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深层砂砾岩中的深部热流体作用及其地质意义
——以渤海湾盆地东营凹陷民丰—盐家地区古近系沙河街组四段为例

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摘要:以渤海湾盆地东营凹陷北部陡坡带东段民丰—盐家地区古近系沙河街组四段(沙四段)深层砂砾岩为例,通过岩心和扫描电镜观察、薄片鉴定、流体包裹体、粘土矿物X射线衍射、镜质体反射率、岩心物性和烃源岩热解参数分析等方法,结合构造演化和岩浆活动背景、地层埋藏史和油气成藏史等研究成果,明确深层砂砾岩中的深部热流体作用标记和时间,并初步探讨其地质意义。结果表明:研究区沙四段砂砾岩中存在爆裂角砾、立方体黄铁矿等和伊/蒙混层-铁白云石-磷灰石、伊/蒙混层-磷灰石-黄铁矿、绿泥石-磷灰石-黄铁矿、磷灰石-黄铁矿等反映深部热流体作用的岩石学特征和矿物(组合);粘土矿物的垂向演化过程中出现伊/蒙混层比值异常增大、高岭石含量短暂激增的现象;在埋深3 400~4 800 m处游离烃含量(S_1)和裂解烃含量(S_2)异常高,埋深5 500 m处S_1和S_2较低,而热解峰温(T_{max})异常高,在埋深4 269~4 800 m处的石英裂缝内有异常高温包裹体;天然气稳定碳同位素中$\delta^{13}C_{CO_2}$值大于-8‰,具有无机成因特征,且具有与深部富CO_2热流体作用相关的$NaHCO_3$型地层水。以上现象均反映出民丰—盐家地区沙四段砂砾岩在馆陶组-明化镇组沉积时期经历了富CO_2幔源成因的深部流体活动。深部热流体进入砂砾岩储层后对物性起到双重改造作用:引发破裂和促进溶蚀从而改善储层物性;沉淀自生矿物堵塞孔隙,阻碍流体运移,损害储层物性。此外,深部热流体参与沙四下亚段烃源岩热演化及油气生成过程,对烃源岩排烃和原油裂解具有潜在影响。

关键词:判识标记;油气生成;储层改造;深部热流体;深层砂砾岩;沙河街组四段;东营凹陷;渤海湾盆地
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Deep hydrothermalism of deep coarse-grained siliciclastic rocks and its geological significance: A case study of the 4th member of the Paleogene Shahejie Formation in Minfeng-Yanjia area, Dongying Sag, Bohai Bay Basin

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Abstract: The deep coarse-grained siliciclastic rocks of the 4th member of the Paleogene Shahejie Formation (Es^4) in Minfeng-Yanjia area of the eastern section of the steep slope zone to the north of Dongying Sag, Bohai Bay Basin, are taken to identify markers and time of deep hydrothermalism and make a preliminary discussion on its geological significance. A variety of data are applied in the study including the core, scanning electron microscopy (SEM), thin section, fluid inclusion, X-ray diffraction (XRD) of clay minerals, vitrinite reflectance (R_o), physical properties of core sample and hydrocarbon source Rock-Eval parameters; besides, the research results of tectonic evolution, magmatic activity, stratigraphic burial and hydrocarbon accumulation history are also taken into consideration. The results show that, there are explosive breccia, cubic pyrite and some mineral assemblages, such as mixed layer illite/montmorillonite-ankerite-apatite, mixed layer illite/montmorillonite-apatite-pyrite, chlorite-apatite-pyrite and apatite-pyrite, which just reflect the deep hydrothermalism in the Es^4 coarse-grained siliciclastic rocks of the study area. The vertical evolution of

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clay minerals is characterized by an abnormal increase of illite/montmorillonite ratio and transient dramatic increase of kaolinite content. The contents of free hydrocarbon (S_1) and pyrolysis hydrocarbon (S_2) are abnormally high at a burial depth ranging from 3 400 m to 4 800 m, while they are relatively low at a burial depth of 5 500 m when the maximum pyrolysis temperature (T_{max}) is abnormally high. At a burial depth of 4 269 m to 4 800 m, there are abnormally high-temperature inclusions in quartz fractures. The $\delta^{13}C_{CO_2}$ in the carbon stable isotopes of natural gas is greater than -8 ‰, indicating inorganic origin and formation water of $NaHCO_3$ type as associated with the deep CO_2-rich hydrothermalism. The characteristics mentioned above all indicate deep fluid activity of mantle-derived CO_2-rich origin in the Es^4 coarse-grained siliciclastic rocks in Minfeng–Yanjia area during the Guantao-Minghuazhen sedimentary period. The deep hydrothermal fluid has played a dual role in reforming the physical properties of the coarse-grained siliciclastic reservoir. On the one hand, it causes fractures and promotes dissolution to improve the reservoir physical properties; on the other hand, the authigenic minerals in precipitation clog pores thereby hinder fluid migration and damage the physical properties of the reservoir. In addition, deep hydrothermal fluid has got involved in the thermal evolution and hydrocarbon generation of source rocks in the lower section of the 4th member of Shahejie Formation (Es^{4L}), which has a potential impact on hydrocarbon expulsion and crude oil cracking of the source rocks.

Key words: identification marker, hydrocarbon generation, reservoir modification, deep hydrothermal fluid, deep coarse-grained siliciclastic rock, the 4th member of Shahejie Formation (Es^4), Dongying Sag, Bohai Bay Basin

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随着深部热流体活动在众多沉积盆地内被发现，其在地质演化过程中所起到的作用、产生的影响日益引起人们的重视[1-5]。本文所探讨的深部热流体为盆地基底以下的热流体，包括深部地壳热流体和上地幔热流体，主要与岩浆-火山活动相关，具有高温和无机成因的特征[6]。深部热流体作用的结果在岩石矿物学上表现为产生与热流体相关的特征矿物，如片钠铝石、(鞍状/铁)白云石、绿泥石、黄铁矿和磷灰石等，且多呈组合方式产出[7-11]。异常高的地层温度、地温梯度或热流值也可以指示深部热流体活动，其中包裹体均一温度是目前最理想的流体示踪剂，能够记录流体活动时的温度背景或流体活动信息；同时，深部热流体通过溶解、萃取岩石中的有机质对Ⅰ型和Ⅱ型干酪根热解参数造成不同影响，可以用于判断流体来源[12-15]。在地球化学方面，常量和微量元素的富集或亏损、同位素组成特征、稀土元素的REE配分模式、ΣREE+Y含量、Ce异常以及Eu异常等均可以反映深部热流体活动[16-21]。

深部热流体作为下地壳和上地幔物质与能量的载体，影响盆地内油气生成、运移、成储和成藏全过程[22]。幔源富CO_2的深部流体以深大断裂为上升通道，其作为良好的热能载体，所携带的大量热能使烃源岩中的有机质快速降解，流体内的金属元素催化有机碳向烃类物质转化，从而促进烃源岩热演化进程[6,23-24]。深部热流体侵入储层后能够增强成岩流体的化学侵蚀能力，促进溶蚀作用的发生[25-27]，而流体活动引起的破裂作用除了能增加储集空间外，还能为流体运移提供通道，沿裂缝发生溶蚀作用使储层物性得到改善[16,28-30]。

相较于常规砂岩，砂砾岩成分和结构成熟度低，深部热流体活动作用的过程更为复杂和隐秘，目前对砂砾岩储层中的深部热流体作用识别和地质作用的研究尚处于探索阶段[31-34]。渤海湾盆地东营凹陷作为砂砾岩油气勘探的典型研究区块具有巨大的资源潜力，已发现该地区具多重成岩环境，存在与热流体相关的裂缝和矿物组合[26,29,35]，因此本文以东营凹陷北部陡坡带东段民丰—盐家地区古近系沙河街组四段(沙四段)砂砾岩储层为例，综合运用多种分析测试手段，开展深部热流体作用特征研究，并结合构造演化史、岩浆活动史、地层埋藏史和油气成藏史等研究成果，初步探讨其油气地质意义，为深入揭示深部热流体侵位下的有机质成烃和深层砂砾岩成储机理奠定基础。

1　地质背景和储层基本特征

民丰—盐家地区位于渤海湾盆地东营凹陷东北部(图 1a),其北部为陈家庄凸起,南邻中央隆起带,东部为青坨子凸起,西部为利津洼陷,构造和沉积演化受北部控陷Ⅰ级断层陈南断层控制(图 1c)。

东营凹陷新生代处于裂陷-拗陷阶段,该阶段与油气成藏过程直接相关。该凹陷古近纪整体为裂陷扩张期,自下而上发育孔店组、沙河街组和东营组,其中沙河街组由下至上可分为沙四段、沙三段、沙二段和沙一段(图 1d)。东营凹陷在孔店组-沙四下亚段(沙河街组四段下亚段)沉积时期为裂陷-扩张初期,受郯庐断裂带和陈南断裂活动影响,呈现“北断南超”特征;沙四上亚段—沙二下亚段沉积时期为裂陷-扩张鼎盛期,断层处于发育高峰;沙二上亚段—东营组沉积末期为裂陷-扩张衰退期,构造抬升剥蚀结束之后,盆地活动转变为拗陷阶段[38]。

东营凹陷发育孔店组二段、沙四段和沙三下亚段 3 套主力烃源岩,在沙三段沉积中期—沙二段沉积末期和馆陶组沉积期至今发生 2 期油气充注[38],且后者以充注凝析油伴生气和裂解干气为主[39-40]。沙四段沉积早期该凹陷气候条件以半干旱为特征,广泛发育一套稳定的膏岩层系,大量陆源碎屑物质伴随间歇性洪水注入湖区,沿着陈南断层下降盘形成了大套的近岸水下扇砂砾岩体,为民丰洼陷巨厚泥岩生成的油气提供了有利的储集体。近年来,民丰—盐家地区沙四段深层砂砾岩油气勘探取得了重大突破,预示东营凹陷深层具有良好的油气勘探前景。

民丰—盐家地区岩心样品物性分析结果显示,沙四段深层砂砾岩体储层岩石类型主要包括各粒级砂岩和砾岩,砂岩主要为岩屑长石砂岩,其次为长石岩屑砂岩和岩屑质长石砂岩,岩屑以变质岩岩屑为主(图 2)。颗粒分选和磨圆差-较差,支撑方式多样。杂基多为泥质,胶结物以碳酸盐和粘土矿物为主,多为孔隙-接触式胶结。全区深层砂砾岩孔隙度分布在 0.3 %~24.8 %,平均为 8.1 %,渗透率分布在 0.004×10^{-3}~$3\,550.170\times10^{-3}\ \mu m^2$,平均为 $18.940\times10^{-3}\ \mu m^2$,总体上为低孔、低渗储层。

2　深部热流体作用特征

2.1　岩石矿物学特征

深部热流体所具有的高温、富 CO_2 等酸性气体和深源溶解物质等特性,使流体和岩石之间发生显著的流-岩反应,改变原岩颜色、结构、构造乃至化学成分,沉淀出保留有深源性质的特征矿物(组合),可供直接追踪深部热流体的活动痕迹。

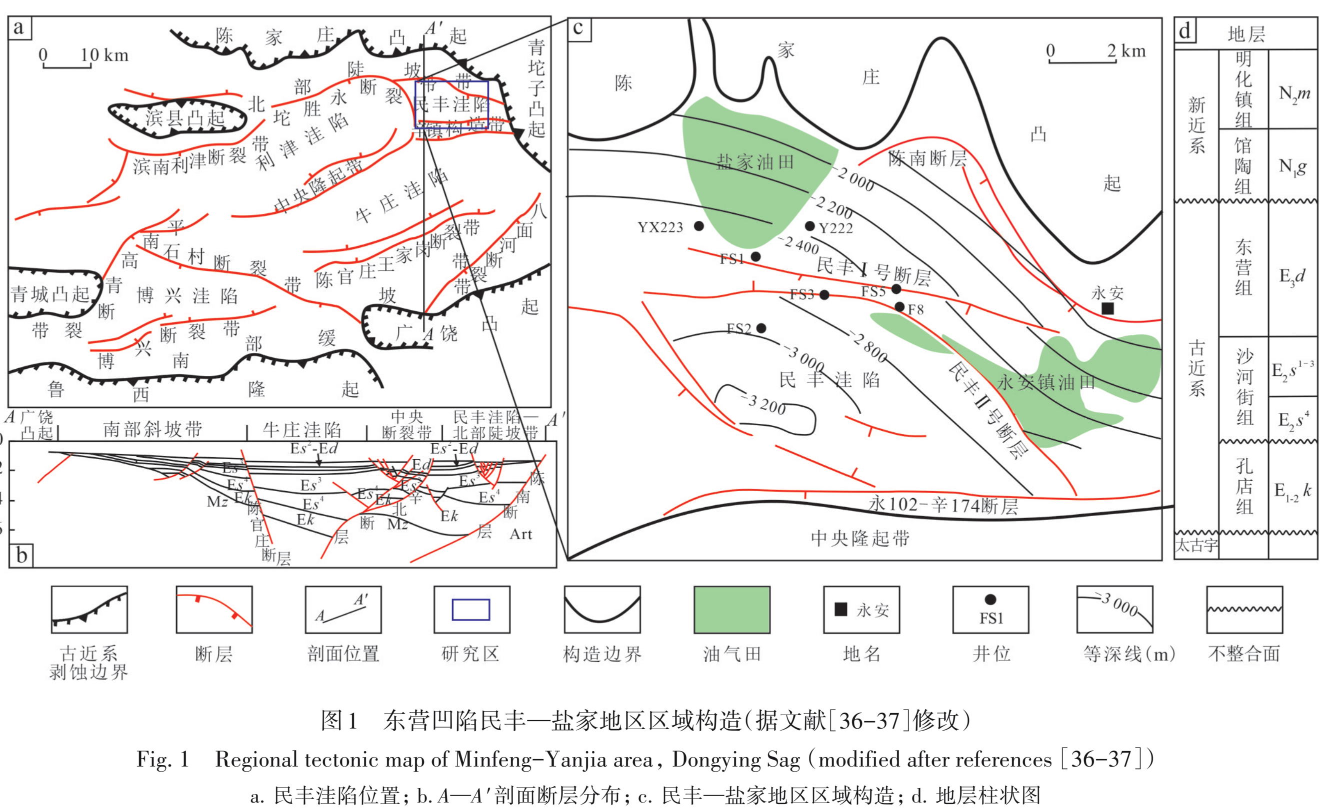

图 1　东营凹陷民丰—盐家地区区域构造(据文献[36-37]修改)

Fig. 1　Regional tectonic map of Minfeng-Yanjia area, Dongying Sag (modified after references [36-37])

a. 民丰洼陷位置; b. *A*—*A*′剖面断层分布; c. 民丰—盐家地区区域构造; d. 地层柱状图

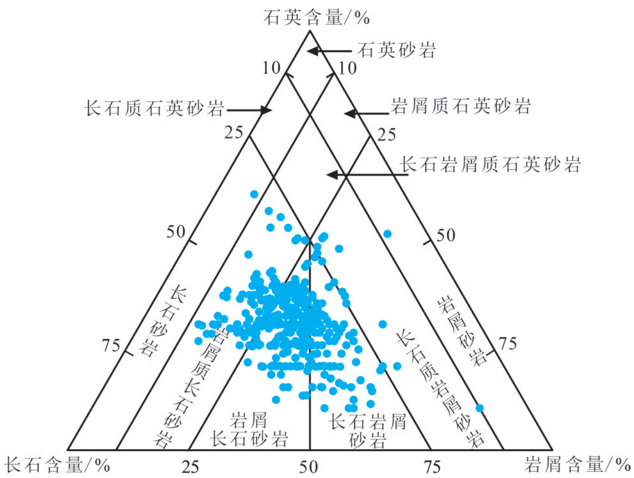

图2 民丰—盐家地区沙四段深层砂砾岩体砂岩类型组分三角图

Fig. 2 Ternary diagram showing sandstone compositions in the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng-Yanjia area

2.1.1 岩石学特征

岩心观察发现，民丰—盐家地区沙四段砂砾岩内常见爆裂角砾，多为灰岩砾石（图3a），且常伴生单质硫；岩心破开面上有时见自形黄铁矿晶粒（图3b），粒径在0.5～2.0 mm；此外，还常见砂砾岩内密集分布形态规则的溶蚀孔洞，疑为黄铁矿晶体溶蚀印痕（图3c）。这种现象可归因为深部热流体侵位造成瞬时高压，引起硬度较小的灰岩岩屑等砾石爆裂为多个边缘可相互拼接的角砾。热流体侵位早期形成的黄铁矿在后续高温条件下发生不协调溶解，被Fe^{3+}置换并与O_2和H_2O反应生成SO_4^{2-}，在离子溶解过程中，发生Fe离子扩散和S^{2-}溶解，形成单质硫[41-42]。

2.1.2 单矿物特征

薄片鉴定和扫描电镜观察表明，民丰—盐家地区沙四段深层砂砾岩内发育片钠铝石、磷灰石、立方体黄铁矿和鞍状白云石等与热流体作用相关的特征矿物。

片钠铝石呈放射状集合体生长于孔隙中（图3d），其形成需要富含Na^+，Al^{3+}以及高CO_2分压值的流体，常与深部热流体活动相伴生，是记录岩浆活动的指示性矿物[43]。磷灰石多呈斑晶短柱状、假六方体状（图3e，i）或呈长纤维簇状与黄铁矿共生（图3g），其作为岩浆和热液蚀变产物，是深部热流体作用的特征矿物。前人[44]将黄铁矿按照形态分成3类：Ⅰ类黄铁矿呈自形立方体，Ⅱ类黄铁矿为半自形立方体，Ⅲ类黄铁矿呈胶状或莓球状。一般认为Ⅰ类黄铁矿与高温热液成矿作用相关，因此黄铁矿的自形立方体形态可以指示热流体活动。Y222井埋深4 016.36 m处的黄铁矿形态为典型立方体特征（图3e），并与磷灰石、绿泥石等热流体特征矿物共生，说明其成因与深部热流体活动相关。FS1井埋深4 323 m处薄片中见鞍状白云石，其晶面弯曲呈马鞍状，具有波状消光（图3f），为热流体成因的矿物学特征[3,30,45]。

2.1.3 矿物组合特征

研究区沙四段砂砾岩内可见伊/蒙混层-磷灰石-黄铁矿（图3e）、磷灰石-黄铁矿（图3g）、流纹状绿泥石-磷灰石-黄铁矿（图3h）和伊/蒙混层-铁白云石-磷灰石（图3i）等矿物组合。鉴于磷元素为地幔流体的重要组成[46]，以磷灰石为特征的矿物组合反映了研究区沙四段砂砾岩受到过来自幔源的深部热流体作用。

2.1.4 粘土矿物特征

粘土矿物X射线衍射分析结果表明，研究区沙四段砂砾岩粘土矿物（组合）主要包括伊/蒙混层、伊利石、高岭石和绿泥石。高岭石在埋深3 500 m以浅含量始终较高，而对温度最为敏感的伊/蒙混层比值在该深度段内两次从20 %增大至75 %。埋深大于3 800 m之后，伊利石和绿泥石含量均较高，高岭石含量出现短暂激增，且伴随出现热流体特征矿物及溶蚀现象（图3b，f，k），反映其可能受突发富酸性深部热流体作用；而流体中富含的大量Fe离子和Mg离子，有利于绿泥石生成，从而造成绿泥石和高岭石共存的现象（图4）。由上可知，伊/蒙混层转化异常、深层高岭石含量的变化和粘土矿物共生组合也标记着研究区发生过深部热流体活动。

2.2 烃源岩热解参数特征

民丰—盐家地区沙四段泥岩有机质干酪根类型为Ⅰ型和Ⅱ型。Ⅰ型和Ⅱ型干酪根在受到热流体高温影响时，最大热解温度（T_{max}）、游离烃含量（S_1）和热解烃含量（S_2）会发生异常变化[30,47]。通常表现为T_{max}异常高，而S_1和S_2较低；或T_{max}无异常变化，S_1和S_2异常高[30]。

分析研究区有机质热解参数随深度变化特征发现：FS2井和F8井在埋深3 400～4 800 m，T_{max}在400～450 ℃，为正常值，S_1和S_2异常高；FS2井在5 500 m以深，T_{max}超过500 ℃，为异常高值，S_1和S_2却异常低（图5）。

造成上述现象的原因在于深部热流体具有的高温能够促使成熟度已然较高的有机质发生过演化，导致T_{max}异常增大而S_1和S_2却极低；同时由于深部热流体具有强烈的化学活动性，能不断萃取地层中的分散有机

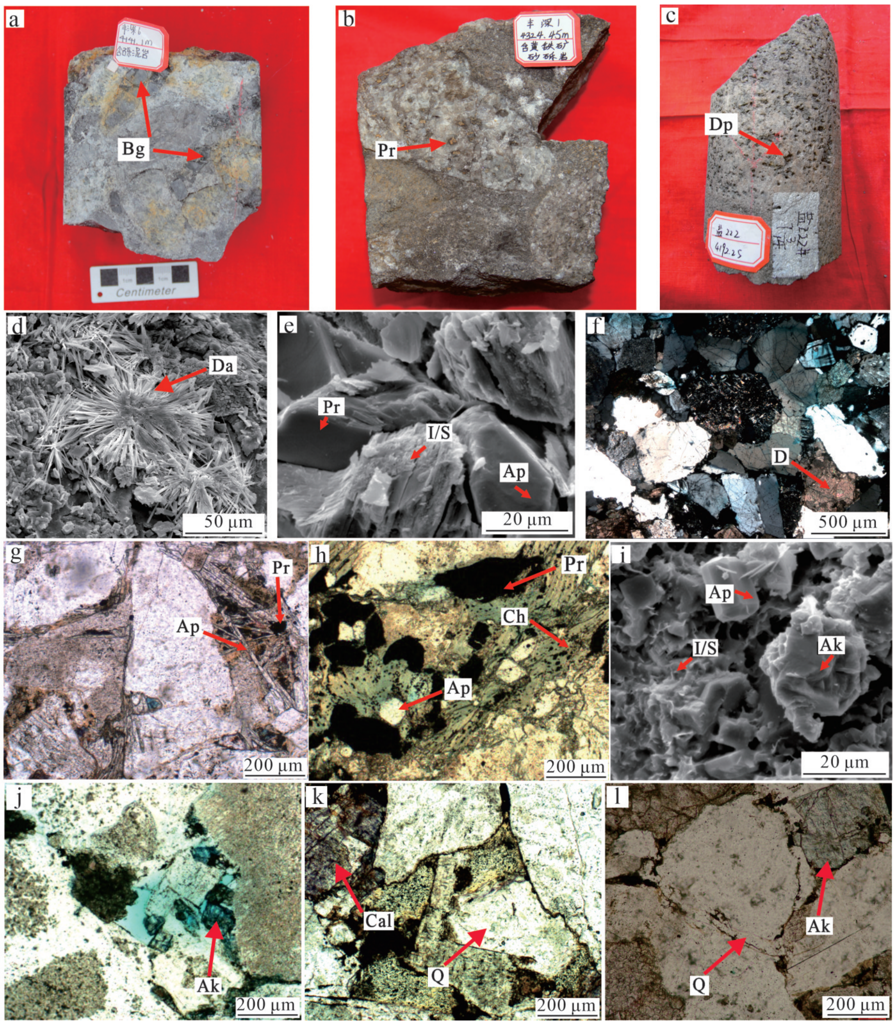

图3　民丰—盐家地区沙四段深层砂砾岩中深部热流体作用的岩石矿物学特征

Fig. 3　Images showing the petrological and mineralogical characteristics caused by deep hydrothermalism in the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng-Yanjia area

a. 爆裂角砾(Bg),埋深4 141.10 m,FS6井,岩心照片;b. 自形黄铁矿(Pr),埋深4 324.45 m,FS1井,岩心照片;c. 溶蚀孔洞(Dp),埋深4 192.25 m,Y222井,岩心照片;d. 片钠铝石(Da),埋深4 866.11 m,FS3井,扫描电镜;e. 伊/蒙混层(I/S)-磷灰石(Ap)-黄铁矿(Pr)组合,埋深4 016.36 m,Y222井,扫描电镜;f. 鞍状白云石(D),埋深4 323.20 m,FS1井,正交光;g. 磷灰石(Ap)-黄铁矿(Pr)组合,埋深3 502.20 m,Y22-22井,单偏光;h. 流纹状绿泥石(Ch)-磷灰石(Ap)-黄铁矿(Pr)组合,埋深4 495.00 m,FS1井,单偏光;i. 伊/蒙混层(I/S)-铁白云石(Ak)-磷灰石(Ap)组合,埋深4 075.25 m,Y222井,扫描电镜;j. 铁白云石(Ak)菱形晶型完整,埋深4 348.25 m,FS1井,单偏光;k. 长石被溶蚀后方解石(Cal)交代长石,其后石英(Q)发生次生加大,埋深4 323.80 m,FS1井,单偏光;l. 铁白云石(Ak)交代长石填充孔隙,其后发生石英次生加大,埋深4 322.40 m,FS1井,单偏光

质,加之深部热流体的加氢作用,使有机质在流体中不断富集,表现为T_{max}虽无异常变化而S_1和S_2升高[47]。由此可见,烃源岩热解参数呈现的上述异常变化反映了研究区沙四段砂砾岩经历过深部热流体活动。

2.3　流体包裹体均一温度特征

盐水包裹体可以反映储层成岩过程及储层与地下流体相互作用的历史,并能提供流体成分、来源、演化、盐度和压力等诸多信息[14-15,48]。通过统计研究区沙四段砂砾岩盐水包裹体均一温度分布特征,发现在埋深4 269~4 800 m的储层中包裹体均一温度峰值区间为120~140 ℃和150~160 ℃(图6),与其古地温相适应,但在FS1井埋深4 322 m处石英裂缝中的盐水包裹体均一温度最高可达180 ℃[49],远高于原地古地温。

2.4　地球化学特征

除盐水包裹体外,在FS1井埋深4 321.7 m处检测到石英裂缝中存在一幕不发光的纯气相包裹体,推测为天然气成因[50]。前人通过拉曼光谱分析研究区包裹体成分,发现FS1井、FS3井和F8井内包裹体有烃类流体和CO_2流体共存的特征[48]。油田实测资料表明,CO_2流体出现的深度范围在FS1井中为4 300~

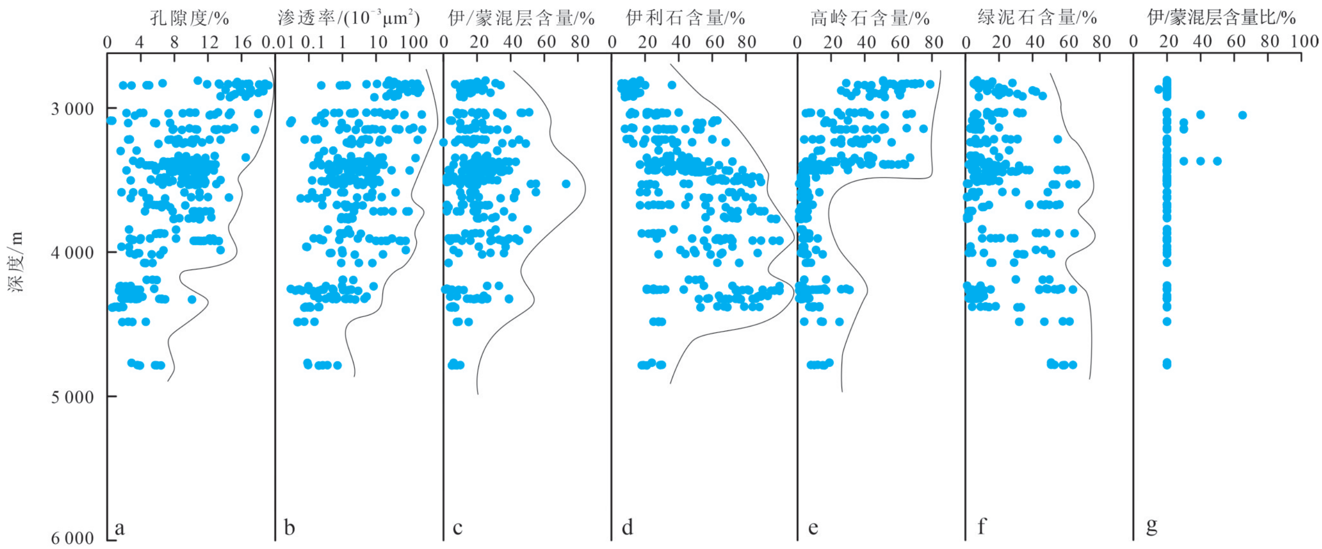

图4 民丰—盐家地区沙四段深层砂砾岩物性和自生粘土矿物含量随深度变化散点图

Fig. 4 Scatter diagrams showing physical properties and authigenic clay minerals contents with depth in the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng-Yanjia area

a. 孔隙度-深度关系; b. 渗透率-深度关系; c. 伊/蒙混层含量-深度关系; d. 伊利石含量-深度关系; e. 高岭石含量-深度关系; f. 绿泥石含量-深度关系; g. 伊/蒙混层含量比-深度关系

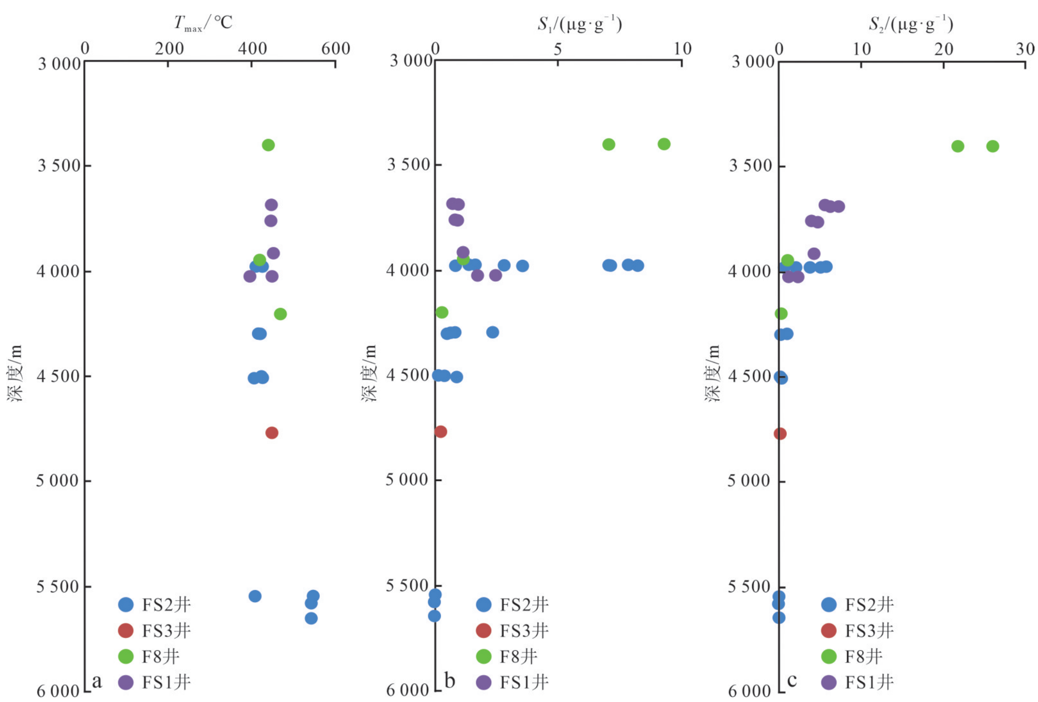

图5 民丰—盐家地区沙四段有机质热解参数特征

Fig. 5 Characteristics of pyrolysis parameters of organic matters in the Es^4 in Minfeng-Yanjia area

a. T_{max}-深度关系; b. S_1-深度关系; c. S_2-深度关系

4 350 m,在FS3井中为4 780~4 870 m,在F8井中为4 170~4 190 m。进一步研究发现,FS1井4 314~4 343 m和4400 m埋深处的天然气稳定碳同位素中$\delta^{13}C_{CO_2}$值大于-8‰,根据前人提出的CO_2成因判别模式[51],判断其具有无机成因特征,推测为深部形成的CO_2沿深大断裂运移到气藏所致[40]。

此外,研究区沙四段地层水在埋深4 170~4 343 m,4 768~4 850 m和5 600 m附近具高矿化度,最高可达296.578 g/L。且上述深度段地层水中K^++Na^+和HCO_3^-浓度较高,FS1井、FS2井和Y222井呈现出高矿化度的$NaHCO_3$型地层水特征(图7)。高矿化度的$NaHCO_3$型地层水通常被认为与富CO_2热流体作用

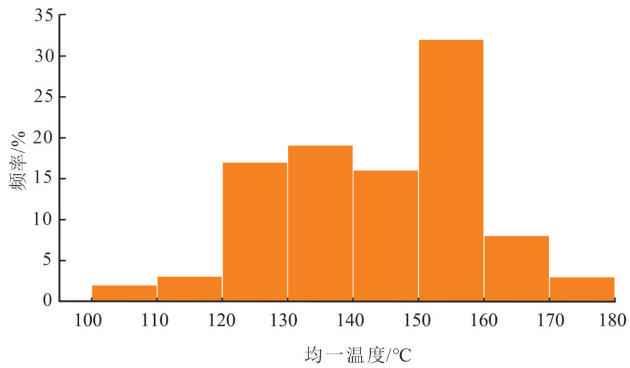

图6　民丰—盐家地区沙四段深层砂砾岩流体包裹体均一温度分布直方图

Fig. 6　Histogram showing homogenization temperatures of fluid inclusions in the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng-Yanjia area

相关[30,52-53]，尽管研究区沙三段与沙四段地层水的混合作用亦可以形成该类地层水，但因其深度与深部热流体特征矿物、烃源岩热解参数异常和无机 CO_2 流体的分布深度有较好的对应关系，亦可以作为研究区上述井段内发生过深部热流体活动的佐证。

3　深部热流体来源及作用时间

3.1　岩浆活动时间

东营凹陷活跃的岩浆活动和新生代以来的构造运动为深部热流体及其活动提供了来源和通道条件。

东营凹陷新生代发生过 3 期深部热流体活动，分别为孔店组-沙四段沉积时期的碱性玄武岩火山活动，沙三段—东营组沉积时期由断裂活动引起的橄榄拉斑玄武岩喷发，以及馆陶组沉积期之后沿断裂带发生的流体活动[54]。东营凹陷深部地幔物质上涌至地壳形成岩浆房，使陈家庄凸起下方的中、下地壳明显加厚，而控盆断裂在新生代发生的拉张活动有利于富含 CO_2 等组分的地幔岩浆释放，沿深大断裂侵入地层[55]。沿利津—陈家庄—东营机场一线零星分布的较小规模的火成岩岩体[56]，以及永 1 井砂砾岩体内厚度近 50 m、面积约 1 km^2 的辉绿岩侵入[57]，均为岩浆活动的直接记录。

渤海湾盆地古近纪拉张活动强烈，加之热地幔柱上升使上地幔温度升高、密度变小，壳幔边界之上的地壳厚度增大[58]。强烈的构造活动使陈南断层东段在古近纪早-中期表现为张性伸展正断层，而在古近纪后期区域构造环境转变为挤压环境，在深部地壳厚度增大、NEE 向区域挤压的控制之下，断层反转为逆冲断层[59]。在此过程中，陈南断层南侧衍生出多条呈 NE 方向展布的二台阶断裂，影响了民丰洼陷的构造格局[60]（图 1d），也成为深部热流体进入盆地的良好通道。

3.2　成岩演化特征

根据成岩矿物演化特征可以推测深部热流体活动的时间。按照中华人民共和国石油天然气行业标准碎屑岩成岩阶段划分规范（SY/T 5477—2003），以镜质体反射率（R_o）、古地温、伊/蒙混层含量比、粘土矿物组合、自生矿物发育等为主要依据，将民丰—盐家地区沙

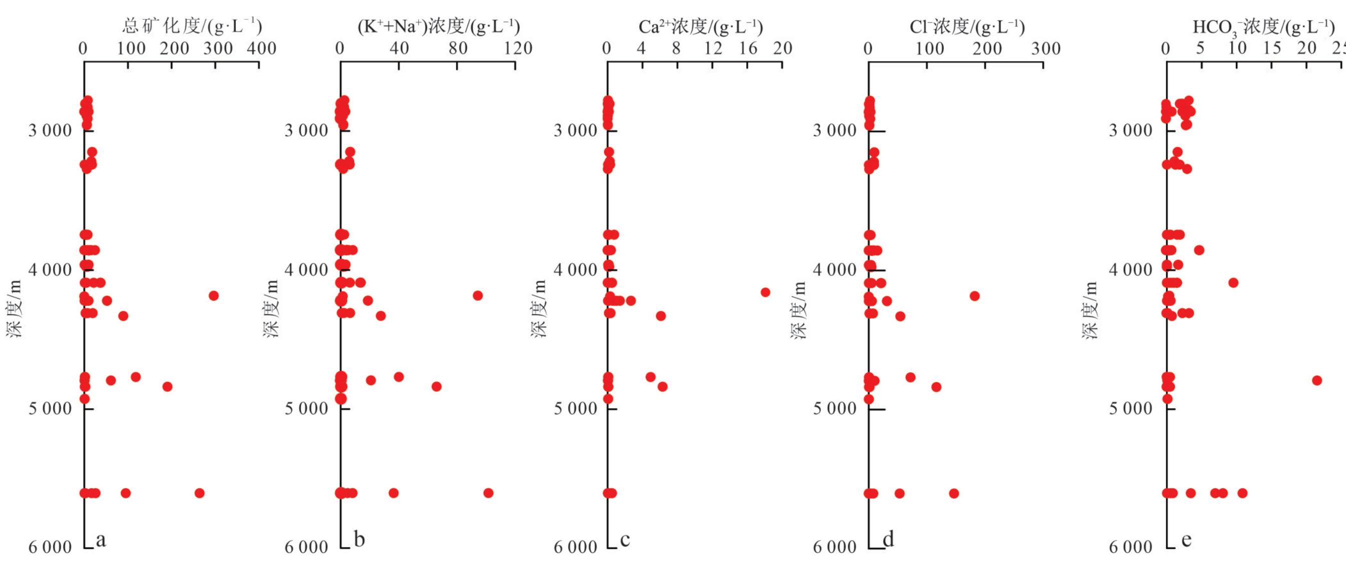

图7　民丰—盐家地区沙四段现今地层水性质

Fig. 7　Physical properties of present formation water in the Es^4 in Minfeng-Yanjia area

a. 总矿化度-深度关系；b. (K^+ + Na^+)浓度-深度关系；c. Ca^{2+}浓度-深度关系；d. Cl^-浓度-深度关系；e. HCO_3^-浓度-深度关系

四段深层砂砾岩经历的成岩作用阶段划分为中成岩A_1、中成岩A_2和中成岩B三个阶段(图8a)。

研究区中成岩A_2初期的自生矿物以富集的自生绿泥石和晚期碳酸盐矿物为主(图4,图8a)。中成岩A_2中期,高岭石含量出现短暂激增,FS1井除可见鞍状白云石、磷灰石和立方体黄铁矿等热流体特征矿物外(图3b,f,h),还有长石溶蚀和石英次生加大等酸性介质条件下的成岩现象(图3j—l)。另外,Y222井和Y22-22井内深部热流体特征矿物磷灰石和立方黄铁矿晚于绿泥石、伊/蒙混层等自生粘土矿物产出(图3e,i),并且见黄铁矿交代石英等碎屑颗粒。上述成岩演化特征表明研究区深部热流体活动最早发生于中成岩A_2中期,且造成酸性流体突发富集,使成岩环境发生由碱性向酸性的转变。

3.3 深部热流体作用时间

根据民丰—盐家地区构造演化史[38]、包裹体均一温度和镜质体反射率(R_o)等恢复地层埋藏史(图8b)。结合岩浆活动时间、成岩演化特征和油气充注历史研究成果[39],推断研究区沙四段砂砾岩在馆陶组-明化镇组沉积时期(中成岩A_2中期,早于第二次油气充注)开始经历富CO_2的幔源流体活动。来自岩浆房的深部热流沿陈南断层进入深部储层后向上运移,参与成岩、成藏和成储过程(图8c)。

4 深部热流体地质意义初探

4.1 对储层物性具有双重影响

深部热流体通过改变成岩场的温度、压力和孔隙水介质条件影响水-岩反应过程,加剧成岩作用对砂砾岩储层的改造或直接参与孔隙演化过程[11,22,61-64],对其产生建设性和破坏性的双重改造效应。

4.1.1 建设性影响

岩心物性分析结果表明,研究区沙四段发育多个次生孔隙带(图4)。进一步分析沙四段深层砂砾岩的孔隙度-渗透率关系散点图发现(图9),其渗透率随孔隙度变化分为两支。其中低孔隙度、较高渗透率的样品深度集中于受深部热流体侵位的4 000~4 500 m,镜下观察发现砂砾岩内微裂缝普遍发育(图10a)。微裂缝的形成与深部热流体侵入储层引起骨架颗粒发生脆性破裂,以及热流体持续注入增温、增压促使地层温度升高而引起的砾、粗砂等颗粒发生碎裂密切相关。广泛发育的微裂缝为流体和烃类提供了有效运移通道,使储层渗透性得以改善。

同时,深部热流体携带的深源物质和CO_2、H^+等进入砂砾岩中可以促进长石颗粒和碳酸盐胶结物等易溶组分发生强烈溶蚀,形成大量酸溶性或碱溶性孔隙,改善储层物性(图10b—d)。例如,在FS3井4 750 m以深发育的次生孔隙发育带内,长石的溶蚀作用较为显著,溶蚀孔隙相对发育(图10b)。

4.1.2 破坏性影响

深部热流体中溶解有大量深源金属离子,其进入储层后会因温压下降发生沉淀,加之受酸性热流体溶解析出的离子不能及时带出,会在孔隙、裂缝中形成标记热流体活动的自生矿物和含铁碳酸盐矿物,降低孔隙度,损害储层物性。

如FS3井4 800 m以深,深部热流体参与成岩反应,随着CO_2的不断消耗,孔隙内Na^+和Al^{3+}含量增多,流体向碱性转变,引起片钠铝石沉淀,以放射状、菊花状充填于颗粒之间或先期形成的溶蚀孔隙内,使孔隙减小(图3d,图10e)。而随温度、压力和流体的迁移变化,石英颗粒发生次生加大,造成孔隙流体中Fe和Mg离子含量增多,导致大量铁碳酸盐类矿物、自生黄铁矿和绿泥石沉淀而使先生孔隙丧失殆尽(图10f)。

4.2 对油气成藏具有潜在影响

馆陶组沉积中期后,民丰洼陷沙四下亚段烃源岩再次达到生烃门限并开始大量生烃[65],深部热流体作为深源物质和能量的载体必然对油气成藏过程构成重要影响。

研究区沙四段硫酸盐矿物中硫元素$\delta^{34}S$明显偏正[66]。薄片观察发现硬石膏发生明显的溶蚀,固体沥青充填硬石膏解理缝和溶蚀孔隙(图10g,h),表明在热作用下油气与硬石膏可能发生了硫酸盐热化学还原反应(TSR)[6,67-68],反应式如下[69]:

$$\text{烃类}+CaSO_4 \rightarrow CaCO_3+H_2S(HS^-)+CO_2(HCO_3^-)+H_2O \quad (1)$$

随着深部热流体的注入,其具有的高温和能量既对有机质生烃起到了催化作用,又使TSR反应向相反方向进行,生成硫酸盐和甲烷,使$\delta^{13}C_{CH_4}$升高[6],促进天然气生成。

研究区沙四段岩石薄片内可见沥青质填充孔隙。如在FS1井中发现有大量沥青聚集,沥青的分布形态呈黑色流动状或边缘清晰的角砾状,与颗粒镶嵌接触(图10i),且填充度较高,表现为明显的焦沥青特征,

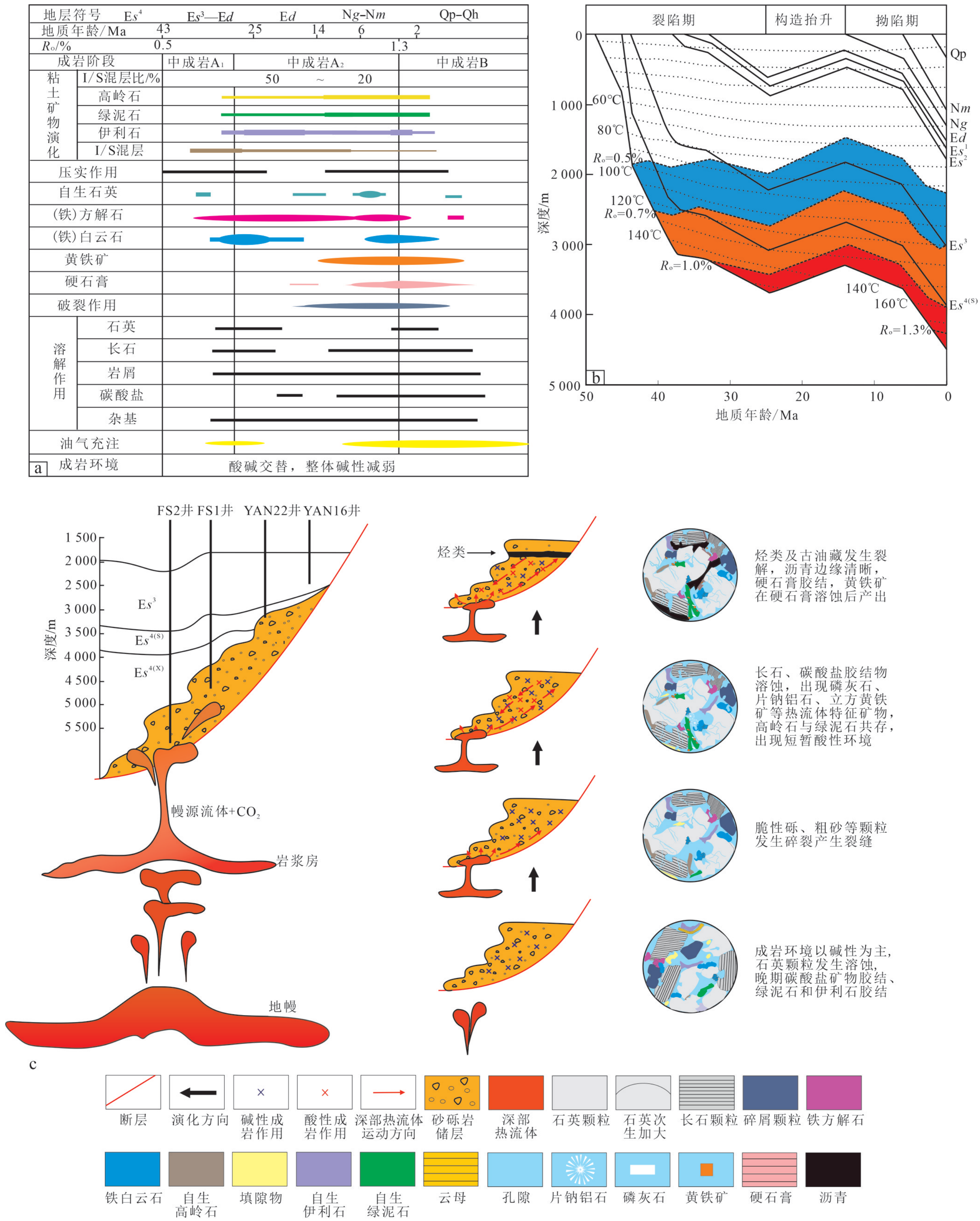

图 8　民丰—盐家地区沙四段深层砂砾岩热流体活动及成岩演化模式

Fig. 8　Diagrams showing the deep hydrothermal activities and diagenetic evolution models of the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng–Yanjia area

a. 成岩作用阶段划分; b. 地层埋藏史; c. 成岩、成藏和成储过程

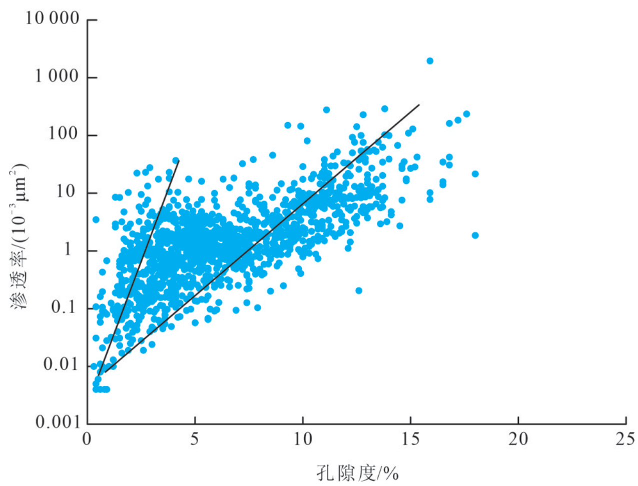

图9 民丰—盐家地区沙四段深层砂砾岩孔隙度-渗透率关系

Fig. 9 Scatter diagram of porosity vs. permeability in the deep coarse-grained siliciclastic rocks of the Es^4 in Minfeng-Yanjia area

为东营组沉积末期古油藏发生原油裂解所致[39]。而深部热流体活动带来的高温有利于裂解反应的发生，并对古油藏进行破坏，从而影响研究区油气藏分布格局[65]。

受幔源CO_2流体活动影响的地区，其烃源岩正构烷烃分布呈现后峰型，未受幔源CO_2流体活动影响的地区烃源岩样品则显示出圆滑前峰型特征[70]。根据研究区油气成藏史[39]，FS3井埋深在4 740.00～4 846.75 m的油气以原油裂解气和干酪根混合成因气产出，同时在该深度内具有富CO_2气源存在的特征[48]，而FS3井埋深4 769.70 m及4 768.75 m处的饱和烃气相色谱中，正构烷烃分布均展现出与受幔源CO_2流体活动影响相似的后峰型特征(图11)，表明深部热流体活动可对烃源岩排烃产生影响。

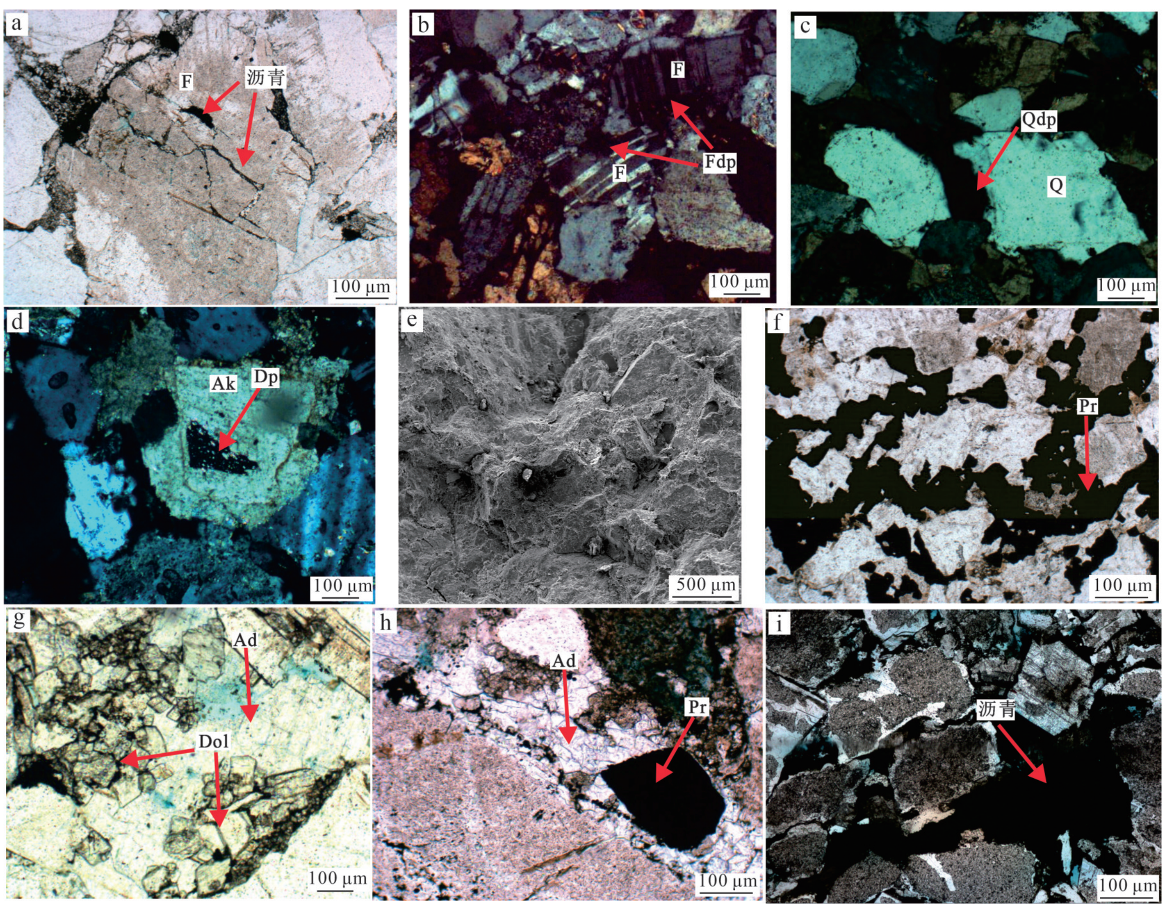

图10 民丰—盐家地区沙四段深层砂砾岩对深部热流体活动的响应特征

Fig. 10 Response characteristics of the deep coarse-grained siliciclastic rocks of the Es^4 to deep hydrothermal activities in Minfeng-Yanjia area

a. 长石(F)内发育破裂缝，裂缝内有沥青残留，埋深4 181.23 m，F8井，单偏光；b. 长石溶蚀作用显著(Fdp)，埋深4 784.70 m，FS3井，正交光；c. 石英(Q)颗粒直接溶蚀(Qdp)，埋深4 200.43 m，F8井，正交光；d. 铁白云石(Ak)内发育溶蚀孔隙(Dp)，埋深4 323.20 m，FS1井，正交光；e. 孔隙不发育，埋深4 784.90 m，FS3井，扫描电镜；f. 自生黄铁矿(Pr)填充孔隙，埋深3 502.20 m，Y22-22井，单偏光；g. 自生白云石(Dol)晚于硬石膏(Ad)出现，硬石膏溶蚀，埋深4 181.23 m，F8井，单偏光；h. 黄铁矿(Pr)晚于硬石膏(Ad)出现，埋深4 181.23 m，F8井，单偏光；i. 沥青填充孔隙，埋深4 323.30 m，FS1井，单偏光

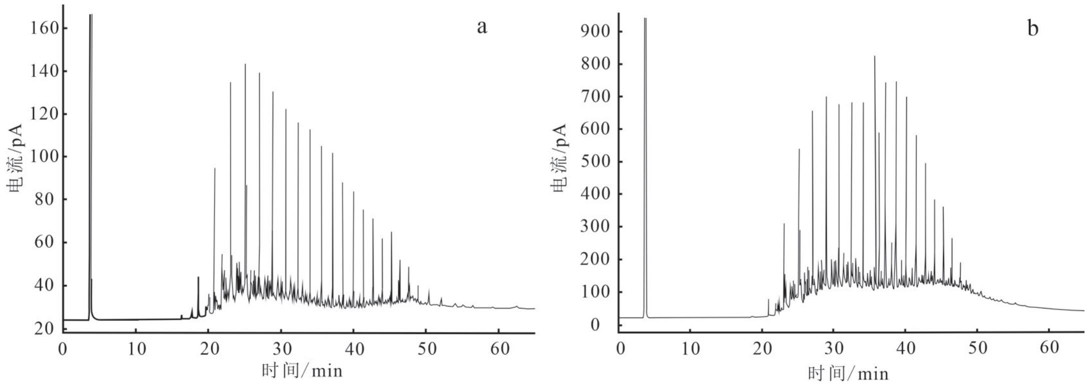

图11　民丰—盐家地区FS3井沙四段原油中饱和烃气相色谱

Fig. 11　Gas chromatogram of the saturated fraction of crude oil sample from the Es^4 in Well FS3, Minfeng-Yanjia area

a. 埋深4 769. 70 m; b. 埋深4 768. 75 m

5　结论

1) 民丰—盐家地区沙四段深层砂砾岩中有指示深部热流体活动的矿物学、古地温和地球化学标记。

2) 沙四段砂砾岩在馆陶组-明化镇组沉积时期经历了富CO_2幔源成因的深部流体活动。

3) 深部热流体对储层物性具有建设性和破坏性双重改造作用,并对油气成藏过程具有潜在影响。因此以动态双重改造机理为理论认识基础,从埋藏深度和平面分布多维度总结深部热流体建设改造深层砂砾岩储层的规律为下一步研究重点。

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