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苏北盆地阜二段页岩油保存条件对比分析

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摘要:苏北盆地溱潼、高邮、金湖和海安凹陷古近系阜宁组二段(阜二段)页岩油勘探相继取得突破,是下一步增储上产的重要领域。各主力凹陷阜二段页岩油成藏演化过程差异较大,页岩油保存条件的差异性、控制因素和地层超压的发育规律认识不清,制约了下一步勘探部署。从主力凹陷差异演化过程研究入手,结合顶底板条件、断层发育及活动性对比分析,明确了各凹陷页岩油保存条件差异性及其影响因素,并揭示了复杂断块区异常高压的保存机制。结果表明,盆地东西部阜二段底板沉积相带的差异性形成现今地层超压差异的基础;吴堡事件各凹陷内断层的活动性和发育程度,以及盆地西侧郑庐断裂带活动性对盆地各凹陷的差异控制作用(从西往东,各凹陷阜二段断层晚期活动性逐渐减弱),是各凹陷现今地层超压差异的核心;盐城组沉积中晚期,盆地东部的海安、盐城凹陷初次进入生烃门限,而中西部的溱潼、高邮和金湖凹陷局部经历加深、加熟和再次生烃,是各凹陷现今地层超压差异的关键。中—高成熟度页岩油首选勘探有利区位于金湖、高邮、溱潼凹陷的深凹稳定区,中—低成熟度页岩油首选勘探有利区位于海安和盐城凹陷的深凹区。此外,凹陷内部,断层规模越大,距离断层越近越不利于页岩油保存。研究成果对陆相断陷盆地页岩油勘探具有指导意义。

关键词:苏北盆地;阜二段;页岩油;保存条件;地层超压

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Comparative analysis of preservation conditions for shale oil in second member of Funing Formation, Subei Basin

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Abstract: Exploration breakthroughs of shale oil have been successively achieved in the second member of the Paleogene Funing Formation in four main sags (Qintong, Gaoyou, Jinhu, and Haian) of the Subei Basin, marking an important area for future increases in reserves and production. The evolution of shale oil accumulation processes differs greatly among major sags. The unclear understanding of the differences in preservation conditions, controlling factors, and the development patterns of formation overpressure for shale oil has constrained further exploration deployment. Starting from the differential evolution processes of the major sags, and combined with a comparative analysis of the top-bottom conditions, fault development, and fault activity, the differences in shale oil preservation conditions and their influencing factors across various sags were clarified. Additionally, the preservation mechanisms of abnormal overpressure in complex fault-block areas was revealed. The results indicated that the differences in the sedimentary facies belts of the second member of the Paleogene Funing Formation's base in the eastern and western parts of the basin formed the basis for current differences in formation overpressure. The activity and development degree of faults within each sag during the Wubao event, as well as the differential controlling effect of the Tan-Lu fault zone on the western part of the basin on each sag (manifested as a gradual weakening of late-stage fault activity in the second member of the Paleogene Funing Formation from west to east), constituted the core of current differences in formation overpressure across the sags. During

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the middle to late stage of sedimentation of the Yancheng Formation, the Haian and Yancheng Sags in the eastern part of the basin first entered the hydrocarbon generation threshold, while the Qintong, Gaoyou, and Jinhua Sags in the central and western part experienced local deepening, increased thermal maturity, and secondary hydrocarbon generation. This process was crucial in the current differences in formation overpressure across the sags. For medium-to-high maturity shale oil, the preferred favorable exploration areas were located in the deep and stable zones of the Jinhua, Gaoyou, and Qintong Sags. For low to medium maturity shale oil, the preferred favorable exploration areas were located in the deep zones of the Haian and Yancheng Sags. Moreover, within a sag, larger fault scales and closer proximity to faults were less favorable for shale oil preservation. The research findings provide guidance for shale oil exploration in continental fault-depression basins.

Keywords: Subei Basin; second member of Funing Formation; shale oil; preservation conditions; formation overpressure

北美页岩油革命取得的成就改变了世界能源格局^[1],引领世界各国页岩油产业的发展^[2-6]。2010年以来,中国先后在松辽盆地^[7-8]、准噶尔盆地^[9-10]、鄂尔多斯盆地^[11-13]、渤海湾盆地^[14]、四川盆地^[15-17]等取得重大突破,累计探明储量近 15×10^8 t(页岩油、致密油)。中国石油、中国石化一批探井获得高产^[18-19],不断刷新中国页岩油单井产量记录,提振了陆相页岩油勘探信心。

苏北盆地古近系阜宁组页岩油资源量大(阜二段和阜宁组四段合计超 20×10^8 t),勘探起步晚,成效好。2019年以来,中国石化江苏油田分公司和华东油气分公司在苏北盆地南部东台坳陷的4个次级凹陷阜二段接连取得勘探突破^[20-21],部署的“1”字号探井均试获工业油流,展现了阜二段广阔的勘探前景。随着勘探深入,不同凹陷、不同井区页岩油井产能差异较大的矛盾日益凸显^[22-25],制约了下一步勘探部署。国内外勘探实践证明,良好的保存条件是页岩油气成藏控产的关键,随着研究的深入,稳定的构造条件、有效的顶底板封盖和页岩自封闭性三者共同决定了页岩油的保存条件,已逐渐成为众多学者的共性认识^[26-29]。因此,从主力凹陷差异演化过程研究入手,结合顶底板条件、断层发育及活动性对比分析,明确各凹陷页岩油保存条件差异性及其影响因素,揭示复杂断块区异常高压的保存机制,以期对阜二段页岩油下一步勘探提供有益指导。

1 苏北盆地阜二段地质概况

苏北盆地新生代以来受仪征、吴堡、三垛三期构造作用控制,经历了断坳、断陷、坳陷3个发展阶段^[30]。阜二段沉积时期,苏北盆地为断坳型陆相湖盆,盆地西部的苏鲁造山带、张八岭隆起是主要物源区,顺物源方向盐度逐渐降低、水深逐渐加深^[31](图1a),由河流、三角洲相逐渐过渡为滨浅湖亚相和半深湖—深湖亚相,沉降中心为溱潼凹陷,沉积厚度超过450 m。阜宁组沉积末期,吴堡事件构造活动强烈,断层发育,将阜二段地层切割成长条形、楔形等复杂断块体^[32]。以吴堡事件为起始的系列构造活动结束了苏北盆地统一的坳陷大湖盆沉积阶段,将盆地分割成若干个北东向箕状小型断陷,并以此奠定了

盆地的基本格局。盆地南部东台坳陷自西向东分布有金湖、高邮、溱潼和海安4个次级凹陷,总体呈北东—南西走向,在构造上具有“南陡北缓”“南断北超”的特征。三垛运动后盆地转为坳陷型沉积,阜二段稳定沉降,断层活动性较弱。

综合岩心观察、测井响应和岩性变化规律等,可将阜二段自上而下分为5个亚段(图1b)。其中,Ⅱ亚段和Ⅲ亚段(上有利层)、Ⅳ亚段(中有利层)、Ⅴ亚段(下有利层)是当前主要的勘探目标层段,其岩性主要为灰黑色层状—纹层状混积岩、长英细粒岩夹薄层白云岩。阜二段Ⅰ亚段的岩性为厚层块状泥岩。受沉积环境影响,西部金湖凹陷靠近物源区,Ⅴ亚段至Ⅳ亚段中部均为常规砂岩储层,页岩油勘探层段主要为上有利层。

2 主力凹陷保存条件对比分析

2.1 顶底板条件

由于阜二段顶部的Ⅰ亚段为块状泥岩,地质评价结果显示其不具备页岩油富集条件,因此,可将阜二段Ⅰ亚段作为勘探有利层的顶板,其厚度普遍大于50 m(表1),顶板条件均较为优越。就底板条件而言,金湖凹陷阜二段Ⅳ亚段中下部和Ⅴ亚段为浅水三角洲前缘相沉积,因此,仅Ⅱ—Ⅲ亚段“甜点”层底板条件较好。高邮、溱潼、海安和盐城凹陷Ⅳ—Ⅱ亚段“甜点”层的顶底板条件均较为优越,仅Ⅴ亚段中下部“甜点”层的底板条件存在差异。阜二段下伏地层为阜一段Ⅰ亚段,在高邮、溱潼凹陷总体为三角洲前缘亚相(图2a),向东渐变为滨浅湖亚相,海安、盐城凹陷阜一段Ⅰ亚段泥页岩厚度可达250~350 m。总的来说,东部海安、盐城凹陷阜二段页岩油的顶底板条

表1 苏北盆地主力凹陷阜二段页岩油顶底板条件

Table 1 Roof-to-floor conditions for shale oil in second member of Funing Formation in main sags of Subei Basin

凹陷	代表井	顶板厚度/m	底板厚度/m
金湖凹陷	T96X井	112	15
高邮凹陷	HY1井	70	22
溱潼凹陷	QY1井	77	50
海安凹陷	FAX7井	87	330

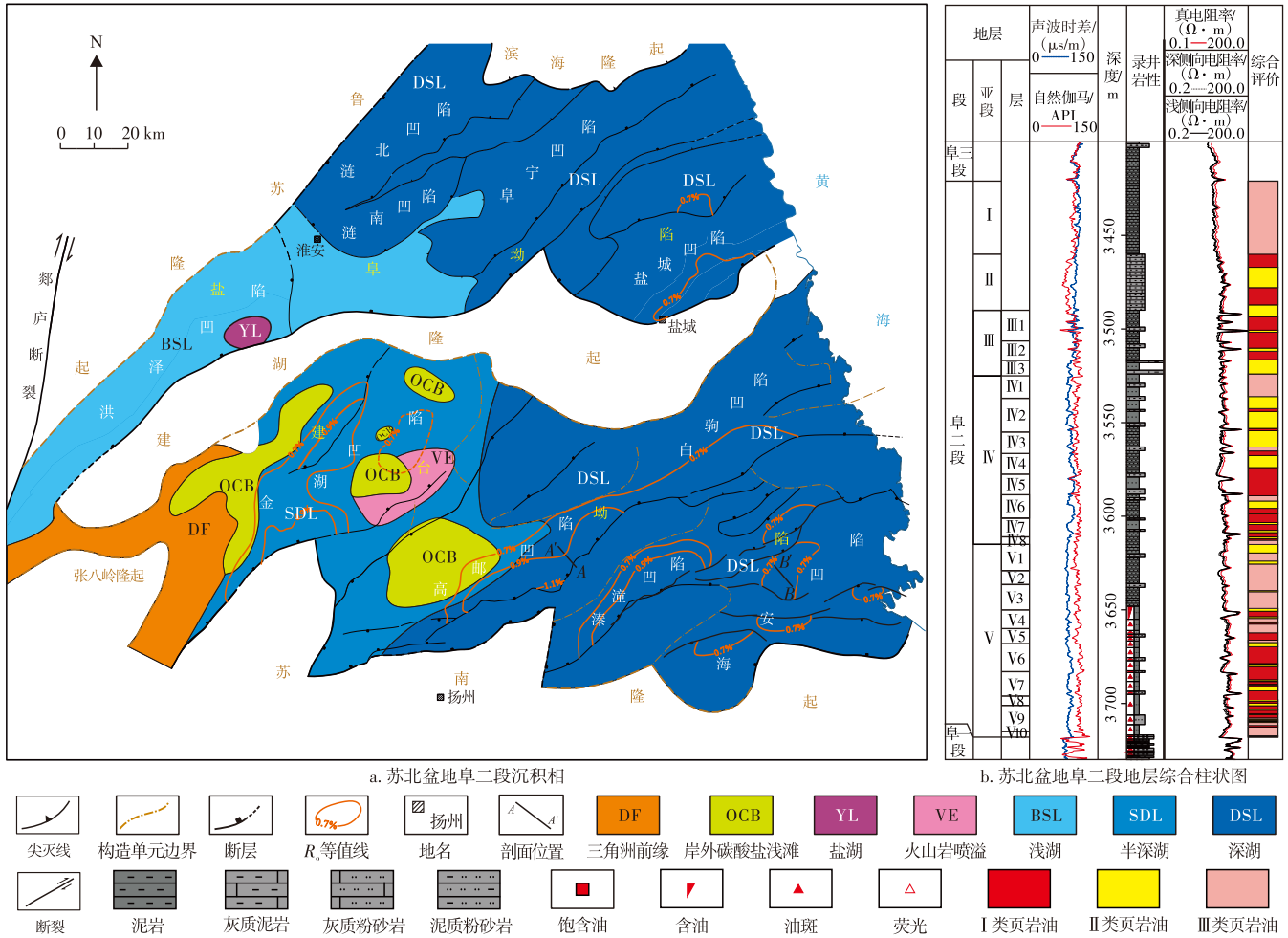


图1 苏北盆地阜二段沉积相与地层综合柱状图

Fig. 1 Sedimentary facies and comprehensive stratigraphic column of second member of Funing Formation, Subei Basin

件优于西部高邮、溱潼凹陷(图2b)。

高邮凹陷和溱潼凹陷阜二段V亚段中下部“甜点”层(V5—V7小层)底板条件存在的差异性影响了页岩油富集程度。以高邮凹陷HY1井区和溱潼凹陷QY1井区为例:HY1井区阜宁组一段(阜一段)I亚段粉砂岩发育,阜二段V亚段“甜点”层底板泥岩厚17 m(图2b);相比之下QY1井区阜一段I亚段砂岩发育程度相对较低,总体为泥岩夹粉砂岩沉积,阜二段V亚段“甜点”层底板泥岩厚42 m。勘探证实QY1区阜二段V亚段“甜点”层地层能量更高、产能更高,即顶底板条件是影响产量差异的重要原因之一。

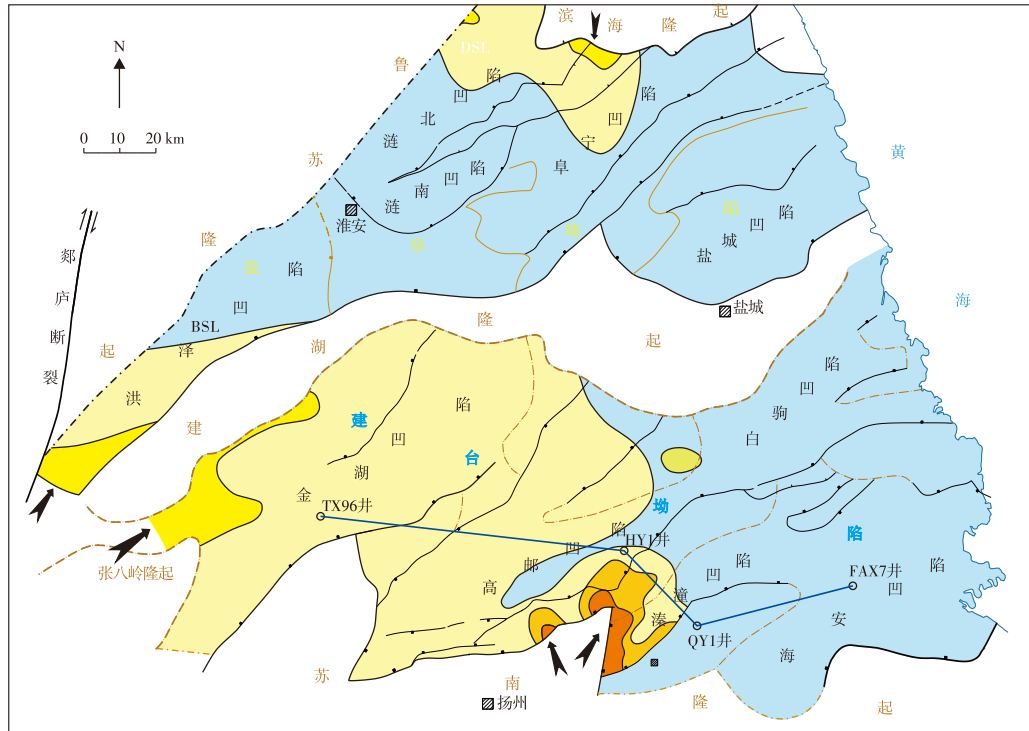
2.2 断层发育及活动性

断层对页岩油气的富集和保存具有重要的影响作用。一方面,断层附近裂缝系统更为发育,有助于改善储层的储集物性,因而相对有利于页岩油富集^[33-34](图3)。但是,东部断陷盆地有别于西部的挤压型盆地^[35-37],整体长时间处于拉张的构造背景,断层的封闭性相对较差,规模较大的断层以及长期活动的断层对页岩油藏具有负向

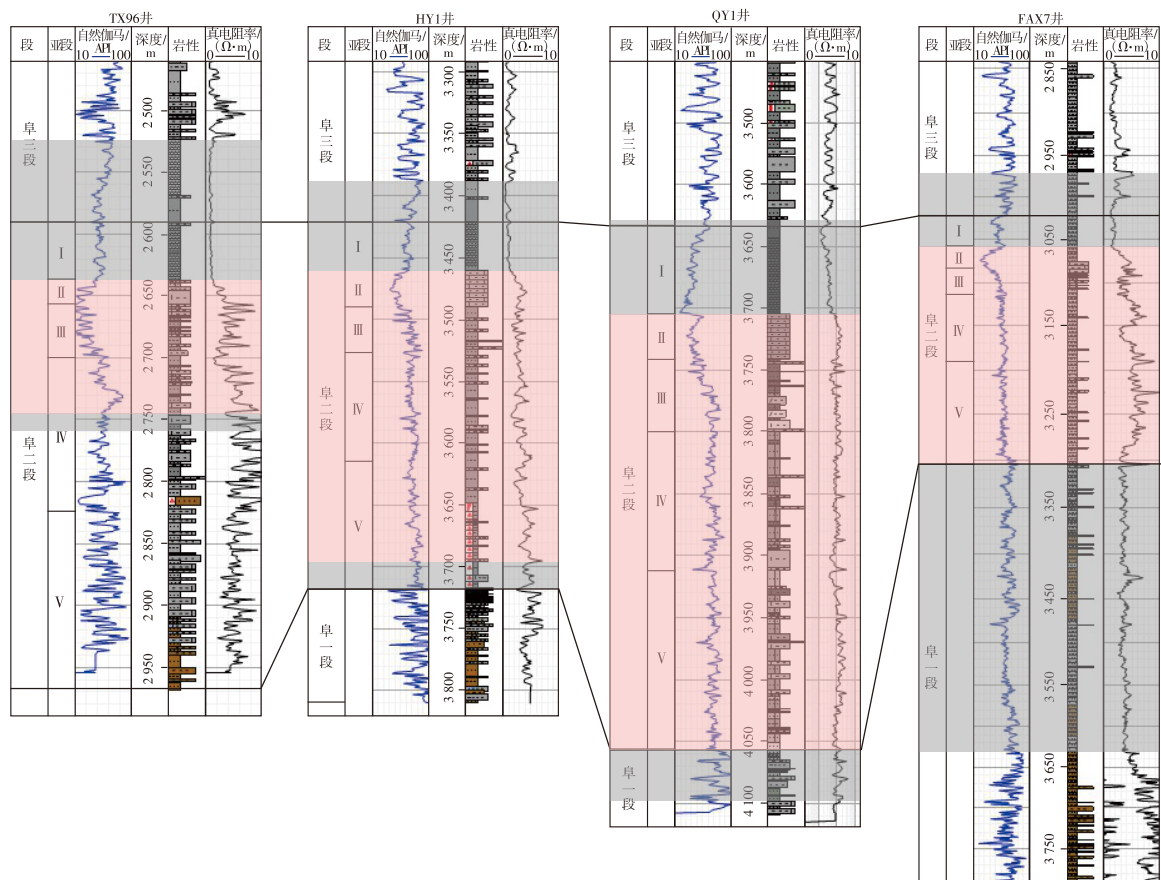
控制作用,其附近一般是常规油藏的勘探有利区^[38]。

对比各凹陷阜二段页岩油有利区内断层发育程度,结果显示盆地东部和西部各凹陷间存在显著差异。与东部的溱潼、海安凹陷阜二段页岩油有利区内构造完整、断层局部较为发育不同(图4),西部高邮、金湖凹陷阜二段断层更为发育、地层更为破碎。以高邮凹陷阜二段为例,级别越低的断层数量越多,断距介于50~100 m的四级断层密度为0.9~1.1条/km,断距小于50 m的五级断层、微断层(裂缝带)密度为2.0~4.5条/km(图4)。前人研究表明,五级断层、微断层(裂缝带)有利于页岩油富集,四级及以上级别断层不利于页岩油保存,且四级断层负面影响范围最高可达200~300 m,控凹边界断层(二级断层)负面影响范围超过550 m^[39]。

对上述情况分析可知,大地构造上,苏北盆地西部紧邻中国东部的郯庐断裂带^[40],其活动强度直接影响了苏北盆地的构造格局和断裂系统发育。晚白垩世至古近纪,古太平洋板块运动方向由早白垩世的北—北西向转为北西向,且运移速度降低,太平洋板块斜向俯冲使东部构造体制由挤压转为拉张环境,并使郯庐断裂带产生右



a. 苏北盆地阜一段I亚段平面沉积相



b. 重点凹陷阜二段有利层顶底板连井对比

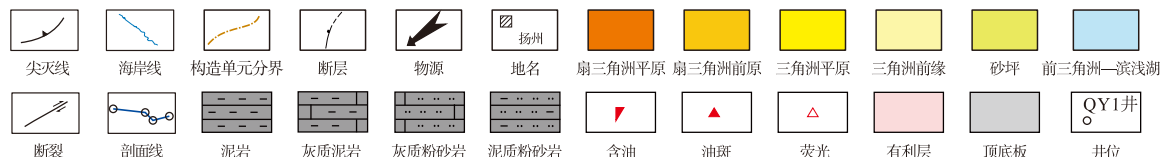


图2 苏北盆地主力凹陷阜二段页岩油富集层段及顶底板条件

Fig. 2 Enrichment intervals and roof-to-floor conditions of shale oil in second member of Subei Basin

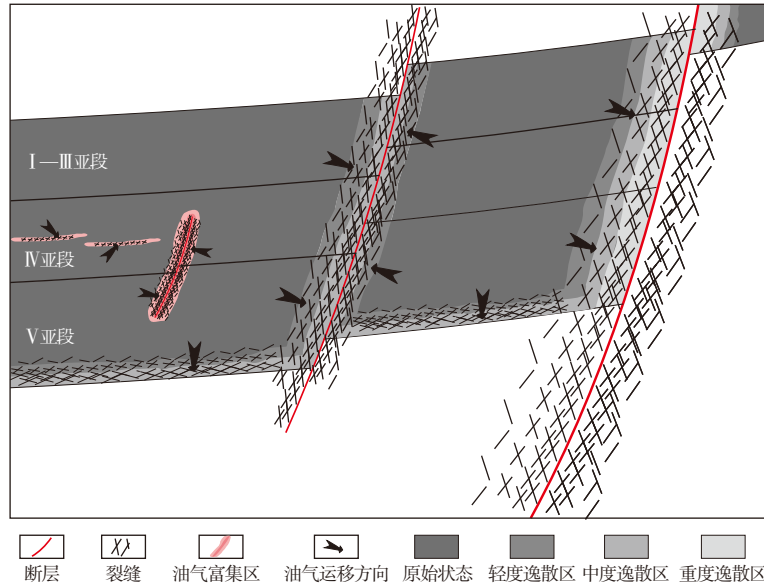


图3 断层、裂缝体系控油作用模式

Fig. 3 Oil-controlling model of fault-fracture system

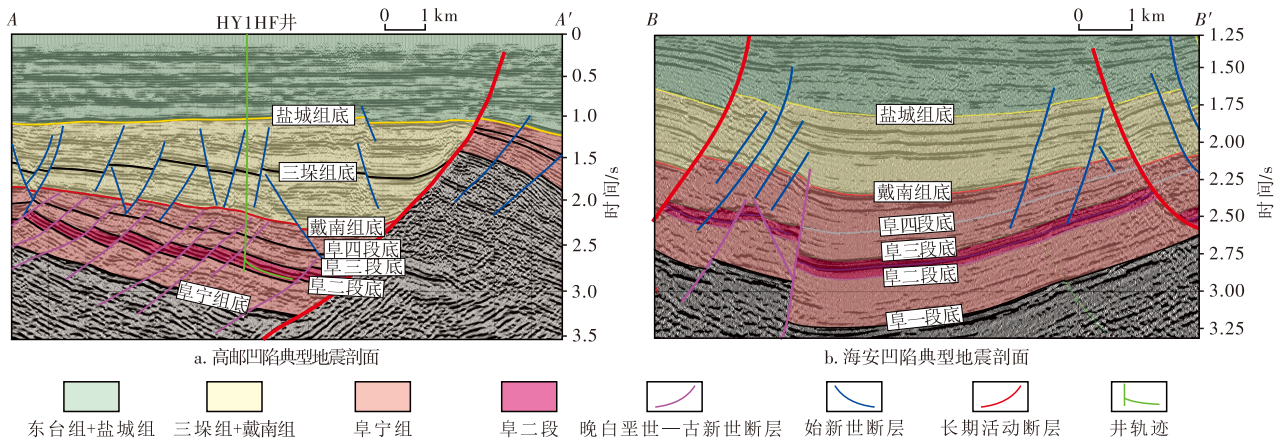


图4 苏北盆地东西部典型凹陷阜二段断层发育特征

Fig. 4 Development characteristics of faults in second member of Funing Formation, typical sags in eastern and western Subei Basin

行走滑作用,直接造成苏北盆地内的凹陷、凸起、断层和褶皱呈现雁列式展布,平面上表现为巨型、北东向发散、南西向收敛的帚状构造^[41]。具体到盆地内部,南西部位的金湖凹陷处于构造收敛的部位,应力相对集中,受郯庐断裂带的影响更为深远(图5a)。

根据前人的研究结果,主力凹陷深凹—斜坡区的断裂体系可以分为上、中、下3套构造层^[39]。T₃⁰界面将阜二段所处的下构造层和戴南组、三垛组构成的中构造层分割(图4a),中、下2套构造层的断裂体系形成于不同构造时期,且鲜有中、上构造层的断裂延伸至下构造层,种种迹象表明下构造层的断裂体系在晚期构造运动中没有明显的位移,但是其晚期活动性值得进一步探讨。

根据金湖、高邮等凹陷阜二段最新的系统取心资料,岩心上观察到多期次的构造裂缝,部分裂缝被方解石所充填。前人对方解石充填物进行了碳氧同位素和流体包裹体测温等分析测试^[42-43],结果表明裂缝形成时期明显晚于阜二段

断层形成时期。分析认为晚期构造活动在阜二段基本未形成新生断层,应变集中于页岩层内,产生多期破裂,间接指示了阜二段吴堡期断层在后期构造活动经历了多期次开启和愈合,活动性较好(图5b)。此外,阜二段岩心上观察到大型、纵向上穿层性好的构造裂缝(图5c),其开启性好,发育程度与其断层相关。岩心观察结果显示,金湖凹陷阜二段大型剪切缝发育密度为2.5条/m,裂缝面含油显示率约为80%;高邮凹陷阜二段大型剪切缝密度为1.3条/m(图5d),裂缝面含油显示均较为饱满。金湖凹陷阜二段大型剪切缝(图5c)条数很多、走向一致、易于纵向上沟通。勘探实践证明金湖凹陷阜二段页岩油有利区地层压力系数也整体低于高邮凹陷阜二段页岩油有利区地层压力系数(图5e),进一步证实了靠近郯庐断裂带的金湖凹陷受其活动的负面影响更为深远,页岩油保存条件整体相对较差。

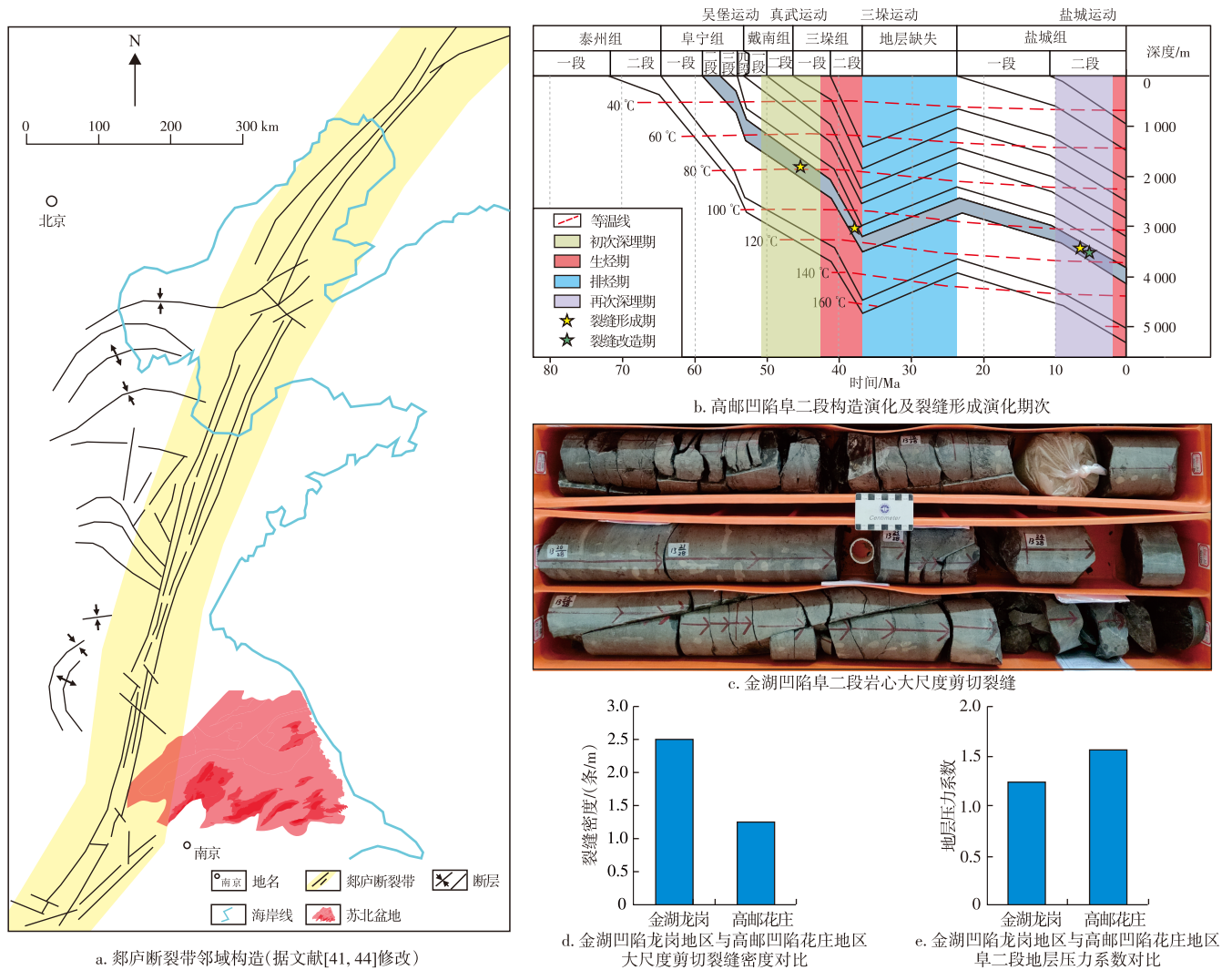


图5 郑庐断裂带影响下的苏北盆地阜二段断层、裂缝发育程度与活动性

Fig. 5 Development degree and activity of faults and fractures in second member of Funing Formation, Subei Basin, influenced by Tan-Lu fault zone

2.3 构造、热演化差异性

苏北盆地西部金湖、高邮、溱潼凹陷阜二段镜质体反射率(R_0)自斜坡区向深凹区逐渐变大(图1a),最高可达1.0%以上;东部海安、盐城凹陷成熟度普遍小于0.8%,东西部热演化程度存在差异,且构造、热演化过程存在差异。

阜二段沉积之后,受吴堡运动影响,盆地整体呈西低东高,西部的金湖、高邮和溱潼凹陷的控凹边界断层活动性强,沉积了较厚的戴南组和三垛组(图6a),阜二段遭受快速深埋,在距今48~44 Ma时进入生烃期(图6c);东部的海安、盐城凹陷戴南组和三垛组沉积厚度相对较薄,彼时阜二段处于未成熟阶段。三垛事件发生时,盆地抬升遭受长时间的剥蚀,西部的金湖、高邮和溱潼凹陷进入缓慢生油阶段。三垛事件后,盐城组沉积时期,盆地整体下降并向东掀斜^[40],东部的海安、盐城凹陷接受巨厚沉积(图6b),盐城组厚度为1 000~2 000 m,在距今5~10 Ma,阜二段初次进入生烃期(图6d);西部的金湖、高邮和

溱潼凹陷盐城组厚度为200~1 000 m,阜二段再次进入深埋阶段,且局部出现加深和加熟现象。

以高邮凹陷为例,边缘凸起区三垛事件剥蚀量超过1 600 m,向深凹区渐变至400 m左右(图7a)^[45-46]。现今,凹陷边缘盐城组厚度最低小于200 m,向凹陷中心渐变至1 600 m以上(图7b)。盐城组厚度超过三垛事件剥蚀量,即现今埋深超过三垛事件前的最大埋深(图7c),选取三垛事件前平均古地温梯度37.0 °C/km和现今平均地温梯度32.0 °C/km^[47]代入计算,现今阜二段地层温度超过三垛事件前最高古地温的区域即表明该区域在三垛事件后热演化程度继续升高(图7d)。

有机质生烃增压为现今地层超压的主要机制^[48],三垛事件导致金湖、高邮和溱潼凹陷阜二段遭受长时间的抬升、降温、泄压,超压环境遭受一定程度破坏;盐城组沉积期后,阜二段重新进入深埋阶段,局部地区热演化程度升高,生成的油气可补充地层压力,提高地层压力系数。

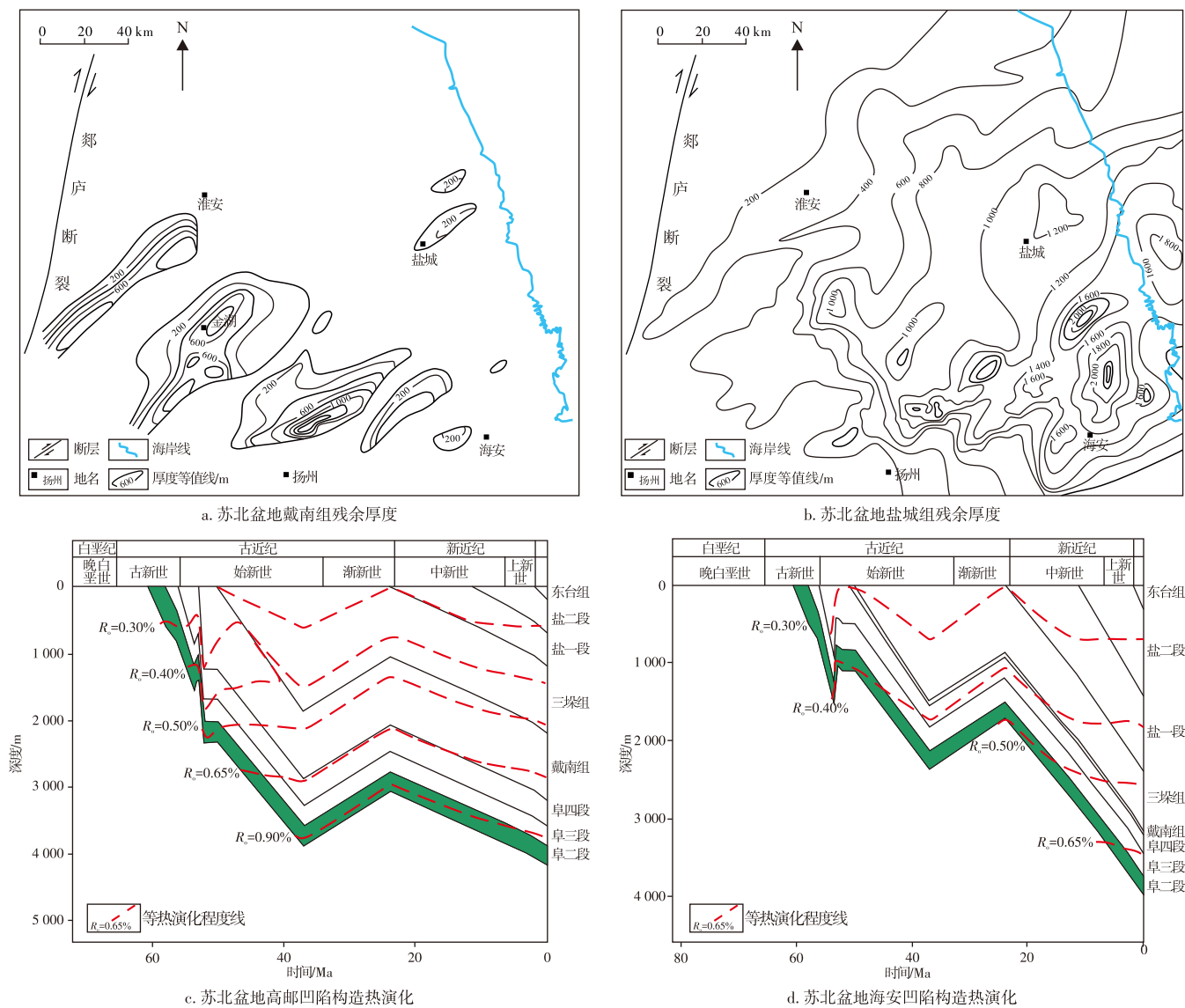


图6 苏北盆地主力凹陷构造演化、热演化过程

Fig. 6 Structural and thermal evolution processes of main sags in Subei Basin

2.4 异常高压

岩石中黏土矿物含量越高,总有机碳含量越高,成烃过程中产生的流体越多,越容易形成压力系数高的局部异常流体高压。前人生热模拟实验揭示,富有有机质泥页岩从未成熟进入生烃门限后初始生烃量较少,随着热演化程度的进一步升高,生烃量呈现指数级上升^[49-50]。阜二段页岩的地层超压主要为有机质生烃增压,因此,在达到生烃高峰之前,地层压力系数与热演化程度呈指数级正相关关系。

苏北盆地阜二段由于经受了一期规模较大的抬升剥蚀,造成阜二段遭受抬升、降温,高邮、金湖和溱潼凹陷深凹区进入生烃门限的地区生烃放缓,但由于埋深减小,静水压力降低,地层孔隙压力不变会导致地层压力系数进一步升高,因此,受限於地层自身的封闭条件和剥蚀时间的漫长,叠加断层的持续活动,超压地层进入长达数百万

年的泄压阶段。

进入盐城组沉积时期,由于盆地沉降速度和盐城组沉积速率较快,阜二段再次进入深埋阶段,各凹陷内热演化进入分异阶段(图8)。一方面,早期进入生烃阶段的高邮、金湖和溱潼凹陷深凹区页岩(R_o 总体大于0.9%)局部经历了加深、加熟作用,再次大量生烃,目前处于中高成熟度、中高地层超压状态;另一方面,早期进入生烃阶段的高邮、金湖和溱潼凹陷斜坡区(R_o 总体小于0.9%)页岩热演化停滞,现今处于中低成熟度、中低地层超压状态;再一方面,早期尚未达到生烃门限的海安、盐城凹陷阜二段,由于其沉积巨厚的盐城组,第一次进入生烃阶段,现今处于中低成熟度(R_o 总体小于0.8%)、中等地层超压状态。

2.5 保存条件对富集高产的影响

异常高压与保存三要素互为表里。地层压力系数

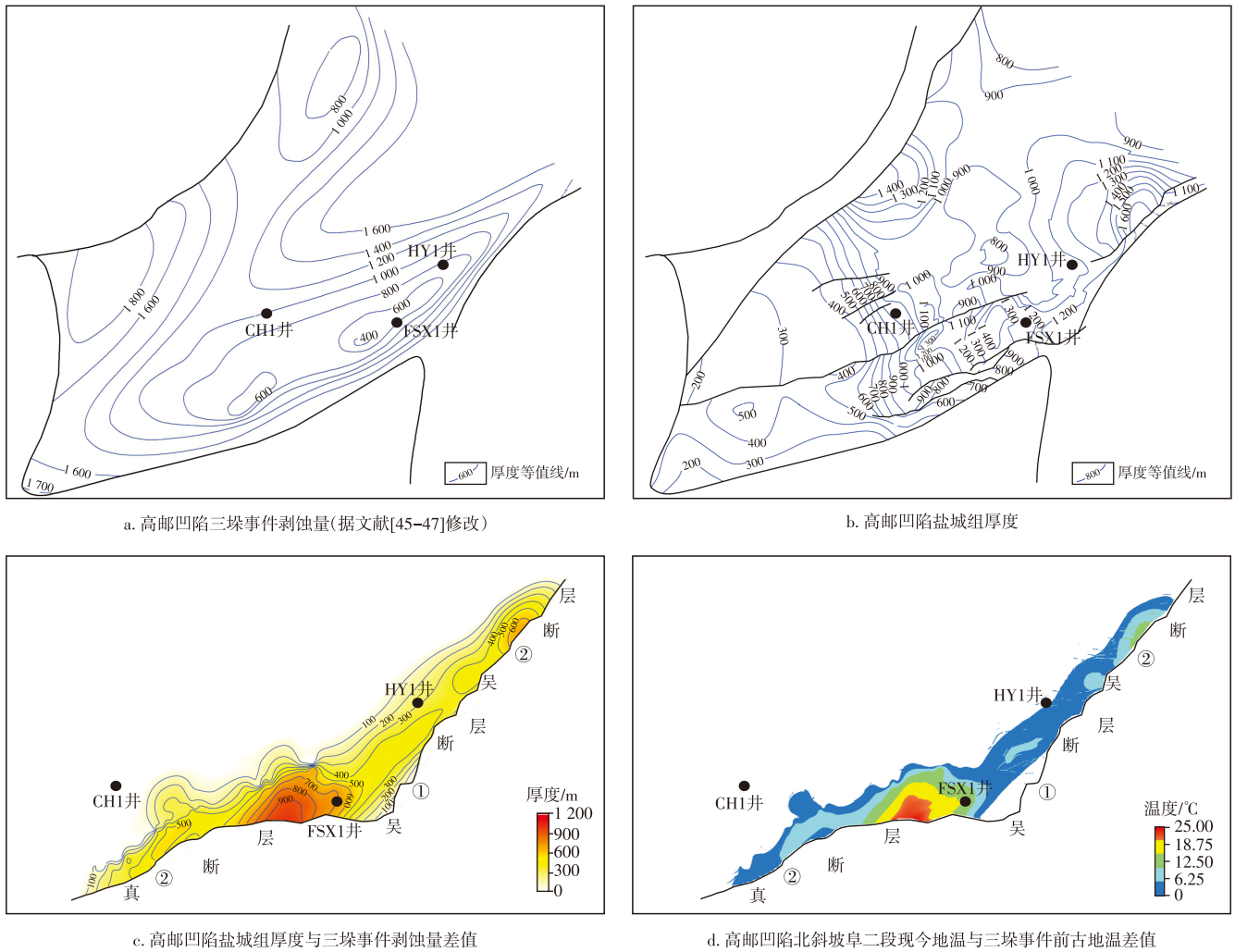


图7 苏北盆地高邮凹陷阜二段局部加深、热演化程度高解析过程

Fig. 7 Burial and thermal evolution of second member of Funing Formation in Gaoyou Sag, Subei Basin

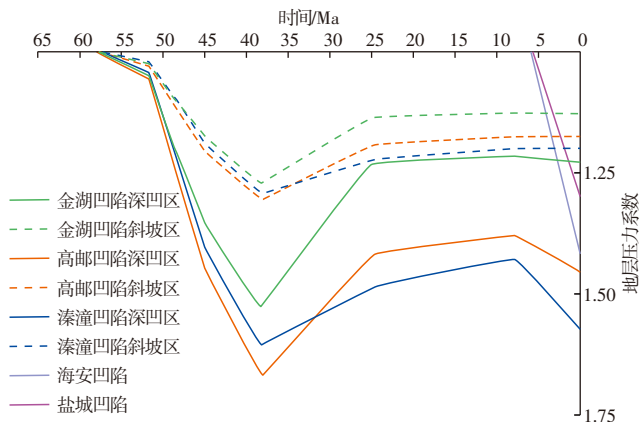


图8 苏北盆地不同凹陷不同部位阜二段页岩地层压力系数演变模式

Fig. 8 Evolution model of pressure coefficient in second member of Funing Formation across different sags and regions within Subei Basin

越高,地层能量越充足,客观反映出在相同工程技术条件和开发方式下,保存条件越好,油井的产量越高,即保存条件对产量的控制作用较为明显(表2)。溱潼凹陷

保存三要素耦合关系较好,其中、下2套有利层的典型井试油产量相对最高;高邮凹陷次之,一方面其构造活动强度大于溱潼凹陷,另一方面,高邮凹陷下有利层的顶底板条件比溱潼差(底板厚度薄),导致保存较差;海安凹陷与溱潼、高邮深凹区经历加深、热演化程度高作用不同,其进入生烃门限较晚且成熟度整体不高,导致页岩油富集程度低于溱潼和高邮凹陷;金湖凹陷相对最差,主要由于其构造活动最为强烈,导致保存条件较差,地层接近于常压。

3 启示与意义

3.1 中高成熟度页岩油勘探有利区

苏北盆地阜二段时代较新,相比于西部的四川盆地五峰—龙马溪组高成熟—过成熟页岩,其镜质体反射率最高不超过1.2%。不同组分生烃动力学的差异决定了不同热演化阶段油气具有不同的组成特征,成熟度越高时,轻质组分等小分子化合物的占比则会越高,从而使得

表2 苏北盆地主力凹陷阜二段三套有利层保存要素对比分析及典型性井试油产量

Table 2 Comparative analysis of preservation factors for three favorable layers in second member of Funing Formation, major sags of Subei Basin, and oil test production of typical wells

重点凹陷	有利层	保存三要素			典型井	试油日产量/t
		顶底板	构造活动	差异沉降		
金湖凹陷	上有利层	好	差	深凹区热演化程度升高	TY1HF井	20.2
	中有利层	差	差	深凹区热演化程度升高		
	下有利层					
高邮凹陷	上有利层	好	中等	深凹区热演化程度升高	H2CHF井	79.2
	中有利层	好	中等	深凹区热演化程度升高		
	下有利层	中等	中等	深凹区热演化程度升高		
溱潼凹陷	上有利层	好	好	深凹区热演化程度升高	QY2HF井	113.1
	中有利层	好	好	深凹区热演化程度升高		
	下有利层	好	好	深凹区热演化程度升高		
海安凹陷	上有利层	好	好	初次生烃	HY1HF井	50.7
	中有利层	好	好	初次生烃		
	下有利层	好	好	初次生烃		

页岩油气油比增加,具有更高的可动性和流动性^[51]。结合大庆古龙、胜利济阳和苏北阜二段的勘探实际,分析认为随成熟度增大,页岩含油性、可动性变好,页岩油富集条件更有利。

基于上述分析,结合目前的勘探成效,总结认为高邮、溱潼凹陷的深凹区, R_o 大于0.8%,是中高成熟度页岩油首选勘探有利区(图9)。尤其是各大主力凹陷的页岩加熟区是页岩油勘探的重要方向。

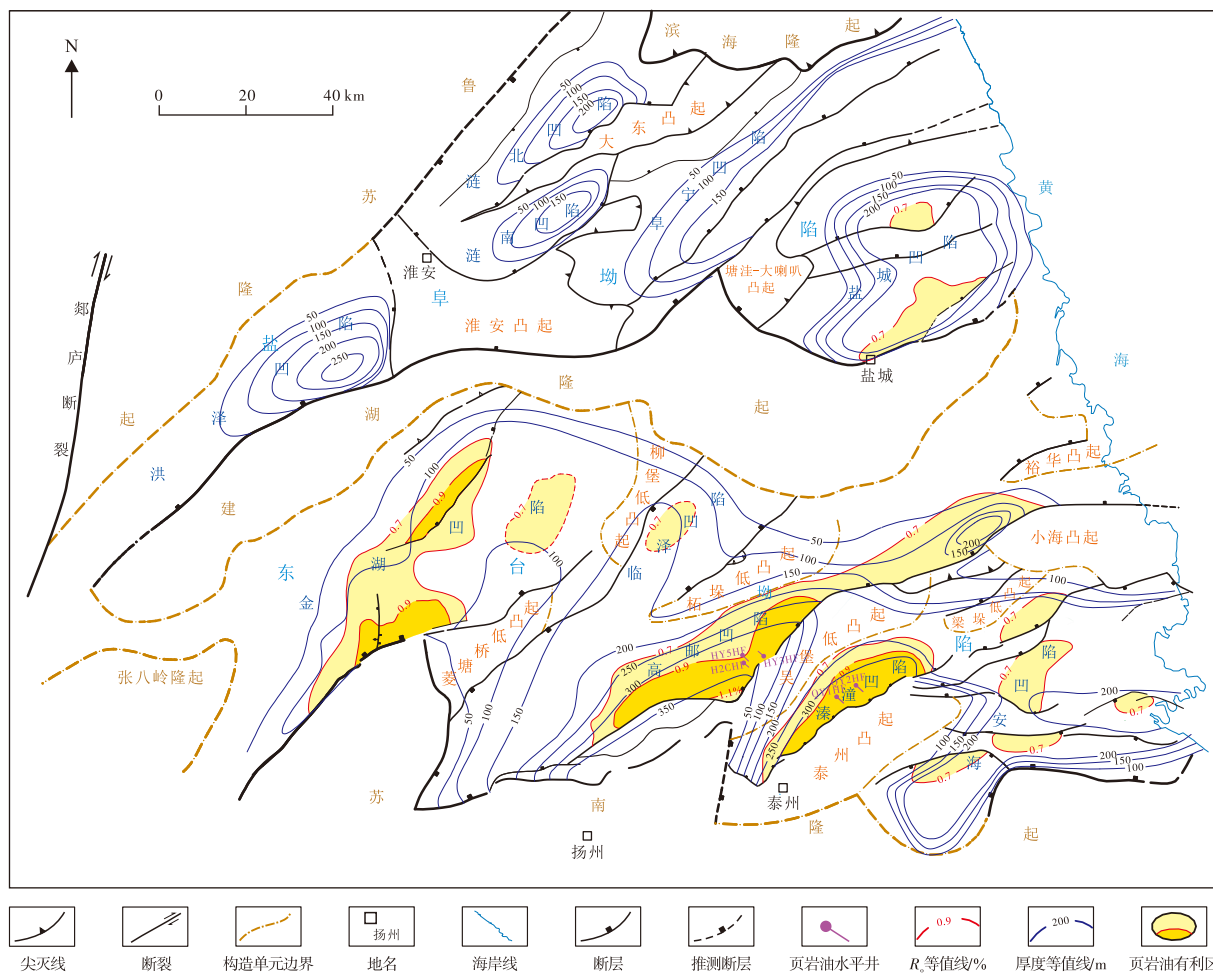


图9 苏北盆地阜二段页岩油的有利区预测

Fig. 9 Favorable area prediction of shale oil in second member of Funing Formation, Subei Basin

3.2 中低成熟度页岩油勘探有利区

根据中国石化“十四五”最新资源评价结果,苏北盆地中—低成熟度(R_o 介于0.5%~0.8%)页岩油资源量超过 5×10^8 t。

盆地自西向东,水体加深,水体变咸,碳酸盐矿物含量变高,有机质类型变好,有机质丰度增高;阜二段底板泥岩逐渐增厚,保存条件变好。海安、盐城凹陷深凹区阜二段页岩渐新世以后再次深埋,初次生烃,现今成熟度 R_o 小于0.8%;这一时期构造活动弱,保存条件好,发育超压,是中低成熟度页岩油首选勘探有利区。溱潼、高邮凹陷斜坡带保存条件较好区域,是中低成熟度页岩油首选勘探较有利区。

4 结论与建议

1)盆地内各凹陷阜二段页岩顶板条件均较为优越,受阜二段V亚段及下伏阜一段I亚段沉积环境的变化,自东向西,底板条件逐渐变差,在高邮凹陷影响V亚段“甜点”层的保存,在金湖凹陷影响上升至IV亚段上部。

2)盆地自北东向西南,断层、裂缝发育程度越高,断层、裂缝历史活动性越好,地层越破碎,阜二段页岩油保存条件越差,盆地中东部的海安、溱潼、海安和盐城凹陷优于西部的金湖凹陷。

3)苏北盆地西部的金湖、高邮和溱潼凹陷现今演化成成熟度相对较高(最高达1.1%),进入生烃门限相对较早(三垛事件之前);东部的海安和盐城凹陷现今热演化程度相对较低(大多小于0.8%),且进入生烃门限相对较晚,距今不超过10 Ma。

4)演化历史的差异、断层发育程度和活性差异、顶底板条件的差异,造就了现今不同凹陷不同部位地层压力系数的差异分布,中高成熟度页岩油首选勘探有利区位于高邮、溱潼凹陷的深凹稳定区,中低成熟度页岩油首选勘探有利区位于海安和盐城凹陷的深凹区。

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