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莺歌海盆地莺东斜坡带南段中深层断裂特征及控藏作用

周 杰,胡 林,胡高伟,廖 俊,郭 璃,刘 政 中海石油(中国)有限公司海南分公司,海南海口 570311

摘 要:为了明确莺东斜坡带南段中深层断裂特征及其对天然气成藏控制作用,基于新三维地震资料,首次对莺东斜坡带南段中深层断裂进行了精细刻画.结合区域构造演化特征,分析了断裂类型、形态及活动性,探讨断裂对天然气成藏的控制作用.结果表明,渐新世一早中新世莺歌海盆地处于左行走滑引起的构造变形应力场中,莺东斜坡带南段位于①号断裂走滑转换带,发育3组NW-SE走向,具左行右阶特征的张扭(局部压扭)走滑断裂.剖面上三组断裂自北向南呈断阶状样式,断层产状陡直,局部表现为花状构造;断裂主要为3期活动:(1)始新世一早新新世,(2)晚渐新世早中期,(3)早中新世;具有"早断早衰"的特征.莺东斜坡带南段中深层断裂多期活动控制了崖城组陆源三角洲及烃源的发育,"二台阶"聚气背景的形成、三亚组砂体空间展布和圈闭的形成.莺东斜坡带南段天然气生、运、聚匹配良好,有望成为莺歌海盆地下一个千亿方级的天然气聚集区.

关键词: 莺歌海盆地;莺东斜坡带;断裂;中深层;天然气成藏;石油地质.

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Characteristics of Middle-Deep Faults in the Southern Segment of the Eastern Belt of Yinggehai Basin and Their Controlling Effect on Natural Gas Accumulation

Zhou Jie, Hu Lin, Hu Gaowei, Liao Jun, Guo Li, Liu Zheng

Haikou Branch of China National Offshore Oil Corporation (CNOOC) Limited, Haikou 570311, China

Abstract: The purpose of this paper lies in clarifying the characteristics of faults in middle-deep layers in the southern segment of the eastern belt of Yinggehai Basin and their controlling effect on natural gas accumulation. Based on the new 3D seismic data, the faults in middle-deep layers in the southern segment of the eastern belt of Yinggehai Basin are described precisely for the first time. Combined with the characteristics of regional tectonic evolution, the types, shapes and activities of the faults are analyzed, and the controlling effect of the faults on natural gas accumulation is discussed. The results show that the Eocene-Early Miocene Yinggehai Basin is in the tectonic deformation stress field caused by left strike-slip. Located in the strike-slip transition zone of the No. 1 fault, the southern segment of the eastern belt of Yinggehai Basin develops three groups of tension-torsion (partialcompression-torsion) strike-slip faults. On the plane, the faults are NW-SE trending, with a left-lateral and right-step distribution. On the section, three groups of the faults are steep in occurrence, and present fault-step-like style and flower-like structures locally. The faults are mainly active in three phases: (1)Eocene-Early Oligocene, (2)Early and Mid-Late Oligocene, (3)Early Miocene, characterized by "early faults early senescence". The multi-stage activities of the faults in middle-deep layers control the development of land source deltas and hydrocarbon sources in the Yacheng Formation, the formulation of the "second step" gas accumulation background, the spatial distribution of sandstone in the Sanya Formation and the formation of traps. With a good match of production, migration

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作者简介:周杰(1988-),男,工程师,主要从事南海西部油气勘探研究工作. E-mail:zhouji14@cnooc.com.cn

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and accumulation, the middle-deep layer in the southern section of the eastern belt of Yinggehai Basin is expected to become a natural gas accumulation area of 100 billion cubic meters in the Yinggehai Basin.

Key words: Yinggehai Basin; the eastern belt of Yinggehai Basin; faults; middle-deep layer; natural gas accumulation; petroleum geology.

随着莺歌海盆地勘探程度不断提高,常规目标 越来越少,勘探需向更新、更深、更隐蔽领域进军. 莺歌盆地目前已发现油气田主要围绕中央凹陷带 底辟隆起分布,先后发现东方1-1、乐东15-1、乐东 22-1、东方13-1、东方13-2等大中型气田,其层系主 要分布于中浅层乐东组及莺一黄组地层,因此近几 年的主要研究和勘探方向都是围绕底辟带中浅层 及底辟周缘峡谷水道领域(裴健翔等,2011;谢玉洪 等,2012;黄银涛等,2018;杨计海等,2018;范彩伟 等,2021;尤丽等,2021). 远离底辟带的斜坡区油气 勘探少有成功,主要由于斜坡区梅山组及以浅层系 缺乏规模成熟烃源与高效油气运移通道,同时构造 以单斜为主,圈闭条件较差.由于盆地新近纪快速 热沉降导致中深层埋深较大,缺乏高品质三维地震 资料,断裂体系不能被准确识别,前人并未认识到 斜坡区中深层(三亚组及以深层系)存在复杂构造 条件,针对莺歌海盆地断裂体系的研究主要集中在 底辟带伴生断层(范彩伟,2018;赖冬等,2019). 缺 乏对斜坡区中深层断裂体系的研究,断裂对中深层 油气成藏的控制作用更是少有提及,导致勘探停滞 不前.随着底辟带勘探潜力变小,莺歌海盆地急需 寻找储量接替区,斜坡区中深层勘探势在必行.同 时,构造活动及断裂体系控制油气成藏(王嘉, 2021;柳保军等,2022;张青林等,2022),系统开展 该领域断裂体系特征研究对重启斜坡区天然气勘 探有着至关重要的作用. 本文通过最新的三维地震 等资料分析入手,首次对莺东斜坡带南段中深层构 造特征及断裂体系进行了精细刻画,明确了断裂体 系对油气成藏的控制作用,为莺歌海盆地新领域拓 展及莺东斜坡带中深层天然气勘探提供地质理论 支撑.

1 区域地质概况

莺歌海盆是世界范围内典型的高温强超压新生代盆地,其发育于印支块体与华南块体、南海北缘块体、中一西沙块体的结合带,为大型走滑一伸展盆地,成菱形展布,面积约8×10⁴km²,其形成与欧亚、印一澳、太平洋板块间的作用,古南海消亡,新南海扩展,印一支块体旋扭,哀牢一红河断裂走

滑与转型现象有关(孙家振等,1995;丁中一等, 1999; 郝芳等, 2001; 宋维宇, 2012; 邓勇等, 2020). 莺歌海盆地由北至南发育河内凹陷和莺歌海凹陷, 其中莺歌海凹陷可划分为莺东斜坡、莺西斜坡、中 央坳陷带等.盆地自下而上发育始新统、渐新统(崖 城组、陵水组)、中新统(三亚组、梅山组、黄流组)、 上新统(莺歌海组)和更新统(乐东组). 新生代以来 莺歌海盆地主要经历了断陷期、热沉降期、加速热 沉降期3幕构造演化阶段(孙珍等,2007;谢玉洪, 2015). 渐新世一中新世左旋到上新世右旋的构造 转型,在盆地边缘发育以NW-SE向①号断裂和莺 东断裂为代表的走滑一伸展(局部挤压)断层.晚中 新世区域右旋走滑剪切构造应力场和强超压的共 同作用,莺歌海盆地发育一系列南北向底辟构造 (张敏强等,1999;何家雄等,2006;杨东辉,2019), 目前围绕底辟隆起中浅层乐东组、莺一黄组已发现 油气近2千亿方.研究区位于莺东斜坡带南段(图 1),处于莺歌海盆地与琼东南盆地构造结合部,断 裂发育,油气运聚活跃,发育大型三角洲沉积体系, 具有形成大中型油气田的地质条件.

2 中深层断裂发育特征及形成期次

2.1 断裂发育特征

莺歌海盆地渐新世一早中新世受印度洋板块和欧亚板块碰撞,哀牢山一红河断裂持续强烈左旋走滑,沿盆地边缘形成一系列左旋走滑变形构造,形成了以①号断裂为代表的NW-SE向走滑断裂系统(Tapponnier,1986; Sun et al., 2003; Zhu et al., 2009; Mazur et al., 2012). 莺东斜坡带南段为①号断裂带向东南方向延伸段,位于莺歌海盆地东部NW向边界断裂带与琼东南盆地NE向北部边界断裂带的共轭转换处,断裂体系发育,在左旋走滑的背景下形成一系列NW向张扭走滑断裂.

依据新三维地震资料,结合最大似然体切片等相关技术(图2),进行精细构造解释.进而对该区断裂的分布及组合特征有了一个全新的认识.从地震剖面上可以看出(图3),莺东斜坡带南段是由一系列向西倾斜的断裂构成的断阶带,主要发育3组构造断裂,断裂倾角相对较大,局部区域近乎直立,同

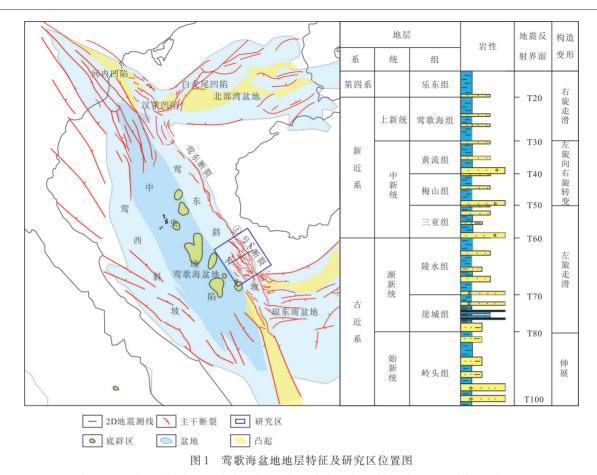


Fig.1 Stratigraphic characteristics of the Yinggehai Basin and location map of the study area

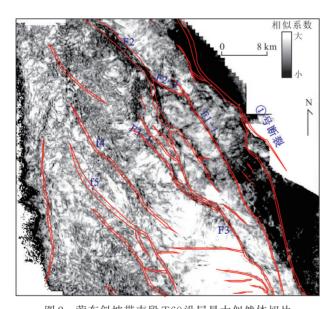


图 2 莺东斜坡带南段 T60沿层最大似然体切片

Fig.2 Maximum likelihood volume slices along the T60 layer in the southern segment of the eastern belt of the Yinggehai Basin

时表现为似花状构造组合特征,走滑效应明显.F1 断层(①号断裂)作为整个莺歌海盆地的东部边界

断层,规模最大,向上断至莺歌海组,向下断至基底,同时在研究区内控制着一个小型的半地堑发育,沿着F1断裂发育一组反向调节断层F1-1等.F2、F3断裂规模次之,向上断至三亚组一段,向下断至基底,剖面上表现出似花状结构,控制了近凹断阶以及凹中隆的形成.另外三亚组沉积晚期发育一组近凹陷中心派生、调节断裂f4、f5与F2、F3断裂近平行展布.

陵水组底界(T70反射界面)与三亚组底界(T60反射界面)断裂平面展布图显示,研究区断层呈NW-SE向展布(图4),盆地内部的断裂具有右阶斜列发育特征,其走向与主干边界的F1断层(①号断裂)呈近似平行,或者与其呈小角度相交,交角一般小于15°.另外,在研究区南部发育一些规模相对较小(长度一般小于10 km)的近W-E向断裂,与主干走滑断层呈锐角相交,指示本盘运动方,整体显示出左旋右阶的展布特征.

2.2 断裂活动期次及构造演化

断裂是控制盆地演化的重要因素,分析断裂活动性可以明确盆地构造演化、断裂发育和相互作用的过

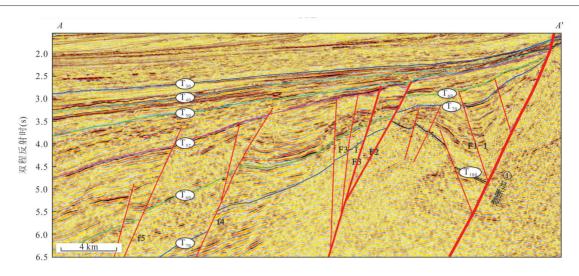


图 3 莺东斜坡带南段中深层典型剖面

Fig. 3 Typical section of middle-deep layer in the southern segment of the eastern belt of the Yinggehai Basin

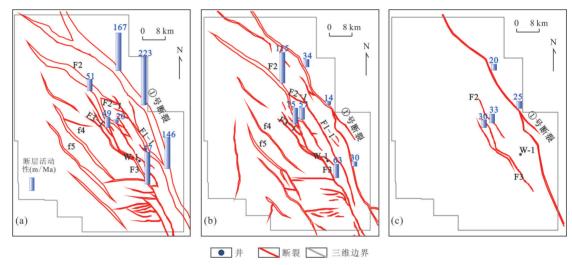


Fig.4 Superimposed map of T70, T60, T52 fault plane distribution characteristics and fault activity in the southern segment of the eastern belt of the Yinggehai Basin

a. T70 界面断裂平面展布特征与始新统一崖城组断裂活动性叠合图;b. T60 界面断裂平面展布特征与三亚组二段断裂活动性叠合图;c. T52 界面断裂平面展布特征与三亚组一段断裂活动性叠合图

程. 斜坡区南段主要断层活动速率(图4)计算结果表明,F1(①号断裂)断裂为控制盆地形成的边界断层,长期发育继承性活动,始新世一早渐新世(始新统一三亚组时期)F1断裂活动性持续高强度活动,断层活动速率可达到146 m/Ma以上,最高为223 m/Ma. 早中新世后F1断层活动明显减弱,断裂活动速率明显降低,一般介于15~35 m/Ma. 而盆地内部的F2、F3断裂的活动特征与F1断裂不同,尽管F2、F3断裂与F1断裂形成时期相同,但始新世一早渐新世,F2、F3断裂活动速率相对较低,普遍小于50 m/Ma,晚渐新世由于走滑挤压强烈,斜坡区南段发生明显构造抬升,此

时F1、F2、F3强烈活动,崖城组地层产生明显褶皱变形,F1-1反向调节断层发育,断层地层两盘地震相突变,显示出明显的走滑断裂特征.早中新世F2、F3断层活动速率增强,可以达到60 m/Ma左右,最高为115 m/Ma,F1断裂活动速率降至30 m/Ma与F2、F3断裂活动性差异明显,导致沉积中心由F1断裂下降盘向西转移至F2、F3断层下降盘.

通过对研究区构造发育史分析表明,该区主要经历了断陷(T100~T70)、断拗转换(T70~T50)、拗陷期(T50~今)3期构造演化(图5):(1)始新世一早渐新世研究区发生走滑拉张变形形成小型断陷盆地;(2)

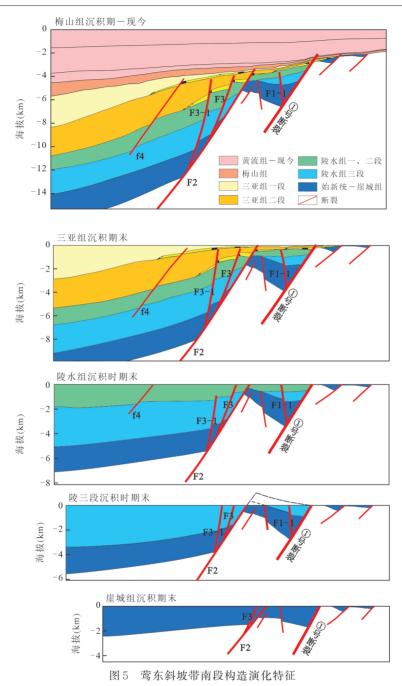


Fig.5 Structural evolution characteristics of the southern segment of the eastern belt of the Yinggehai Basin

晚渐新世一走滑挤压隆升形成凹中隆及"二台阶"背景,早中新世斜坡区南段进入断拗转换期,莺东斜坡宽缓斜坡背景逐渐发育,早中新世晚期断裂活动停止,宽缓斜坡背景形成;(3)中中新世后斜坡区南段进入快速沉降期,形成现今高陡、单斜的斜坡背景.

2.3 成因机制探讨

盆地发育早期的先存断裂往往是基底断裂,并逐渐成为控盆断裂,其运动学特征决定盆地或凹陷的形成和发展历史,几何学和运动学差异导致不同的构造样式和断层组合形态的差异(Gibbs,1989;漆家福等,

2004). 盆地内部断裂的分布和成因与主边界断层的产状和运动学特征有关,特别是主干断层位移常引起断层上盘变形,形成与主干正断层倾向一致的同向调节断层、反向调节断层、构造斜坡上的共扼断层等. 断裂带的成因机制分析应从其所处盆地的区域构造背景出发,基于区域应力场的分析明确各断裂带所受的力学机制. 若伸展方向与先存构造的走向斜交,断层发生斜向滑动,这里既包含了垂直于断层走向的伸展变形分量,也包含了平行断层走向的走滑变形分量(Morley et al., 2004; 童亨茂等, 2009; Tong et al.,

2014). 印支块体挤压逃逸, 哀牢山一红河断裂持续强 烈左旋,形成了分别以①号断裂和中建西断裂为主支 的两个帚状构造,斜坡区南段处于两个帚状构造的叠 接区,在先期拉张基础上被走滑改造,盆地内部在左 旋走滑的过程中自西北向东南运动,受到中建隆起阻 挡,形成走滑挤压构造,局部强烈抬升;自渐新世晚期 以来,受南海扩张等周缘板块运动影响,区域伸展方 向转变为近 N-S 向,这种区域伸展方向与哀牢山一红 河断裂左旋走滑应力场相互协调一致,NW-SE走向 莺东断裂带和①号断裂作为先存断层发生斜向伸展 变形,首先是①号断裂发生复活,以及形成与主干断 层走向近似平行的断裂体系,另外形成与F1断裂呈小 角度相交的,右阶斜列展布的,先存断裂伴生的次级 断层,以及近E-W向的新生断层.中新世中期以来哀 牢山一红河断裂由左行走滑开始向右行走滑转变,① 号断裂再次活动,但活动量有所减弱.

3 断裂对油气成藏的控制作用

3.1 断裂活动控制了古近系烃源的发育

目前对于莺歌海盆地的勘探主要以研究中新统 烃源为主(徐新德等,2015;郭潇潇等,2017),但在斜 坡区靠近①号带中新统烃源大部分未熟,不足以支撑 大中型油气田勘探, 而紧临莺东斜坡区南段的琼东南 盆地崖南凹陷以崖城组大型陆源三角洲形成的海陆 过渡相烃源为主力源岩,同时W-1井在斜坡区南段三 亚组二段钻遇气层,并揭示崖城组地层.气源对比表 明,斜坡区南段乐东10区典型中新统烃源供烃天然气 $\delta^{13}C_2$ 值 $-23.13\%\sim-20.26\%$,而 W-1 井三亚组天然 气δ¹³C₂值为-24.70%,整体偏轻,与崖城13-1、陵水17 -2气田天然气特征相似,与乐东10区典型中新统烃源 存在差异(图6),表明其天然气可能具有渐新统烃源 岩贡献. W-1 井钻遇的崖城组前三角洲泥岩有机质丰 度为 $0.85\%\sim0.90\%$,生烃潜量 (S_1+S_2) 含量较高,为 3.16~4.14 mg/g,为中等级别的烃源,有机质类型为 Ⅱ₂型~Ⅲ型. 从整个盆地的充填演化特征来看,斜坡 区古近系以断陷为主,与崖南凹陷构造条件相似.始 新统一渐新世崖城组沉积时期,沿①号断裂带发育了 多个陆源三角洲体系,面积480 km²,大部分埋深5000 m以下,该三角洲群与崖南凹陷崖城组辫状河三角洲 特征类似,表现为中一低频、中等连续、中强强振幅特 征,可形成煤系及陆源海相烃源(图7),奠定了斜坡区 大规模气源岩生成的物质基础.

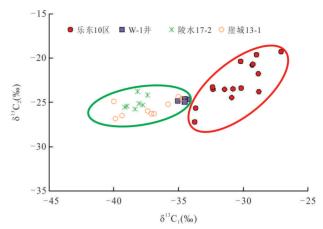


图 6 莺琼盆地天然气δ¹³C₁~δ¹³C₂相关图

Fig. 6 Correlation map of natural gas $\delta^{13}C_1 \sim \delta^{13}C_2$ in Yingge-hai-qiongdongnan Basin

3.2 断裂控制了中新统大型圈闭的形成

早中新世莺东斜坡宽缓的斜坡背景逐渐形成,斜 坡区南段三亚组沉积早期其沉积边界主要受①号断 层控制,其上升盘抬升剥蚀,成为物源区,持续向凹陷 中心供应物源,同时F2、F3斜向下掉形成转换斜坡背 景,并造成相对较低洼的古地形条件,在断层下降盘 形成断槽,形成了斜坡区南段大型缓坡三角洲沉积格 局,控制了砂体自北向南呈阶梯状展布.地震剖面上 可以见到三亚组二段两期三角洲沉积,地震反射特征 表现平行一亚平行一前积内部结构、强一中振幅连续 反射特征(图8). W-1 井揭示了同时期另一三角洲的 发育,该井钻遇一套三亚组三角洲沉积体,以中砂岩 为主,砂体总计厚度180 m左右,揭示了该时期以发育 大型富砂三角洲为主. 以往认为莺东斜坡普遍表现出 单斜背景,其圈闭侧封条件是成藏的关键,因此在莺 东斜坡中深层断裂对圈闭条件的控制不容忽视. 早中 新世晚期F2、F3断裂的剧烈活动,形成断阶,控制了 该三角洲由北向南展布,砂体展布方向与构造高部位 呈大角度相交,能够形成岩性尖灭的条件,后期断层 进一步活动形成断块,潜在目的层砂体被泥岩侧向封 堵,同时走滑断裂形成局部增压区亦能增加圈闭的侧 向封堵性. 早中新世晚期,断裂活动趋于停止,斜坡区 以热沉降为主,圈闭基本定型,从而形成了较好的圈 闭发育条件,发育与断层相关的构造或构造+岩性圈闭.

3.3 断裂活动形成优势运移通道,晚期封闭保存有利

莺歌海盆地运移通道的研究主要集中在对底辟构造及微裂隙研究(何家雄等,2000;童传新等,2012;吴迅达等,2021),对斜坡区中深层断层为主的运移通道少有提及.构造活动形成了广泛分布于斜坡区南段

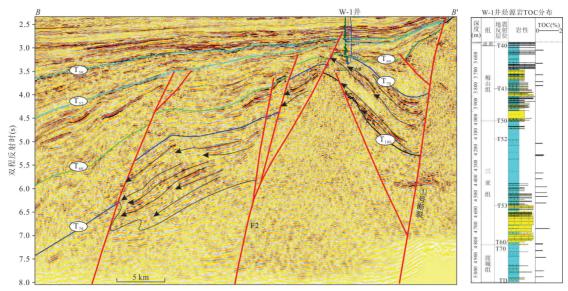


Fig.7 Large-scale terrigenous delta seismic profile of Yacheng Formation and histogram of T0C distribution in Well W-1 in the southern segment of the eastern belt of the Yinggehai Basin

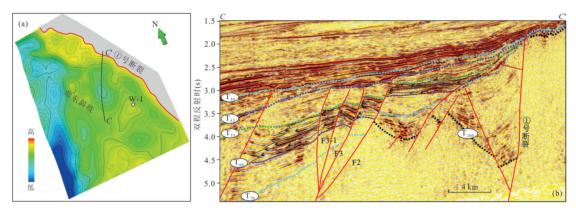


图 8 莺东斜坡带南段早中新世三亚组古地貌图与三角洲典型剖面

Fig. 8 Early miocene Sanya formation paleomorphology map and typical delta section in the southern segment of the eastern belt of the Yinggehai Basin

中深层与崖城组烃源沟通的大型断裂体系及继承性发育的"二台阶"聚气背景.根据生烃模拟结果,斜坡区南段崖城组烃源岩在中新世开始大量排烃,一直持续到现今.晚渐新世强烈的走滑挤压隆升形成了由基底至陵水组地层继承性发育的凹中隆,形成了深部大面积的汇气背景.F1、F2、F3向下断至T70以下,沟通崖城组成熟烃源岩,向上断至三亚组一段地层,沟通三亚组二段圈闭,油气可沿这些断层向上运移,并在三亚组二段砂体中横向运移,形成"阶梯状"输导体系,从而聚集在该层段圈闭中.中新统圈闭主要形成于三亚组二段沉积期,此后断裂活动趋于停止,斜坡区南段没有发生大规模构造运动,形成了厚层的浅海相泥岩盖层(W-1井钻遇三亚组二段之上纯泥岩盖层 542

m),圈闭形成时间和油气运移时间配置较好,与上覆厚层浅泥岩盖层形成很好的封盖,断层终止在三亚组一段厚层泥岩中,"早断早衰"特征明显,油气保存条件较好.形成了莺歌海盆地渐新统烃源、中新统大型三角洲储集体断块、构造一岩性圈闭、沟源断裂高效运移相组合的另一种全新成藏模式,斜坡区南段中深层有望成为莺歌海盆地下一个千亿方级天然气聚集区(图9).

3.4 有利勘探层系

随着莺歌海盆地底辟带油气勘探程度的日益提高,莺东斜坡中深层油气勘探势在必行,认识该区的构造条件成为该领域天然气勘探突破的关键.莺东斜坡中深层与底辟带构造条件差异明显,断裂体系的发

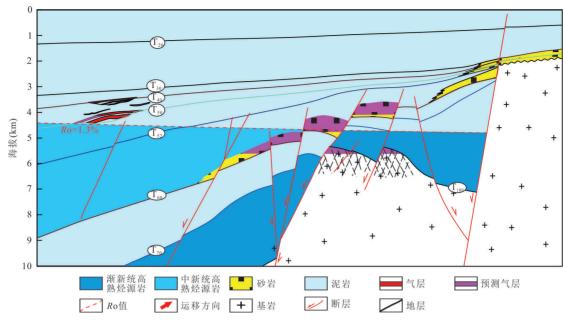


图 9 莺东斜坡带南段中深层天然气成藏模式

Fig. 9 The accumulation model of middle-deep natural gas in the southern segment of the eastern belt of the Yinggehai Basin

育是其显著特点,一方面控制了烃源岩、储层的发育, 另一方面控制了油气的运移聚集.油气主要沿汇聚背 景及输导断裂聚集,而三亚组发育大规模富砂三角洲, 被一组走滑断裂切割形成一系列构造或构造十岩性 圈闭,临近生烃中心,油气源充足,目的层侧封条件良 好,储层与上覆浅海泥岩形成良好储盖组合,这些构 造十岩性圈闭可作为勘探突破的重点目标.综合认为 斜坡区南段中深层三亚组成藏条件良好,为下一步斜 坡区中深层新领域勘探突破的重点层系.

4 结论

(1)受渐新世一早中新世左行走滑应力场及莺琼结合部遮挡的控制,莺东斜坡带南段发育一系列张扭(局部压扭)走滑断层;平面上呈NW-SE向、左行右阶展布;剖面上中深层(三亚组及以深层系)共发育三组构造断裂,产状陡直,局部表现为花状构造,呈断阶状样式.断裂主要为3期活动:(1)始新世一早渐新世,(2)晚渐新世早中期,(3)早中新世;具有"早断早衰"的特征.

(2) 莺东斜坡南段断裂控制了渐新统崖城组煤系 烃源及陆源海相烃源的发育,控制了三亚组大型富砂 三角洲的发育及圈闭的形成,同时形成了凹中隆的汇 气背景,并为主要的油气运移通道.中深层三亚组发 育时期发育大型构造、构造十岩性圈闭,油气生、运、 聚配置关系好,断层早断早衰有利于天然气保存,为 有利的勘探层系.斜坡区南段中深层有望成为莺歌海 盆地下一个千亿方级天然气聚集区.

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