文章编号: 0253- 9985(2003) 03- 0269- 05

牛庄洼陷第三系古沉积环境及其控油气作用*

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摘要: 地质与地球化学分析结果表明, 东营凹陷牛庄洼陷及其邻区的两套主力烃源岩即沙河街组三段中、下亚段与沙河街组四段上亚段具有不同的原始沉积环境。沙河街组四段上亚段烃源岩可溶物及其相关原油具有 Pr/ Ph 小于 1、高含量伽马蜡烷、升藿烷"翘尾"及硫芴含量相对较高的还原相、咸化湖相成因特征; 沙河街组三段中、下亚段烃源岩及相关原油具有 Pr/ Ph 大于 1、藿烷和氧芴系列含量相对较高的淡水湖相成因特征。研究区甲基甾烷、甲藻甾烷分布具有重要的沉积环境与生物属种标定意义, 沉积环境及相关生源指标显示沙河街组四段"咸水型"油气与南斜坡原地富藻类未熟- 低熟页岩没有直接联系。该区油气分布及其成因类型明显受控于烃源岩的性质及其展布。沙河街组三段"淡水型"原油主要分布于牛庄洼陷, 属自生自储的"淡水型"透镜体油藏; 沙河街组四段"咸水型"原油主要分布于偏离生油洼陷的南斜坡等周边地区, 具有相对较远的油气运移距离。沉积环境指标反映广利洼陷是广利油田及八面河油田北部"咸水型"油藏的主要贡献者。

关键词: 牛庄洼陷; 古环境; 烃源岩; 原油; 生物标志物

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中图分类号: TE112. 133　　文献标识码: A

东营凹陷石油地质条件复杂, 形成了具有不同成因的多种油气藏, 如著名的八面河油田即位于凹陷东南部的牛庄洼陷南斜坡之上, 该油田以往一直被当作经典的未熟- 低熟油田; 东营凹陷还是研究隐蔽油气藏的重要发源地。从油气成因角度, 东营凹陷既有咸化湖相油, 也有淡水湖相油; 既产未熟- 低熟烃类, 也产正常烃类。此外, 东营凹陷四周如北坡带还有相当量的稠油资源量。复杂的油气藏类型与多成因特性既受控于宏观的地质因素, 也取决于微观的地球化学因素。本文以东营凹陷牛庄洼陷为例, 分析该区第三系古沉积环境及其对油气分布的控制作用。

1　烃源岩发育环境及其展布

东营凹陷第三系自下而上包括下第三系孔店组、沙河街组、东营组、上第三系馆陶组、明化镇组。孔店组主要为粗碎屑红层, 不整合覆盖于中生界之上。沙河街组广泛分布于整个凹陷, 进一步分为 4 段, 其中三段中、下亚段及四段上亚段具有重要的生油潜能, 为主力烃源岩。早期研究普遍认为, 沙河街组四段沉积早、中期沿袭孔店组干旱- 半干旱的气候特征, 为闭塞的沉积环境[1,2], 导致沙河街组四段盐湖的形成。但最近有人提出东营凹陷沙河街组四段盐湖的深水成因模式[3], 蒸发岩类的物质基础是深层卤水, 深部古老地层中的盐类物质是其盐源。沙河街组三段沉积于湖盆的早、中期, 以差异沉降为特征, 湖盆变宽变深, 高位水系将碎屑物带进盆地, 形成湖底扇与浊积体沉积。该层系主要为深灰- 灰色泥岩和油页岩, 间夹浊积透镜体。除了岩性特征外, 水化学与微量元素资料表明, 沙河街组三段的沉积环境与沙河街组四段有本质的区别(表 1) , 沙河街组四段矿化度偏高、偏碱性, 硼含量与 Sr/ Ba 及古盐度均高于沙河街组三段, 属咸化- 半咸化沉积环境; 而沙河街组三段属淡水环境。本区第三纪湖盆的发育与构造变动和古气候条件密切相关。

根据钻井、测井与地震统计资料, 牛庄洼陷沙河街组四段上亚段充满了整个洼陷, 总的趋势是东厚西薄。以莱 1、莱 2、莱 71 井地区最厚, 向西南及南北两侧变薄至百米以下。由此可见, 沙河街

*　国家重点基础研究项目(编号 G199943310) 资助
收稿日期: 2003- 05- 26

表 1 水化学条件对比表[4]

Table 1 Comparison of hydrochemical conditions

地区	层位	Sr/ Ba	B/ 10^{-6}	古盐度/ %	水介质
牛庄洼陷	$Es_3^{中}$	< 1	40~ 60	0.8~ 1.2	淡水
南斜坡	$Es_4^{上}$	1~ 2	46~ 130	> 1.5	半咸水

组四段上亚段沉积时期, 牛庄洼陷的沉降中心偏向于北侧(图 1) 。斜坡边缘带底栖藻异常繁茂; 远滨带以浮游藻、细菌等微生物和水生动物为主, 深部水体供氧有局限性, 沉积有机质可能有别于近滨浅水带。

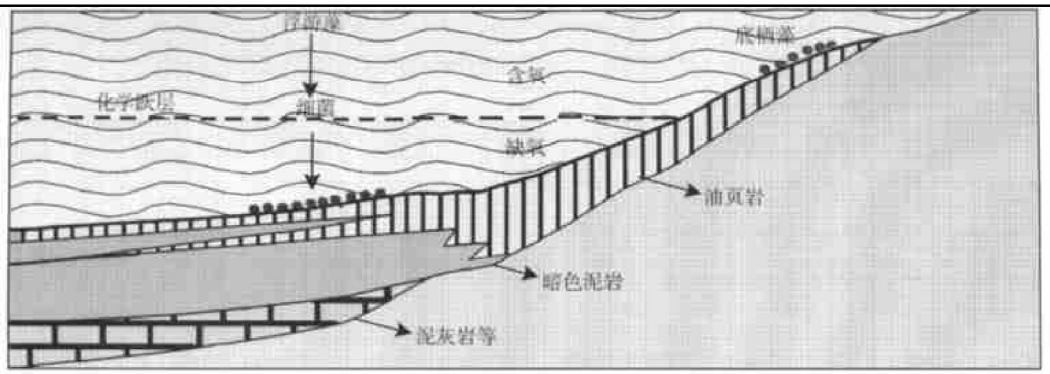

图 1 牛庄洼陷及其邻区沙河街组四段沉积剖面示意图

Fig. 1 Schematic diagram showing Es_4 sedimentary section in Niuzhuang subsag and adjacent area

2 古环境恢复

2.1 饱和烃组成特征

牛庄洼陷及其斜坡带烃源岩饱和烃气相色谱显示, 沙河街组四段页岩与泥岩含有丰富的植烷系列类异茂二烯化合物, 具低 Pr/ Ph 值。分布于南斜坡的沙河街组四段未熟– 低熟烃源岩具有明显的 nC_{14}, nC_{16}偶数碳或奇数碳优势, 链状与环状烃类占有相当的比例; 对于埋藏较深的成熟烃源岩, 正构烷烃含量相对增加, 奇偶或偶奇优势降低。沙河街组三段泥岩以较高的 Pr/ Ph 值明显区别于沙河街组四段烃源岩, 姥鲛烷对植烷优势随成熟度增加而更为明显。饱和烃气相色谱特征指示, 沙河街组三段与沙河街组四段为不同的原始沉积环境, 后者偏向还原性。依据 Hughes 等的分类[5], 牛庄洼陷及其斜坡沙河街组四段落于超盐湖分布区, 沙河街组三段泥岩落于湖相岩区, 原油与沙河街组四段烃源岩归于同区。

沙河街组三、四段烃源岩具有类似的 C_{27}, C_{28} 与 C_{29}规则甾烷相对分布, 反映相似的低等微生物藻类母源, 但不同层位甾类化合物丰度与甲基甾烷的分布具有明显的差异, 指示局部微相及藻类微生物特定属种仍有差异, 藻类的生长场所是有选择性的。沙河街组四段烃源岩明显比沙河街组三段富含甾类化合物, 说明前者藻类生源输入较多。随成熟度或埋深增加, 甾类化合物含量一般大幅度降低, 但牛庄洼陷南斜坡沙河街组四段页岩中的甾类化合物丰度远高于洼陷深部页岩, 不仅仅是成熟度因素, 可能有沉积微相分异因素。

烃源岩中萜类化合物分布与组成特征同样有效地体现了烃源岩分布与古环境的差异。牛庄洼陷南斜坡沙河街组四段页岩富含伽马蜡烷, 该化合物常为 m/ z 191 质量色谱图中的主要高峰(图 2) 。伽马蜡烷一般用来反映咸化或膏盐的原始沉积环境, 最近也常用来反映分层的水体环境[6]。沙河街组四段烃源岩富含伽马蜡烷指示咸化的水体环境和/ 或古沉积环境的水体分层现象。沙河街组四段烃源岩特别是南斜坡页岩升藿烷有明显的“翘尾”现象(图 2) , 指示咸化水体特征。藿烷主要以细菌为原始生物母质, 沙河街组三段细菌类母源输入量应该明显高于沙河街组四段, 可能说明沙河街组三段淡水环境适合于某些细菌繁衍。

2.2 芳烃组成特征

八面河地区烃源岩中芳烃的总体分布相似, 萘、菲和三芳甾烷系列为主要的芳烃化合物, 其次为氧芴、硫芴与脱羟基维生素 E。具有环境与生源指示意义的一般是芳香甾萜等非常规芳烃类。八面河地区烃源岩与原油中除含有丰富的三芴系列、脱羟基维生素 E 及三芳甾烷外, 也检测到少量苯并藿烷等其他芳香甾萜类。三芴系列是常用的

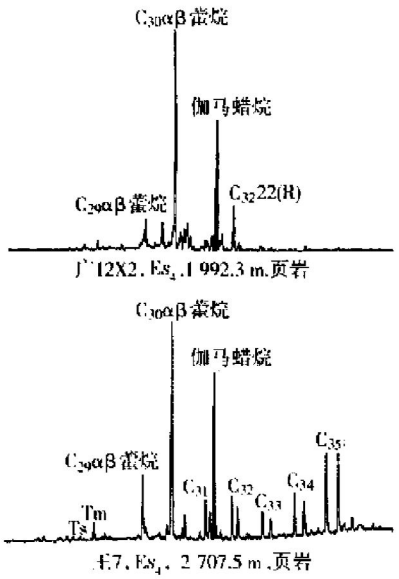

图 2　烃源岩 m/ z191 五环三帖烷质量色谱图

Fig. 2　Gas chromatograms of some Es_3 and Es_4 source rocks in Niuzhuang subsag and slope area

反映古环境的指标[7] 。牛庄洼陷及其邻区泥岩相对富含氧芴, 页岩相对富含硫芴(图3) , 结合其他

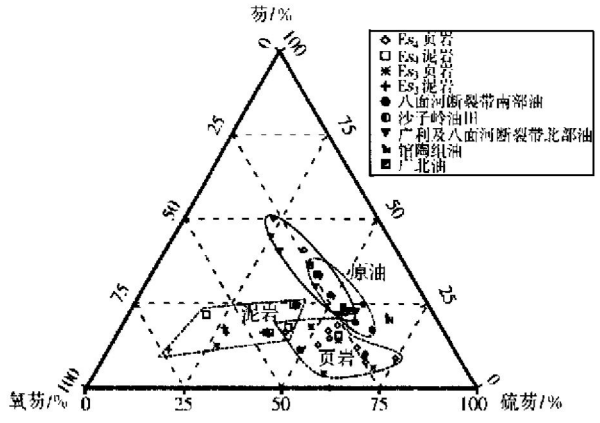

图 3　三芴系列相对分布图

Fig. 3　Relatively distribution of flouorence, dibenzofuran and dibenzothiophen

环境指标如 Pr/ Ph, 推测沙河街组三段泥岩形成于偏氧化性的湖相环境, 而沙河街组四段页岩形成于闭塞的还原咸化环境。与饱和烃中高丰度的甾烷相一致, 芳烃中三芳甾烷占统治地位; 与沙河街组四段页岩中低丰度的藿烷相对应, 沙河街组四段页岩芳烃中苯并藿烷的丰度极低。

不同成因烃源岩中脱羟基维生素 E 具有不同的异构体分布型式。沙河街组三段烃源岩分布型式类似, 以 α 构型为主, δ, β, ɣ, ε, α 相对丰度呈反“L”型; 而沙河街组四段烃源岩在较低的演化阶段含有较高的 δ, ɣ 构型, 异构体 δ, β, ɣ, ε, α 大致呈“W”型分布。上述脱羟基维生素 E 分布型式的差异指示原始生源特征对其有控制作用。已知脱羟基维生素 E 的丰度与分布也与成熟度有关, 低熟样品中该化合物含量一般较高, 随着成熟度增加, 丰度降低、热稳定性较低的 ɣ 与 δ 异构体相对含量降低。牛庄洼陷南斜坡沙河街组四段页岩高丰度的脱羟基维生素 E 的存在表明其咸化的强还原环境。原油中脱羟基维生素 E 的分布与沙河街组四段烃源岩有较好的相关性。

3　烃源岩分布对油气的控制作用

牛庄洼陷及其周边地区油气资源丰富, 其中, 洼陷中牛庄油田, 洼陷南斜坡八面河油田、王家岗油田, 邻区还有广利油田、羊角沟油田、沙子岭油田。牛庄油田以沙河街组三段透镜体油藏为主, 其油源为沙河街组三段泥岩, 属正常成熟油[1] 。八面河等油田原油主要来自沙河街组四段正常油窗内的成熟烃源岩[2,6], 主体仍为成熟油, 少量未熟– 低熟烃混入, 因为牛庄洼陷南斜坡未熟– 低熟页岩并不具备大量生、排烃地质条件。

油藏类型与原油特征受控于烃源岩的分布及其形成环境。沙河街组三段泥岩多为块状, 缺少与外部圈闭沟通的有效通道, 以自生自储的透镜体油藏为主要类型, 原油特征表现为沙河街组三段淡水相特征[1] 。王家岗、八面河及羊角沟油田位于牛庄洼陷南斜坡, 原油显示咸化湖相特征, 指示沙河街组四段烃源岩为其主要油源岩。可见, 沙河街组三段油源油气主要分布于洼陷内部, 沙河街组四段主要分布于偏离生油洼陷的周边地区(图 4), 东营凹陷北部郑家– 宁海一带亦为此情形。该现象可能与烃类生成、圈闭形成时期及与有利运移通道的配置直接相关。咸化环境的沙河街组四段烃源岩生烃时间早于上覆的淡水相, 王家岗深部断裂及沙河街组三段与沙河街组四段间的不整合面、连接油源与圈闭的储集层均可为油气运移的优势通道。此外, 八面河断裂带北侧的羊角沟油田、广利油田的油气稍不同于八面河油田, 指示广利洼陷对该区具有成油贡献。地球化学指标及水化学与微量元素特征指示广利洼陷原始沉积环境稍有别于牛庄洼陷及其南斜坡。这种差异进一步说明烃源岩分布对油气的主导控制作用。

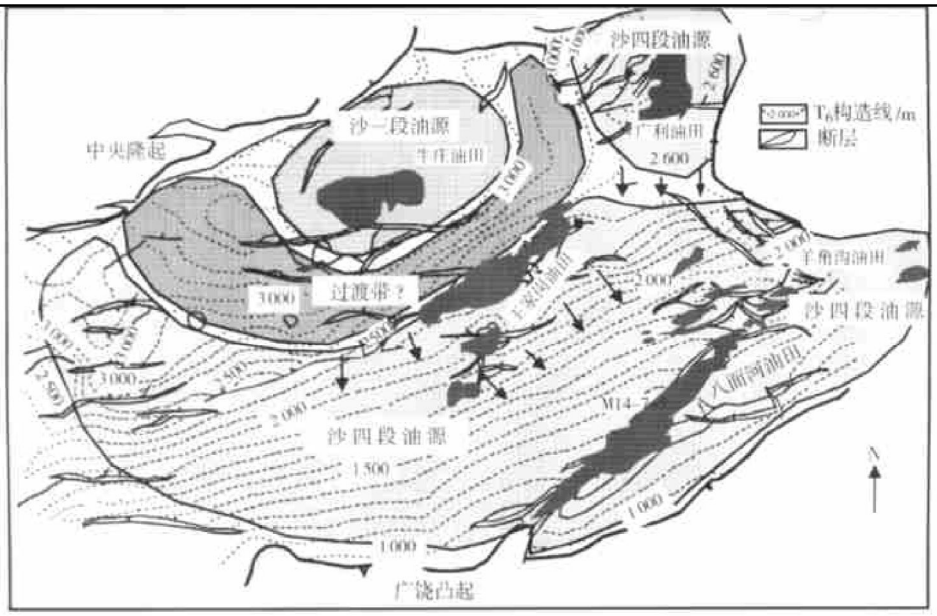

图 4 牛庄洼陷油气分布规律

Fig. 4 Petroleum distribution in Niuzhuang subsag

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PALEOSEDIMENTARY ENVIRONMENT IN TERTIARY AND ITS EFFECT ON PETROLEUM DISTRIBUTION IN NIUZHUANG SUBSAG, DONGYING SAG

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Abstract: 31 rock samples and 20 oil samples have been collected from Niuzhuang subsag and its southern slope for detail GC, andGC-MS analyses. The rocks have been sampled from Es_3 and Es_4 members, which are respecting the two main source rocks being deposited in freshwater lake and brackish to saline lake environments, respectively. The oils have been sampled from Bamianhe, Guangli and Shaziling oilfields in the southern slope of Niuzhuang subsag. Our oil-oil and oil-rock correlations show that there are two genetic types of oils in Niuzhuang subsag and its periphery. They are separately corresponding to the two major source rocks in middle to lower Es_3 and upper Es_4 members. Rock extracts of Es_4 member and the related oil are characterized by Pr/Ph< 1, high gammacerane, sterane and dibenzothiophene contents, relatively low diasterane content, and high C_{35}/C_{34} homohopane ratios, suggesting that they have been generated in a reduction and brackish to saline lacustrine paleoenvironment. However, rock extracts of

middle to lower Es_3 and the related oil are characterized by Pr/ Ph> 1, and relatively high concentration of hopane and dibenzofuran contents, representing freshwater lacustrine genesis. It is found that methylsteranes including dinosteranes are of importance to indicating sedimentary environment and even specific species of organisms. The alge-rich Es_4 shales deposited in brackish water in the southern slope of Niuzhuang subsag are rich in C_{28-30} 4-methyl steranes and dinosteranes, and but very small amount of dinosterane in the Es_4 source rock buried at a depth over 2700 m. Similar phenomenon has been observed in Es_3 mudstones deposited in fresh water, i. e. C_{28}, C_{29}, C_{30} 4α methyl-αααR-20 Rsterane of Es_3 mudstone distribute in the shape of "V" in the m/ z 231 mass chromatogram, while those in Es_4 source rock have a linear distribution, suggesting that they have apparently different paleoenviornment and related geochemical environment. Analyses of formation water and trace element also show that the sedimentary environments in Es_3 and Es_4 are quite different. The Sr/ Ba ratio, boron content, paleo-salinity and saltiness in Es_4 are relatively higher than those in Es_3. In a word, the development of the Tertiary lake in this area has been closely related to the tectonic movement and paleo-climates. Sedimentary environment and biomarker index show that the oil field in the deeper part of Niuzhuang subsag have mainly been sourced by the Es_3 source rocks. They are actually of lenticular oil reservoirs characterized by short-distance migration and indigenous oil generation and accumulation. The oils generated from Es_4 have mainly been accumulated in the tectonically high position, such as southern slope of Niuzhuang subsag and the adjacent area. They are characterized by relatively long-distance migration. The sedimentary environment indexes indicate that most of the oils discovered in the southern slope have been sourced from Niuzhuang subsag, only Guangli oilfield and the oil pools in northern Bamianhe oilfield have been sourced from Guangli subsag and adjacent area. It can, therefore, be concluded that papleoenvironment is one of the most important factors having controlled oil and gas distribution in the area.

Key words: Niuzhuang subsag; paleoenvironment; source rock; oil; biomarkers

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APPLICATION OF GEOCHEMICAL METHODS IN THE RECOGNITION OF HIGH-RESOLUTION SEQUENCE BOUNDARY

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Abstract: Clay minerals and trace elements are widely distributed in the different types of sediments, which are so sensitive to environment change. The characteristics of clay minerals (sedimentary differentiation, mineral assemblages, and mineral composition and contents) has provided the information of environment change during their formation process. After studying the typical lithogeochemical parameters of high-resolution sequence units in the 3rd and 4th of Shahejie Fm in the fall-wall of Shengbei fault, Dongying depression, it has been found that mineral composition (including clay minerals and cements) , chemical constituents (trace elements) would be periodically changed with the pace of change cycle of lake surface controlled by paleoclimate. The contents of illite + mixing-stratified illite/ semectite and kaolinite + chlorite as well as paleosalinity show distinct change features above and below high-resolution sequences boundary. In the water transgressive system, the content of kaolinite is increased but the content of semectite and value of paleosalinity are gradually reduced from bottom to top. However these characteristics in water regressive system would be opposite. On the sequence boundary under different transgressive and regressive water systems, the contents of dolomitic cement is relatively high, while the contents of calcitic and mixing cements is relatively low.

Key words: clay minerals; trace element; cement; paleosalinity; high-resolution sequence stratigraphy; Dongying depression