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石油充注对储层成岩矿物演化的影响*

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摘要: 油饱和带(油层) 中石英次生加大和钾长石颗粒的钠长石化程度均低于水饱和带(水层), 石英次生加大边中的流体包裹体显微测温(60~ 140 ℃) 表明, 油饱和带与水饱和带中包裹体的温度相近, 这说明油饱和带中石英次生加大在石油侵入后继续发育, 但与水饱和带相比这种作用受到抑制。同样, 方解石、白云石在含水饱和带及低含油饱和带与高含油饱和带相比也较发育; 粘土矿物伊利石也具有此特征。但长石的溶蚀却在含油饱和带中明显高于含水饱和带, 这说明石油充注改变储层孔隙中矿物生长的微环境(矿物成分、pH 值、Eh、CO_2 分压及其他孔隙流体性质), 从而对其成岩作用产生不同程度的抑制作用。

关键词: 石油充注; 储层矿物; 成岩演化; 油饱和带; 水饱和带; 流体包裹体
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碎屑岩储层的成岩作用主要受碎屑矿物成分、地层水组成、pH 值和温度等因素的控制, 同时孔隙流体的流动对成岩作用也起着重要的作用。石油在储层中的聚集改变了孔隙水的化学组成, 导致孔隙水中无机离子浓度降低, 并通过改变 pH 值或通过烃类流体部分替换孔隙水而阻碍了矿物- 离子之间的质量传递, 从而抑制了自生矿物的形成以及矿物的交代和转化, 也即抑制了胶结、交代、重结晶等成岩作用过程。有些学者曾经认为, 石油聚集将导致储层成岩作用的终止[1]。实际上这个过程可能比早期的认识要复杂得多。Walderhang[2], Nedkvitne[3] 认为石油的聚集并不一定会使储层成岩作用完全终止, 但有不同程度的影响。目前有关石油聚集对成岩作用的影响研究方面并没有突破性的进展。本文主要根据济阳坳陷的实际地质资料对这一问题作初步探讨。

1 对石英矿物成岩演化的影响

石英的次生加大作用所涉及的地球化学问题主要包括 SiO_2 沉淀的环境介质及硅质增生中 SiO_2 的来源。硅质增生中的 SiO_2 主要有两个来源。

(1) 在酸性介质条件下, 长石等不稳定组分的溶解, 如钾长石在转化成高岭石的过程中释放出 SiO_2。

$2KAlSi_3O_8$ (钾长石) + $16H_2O \rightarrow 2K^+ + 2Al^{3+} + 8OH^- + 6H_4SiO_4 \rightarrow Al_2Si_2O_5(OH)_4$ (高岭石) + $4SiO_2 + 2K^+ + 2OH^- + 13H_2O$;

(2) 粘土矿物的转化, 即由蒙脱石转化为无序混层, 再转化为有序混层, 进一步转化为伊利石的过程也产生 SiO_2。

此外, 硅质增生的转化及碎屑石英颗粒的压溶作用也可能提供 SiO_2。在酸性环境下, SiO_2 易形成石英的次生加大边(图 1a) 或硅质胶结物。

根据东营凹陷、沾化凹陷和惠民凹陷部分钻井储层样品分析, 在石英的次生加大边及裂缝中均含有大量的含烃包裹体(图 1 c), 在荧光下液态烃发白色光居包裹体四周, 气态烃不发光居包裹体中间, 并且在部分样品中, 烃类包裹体外部还存在较宽的加大边。这表明烃类充注后仍然有 SiO_2 沉淀, 含油饱和度高的油层中石英加大边外部晶体结晶不好, 呈港湾状, 外部分布有原油; 而水层中石英加大边结晶一般较好, 有些胶结较致密。从临 10- 1 井包裹体资料可以看到(图 2), 裂缝中包裹体均一化温度主要分布在 90~ 110 ℃, 石英次生加大边上均一化温度为 60~ 140 ℃, 集中在 120~ 140 ℃。石英加大边中含有烃包裹体, 均一化温度总体上较裂缝中的高, 且不呈正态分布, 表明温度愈高, 包裹体越发育。这说明: (1) 石英缝中包

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裹体形成早于石油大规模聚集; (2) 石英加大边中包裹体内烃类广泛分布, 加大边是在烃聚集期间形成的, 且不同含油级别的储层中均一温度差别不大。这也可间接地说明储层中石英的次生加大作用并不因为石油的注入而终止。但石油充注对石英的次生加大及硅质胶结还是有抑制作用的。

2　对长石矿物的影响

长石类矿物的成岩变化主要有溶解作用(图 1b) 、碳酸盐化作用(图 1f) 、高岭石(图 1e) 及伊利

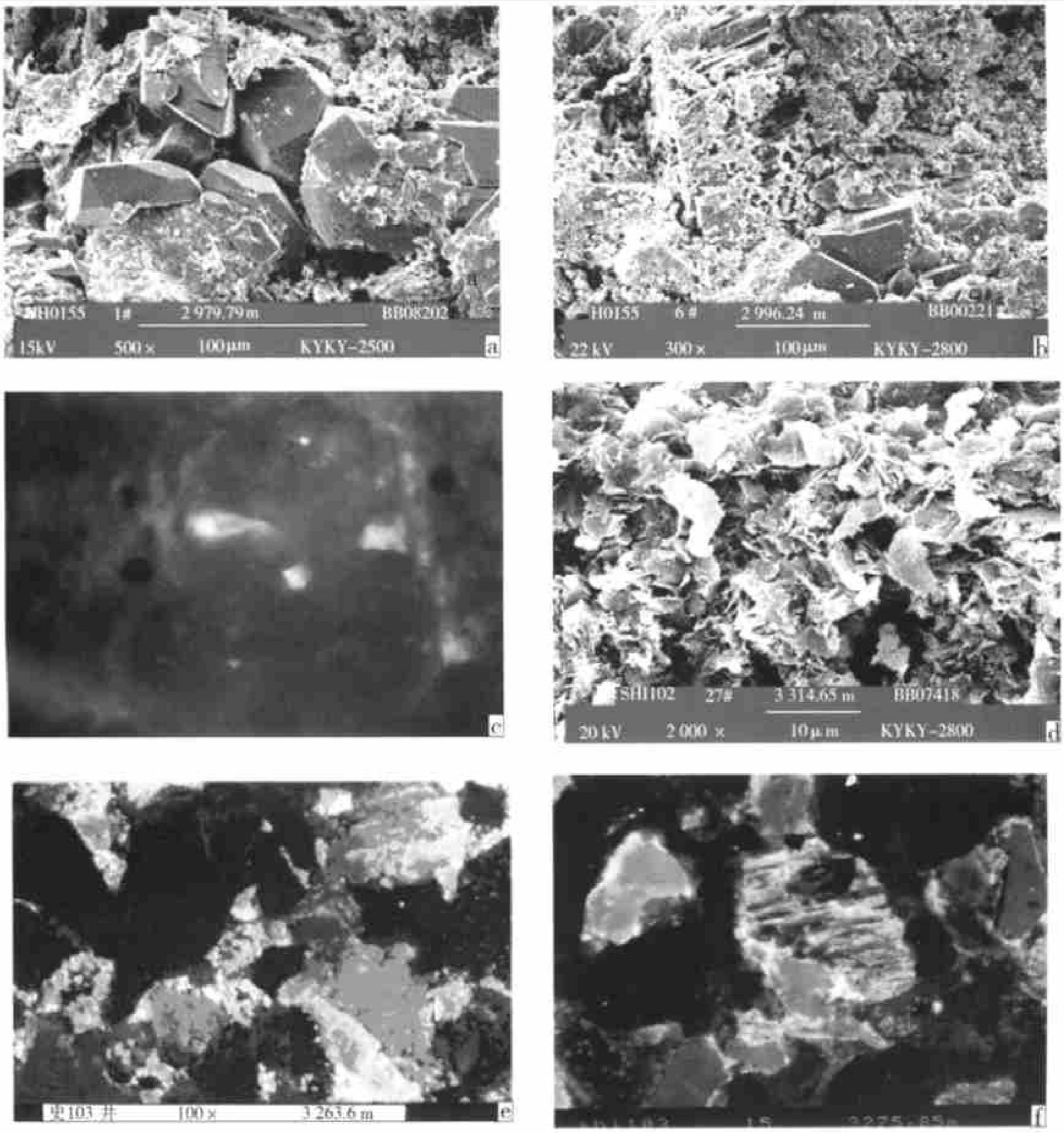

图 1　石油充注对储层矿物的影响

Fig. 1　Effect of oil charging on reservoir mineral evolution

a. 石英次生加大, 河 155 井, 2 979. 79 m, 500× , 扫描电镜;

b. 长石(Fs) 溶蚀及石英(Q) 加大, 河 155 井, 2 996. 24 m, 300× , 扫描电镜;

c. 石英中气液包裹体, 临 10- 1 井, 3 182. 72 m, 450× , 荧光;

d. 丝片状伊利石充填粒间孔, 史 102 井, 3 314. 65 m, 2 000× , 扫描电镜;

e. 石英发棕 、紫色光, 发蓝白色光钾长石四周被发靛蓝色光的高岭石包围, 显示钾长石的高岭石化, 孔隙中被发桔黄色- 桔红色光的不同世代的方解石充填, 100× , 史 103 井, 3 263. 6 m;

f. 长石沿节理缝溶蚀后被方解石充填, 牛 35 井, 2 975. 87 m, 阴极发光。

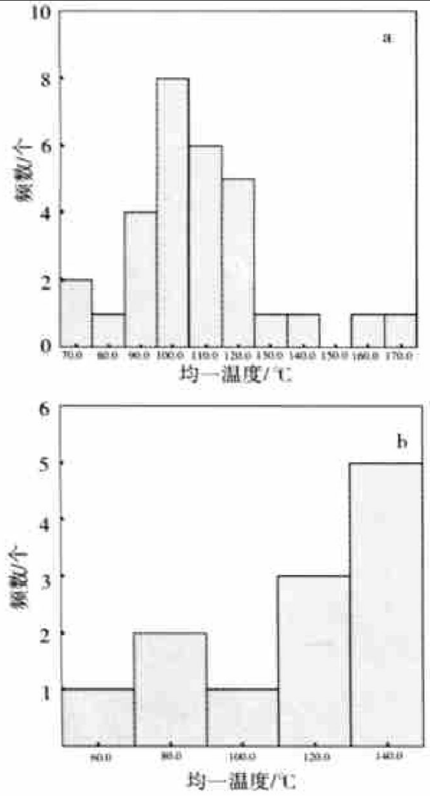

图2 惠民凹陷临10–1井 Es_3 储层中流体包裹体均一温度分布图

Fig. 2 Homogenization temperatures of fluid inclusion in Es_3 reservoir encountered in Lin10–1 well in Huimin sag

a—矿物裂缝中; b—石英加大边中

石化作用和钠长石化作用等, 成岩时期孔隙水的 pH 值及二氧化碳浓度(分压 P_{CO_2}) 对长石溶解起重要的作用。

(1) 钾长石溶解作用

$$KAlSi_3O_8(s) + 4H^+ \rightarrow Na^+ + Al^{3+} + 3SiO_2(s) + 2H_2O$$

$$[2KAlSi_3O_8(s) + 2H^+(aq) + H_2O(l) = Al_2Si_2O_5(OH)_4(s) + 4SiO_2(s+aq) + 2K^+(aq)]$$

$$KAlSi_3O_8(s) + 2H_2O \rightarrow Na^+ + Al(OH)_4^- + 3SiO_2(s)$$

(2) 斜长石溶解作用

$$CaAl_2Si_2O_8(s) + 8H^+ \rightarrow Ca^{2+} + 2Al^{3+} + 2SiO_2(s) + 4H_2O$$

$$[CaAl_2Si_2O_8(s) + 2H^+(aq) + H_2O(l) = Al_2Si_2O_5(OH)_4(s) + 4SiO_2(s+aq) + Ca^{2+}(aq)]$$

长石溶解后出现3种情况。

(1) 溶解物质全部进入溶液迁移到它处, 这种情况最有利于形成次生孔隙。溶解物质的迁移能力主要取决于: ①孔隙水的渗流性能, 储层的孔隙物性和含油饱和度对孔隙水的渗流性能均有影响; ②孔隙水的性质, 孔隙水中所含的有机酸有利于溶解矿物质形成金属有机络合物, 促进溶解物质的迁移, 同时孔隙水中有机酸浓度的增加可形成有利于 SiO_2 沉淀和某些粘土矿物形成的酸性环境。

(2) K^+, Na^+, Ca^{2+} 等离子迁移释放进入孔隙水中, 促使粘土的形成与转化, 进一步形成伊利石等粘土矿物, 而 SiO_2 和 Al_2O_3 等在附近形成高岭石(图1 e) 和 SiO_2 沉淀, 或产生钾长石的钠长石化, 形成自生钠长石或钠长石次生加大边。

(3) 剩下的 SiO_2 形成硅质填隙物、硅质骨架或“硅球”堆积[4]。

与水层钾长石的钠长石化程度相比, 油层的程度要小得多。但长石的溶蚀作用并不因为石油的充注而立即停止。根据东营凹陷牛庄油田和胜坨油田部分样品分析, 凡是含油砂岩都发育良好的次生孔隙, 长石及碳酸盐矿物的溶解非常强烈; 而不含油的砂岩中次生孔隙大多发育差, 矿物溶解也相对较弱, 但也有局部发育良好者。如牛11井3 166 m处不含油砂岩与3 317 m处含油砂岩(图3a, b) 对比可以发现, 后者长石溶解强度远大于前者, 故其次生孔隙发育, 前者不发育。又如胜坨油田坨32井, 在1 500 m附近的含油砂岩中, 胶结物大量溶解, 长石也发生溶解(图3c, d), 含油流体灌入, 胶结物缺乏, 岩石呈接触式或基底式为含油泥质所包围。而其下部深度为1 794 m处的砂岩, 具有较好的胶结, 除少量微小的原生孔隙外, 基本不发育次生孔隙, 长石的溶解也很微弱(图3e)。再向下到2 255 m的含油砂岩, 溶解作用又再度强烈, 次生孔隙再度发育。由此看来, 无论是浅部或深部, 凡含油砂岩中, 长石类及碳酸盐类矿物的溶解都十分强烈, 次生孔隙都很发育; 而不含油的砂岩, 无论在深部(如牛11井3 166 m处), 还是在浅部(如坨32井1 794 m处), 矿物的溶解及次生孔隙发育一般都较差。

上述现象表明, 含油流体的灌入促进了砂岩中次生孔隙的进一步发育。(1) 在含油砂岩中, 长石进一步溶解析出的 SiO_2 往往在附近沉淀而形成大量“硅球”堆积, 而在不含油砂岩中没有见到这种情况。SiO_2 的就近沉淀说明流体的粘度大(不易发生化学扩散), 且流动性差, 这往往是含油流体灌入后的特点。(2) 含油砂岩中有些长石发生不均匀溶解, 如坨32井1 498 m处长石矿物一端

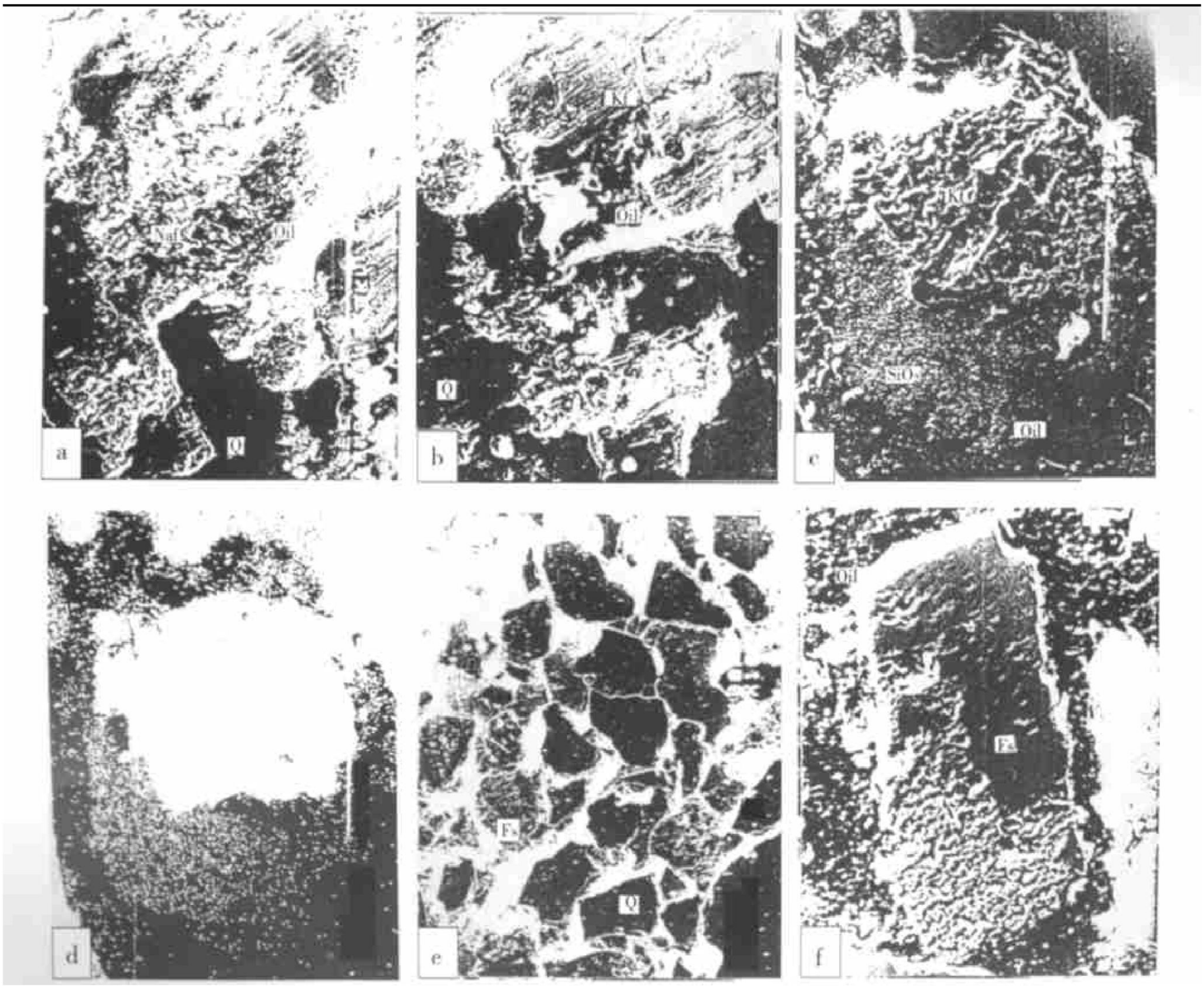

图 3　东营凹陷石油充注对长石类矿物的影响

Fig. 3　Effect of oil charging on feldspar mineral in Dongying sag

a. 次生孔隙发育, 钠长石碎屑溶解, 并被含油流体灌注, 牛 11 井, 3 317 m;

b. 砂岩中发育的次生孔隙, 由钾长石溶解形成, 并被含油流体灌入, 牛 11 井, 3 317 m;

c. 钾长石溶解成残余骨架, SiO_2 就近形成硅球沉淀, 二次电子成像, 坨 32 井, 1 498 m;

d. 上一照片视域的硅元素 X- 射线扫描图像, 坨 32 井, 1 498 m;

e. 具有较好胶结的砂岩, 除少量微小原生孔隙外, 基本上不发育次生孔隙, 长石溶解也较弱, 坨 32 井, 1 794 m;

f. 斜长石矿物发生不均匀溶解, 下部溶解显著, 上部未见溶解, 保留完好, 表明孔隙微环境有所差别, 坨 32 井, 1 498 m 。

发生溶解, 另一端完整无缺(图 3f) , 说明这些长石颗粒两端所处的微环境不同, 一端可能与酸性水溶液接触, 发生溶解; 另一端可能被油滴包围而不发生溶解, 从而保持完整面貌。(3) 很多油砂都比较松散, 也表明被油水充满的砂岩所遭受的溶解远强于一般水溶液。

造成这一现象的主要原因是石油的充注对孔隙水性质的改变。在石油中含有一定量的有机酸, 石油运移进入储层后, 由于部分包括有机酸在内的水溶性有机质溶解于地层水中, 使地层水 pH 值降低(pH 可降至 3~ 5) , 从而使与石油伴生的孔隙水酸性增强, 促进了长石和方解石的溶解。由长石溶解所产生的 SiO_2, 在酸性水中不易迁移而在邻近的孔隙中就近沉淀形成所谓的“硅球”。如果含油饱和度继续增大, 含油级别为富含油或油浸时, 孔隙水的流动受到抑制, 从而阻碍了溶解-沉淀等成岩作用的继续进行。

3　对晚期胶结作用的影响

碳酸盐矿物的沉淀与溶解作用主要取决于羧酸浓度与 CO_2 分压(P_{CO_2}) 的分布状况、孔隙水中的 Ca^{2+} 浓度及 pH 值等因素。随着埋藏深度的增

大，温度升高达到 100 ℃左右时，羧酸开始脱羧，造成 P_{CO_2} 增大，但系统仍为外缓冲，pH 保持在 6 左右，碳酸盐溶解度降低，从而变得稳定。在 120~160 ℃时，羧酸阴离子减少，其缓冲能力很快降低，碳酸盐系统变成内缓冲，碳酸盐沉淀。形成的碳酸盐沉淀物主要为铁方解石和铁白云石，反应式可表示为

$$方解石: 2CO_2 + H_2O + Ca^{2+} \rightarrow CaCO_3 + 2H^+$$

$$白云石: 2CO_2 + 2H_2O + Ca^{2+} + Mg^{2+} \rightarrow CaMg(CO_3)_2 + 4H^+$$

$$铁方解石: CaCO_3 + xFe^{2+} = Ca_{1-x}Fe_xCO_3 + (1-x)Ca^{2+}$$

$$\left| CaCO_3 + 0.05Fe^{2+} = Ca_{0.95}Fe_{0.05} + 0.05Ca^{2+} \right|$$

$$铁白云石: CaMg(CO_3)_2 + 0.36Fe^{2+} = CaMg_{0.64}Fe_{0.36}(CO_3)_2 + 0.36Mg^{2+}$$

根据东营凹陷下第三系碎屑岩储层矿物成分的镜下观测与统计分析，油层中方解石、白云石含量一般比水层低，在深层尤为明显。从图 4 及图 5 中可以看出在含油层和油浸级别的储层中，方解石、白云石含量一般较低，除个别深度段外，大部分都小于 20%，但含油级别较低的储层中方解石含量较高，且随含油级别的降低，方解石、白云石含量有升高的趋势。造成这一现象的原因比较复杂，控制储层中方解石沉淀的因素很多，但在深部储层中油层与水层或油水层之间碳酸盐矿物(尤其是白云石)间存在明显的差别，与原油充注抑制碳酸盐矿物的沉淀有着必然联系。总之，含油级别较高的储层中方解石、白云石含量相对较低；含油级别较低的储层中方解石、白云石的含量相对较高。主要原因是石油的充注，一方面限制了地

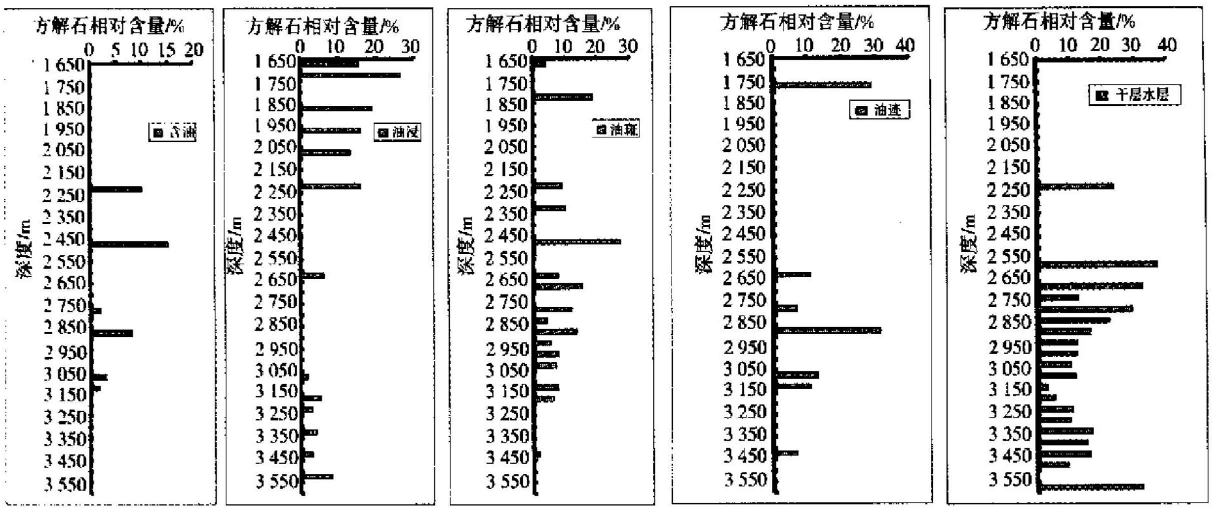

图 4　东营凹陷中央隆起带不同含油级别储层中方解石含量分布图

Fig. 4　Calcite contents in reservoirs with different oil saturations in central uplift belt, Dongying sag

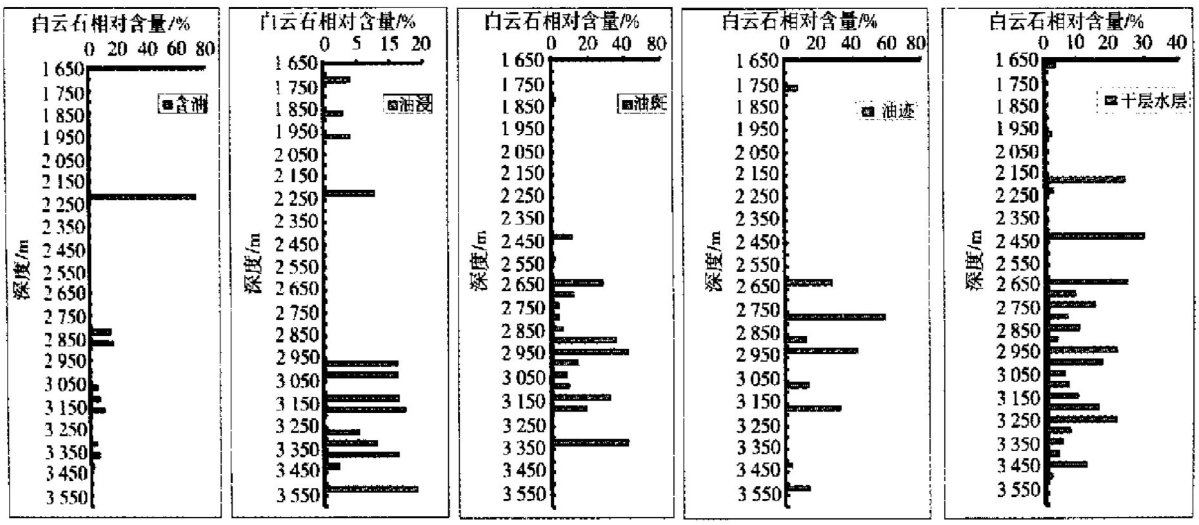

图 5　东营凹陷中央隆起带不同含油级别储层中白云石含量分布图

Fig. 5　Dolomites contents in reservoirs with different oil saturations in central uplift belt, Dongying sag

层水的流动, 另一方面造成地层水的 pH 值降低, 不利于方解石和白云石沉淀。

在显微镜下, 虽然含油砂岩中碳酸盐胶结物也有较高的含量, 但胶结较为疏松, 次生孔隙较为发育, 而不含油砂岩中碳酸盐矿物胶结较为致密, 无论是原生孔隙还是次生孔隙往往均被晚期铁方解石充填(图 1 e)。

4　对粘土矿物成岩演化的影响

在砂岩储层中, 自生伊利石是储层埋藏成岩过程中形成的。从理论上讲, 烃类充注引起孔隙流体性质的改变, 使成岩环境发生了变化, 其结果将导致伊利石停止生长。因此, 在不同含油级别砂层中, 伊利石含量会有所不同。根据东营凹陷粘土矿物 X 衍射资料分析, 饱含油层或富含油层中, 伊利石含量较少, 而含油级别较低的砂层中, 如油斑、荧光及水层中, 伊利石含量较高, 但低含油饱和度的储层中, 伊利石的含量与含油程度之间没有明显的对应关系(图 6)。这说明烃类的充注, 引起了伊利石成岩环境的变化, 在饱含油层或富含油层中, 伊利石生长受到抑制, 导致其含量减少。相反, 烃类未充注或含油饱和度较低的砂层, 其成岩环境未遭到破坏, 伊利石继续生长, 其含量较高。

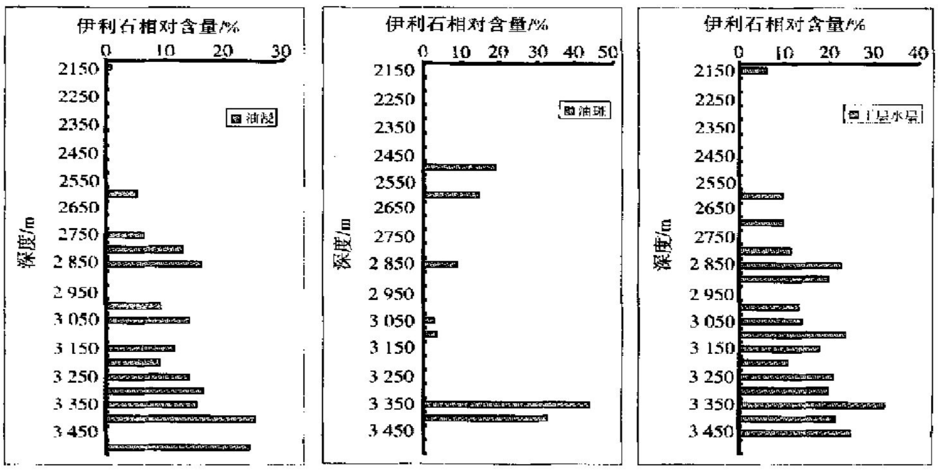

图 6　东营凹陷中央隆起带下第三系储层中伊利石分布特征

Fig. 6　Characteristics of illite distribution in Paleogene reservoirs in central uplift belt, Dongying sag

从东营凹陷部分井的资料分析, 在埋深 2 500~ 3 300 m(3 500 m) 范围内, 不同含油级别的储层中, 随深度变化伊利石含量都有增大的趋势(图 7a), 富含油层中伊利石含量增加幅度相对较小, 而其他含油级别的储层中伊利石含量的变化不大。绿泥石相对含量的变化与此相似(图 7b)。

从伊利石的显微特征也可以看出, 中浅层储层中主要发育伊蒙混层和绿蒙混层, 而在中深层储层中无论是含油层还是含水层, 均广泛分布有丝片状伊利石和片状绿泥石, 在水层和油层中均普遍存在伊蒙混层和绿蒙混层向伊利石和绿泥石转化的现象。但在水层和油层中伊利石的发育程度及特征有所差别, 在水层中伊利石相对比油层中的发育(图 1d)。这种现象可能有两种解释, 其一, 原油充注后, 未占据伊利石晶体的生长空间, 对伊利石的成岩环境未造成决定性影响, 伊利石

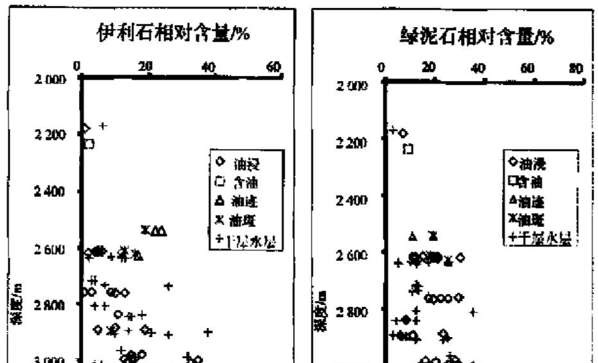

图 7　东营凹陷不同含油级别储层中粘土矿物演化特征

Fig. 7　Characteristics of clay mineral evolution in reservoirs with different oil saturations in Dongying sag

仍继续生长,但在富含油的储层中,由于含油饱和度高,阻碍了孔隙流体的流动,从而对伊利石的生长有一定的抑制作用;其二,原油是在成岩作用晚期进入储层的。但从本区的实际资料分析,东营凹陷下第三系烃源岩在2 200 m左右进入生烃门限,在2 000~ 3 400 m,原油开始大量进入储层中,也就是说,在伊利石矿物大量形成之前石油已经进入储层,表明原油进入储层后伊利石并未立即停止生长。

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EFFECT OF OIL CHARGING ON RESERVOIR'S DIAGENETIC MINERAL EVOLUTION

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Abstract: All secondary enlargement of quartz and albitization of potash feldspar in water-saturated zone (water layer) are stronger than those in oil-saturated zone. Homogenization temperatures of fluid inclusions in quartz overgrowth (60~ 140 ℃) shows that both the temperatures of fluid inclusions in oil-saturated and water-saturated zones are very similar, which proves that the enlargement process of quartz in oil-saturated zone has been continuous after the charging of oil, but the process has been restrained in contrast to that in water-saturated zone. There are mainly five kinds of diagenetic changes for feldspar minerals, including dissolution, carbonatization, kaolinization, illitization and albitization. The pH of pore water and concentration of carbon dioxide (fractional pressure) play an important role in feldspar dissolution. Three different results would occur after feldspar dissolution: (1) all the dissolved substances would migrate along with the solution to other places, which is advantageous to the formation of secondary pores. Migration capacity of dissolved substances depends on the transport capacity of pore water or percolating capability of pore water. Both the poroperm characteristics and oil saturation of the reservoir can affect the percolating capability of pore water. Besides, it is also affected by the property of the pore water. The organic acid in the pore water is favorable to the formation of metal organic complex, thus accelerating the migration of dissolved substances. At the same time, the increase of organic acid concentration would cause the precipitation of SiO_2 and the formation of some clay minerals. (2) K^+ Na^+ and Ca^{2+} cations in the pore water lead to the formation and transformation of clay minerals, such as illite; while SiO_2 and Al_2O_3 precipitate nearby as kaolinite and SiO_2, cause the albitization of potash feldspar, or even become authigenic albite or albite overgrowth. (3) The remaining SiO_2 then become the pore filling material, silicon framework or "silicon ball" accumulation. It is the alteration of pore water property caused by oil charging that creates this phenomenon. Since there is a certain amount of organic acid in the oil, and when oil migrate into the reservoir, some of the water soluble substances, such as organic acid, dissolve in formation water, which reduce the pH of

(Please Turn to Page 295)

of interpreters, whose effect is subject to better geological conditions, simple predicted objects, and higher S/N in original seismic data. However, under the other conditions, the effect of prediction is worse. In fact, there exist complex relations between predicted objects and their seismic attributes. The seismic attributes sensitive to predicted objects are not totally the same in different areas and reservoirs. They are also somewhat different even for same reservoir and same area. The optimization technique of seismic attributes is an effective means for solving the above questions. The optimum methods of seismic attributes mainly include the dimension-reduced projected profile and cluster analysis etc. Its purpose is to optimize the minimum seismic attributes or seismic attributes group, which are the most sensitive (or most effective, most representative) to studied problem, in order to increase reservoirs prediction precision and to improve the effect of processing and interpretation related to seismic attributes. The obvious effect of reservoir prediction in CB31 area has been achieved by using the optimum method of seismic attributes. This area is located at the graben belt that is between the drape structures of CB30 buried hill and the drap structures of Changdi buried hill. Its main reservoirs are the sand bars, formed by meander river sediment, in Neogene Guantao Fm, with poor continuity and small distribution. Because the distribution of depositional sand bodies are unstable in lateral and vertical direction and because the drilled thickness of sand bodies is usually less than 10m, the sand bodies have no corresponding reflection on seismic sections, resulting in the bigger difficulty in reservoir prediction and description. Therefore, the recognition of its pool-forming factors and hydrocarbon accumulation rules has been disputed for many years. With the help of the theory and methods of seismic attribute optimization, the seismic attributes of predicted reservoir are optimized. Meanwhile, one of the optimized seismic attributes, the wave peak number, is verified with seismic forward modeling, and demonstrating the reliability of the method. Based on the above works, the stratigraphy, reflected wave velocity, structure and electric property have been studied; the pool-forming factors and hydrocarbon accumulation have been analyzed; the areal distribution of sand bodies have been basically identified; more than 30 sand bodies have been described. As a result, the oil in place reserve in the CB31 wellblock is estimated to be 40 million tons.

Key words: reservoir prediction; seismic attribute; attribute optimization; forward modeling

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formation water and lead to the increase of acidity of pore water, associated with oil with a pH of 3~ 5, thus boost the dissolution of feldspar. The SiO_2 generated from the dissolution of feldspar, cannot easily migrate in the acidic water, it thus precipitates as the so-called “silicon ball”. But if the oil saturation is continuously increasing so that the reservoir to be rich in oil or immersed in oil, the flowing of pore water would then be restrained, and the diagenesis, including dissolution and precipitation processes, would be impeded. Similarly, the development of calcite and dolomite is better in water-saturated and low oil-saturated zones than in high oil-saturated zone. Theoretically, charging of hydrocarbons alters the property of fluid in the pores, and the diagenetic environment alters accordingly and leads to the ceasing of illite growth. Therefore, the amount of illite is always different in sands containing varying amount of oil. In oil-saturated or oil-rich zone, illite is relatively low, while in sands with small amount of oil, such as the oil patch sands, or with only trace of oil and water layer, illite content is relatively high. The relative content of chlorite in sands varies similarly as that of illite. All mentioned above show that oil charging can change the microenvironment for growing of minerals in reservoir pores, and thus would restrain, to some extent, the diagenesis of reservoir rock.

Key words: oil charging; reservoir mineral; diagenetic evolution; oil-saturated zone; water-saturated zone; fluid inclusion