到近南北向拉伸,近东西向断层大量发育。同时,郯庐断裂在该时期发生强烈右旋走滑,导致研究区断裂具有一定的走滑性质。中新世(23.5 Ma),菲律宾板块因与印澳板块碰撞而向北运动,顺时针楔入西太平洋板块与欧亚板块之间(任建业,2018)。中国东部受到南东向挤压应力,区域应力整体减弱,各向断层均活动性减弱(图2)。

研究区地层由深到浅主要发育有中生代火山碎屑岩与浅部新生代河湖碎屑岩。新生代地层主要包括孔店组、沙河街组、东营组、馆陶组、明化镇组及平原组,多期不整合发育。其中,孔店组、沙河街组及东营组湖相泥岩是该区的主力烃源岩层(Hao Fang

et al., 2011)。

2 断裂网络几何学特征

2.1 断裂发育特征

研究区主要发育北西、北北东、近东西向3组断层,断裂网络复杂(图3)。北西向断层中生代开始发育,是该区的先存断层;北北东向断层受郯庐断裂影响,走滑作用较强;近东西向断层主要形成于新生代,大多为正断层(吴智平等,2022; Wang Di et al., 2023)。

北西向断层平面上发育较少,主要是西部的孤西断裂及东部的埕北断裂。由深至浅,埕北断裂规模稳定,连续性较好,次级断层数量逐渐增多;孤西断层仅在深部发育,连续性好,浅部发育停止,周围次级断裂较少。

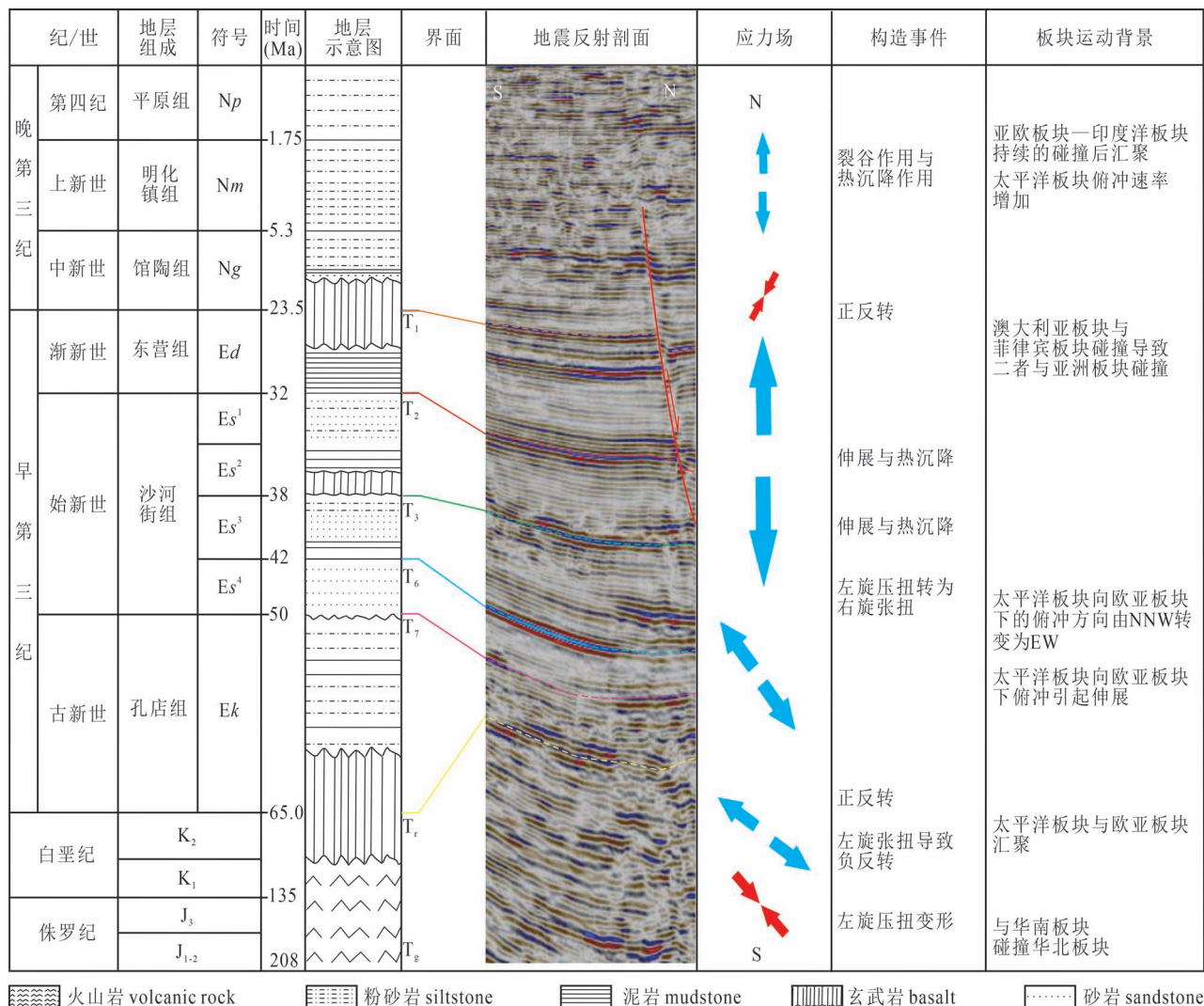


图2 渤海湾盆地济阳拗陷滩海地区地层格架图(据 Wang Di et al., 2021)

Fig. 2 Stratigraphic framework of Tanhai area, the Jiyang Depression, Bohai Bay Basin (from Wang Di et al., 2021)

北北东向断层主要分布于该区东部,长堤断层、孤东断层及垦东断层呈雁列式展布,周围次级断层大量发育。其中,长堤断层深部连续,浅层表现为一系列北东向次级断裂沿北北东向雁列式展布;孤东断层南部连续性较好,尾端发育一系列次级断裂呈马尾状展布,北部由一系列北东向次级断裂组成;垦东断层规模较大,整体连续性好。近东西向次级断裂在北北东向主干断裂叠覆处大量发育,与主断层侧接构成走滑双重构造。

近东西向断层是新生代发育的新生断层,在研究区整体发育,数量多。从深层至浅层,其在该区东部发育数量变多,特别是东北部黄河口凹陷一带;在西部发育数量呈减少趋势。

因应力方向改变及深大走滑断裂活动性差异,

研究区不同层位断裂体系差异较大。深层继承早期构造格局,同时受北北西向伸展作用,北西、北北东向断层连续性好,近东西向断层发育较少;中浅层受南北向拉伸作用及郯庐断裂走滑作用影响,北北东向断层走滑作用明显,近东西向断层大量发育。受局部应力影响,不同走向断层交汇区及走滑断层叠覆区断层密集发育,断裂网络复杂,如不同走向断层共轭的桩西洼陷一带(图3)。

2.2 拓扑结构

拓扑学是数学的一个领域,是通过抽象与概况处理空间关系的一种方法,如网络体系中的连通性与持续性(Sanderson and Nixon, 2015)。断裂网络体系的拓扑参数可以分为节点和分支两类:节点分为3类①I节点(独立断层);②Y节点(侧接或派生

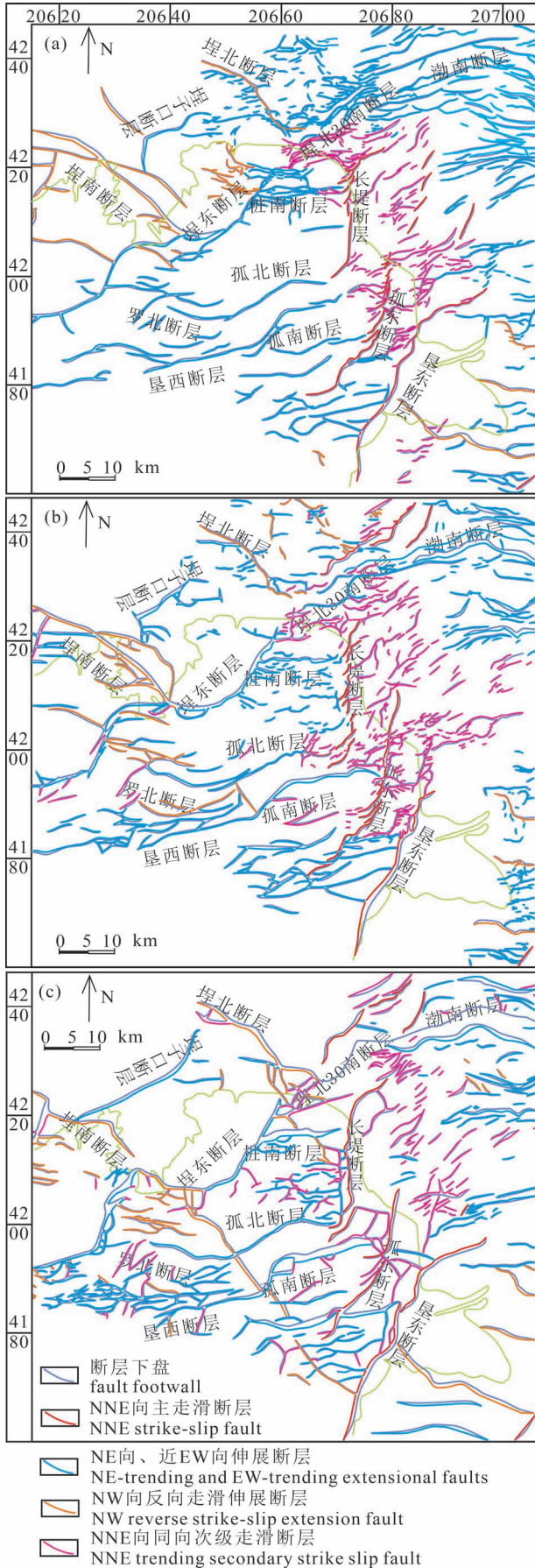


图3 济阳拗陷滩海地区古近纪主要层面断裂体系图：
(a) T_1 界面断裂体系图；(b) T_2 界面断裂体系图；
(c) T_6 界面断裂体系图

Fig. 3 Main fault system of Paleogene in Tanhai area, the Jiyang Depression: (a) T_1 interface fracture system diagram; (b) T_2 interface fault system diagram; (c) T_6 interface fracture system diagram

断层)；③X节点(共轭断层)。依据断层分支末端的节点类型,将分支划分为I-I型、I-C(X或Y节点)型及C-C型(Ortega and Marrett, 2000)(图4)。

不同类型节点和分支的比例反映不同的拓扑结构,将其投点于节点和分支三角图上,可对断裂网络的连通性进行比较。在自然界中,X节点较少,主要发育Y节点,所以在节点三角图中多投点于靠近I-Y轴位置,节点三角图灵敏性较低;而在分支三角图中,因统计分支时将Y节点与X节点均视为连接节点(C节点)进行统计,使分支三角图的投点分布能够遍布三角图中,有利于区别不同点的异同。由各类型节点、分支的数量等参数推导出一系列新的拓扑参数(Duffy et al., 2017),如连接节点数 N_C 。笔者等利用 Arc GIS 软件中的 Network GT 对断裂网络体系的拓扑结构定量表征(Nyberg et al., 2018),获得拓扑参数及等值线图(连接节点,分支),并将拓扑参数投点于对应三角图中进行分析。

T_6 界面,主要发育I节点(85.35%)及Y节点(14.47%)(表1),在节点三角图上投点于靠近I-Y轴偏I角位置(图5a);I-I分支(51.08%)、I-C分支(31.37%)及C-C分支(17.55%)发育(表2),在

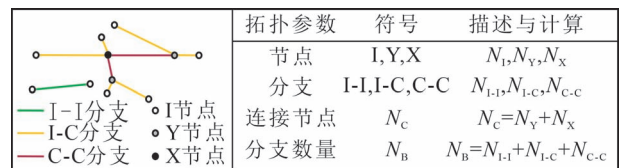


图4 拓扑方法示意图

Fig. 4 Schematic diagram of topological method

N_I 为I节点数量; N_Y 为Y节点数量; N_X 为X节点数量; N_N 为节点总数; N_{I-I} 为I-I分支数量; N_{I-C} 为I-C分支数量; N_{C-C} 为C-C分支数量; N_B 为分支总数

N_I indicates the number of I nodes; N_Y is the number of Y nodes; N_X is the number of X nodes; N_N is the total number of nodes; N_{I-I} is the number of I-I branches; N_{I-C} indicates the number of I-C branches; N_{C-C} is the number of C-C branches; N_B is the total number of branches

表 1 渤海湾盆地济阳拗陷滩海地区拓扑节点统计表

Table 1 Statistical table of topological nodes in Tanhai area, the Jiyang Depression, Bohai Bay Basin

界面	N_I	N_Y	N_X	N_c
T ₁	1105	157	6	163
T ₂	940	158	11	169
T ₆	466	79	1	80

表 2 渤海湾盆地济阳拗陷滩海地区拓分支统计表

Table 2 Statistical table of extension branch in Tanhai area, the Jiyang Depression

界面	N_{I-I}	N_{I-C}	N_{C-C}	N_B
T ₁	404.5	289.5	96	790
T ₂	339	245	123	707
T ₆	177.5	109	61	347.5

分支三角图上投点于三角图中心远离 C-C 角位置 (图 5b)。平面上, N_c 高值区与 N_B 高值区主要是断层叠覆、连接处, 整体表现为北西向展布的特点, 二者分布具有较好的一致性 (图 6)。

T₂ 界面, 分支与节点数相对 T₆ 增多 (表 1 和表 2)。其主要发育 I 节点 (84.76%) 及 Y 节点

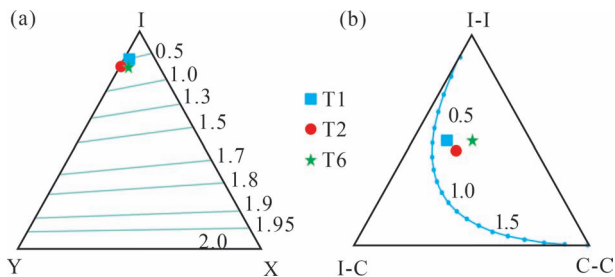


图 5 渤海湾盆地济阳滩海地区节点分支三角图

Fig. 5 Triangular diagram of node branches in Tanhai area, the Jiyang Depression, Bohai Bay Basin

(14.25%) (表 1), 在节点三角图中投点紧邻 T₆ 界面投点 (图 5a); I-I 分支 (47.95%)、I-C 分支 (34.65%) 及 C-C 分支 (17.40%) 发育 (表 2), 分支三角图中投点相对 T₆ 靠近中心 (图 5b)。平面上, N_c 高值区与 N_B 高值区北北东向展布, 主要为三支走滑断层的叠覆部位 (图 6)。

T₁ 界面, 节点与分支数相对 T₂ 增多 (表 1 和表 2)。该界面主要发育 I 节点 (87.15%) 及 Y 节点 (12.38%) (表 1), 在节点三角图中投点靠近 I-Y 轴

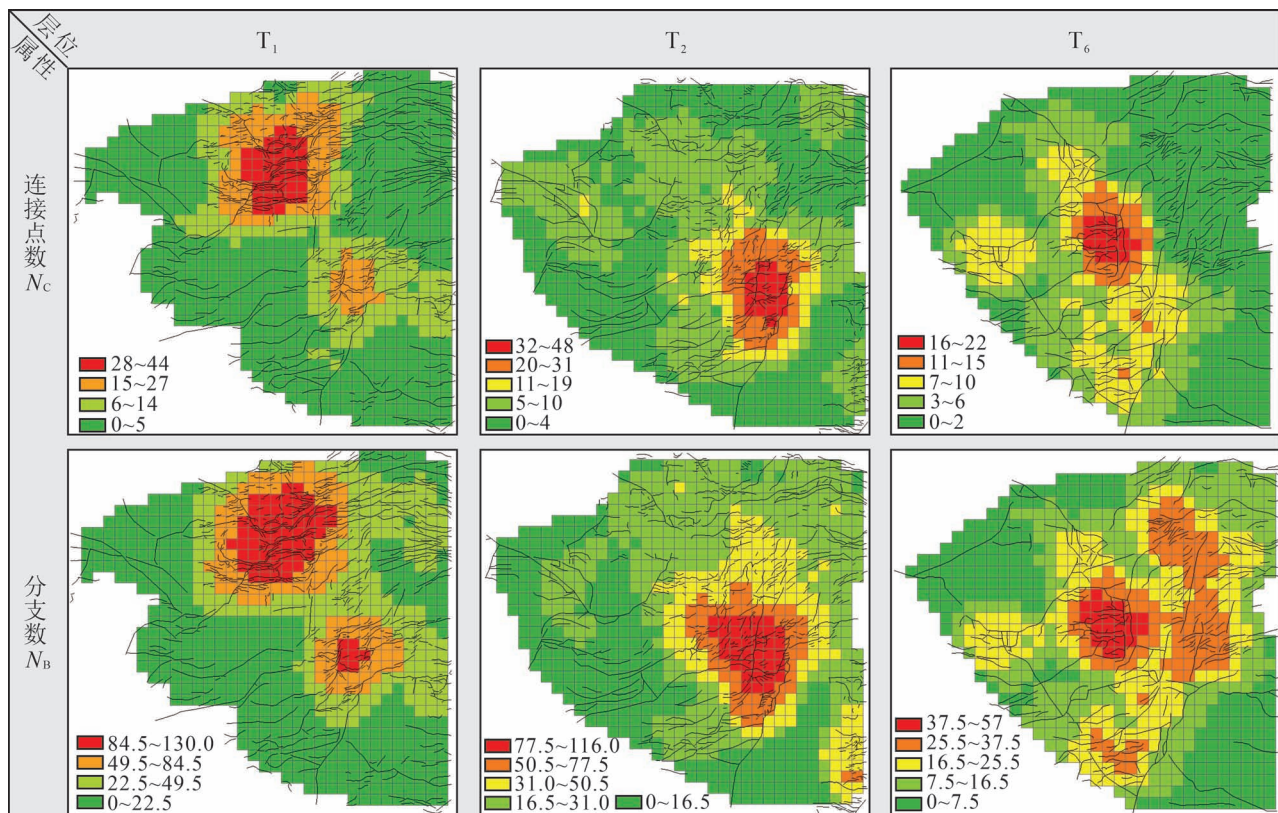
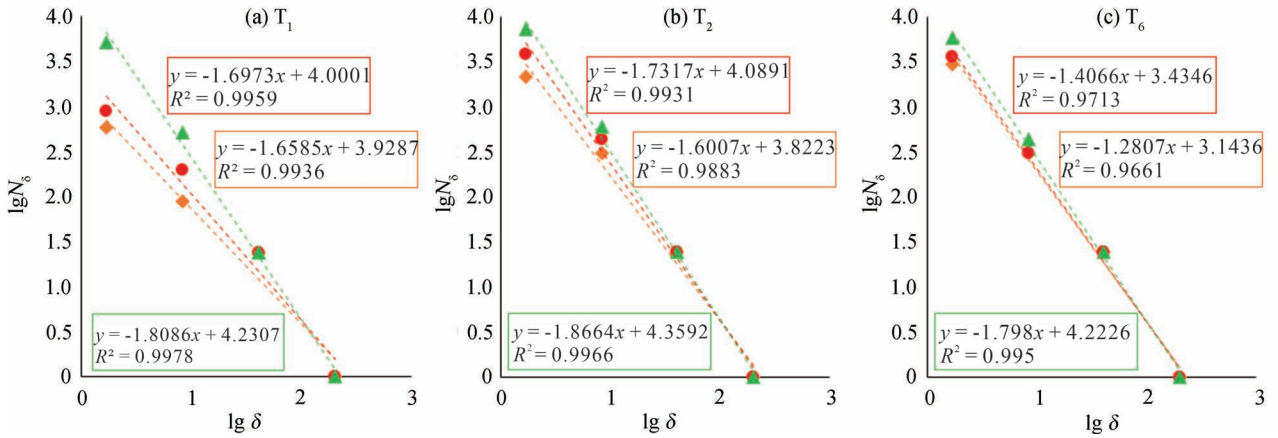


图 6 渤海湾盆地济阳拗陷滩海地区拓扑结构平面图

Fig. 6 Topological structure plan of Tanhai area, the Jiyang Depression, Bohai Bay Basin

图7 $\log N_s$ 与 $\log \delta$ 相对应图Fig. 7 $\log N_s$ corresponds to $\log \delta$

(图5a)。I-I分支(51.20%)、I-C分支(36.65%)及C-C分支(12.15%)发育(表2),在分支三角图中投点相对 T_6 、 T_2 靠近 I-I—I-C轴(图5b)。平面上, N_c 高值区与 N_b 高值区主要是桩西洼陷不同走向断层共轭区及北北东走向滑断层叠覆区域。

各界面在节点三角图上均投点于紧邻 I-Y 轴靠近 I 角位置,主要发育 I 节点;在分支三角图中均投点于中心远离 C-C 角位置,发育 I-I 分支、I-C 分支及 C-C 分支。平面上,拓扑参数的分布具明显的差异性,在北西及北北东向断层发育部位,特别是不同走向断层共轭区及断层叠覆区,拓扑值较高,断裂网络连通性好。由深至浅,西部孤西断层一带拓扑值(N_b 及 N_c)逐渐减少,断裂网络连通性变差;东部埕北断层及北北东走向滑断层发育部位,拓扑值逐

渐增大,断裂网络连通性变好。

2.3 分形特征

断裂网络是具自相似特性的复杂体系,可用定量描述几何不规则性的分维指标来定量评价其复杂程度(王迪,2021)。一般采用盒维数对断裂网络(F)的分维指标进行计算。即用一系列边长为 δ 的方形“盒子”覆盖断裂网络,统计不同 δ 值的“盒子”与 F 的相交个数 $N_s(F)$,由函数 $\log N_s(F)$ 相对 $\log \delta$ 图的斜率值的相反数估计分维值(Falconer, 1990)。笔者等采用的“盒子”长度依次为 10 km、5 km、2.5 km 及 1.25 km。对相关系数大于 0.9(图7)的分维值进行统计,导入 Suffer 软件,绘制断裂网络分维值平面图(图8)。

T_6 界面,高分维值区(>1.6)呈四条带状展布。

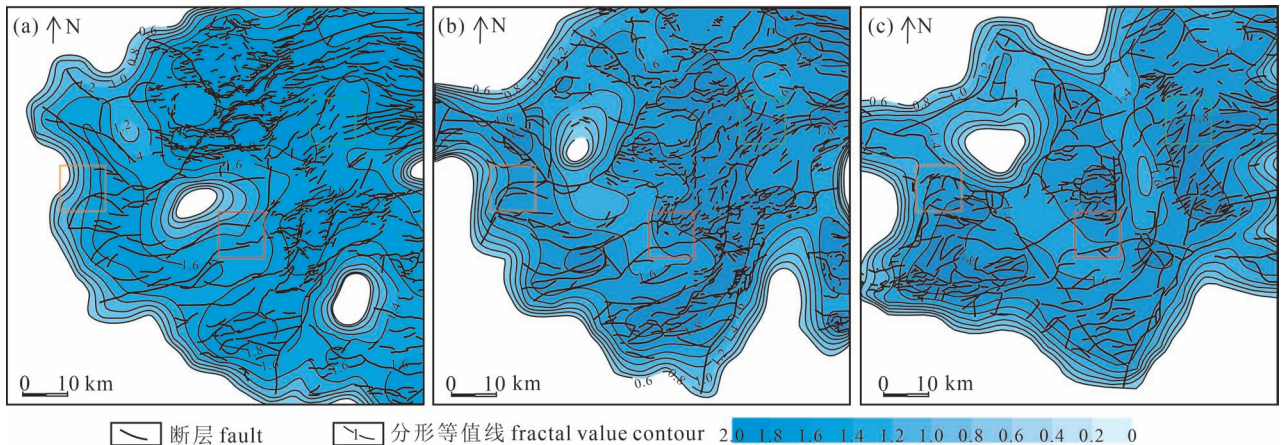


图8 济阳拗陷滩海地区古近系地层主要层面分维度等值线图

Fig. 8 Contour map of the main layers of Paleogene strata in Tanhai area, the Jiyang Depression, Bohai Bay Basin

(a) T_1 界面分维等值线图; (b) T_2 界面分维等值线图; (c) T_6 界面分维等值线图(a) fractal contour map of T_1 interface; (b) fractal contour map of T_2 interface; (c) fractal contour map of T_6 interface

其在北部沿孤西—埕南断层、五号桩—埕北断层以及西支二号断层呈北西向带状展布;在南部沿孤东断层及垦东断层北东向展布(图8c)。

T_2 界面,分维值东高西低。高分维值区在西部沿孤西—埕南断层径迹北西向展布;在东部沿长堤断层、孤东断层及垦东断层北北东向展布。相对 T_0 界面,分维值在东部增大,在西部减少(图8b)。

T_1 界面,分维值东北高,西南低。高分维值区在西南部沿孤西—埕南断层径迹北西向延伸;在东南部沿孤东断层与垦东断层北北东向展布;在北部多向断层共轭部位及黄河口凹陷东西向断层密集发育部位大面积发育。相对 T_2 界面,分维值在南部减小,在北部增加(图8a)。

由上述分析可知,分维值的分布差异性明显,高值区主要沿北西向先存断层及北北东向走滑断层发育。同一层位,高值区在东部呈北北东、东西向展布;在西部呈北西向展布。多向断层共轭区及走滑断层叠覆区具更高的分维值。不同层位,由深至浅,在西部,分维值呈减小趋势,高值区北西向展布趋势减弱;在东部,分维值整体变大,高值区北东、东西向展布趋势增强。

3 油气分布特征

该区油气资源丰富,中石化胜利油田在该区进行了多年的勘探开发。笔者等选取 T_0 和 T_1 两个界面进行油气展布分析。

T_0 界面,油藏主要沿北西向埕北断层、孤西断层、北东向埕北30南断层及北北东向长堤断层分布(图9b)。沿孤西断层,油藏集中分布在其与北东向埕东断层及北东东向、近东西向孤北断层、孤南断层侧接发育的沾化凹陷及孤岛凸起。在不同走向断层共轭的桩西洼陷,油藏大面积展布。

T_1 界面,油藏主要沿北西向埕北断层及北北东向长堤断层、孤东断层、垦东断层分布(图9a)。同 T_0 界面相似,不同走向断层共轭的桩西洼陷一带,油藏大面积展布。在北北东向长堤断层附近及孤东断层北部,油藏主要表现为小型断块,发育规模较小,数量较多。较 T_0 界面,油藏规模减小,数量增多。

剖面上,在研究区北部,埕北断层沟通深部的烃源岩和浅部的储层,将油气运移至不同层位,形成构造油藏及岩性油藏(图10a)。中部桩南断层起到与埕北断层类似的作用(图10b)。长堤断层沟通深部

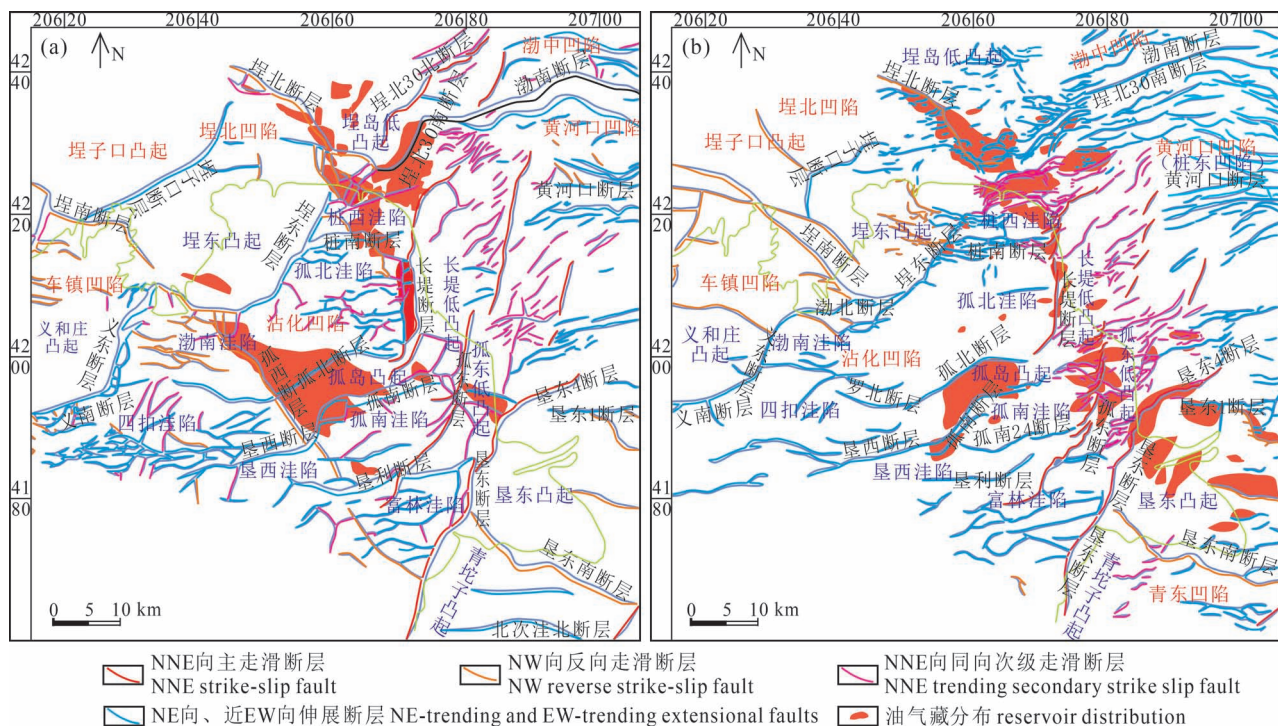


图9 济阳拗陷滩海地区古近系地层油藏平面图:(a) T_0 界面,沙四段顶;(b) T_1 界面,东营组顶

Fig. 9 Reservoir plan of Paleogene strata in Tanhai area, the Jiyang Depression, Bohai Bay Basin:

(a) T_0 interface, top of Es_4 ; (b) T_1 interface, top of Ed

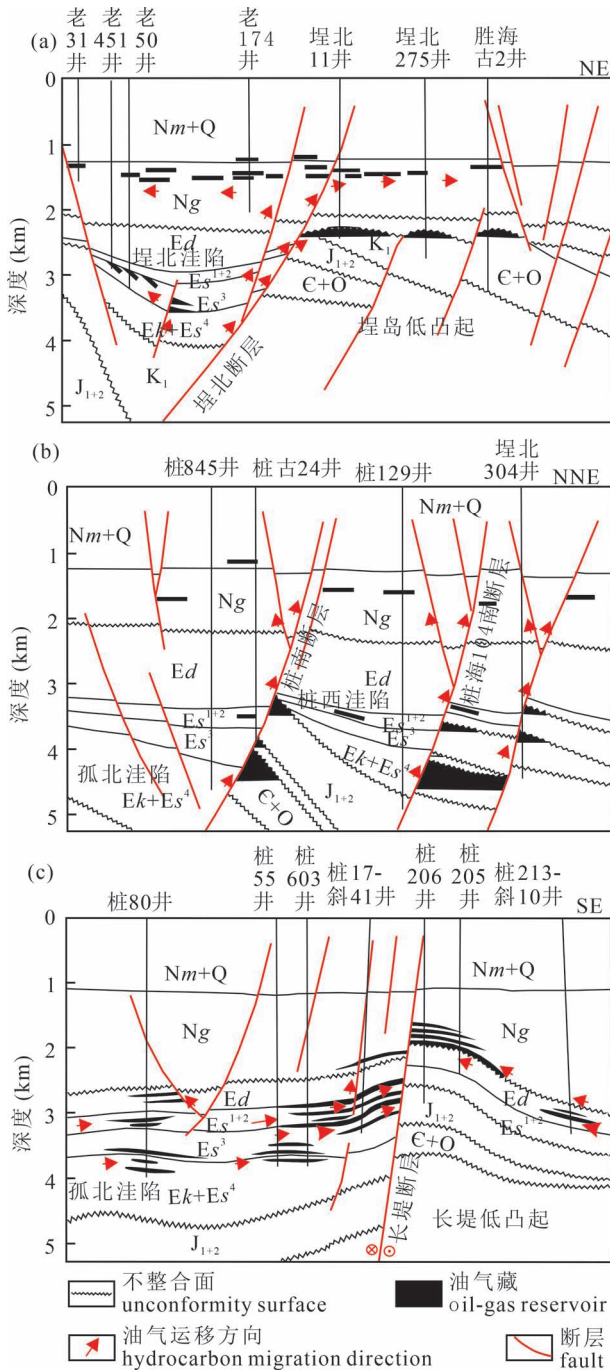


图 10 济阳拗陷滩海地区油藏剖面图 (据吴智平等, 2022)
Fig. 10 Reservoir profile in Tanhai area, the Jiyang Depression, Bohai Bay Basin
(from Wu Zhiping et al., 2022)

的烃源岩和浅部的储层,起到垂向运移通道的作用,断层上盘发育的断控砂体即是油气侧向运移的疏导层,也可被长堤断层侧向封堵构成断层圈闭;浅部发育的次级断裂具有较好的封闭性,形成小规模断层圈闭(图 10c)。

4 讨论

4.1 断裂网络体系分形特征与拓扑结构

滩海地区断裂网络的分形特征与拓扑结构具有明显的差异性,主要是受区域应力改变、郯庐断裂走滑作用及先存断裂的共同作用。

研究区中深层,在后期近南北向斜向拉伸作用及郯庐断裂走滑作用影响下,北西向先存断层发育部位、北北东向走滑断层叠覆区及不同走向断裂共轭区具伸展和走滑双重性质。上述区域,在主干断裂的尾端产生一系列与主断层侧接的近东西向次级断裂,形成马尾状组合;在多条断裂相互作用处,发育大量近东西向次级断裂,不同走向断裂之间发生侧接,构成复杂的断裂网络体系。上述过程使断裂网络体系 Y 节点、I-C 分支、C-C 分支比例增加,连通性变好。其它区域断裂数量少,断裂网络简单,连通性差。

研究区浅层,随着区域应力的减弱,北西向主干断裂逐渐停止活动,发育大量次级断裂,呈平行式或雁列式展布,数量较多,规模较小,难以发生斜交,连接节点数量较少,但分维值较高。北北东向断层叠覆区及不同走向断裂相互作用的共轭区域,受郯庐断裂走滑作用影响,不同级序断裂间发生斜交,形成较复杂的断裂网络,断层间连通性较好。

通过上述分析,笔者等认为先存断裂受到后期斜向拉伸部位及走滑断层发育部位通常具有高分维高拓扑的特征。若先存断层发育,在高角度(后期伸展相对先存断层走向)拉伸条件下,应变大多为先存断裂吸收,次级断层欠发育,断裂网络分维值与拓扑值较低;在低角度拉伸条件下,先存断裂对应应变吸收较差,次级断层大量发育,形成复杂的断裂网络,高分维高拓扑(Duffy et al., 2017; 王迪等, 2023)。在走滑断层周围,随应变增加,主应力方向旋转(Naylor et al., 1986),形成次级断层与先存断层侧接,导致复杂的断裂网络,具有高分维高拓扑的特征。

4.2 断裂网络体系分形特征及拓扑结构与含油性关系

在对研究区分形特征和拓扑结构差异性展布分析的基础上,进一步讨论其差异展布和油气分布的耦合关系。下面结合实际勘探资料,对不同地区进行讨论。

不同走向断层共轭的桩西洼陷次级断层发育,断裂网络具高分维、高拓扑的特点,油气成藏条件较

好。该区及邻近区的桩西洼陷、埕北凹陷、黄河口凹陷烃源岩发育(阎毓霞, 2008)并在古近系开始生烃(蒋有录等, 2021), 发育的埕北断层、埕东断层、桩南断层等活动速率高(刘一鸣等, 2019), 将油气由烃源岩疏导至储层(蒋有录等, 2022)。同时, 活动速率较低的东西向断层发育, 在浅层与不整合共同作用形成构造圈闭(图 11)。

研究区南部的孤岛凸起紧邻烃源岩发育的沾化凹陷, 古近纪烃源岩开始生烃; 储层发育, 下盘主要发育不整合储层, 上盘沿断层扇三角洲砂体发育(王琳, 2016)。T₀ 界面, 断裂网络高分维、高拓扑, 断层活动性较强, 油藏大面积展布。T₁ 界面, 断裂网络高分维、低拓扑, 断层活动性减弱, 断层对油气疏导能力下降, 油藏分布收缩。

研究区东部走滑断层叠覆区紧邻古近纪开始生烃的桩西洼陷、黄河口凹陷及沾化凹陷等生烃凹陷; 在侧列展布的长堤凸起、孤东低凸起、垦东凸起不整合储层发育(陈涛, 2009)。断裂网络高分维、高拓扑, 走滑断层向下切割烃源岩, 沟通烃源岩与断层各层位, 起到油气垂直运移通道的作用。T₀ 界面, 走滑断层活动性较弱, 油藏布局局限。T₁ 界面, 走滑断层活动性强(张晓庆, 2020), 油藏主要分布于走滑断层的增压段(卢妹男等, 2018)。

通过上述分析可以发现, 相较于其它构造部位, 油气更倾向于沿构造裂缝运移。高拓扑值区, 不同级序的断裂间发生连接, 提高了断裂网络体系的连通性, 利于油气的运移(Gartrell et al., 2004); 高分维值区, 大量次级断裂发育, 利于圈闭的形成。因此, 具高分维值、高拓扑值的区域更有可能成为油气藏发育的有利区带。油气成藏除受到断裂网络体系

连通性与复杂性的影响外, 还受断层的活动速率、局部异常压力、烃源岩生排烃状况等因素影响。例如在埕北 30 断层, T₀ 界面上覆沙三段为该区主要烃源岩, 生烃强度较高, 虽然拓扑值低, 但由于邻近烃源岩且存在油源断层作为运移通道, 具有较好的油气发育; T₁ 界面的东营组烃源岩成熟度较低, 生烃强度较弱, 虽然断裂网络拓扑值较高, 但这些新生断层未沟通下部成熟烃源岩(赵凯, 2019), 油藏发育较差。

5 结论

笔者等通过对断裂网络体系分形特征和拓扑结构进行描述, 定量表征了研究区断裂网络体系的复杂性和连通性, 并对其差异分布的影响因素进行了讨论。最后, 将断裂网络的分形特征及拓扑结构同油气勘探结果相结合, 建立了分形特征与拓扑结构同区域油气分布之间的联系。

(1) 滩海地区断裂网络的高分维值区与高拓扑值区均具有沿北西向先存断裂及北北东向走滑断裂展布的特点。受南北向拉伸作用及郯庐断裂北北东向走滑作用的影响, 研究区东部高分维值与高拓扑值区主要呈北东、东西向展布; 西部高值区主要呈北西向带状展布。由深至浅, 分维值与拓扑值在东部逐渐增大; 在西部逐渐减小。

(2) 断裂网络体系的分形特征与拓扑结构受先存断裂、区域应力以及走滑断裂的共同影响。先存断裂的低角度拉伸导致断裂网络的连通性与复杂性增加; 高角度拉伸使断裂网络断层数量增多, 更加复杂, 但连通性提升有限。走滑断层随应变增加, 复杂性与连通性均有较大增长。

(3) 油藏发育受到断裂网络体系的分形特征及拓扑结构的影响。高拓扑值区域, 不同级序的断裂间相互连接, 提高了断裂网络体系的连通性; 高分维值区域, 大量次级断裂发育, 利于圈闭的形成。因此, 高分维值、高拓扑值的区域是油气藏发育的有利区带。

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参 考 文 献 / References

- (The literature whose publishing year followed by a “&” is in Chinese with English abstract; The literature whose publishing year followed by a “#” is in Chinese without English abstract)
- 陈涛. 2009. 济阳拗陷第三系不整合结构与输导机理研究. 导师: 蒋有录, 宋国奇. 东营: 中国石油大学博士学位论文; 1~137.
- 蒋有录, 苏圣民, 刘华, 赵鹤皓. 2021. 渤海湾盆地油气成藏期差异性及其主控因素. 石油与天然气地质, 42(6): 1255~1264.

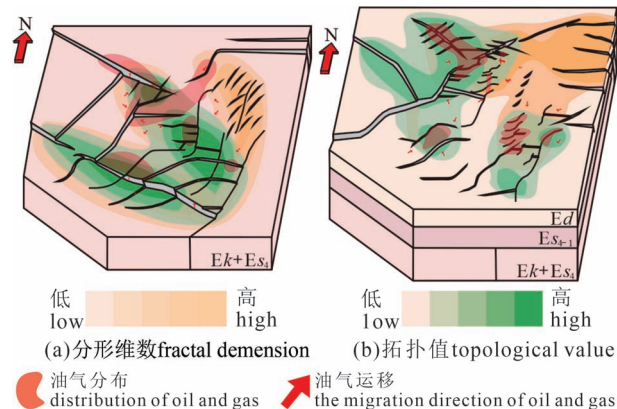


图 11 分形拓扑特征及含油性模式

Fig. 11 Fractal and topological features and oiliness patterns

- 蒋有录, 苏圣民, 赵凯. 2022. 油源断层输导能力与非生烃层系油气富集的关系——以渤海湾盆地埕岛地区为例. 石油学报, 43(8): 1122~1131+1184.
- 刘一鸣, 吴智平, 刘丽芳, 张晓庆, 李伟, 陈少平, 郝鑫. 2019. 埕北凹陷及邻区新生代断裂体系与构造格局. 大地构造与成矿学, 43(6): 1133~1143.
- 卢妹男, 吴智平, 程燕君, 李旭. 2018. 孤东地区走滑作用对油气成藏的控制. 东北石油大学学报, 42(1): 32~39+85+123.
- 马赛婷, 胡林, 李明, 王迪, 陈林, 程燕君, 徐彬, 吴智平. 2024. 珠江口盆地文昌 A 凹陷西部地区断裂体系的拓扑结构、分形特征及其与油气藏分布的关系. 高校地质学报, 30(1): 36~46.
- 任建业, 于建国, 张俊霞. 2009. 济阳拗陷深层构造及其对中新世盆地发育的控制作用. 地学前缘, 16(4): 117~137.
- 任建业. 2018. 中国近海海域新生代成盆动力机制分析. 地球科学, 43(10): 3337~3361.
- 王迪, 吴智平, 宋国奇, 贾光华. 2021. 断裂网络体系拓扑结构与油气运移的关系——以临南洼陷为例. 中国矿业大学学报, 50(1): 154~162.
- 王迪, 吴智平, 杨林龙, 王喜冬. 2023. 含油气盆地多级序断裂网络体系拓扑特征: 以济阳拗陷为例. 地质科学, 58(4): 1226~1241.
- 王琳. 2016 车镇凹陷北带中段沙河街组沉积储层特征及成藏规律研究. 导师: 张善文. 东营: 中国石油大学(华东)硕士学位论文.
- 吴智平, 张劭, 张晓庆, 王迪, 程燕君. 2022. 渤海湾盆地“埕北-垦东”构造转换带形成演化及成藏特征. 石油与天然气地质, 43(6): 1321~1333+1358.
- 徐长贵. 2016. 渤海走滑转换带及其对大中型油气田形成的控制作用. 地球科学, 41(9): 1548~1560.
- 阎毓霞. 2008. 胜利油区埕岛地区原油地球化学特征与油源分析. 油气地质与采收率, 15(4): 30~32+113.
- 于英华, 陈达, 袁红旗, 张亚雄, 曹文瑞. 2021. 渤海湾盆地冀中拗陷大柳泉地区 F₈ 断裂不同时期输导油气能力对油气成藏贡献. 地质论评, 67(5): 1478~1486.
- 曾联波, 金之钧, 李京昌, 汤良杰, 由福报, 雷兵足. 2001. 柴达木盆地北缘断裂构造分形特征与油气分布关系研究. 地质科学, 36(2): 241~247.
- 张晓庆, 宋明水, 侯中帅, 郝冉冉, 张强, 刘一鸣, 陈少平, 吴智平. 2019. 裂陷盆地构造-沉积耦合关系及其控藏作用——以渤海湾盆地埕北凹陷古近系为例. 中国矿业大学学报, 48(6): 1317~1329.
- 张晓庆. 2020 渤海湾盆地“埕北-莱州湾”地区构造特征的时空差异及成因机制. 导师: 吴智平, 东营: 中国石油大学(华东)博士学位论文: 1~129.
- 赵凯. 2019 埕岛地区新近系断裂控藏作用研究. 导师: 蒋有录. 东营: 中国石油大学(华东)博士学位论文: 1~109.
- Chen Tao. 2009. The Unconformity Structures and Transformation Mechanism of Tertiary Unconformity in Jiyang Depression. Supervisor: Jiang Youlu, Song Guoqi. Dongying: China University of Petroleum (East China) Doctoral dissertation: 1~137.
- Deng Chao, Gawthorpe R L, Finch E, Fossen H. 2017. Influence of a pre-existing basement weakness on normal fault growth during oblique extension: Insights from discrete element modeling. Journal of Structural Geology, 105: 44~61.
- Dong Yuexia, Xiao Long, Zhou Haimin, Du Jingxia, Zhang Ning, Xiang Hua, Wang Chunzeng, Zhao Zhongxin, Huang Hongxiang. 2010. Volcanism of the Nanpu Sag in the Bohai Bay Basin, Eastern China: Geochemistry, petrogenesis, and implications for tectonic setting. Journal of Asian Earth Sciences, 39(3): 173~191.
- Duffy O B, Nixon C W, Bell R E, Jackson C A L, Gawthorpe R L, Sanderson D J, Whipp P S. 2017. The topology of evolving rift fault networks: Single-phase vs multi-phase rifts. Journal of Structural Geology, 96: 192~202.
- Falconer K. 1990. Fractal geometry: Mathematical foundations and applications. Biometrics, 46(3): 886.
- Gartrell A, Zhang Yanhua, Lisk M, Dewhurst D. 2004. Fault intersections as critical hydrocarbon leakage zones: Integrated field study and numerical modelling of an example from the Timor Sea, Australia. Marine and Petroleum Geology, 21(9): 1165~1179.
- Hao Fang, Zhou Xinhua, Zhu Yangming, Yang Yuanyuan. 2011. Lacustrine source rock deposition in response to co-evolution of environments and organisms controlled by tectonic subsidence and climate, Bohai Bay Basin, China. Organic Geochemistry, 42(4): 323~339.
- Hirata T. 1989. Fractal dimension of fault systems in Japan: Fractal structure in rock fracture geometry at various scales. Pure and Applied Geophysics, 131(1): 157~170.
- Jiang Youlu, Su Shengmin, Liu Hua, Zhao Honghao. 2021. Differences in hydrocarbon accumulation stages and main controlling factors in the Bohai Bay Basin. Oil & Gas Geology, 42(6): 1255~1264.
- Jiang Youlu, Su Shengmin, Zhao Kai. 2022. Relationship between transporting ability of oil-source faults and hydrocarbon enrichment in non-hydrocarbon generating strata: A case study of Chengdao area of Bohai Bay Basin. Acta Petroli Sinica, 43(8): 1122~1131+1184.
- Karlsen D A, Skeie J E. 2006. Petroleum migration, faults and overpressure, part I: Calibrating basin modelling using petroleum in traps - a review. Journal of Petroleum Geology, 29(3): 227~256.
- Li Sanzhong, Suo Yanhui, Santosh M, Dai Liming, Li Xiyao, Suo Yanhui, Guo Lingli, Wang Yongming, Liu Xiaochun, Lan Haoyuan, Zheng Qiliang, Wang Pengcheng. 2013. Mesozoic to Cenozoic intracontinental deformation and dynamics of the North China Craton. Geological Journal, 48(5): 543~560.
- Liu Yiming, Wu Zhiping, Liu Lifang, Zhang Xiaoqing, Li Wei, Chen Shaoping, Hao Xin. 2019. Cenozoic fault system and tectonic framework of Chengbei Sag and its adjacent areas, Bohai Bay basin. Geotectonica et Metallogenia, 43(6): 1133~1143.
- Lu Shunan, Wu Zhiping, Cheng Yanjun, Li Xu. 2018. Control of strike-slip on reservoir formation of oil and gas in Gudong area. Journal of Northeast Petroleum University, 42(1): 32~39+85+123.
- Ma Saiting, Hu Lin, Li Ming, Wang Di, Chen Lin, Cheng Yanjun, Xu Bin, Wu Zhiping. 2024. Topological structures, fractal characteristics of fault systems and their relationships with hydrocarbon accumulation in the western Wenchang A sag, the Pearl River mouth basin. Geological Journal of China Universities, 30(1): 36~46.
- Morley C K, Nixon C W. 2016. Topological characteristics of simple and complex normal fault networks. Journal of Structural Geology, 84: 68~84.
- Naylor M A, Mandl G, Supesteijn C H K. 1986. Fault geometries in basement-induced wrench faulting under different initial stress states. Journal of Structural Geology, 8(7): 737~752.
- Nyberg B, Nixon C W, Sanderson D J. 2018. NetworkGT: A GIS tool for geometric and topological analysis of two-dimensional fracture networks. Geosphere, 14(4): 1618~1634.
- Ortega O, Marrett R. 2000. Prediction of macrofracture properties using microfracture information, Mesaverde Group sandstones, San Juan basin, New Mexico. Journal of Structural Geology, 22(5): 571~588.

- Qi Jiafu, Yang Qiao. 2010. Cenozoic structural deformation and dynamic processes of the Bohai Bay basin province, China. *Marine and Petroleum Geology*, 27(4): 757~771.
- Ren Jianye, Yu Jianguo, Zhang Junxia. 2009. Structures of deep bed in Jiyang Sag and their control over the development of Mesozoic and Cenozoic basins. *Earth Science Frontiers*, 16(4): 117~137.
- Ren Jianye. 2018. Genetic dynamics of China offshore Cenozoic basins. *Earth Science*, 43(10): 3337~3361.
- Sanderson D J, Nixon C W. 2015. The use of topology in fracture network characterization. *Journal of Structural Geology*, 72: 55~66.
- Sanderson D J, Peacock D C P, Nixon C W, Rotevatn A. 2019. Graph theory and the analysis of fracture networks. *Journal of Structural Geology*, 125: 155~165.
- Su Jinbao, Zhu Wenbin, Lu Huaifu, Xu Mingjie, Yang Wei, Zhang Zhiyong. 2009. Geometry styles and quantification of inversion structures in the Jiyang depression, Bohai Bay Basin, Eastern China. *Marine and Petroleum Geology*, 26(1): 25~38.
- Valentini L, Perugini D, Poli G. 2007. The “small-world” topology of rock fracture networks. *Physica A: Statistical Mechanics and Its Applications*, 377(1): 323~328.
- Wang Di, Wu Zhiping, Song Guoqi, Jia Guanghua. 2021. Topological structure of fault network system and its relationship with hydrocarbon migration: Taking Linnan sag as an example. *Journal of China University of Mining & Technology*, 50(1): 154~162.
- Wang Di, Wu Zhiping, Yang Linlong, Li Wei, He Chuan. 2021. Influence of two-phase extension on the fault network and its impact on hydrocarbon migration in the Linnan sag, Bohai Bay Basin, East China. *Journal of Structural Geology*, 145: 104289.
- Wang Di, Wu Zhiping, Yang Linlong, Wang Xidong. 2023. Topological characteristics of multistage sequence fault networks in petroliferous basins: A case study of Jiyang Depression. *Chinese Journal of Geology (Scientia Geologica Sinica)*, 58(4): 1226~1241.
- Wang Di, Yang Linlong, Li Wei, Wang Xidong. 2023. The impact of pre-existing faults on fault geometry during multiphase rifts: The Jiyang depression, Eastern China. *Journal of Marine Science and Engineering*, 11(10): 1971.
- Wang Di, Zhang Xiaoqing, Yang Linlong, Chen Xingpeng, Ma Saiting, Wu Zhiping. 2022. Influence of pre-existing faults on Cenozoic structures in the Chengbei sag and the Wuhaozhuang area, Bohai Bay Basin, East China. *Marine and Petroleum Geology*, 138: 105539.
- Wang Lin. 2016. The Characteristics of Reservoirs and Hydrocarbon Accumulation in the Middle Section of the Steep Slope Zone in Chezhen Depression. Supervisor: Prof. Zhang Shanwen. Dongying: China University of Petroleum (East China) Master dissertation; 1~67.
- Wu Zhiping, Zhang Meng, Zhang Xiaoqing, Wang Di, Cheng Yanjun. 2022. Evolution and reservoir characteristics of the “Chengbei-Kendong” structural transfer zone in the Bohai Bay Basin. *Oil & Gas Geology*, 43(6): 1321~1333+1358.
- Xu Changgui. 2016. Strike-slip transfer zone and its control on formation of medium and large-sized oilfields in Bohai Sea area. *Earth Science*, 41(9): 1548~1560.
- Yan Yuxia. 2008. Analysis of geochemical characteristics and oil sources in Chengdao area, Shengli petroliferous district. *Petroleum Geology and Recovery Efficiency*, 15(4): 30~32+113.
- Yu Yinghua, Chen Da, Yuan Hongqi, Zhang Yaxiong, Cao Wenrui. 2021. Contribution of hydrocarbon transport capacity of the Fault F₈ to hydrocarbon accumulation in different periods in Daluquan area, Langgu Sag, Jizhong Depression, Bohai Bay Basin. *Geological Review*, 67(5): 1478~1486.
- Yu Yinghua, Chen Da, Yuan Hongqi, Zhang Yaxiong, Cao Wenrui. 2021. Contribution of hydrocarbon transport capacity of the fault F₈ to hydrocarbon accumulation in different periods in Daluquan area, Langgu Sag, Jizhong Depression, Bohai Bay Basin. *Geological Review*, 67(5): 1478~1486.
- Zeng Lianbo, Jin Zhijun, Li Jingchang, Tang Liangjie, You Fubao, Lei Bingzu. 2001. Fractal characteristics of fractural structures and its relation to oil-gas distribution in north Qaidam basin. *Scientia Geologica Sinica*, 36(2): 241~247.
- Zeng Lianbo, Jin Zhijun, Li Jingchang, Tang Liangjie, You Fubao, Lei Bingzu. 2001. Fractal characteristics of fractural structures and its relation to oil-gas distribution in north Qaidam Basin. *Chinese Journal of Geology*, (2): 241~247.
- Zhang Xiaoqing, Song Mingshui, Hou Zhongshuai, Hao Ranran, Zhang Qiang, Liu Yiming, Chen Shaoping, Wu Zhiping. 2019. Coupling relationship between structure and sedimentation and the controlling effect on hydrocarbon accumulation in the rift basin: A case study of the Paleogene in the Chengbei sag, Bohai Bay basin. *Journal of China University of Mining & Technology*, 48(6): 1317~1329.
- Zhang Xiaoqing, Song Mingshui, Hou Zhongshuai, Hao Ranran, Zhang Qiang, Liu Yiming, Chen Shaoping, Wu Zhiping. 2019. Coupling relationship between structure and sedimentation and the controlling effect on hydrocarbon accumulation in the rift basin: A case study of the Paleogene in the Chengbei sag, Bohai Bay basin. *Journal of China University of Mining & Technology*, 48(6): 1317~1329.
- Zhang Xiaoqing. 2020. Spatial and Temporal Differences of Structural Characteristics and Its Formation Mechanism of the “Chengbei-Laizhouwan” Area in the Bohai Bay Basin. Supervisor: Prof. Wu Zhiping. Qingdao: China University of Petroleum (East China) Doctoral dissertation; 1~129.
- Zhao Kai. 2019. Studies on the Control of Faults on Hydrocarbon Accumulation in Neogene of Chengdao Area. Supervisor: Prof. Jiang Youlu. Qingdao: China University of Petroleum (East China) Doctoral dissertation; 1~109.
- Zhao Kai. 2019. Study on reservoir control of Neogene faults in Chengdao area. Dongying: China University of Petroleum (Huadong) Doctoral Dissertation.
- Zhu Rixiang, Zhang Hongfu, Zhu Guang, Meng Qingren, Fan Hongrui, Yang Jinhui, Wu Fuyuan, Zhang Zhiyong, Zheng Tianyu. 2017. Craton destruction and related resources. *International Journal of Earth Sciences*, 106(7): 2233~2257.

Relationship between topological structure and fractal characteristics of fault network system and oil and gas distribution in Tanhai area, Jiyang Depression, Bohai Bay Basin

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Objectives: The distribution of hydrocarbon resources in the Paleogene strata in Tanhai area, the Jiyang Depression, Bohai Bay Basin, is affected by the development characteristics of fault network. In this paper, we hope to define the plane geometric features of the fault network and establish the relationship between the geometric features of the fault network and the oil and gas distribution.

Methods: Based on structural interpretation of seismic data, fractal and topological methods are used to analyze the development characteristics of the fault network on the plane.

Results: On the T_6 interface, the high value area of fractal dimension and topological value spread out in NW, with the characteristics of high in south and low in north; At the T_2 interface, the NNE of the high value area of fractal dimension and topological value spreads out in the direction, which is high in the east and low in the west. On T_1 interface, the NE of the high value area of fractal dimension and topological value spreads out in the direction, which is high in the east and low in the west. The fractal dimension and topological value are higher along the existing faults, especially in the intersection area of multi-directional faults and strike-slip fault overlapping area. The reservoir is mainly developed in the parts with complex fault development with high fractal dimension and high topological value.

Conclusions: The fractal characteristics and topological structure of fault network system are affected by preexisting faults, regional stresses and strike-slip faults. Reservoir development is influenced by the fractal characteristics and topological structure of fault network system. The regions with high topological values are connected with faults of different order, which improves the connectivity of the fault network system. A large number of secondary faults are developed in the high fractal dimension region, which is conducive to the formation of traps.

Keywords: fracture network system; topological structure; fractal characteristics; fracture network connectivity; hydrocarbon distribution; Tanhai area, Jiyang Depression

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