第43卷 第3期 2025年6月
沉积学报 ACTA SEDIMENTOLOGICA SINICA
Vol.43 No.3 Jun.2025

文章编号:1000-0550(2025)03-1059-13

吐哈盆地深部砂岩储层方解石胶结及成储效应

徐慧[1,2],程甜[3],陈安清[1],徐胜林[1],陈旋[3],武超[3],杨帅[1],李富祥[1],周港[1]

1.成都理工大学深时地理环境重建与应用自然资源部重点实验室,成都 610059
2.安徽省勘查技术院,合肥 230031
3.中国石油吐哈油田公司,新疆哈密 839009

摘 要 【**目的**】吐哈盆地鲁克沁地区上二叠统梧桐沟组具备良好的油气勘探潜力,是深层勘探重点层系。成岩作用分析显示方解石胶结物是该地区梧桐沟组储层发育的主要自生矿物之一,但对于其成岩期次及其如何影响储层质量缺乏研究。【**方法**】通过薄片鉴定、物性分析、扫描电镜、阴极发光等测试方法,对鲁克沁地区上二叠统梧桐沟组深埋砂岩储层中普遍存在的方解石胶结物期次及成岩演化进行系统研究,探讨方解石胶结物对储层质量的影响。【**结果**】鲁克沁地区梧桐沟组储层的方解石胶结物面积含量在1.0%~8.0%最有利于储层发育,高于等于8.0%的样品显示原生孔几乎被方解石等充填殆尽,低于等于1.0%的样品表现为压实作用过于强烈而不利储层发育;显微镜下的充填关系指示了三期方解石胶结物,Ⅰ期泥晶方解石,含量占比为25%;Ⅱ期连晶胶结方解石,含量占比为60%;Ⅲ期为长石等粒内溶孔充填状方解石,含量占比为15%。方解石胶结物含量与物性没有明显的相关性,说明其主要为保持性成岩作用,以孔隙充填形式出现,占据剩余粒间孔的同时又能增强碎屑颗粒骨架的抗压实能力。【**结论**】方解石胶结物是鲁克沁地区梧桐沟组深部砂岩储层发育的关键因素。

关键词 方解石胶结物;胶结作用;深埋砂岩储层;梧桐沟组;吐哈盆地

第一作者简介 徐慧,女,1996年出生,硕士研究生,沉积学,E-mail: xuhui752@163.com

通信作者 陈安清,男,教授,博士生导师,E-mail: aqinth@163.com

中图分类号 P618.13 **文献标志码** A

DOI: 10.14027/j.issn.1000-0550.2023.057

CSTR: 32268.14/j.cjxb.62-1038.2023.057

0 引言

方解石胶结物是大多数碎屑岩中含量较为丰富的自生胶结物之一[1],是成岩过程中流体—岩石相互作用的产物[2-4],其相对含量、产状类型、赋存状态及形成机制等对储层质量有重要影响[5-7]。因此,方解石胶结物的物质来源及其对储层质量的影响一直是近些年的研究热点[8-9]。以往研究表明,方解石胶结物的沉淀可以发生在成岩作用的各个阶段[10-11],方解石胶结物的来源通常包括碳的来源和钙离子的来源[12],其中,碳源包括海洋、湖泊和大气降水、有机质成熟度、岩浆源和细菌硫酸盐还原等[13-15];钙源可能来源于地表水、碎屑颗粒(长石、碳酸盐岩屑等)的溶解、黏土矿物的转化、长石等铝硅酸盐矿物的水化作用等[16-20]。一般认为,方解石胶结物对孔隙的充填使得储层的孔隙度和渗透率大大降低[21-22];同时,也有学者认为不同期次的方解石胶结物对储层质量具有不同的影响,如早期在机械压实作用前或浅埋藏阶段析出的方解石胶结物能增强碎屑骨架,有效抵御压实作用,随后发生溶蚀作用促进次生孔隙的形成[23-25],而在晚期所形成的铁方解石沉淀充填粒间或粒内孔隙,导致储层物性变差。因此,方解石胶结物对储层质量的影响是复杂的[26-27]。

鲁克沁地区是吐哈盆地油气勘探的重要区域。目前,在浅埋藏深度已取得了较好的油气勘探效果,揭示出该地区具备良好的沉积物质基础与成藏条件[28-31]。随着油气勘探与研究工作的持续深入,逐步向更深区域的二叠系梧桐沟组等层系寻求资源。2018年,在鲁克沁地区埋藏5 800~6 100 m深度的YT1井梧桐沟组中获得油气发现,初步揭示了梧桐沟

收稿日期:2022-11-17;**修回日期**:2023-07-02;**录用日期**:2023-07-26;**网络出版日期**:2023-07-26

基金项目:国家自然科学基金项目(42272132);四川省科技计划项目(2023NSFSC1986)[**Foundation**: National Natural Science Foundation of China, No. 42272132; Sichuan Provincial Science and Technology Program Project, No. 2023NSFSC1986]

组深层致密砂岩较好的油气勘探前景。当前该组的勘探程度非常低、研究非常薄弱，仅有的少量研究认为深埋条件下机械压实和胶结作用是导致鲁克沁地区梧桐沟组砂岩储层致密的两个主要因素[32]。然而，对黏土矿物、方解石、硅质等多种不同的胶结作用缺乏针对性研究。通过储层胶结物分析发现，研究区梧桐沟组深层砂岩储层发育不同产状的方解石胶结物，并且不同方解石胶结物含量的储层物性具有显著差异。分析不同期次方解石胶结物的发育程度，及哪期是建设的、哪期是破坏性的成岩作用对明确方解石胶结物对储层物性的潜在影响和储层预测具有重要意义。

因此，本文选取方解石胶结物为对象，基于岩心观察、物性分析、薄片鉴定、扫描电镜、阴极发光等测试分析，系统开展鲁克沁地区上二叠统梧桐沟组深埋储层特征研究，详细观察砂岩中方解石胶结物的赋存状态及产状，明确方解石胶结物发育特征及期次，探讨方解石胶结物成岩演化及其对储层质量的影响。

1 地质背景

鲁克沁地区位于吐哈盆地西部地区，主体处于台北凹陷，西南为鲁西凸起，东南为库木凸起(图1)，东西长40 km，南北宽10~20 km，面积约为800 km^2[34]。鲁克沁地区自下而上发育3套含油层系[35-37]：依次为二叠系(梧桐沟组P_3w)、三叠系(克拉玛依组$T_{2\text{-}3}k$)、侏罗系(西山窑组J_2x、三间房租J_2s、七克台组J_2q)。在第四次资源评价中[38]，吐哈盆地下含油气系统石油地质资源量为5.25×10^8 t，其中二叠系为2.19×10^8 t，三叠系为3.06×10^8 t，勘探潜力大，且主要集中在台北凹陷。

鲁克沁地区是台北凹陷唯一且最大的稠油富集带，勘探面积约为1 160 km^2，是吐哈盆地台北凹陷油气勘探开发的重点地区。自1995年AC1井发现稠油油砂，三叠系克拉玛依组一直是鲁克沁地区主要稠油勘探目的层系[39-41]。2012年，吐玉克区块YB1井上二叠统梧桐沟组首次发现稠油藏，并成为该地区的主要产油层之一。目前已发现鲁克沁地区二叠系和三叠系三级石油地质储量2.36×10^8 t，其中探明储量1.47×10^8 t，具有良好的油气勘探潜力。

鲁克沁地区上二叠统梧桐沟组早期表现为断陷和盆地，具有较高的可容纳空间和充足的物源供给背景，沉积巨厚层扇三角洲水下河道砂砾岩，砂体受沟槽控制，横向尖灭较快；中晚期转变为构造较为稳定的凹陷盆地辫状河三角洲沉积，砂体受坡折带控制，发育相对较薄但横向延展较广[34]。纵向上，梧桐沟组自下而上可分为一段、二段和三段(图1c)。梧桐沟组一段以分选磨圆较差、快速混杂堆积的扇三角洲砂砾岩为主，常见块状层理、平行层理、板状交错层理以及底冲刷等沉积构造，表明沉积时水动力强；梧桐沟组二段以中细砂岩和滨浅湖沉积为特征，发育棕红色泥岩，反映水动力较弱；梧桐沟组三段下部部分发育深灰色砂砾岩，砾石磨圆较好、但分选差，反映了早期有较强水动力，物源供给再次加强[42]。储集层主要集中在梧桐沟组一段和三段。

2 砂岩储层特征

2.1 储层岩石类型及方解石胶结物特征

鲁克沁地区梧桐沟组深部储层砂岩类型主要为岩屑砂岩和长石岩屑砂岩，显微镜下估算的石英含量介于27.0%~62.5%(均值为46.7%)、长石含量介于2.3%~27.5%(均值为10.6%)、岩屑含量介于25.0%~56.2%(均值为42.7%，主要为泥岩、千枚岩及花岗岩岩屑)；碎屑颗粒次圆—次棱状，分选中等—好，以点接触和线接触为主。全岩X射线衍射结果分析显示，梧桐沟组深层砂岩石英含量均值为42.8%，长石含量均值为22.7%，且斜长石含量高于钾长石。填隙物均值为9.7%，主要由碳酸盐胶结物、浊沸石和黏土矿物组成，黏土矿物含量较低。X射线衍射结果表明黏土矿物主要为绿泥石(均值为51.5%)，其次为伊蒙混层(均值为26.9%)，高岭石和伊利石含量基本一致。

鲁克沁地区梧桐沟组储层普遍发育方解石胶结物，是该致密储层的一个典型特征。为了深入分析方解石胶结物的发育特征，将梧桐沟组65件岩心样品制成的普通薄片并用铁氰化钾和茜素红染色剂进行染色，在偏光显微镜下观察方解石胶结物产状；再利用CL8200MK5发光显微系统，在18 kV、200 UA、温度20 ℃，相对湿度60%的工作环境下，对具有代表性的48个含碳酸盐胶结物的岩心样品进行阴极发光(CL)观察。显微镜下鉴定出3种方解石胶结物类型，包括泥晶方解石(图2a~d)、连晶方解石(图2d~f)和铁方解石(图2f~i)。泥晶方解石含量较低，充填在颗粒之间，呈蠕虫状，染色薄片镜下为红色，阴极发光呈暗橙色(图2b)；连晶方解石含量占主导，充填粒间孔隙使颗粒呈漂浮状，相邻粒间孔所充填的该类方解石具有一致的解理，表面干净，单偏光染色薄片

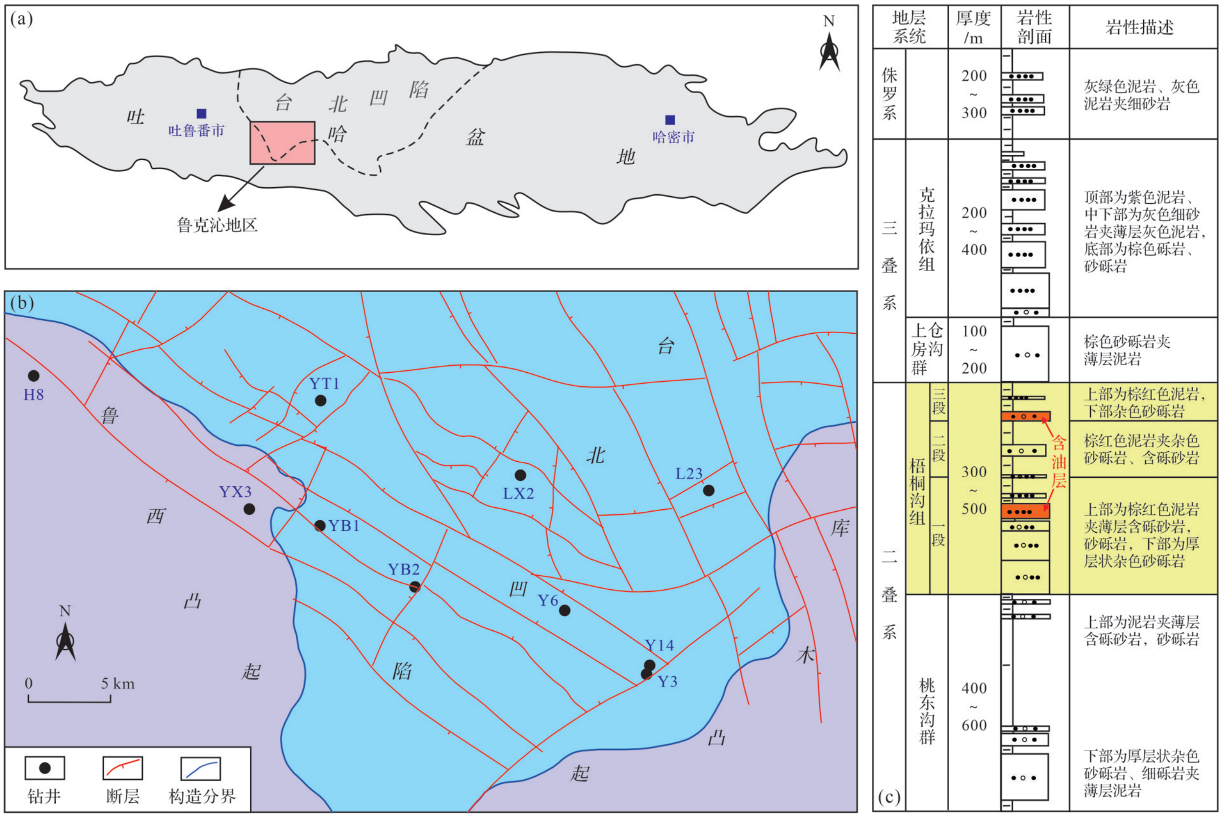

图1　地质背景图

(a)吐哈盆地及研究区位置;(b)鲁克沁地区构造纲要图;(c)岩性柱状图[33]

Fig. 1　Geological background map

(a) location of the Turpan-Hami Basin and the study area; (b) tectonic outline of the Lukeqin area; (c) lithological column[33]

镜下为浅红色,阴极发光呈橙色(图2h);铁方解石常见充填于溶蚀孔隙中,含量亦较低,染色薄片镜下为深红色,阴极发光下表现为几乎不发光(图2h)。

2.2　储层物性及储集空间类型

鲁克沁地区上二叠统梧桐沟组深部砂岩储层物性分析显示,孔隙度范围介于4.6%~11.4%,平均值为7.3%,主要分布在7.0%~9.0%;渗透率范围介于(0.005~17.270)×10^{-3} μm^2,平均值为1.436×10^{-3} μm^2,主要集中在(0.100~1.000)×10^{-3} μm^2范围内。孔隙度与渗透率呈明显的正相关关系(图3),说明梧桐沟组深部砂岩储层为孔隙型储层。物性较好的样品中方解石胶结物面积含量分布在1.0%~8.0%,方解石胶结物面积含量大于等于8.0%和小于等于1.0%的样品物性均较差。

基于扫描电镜与铸体薄片资料对矿物的孔隙结构和形态进行了分析,发现鲁克沁地区梧桐沟组储集空间类型包括剩余原生粒间孔(图4a,b)、次生孔隙(图4b~g)、微裂缝(图4h,i)。次生孔隙以粒内溶孔为主,铸体薄片镜下主要表现为长石粒内溶蚀孔(图4d,e)、岩屑溶蚀孔(图4b,f),扫描电镜可见方解石晶体溶蚀形成的晶间孔(图4g)。此外,裂缝较为发育,多为构造应力、强压实作用下的微裂缝(图4h)和贴粒缝(图4i),一般沿粒间形成,个别微裂缝切穿碎屑颗粒。

3　方解石胶结物成岩演化及对储层的影响

3.1　方解石胶结物期次

方解石胶结物是致密砂岩储层中常见的胶结物类型,具有多期次、多成因、分布普遍等特点[43-44],对储层物性具有重要的影响。前文已述,普通薄片下观察到方解石胶结物经铁氰化钾/茜红素混合溶液染色后主要表现为浅红色、红色和深红色,阴极发光下观察到橙色、暗橙色和几乎不发光三种不同程度的发光特性。进一步结合方解石胶结物间的交切关系及其与颗粒或者孔隙的接触关系,判定了它们的发育期次。泥晶方解石为最早发育的Ⅰ期方解石胶结

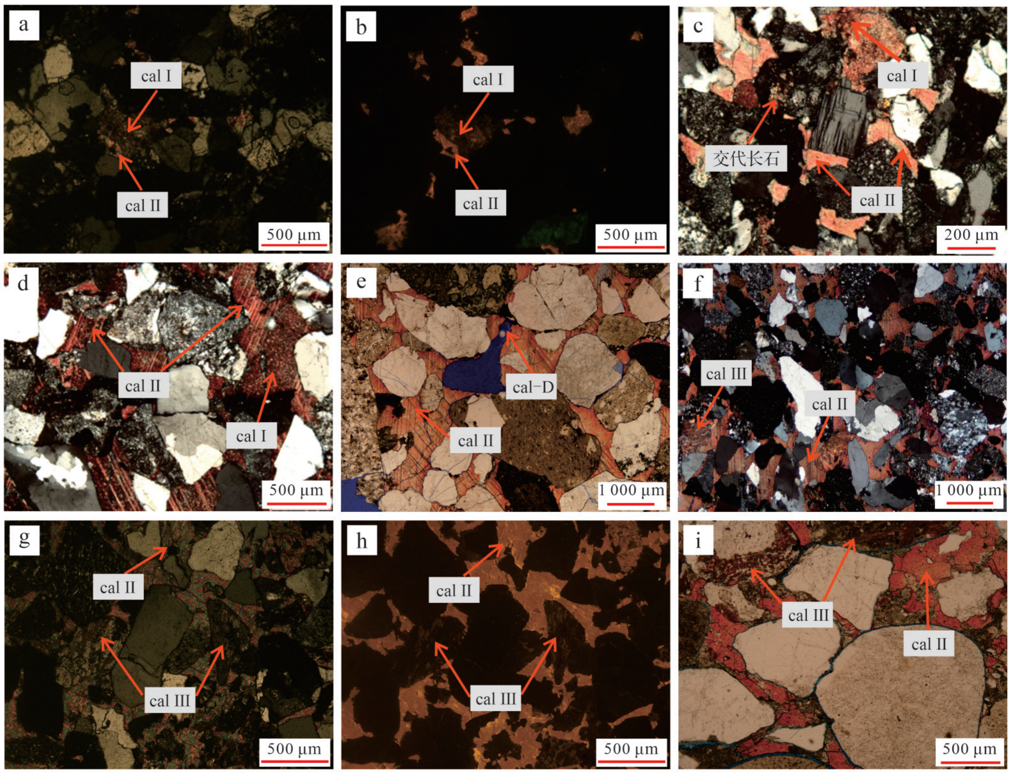

图 2 鲁克沁地区上二叠统梧桐沟组方解石胶结物典型特征薄片照片

(a)Ⅰ期泥晶方解石胶结物充填粒间，Ⅱ期方解石胶结物包裹Ⅰ期泥晶方解石，(−)，YT1井，6 048.82 m，P_3w^1；(b)Ⅰ期泥晶方解石胶结物阴极发光呈暗橙色，Ⅱ期方解石胶结物发橙光，(CL)，YT1井，6 048.82 m，P_3w^1；(c)方解石胶结物发育，Ⅱ期方解石胶结物呈弱交代性，(+)，YT1井，6 047.44 m，P_3w^1；(d)方解石胶结物发育，(+)，YT1井，5 829.55 m，P_3w^3；(e)Ⅱ期连晶方解石胶结物，早期方解石胶结物溶蚀，(−)，YT1井，5 829.38 m，P_3w^3；(f)Ⅱ期连晶方解石胶结物发育，Ⅲ期方解石充填溶蚀孔，(+)，YT1井，5 829.41 m，P_3w^3；(g)Ⅱ期连晶方解石胶结物，Ⅲ期铁方解石充填次生溶孔，(−)，YT1井，5 828.60 m，P_3w^3；(h)Ⅱ期连晶方解石胶结物发橙光，Ⅲ期铁方解石胶结物几乎不发光，(CL)，YT1井，5 828.60 m，P_3w^3；(i)方解石胶结物发育，Ⅱ期连晶胶结，Ⅲ期充填溶蚀孔隙，(−)，YT1井，5 827.78 m，P_3w^3；cal Ⅰ.Ⅰ期方解石胶结物；cal Ⅱ.Ⅱ期方解石胶结物；cal Ⅲ.Ⅲ期方解石胶结物；cal-D.方解石胶结物溶蚀

Fig. 2 Thin section photos of typical characteristics of the calcite cement from the Upper Permian Wutonggou Formation in the Lukeqin area

(a) phase I mud crystal calcite cement filling the intergranular pores, phase II calcite cement wrapping mud crystal calcite in Phase I, (−), well YT1, 6 048.82 m, P_3w^1; (b) phase I mud crystal calcite cement is dark orange, and phase II calcite cement is orange, (cathodoluminescence, CL), well YT1, 6 048.82 m, P_3w^1; (c) calcite cement developed, phase II calcite cement is weakly metasomatic, (+), well YT1, 6 047.44 m, P_3w^1; (d) calcite cement developed, (+), well YT1, 5 829.55 m, P_3w^3; (e) phase II continuous crystalline calcite cement developed, early calcite cement dissolved, (−), well YT1, 5 829.38 m, P_3w^3; (f) phase II continuous crystalline calcite cement developed, phase Ⅲ calcite cement filling dissolution pore, (+), well YT1, 5 829.38 m, P_3w^3; (g) phase II continuous crystalline calcite cement, phase Ⅲ iron calcite filling dissolution pore, (−), Well YT1, 5 828.60 m, P_3w^3; (h) phase II continuous crystalline calcite cement emits orange light, and phase Ⅲ iron calcite cement of hardly emits light, (CL), well YT1, 5 828.60 m, P_3w^3; and (i) calcite cement developed, with continuous crystal cementation in phase II and phase Ⅲ filling dissolved pores, (−), well YT1, 5 827.78 m, P_3w^3; cal Ⅰ. phase I calcite cement; cal Ⅱ. phase II calcite cement; cal Ⅲ. phase Ⅲ calcite cement; cal-D. calcite cement developed

物，连晶方解石为Ⅱ期方解石胶结物，铁方解石为Ⅲ期方解石胶结物。泥晶方解石胶结物晶粒较小，呈蠕虫状，贴颗粒胶结，以孔隙式充填在颗粒之间（图2a~d），阴极发光下颜色较弱，呈暗橙色（图2b），为Ⅰ期方解石胶结物；连晶状方解石胶结物的晶粒粗大且洁净，阴极发光表现为橙色（图2h），染色照片为浅红色—红色（图2c~f），镜下连晶状方解石胶结物表现为包裹Ⅰ期泥晶方解石胶结物（图2c，d），或弱交代长石颗粒（图2c），充填剩余粒间孔隙，说明其形成时间晚于Ⅰ期泥晶方解石，为Ⅱ期方解石胶结物；铁方解石胶结物充填在溶蚀孔隙中，表明其形成于溶蚀作用之后，为Ⅲ期方解石胶结物，阴极发光下表现为几乎不发光（图2h），含量较少，薄片染色照片为深红色（图2i）。

3.2 成岩作用阶段及典型成岩序列

现有资料表明，研究区上二叠统梧桐沟组深部砂岩储层成岩矿物组合特征为：颗粒间以线接触为主，部分样品中可见凹凸接触关系（图5a，b），发育溶蚀孔（图5c）；见浊沸石（图5a）、含铁碳酸盐类胶结物、石英次生加大边（图5b）、自生石英晶体（图5d）等；黏土

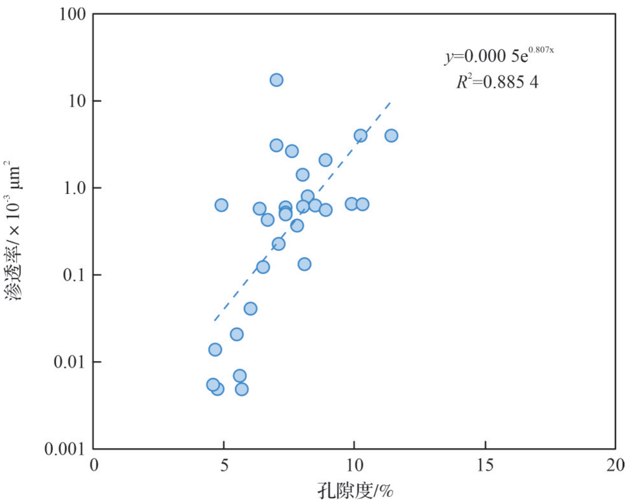

图3　梧桐沟组砂砾岩储层孔隙度与渗透率关系图

Fig. 3　Relationship between porosity and permeability for the glutenite reservoir in the Wutonggou Formation

矿物包括针叶状伊利石(图5d)、自生高岭石(图5e)、绿泥石集合体(图5f)等。镜质体反射率R_o值介于0.77%~1.25%。从研究区黏土矿物X射线衍射分析结果来看,黏土矿物以绿泥石为主,I/S中S介于10%~50%,个别样品大于50%,处于有序混层带。综合上述成岩特征,根据碎屑岩成岩阶段划分标准(SY/T 5477—2003)[45],认为梧桐沟组深部砂岩储层成岩阶段主要处于中成岩A期,部分达到中成岩B期。

综上分析,建立了研究区深部砂岩储层成岩作用演化图(图6)。同时,结合前文已述的方解石胶结物矿物学特征和赋存状态,以及成岩组构之间的关系,将该区砂岩储层的成岩序列进行梳理归纳:Ⅰ期方解石沉淀—早期机械压实—长石和岩屑颗粒轻微溶解;Ⅱ期方解石沉淀—长石和岩屑强烈溶蚀、自生高岭石发育、石英次生加大;Ⅲ期方解石充填孔隙。

3.3　储层演化模式

本文以埋深5 800~6 100 m的YT1井为典型代表,对其出油井段和失利井段储层演化进行对比研究,建立了如下储层演化模式图(图7)。YT1井出油井段埋深为5 827~5 830 m,主要为粗中粒岩屑砂岩和砂砾岩,碎屑颗粒多呈棱角状—次圆状,分选差—中等,具有低结构成熟度和成分成熟度,该深度段储层富方解石胶结物。失利井段埋深为6 051~6 055 m,主要为细中粒长石岩屑砂岩,碎屑颗粒次棱—次圆状,分选中等—好,成分成熟度低、结构成熟度中等,方解石胶结物含量相对较少。

在准同生期,有机质未成熟,岩石呈弱—半固结状态,原生孔隙发育,胶结作用较弱。显微镜下,出油井段储层观察到原生粒间孔中充填着泥晶状的方解石胶结物,发育该类胶结物的砂岩碎屑颗粒以点接触或基底式胶结为特征,常呈包壳状裹挟碎屑颗粒(图2c,d),指示该方解石胶结物为Ⅰ期。这一阶段,压实作用使孔隙度和排水量迅速减少,对孔隙空间的影响最大。

研究区梧桐沟组砂岩主要为陆相三角洲沉积环境[46],在早成岩期浅埋藏阶段,成岩环境以碱性为主,岩石呈半固结—固结,沉积物呈点—线接触。该阶段砂岩仍未有较强压实,长石发生轻微溶解,并伴随着相应的高岭石生成。由于深度相较于上一阶段有所增加,地温也有一定的升高,蒙皂石变得不稳定,开始向伊蒙混层转化,转化过程中的Si^{4+}、Ca^{2+}、Na^{+},Fe^{2+},Mg^{2+}等离子从蒙脱石中释放出来,形成石英次生加大,方解石胶结物等。显微镜下可见出油井段储层发育连晶状方解石胶结物,表现为非常干净的亮晶方解石,也从侧面说明该类方解石仍然形成于不受陆源细碎屑杂基污染的埋藏阶段,并且可见到连晶方解石胶结物包裹Ⅰ期方解石的现象(图2c,d),说明其产出晚于Ⅰ期方解石胶结物,为Ⅱ期胶结。这一阶段富方解石胶结物的砂岩储层受压实和胶结作用的双重影响。

随着成岩作用的不断进行,进入中成岩阶段,随着埋深逐渐增加,沉积物呈点—线、线接触,有机质逐渐成熟。此过程中生成大量有机酸和CO_2,导致长石、早期碳酸盐胶结物和富铝硅酸盐等矿物溶解,形成大量溶蚀孔,为成岩作用中晚期提供了Ca^{2+},蒙皂石通过伊蒙混层向伊利石转化过程中释放部分Fe^{3+},形成Ⅲ期方解石胶结物充填在溶蚀孔隙中(图2i),含量相对于Ⅱ期连晶方解石较少。这一阶段溶蚀作用能有效改善储集性能,虽然Ⅲ期方解石胶结物占据部分溶蚀孔隙空间,但因其数量有限及溶蚀作用的发育,整体上孔隙度有所增加。

3.4　方解石胶结物对储层的影响

成岩过程中机械压实的物理作用和矿物溶解沉淀的化学作用是砂岩储层致密化的主要因素。研究区深部储集砂岩埋深介于4 500~6 000 m,普遍受到强烈的压实改造作用,物性通常较差。从方解石胶结物与储层发育的显著关系可知,方解石胶结物的沉淀与溶解是研究区影响储层非均质性的关键成岩

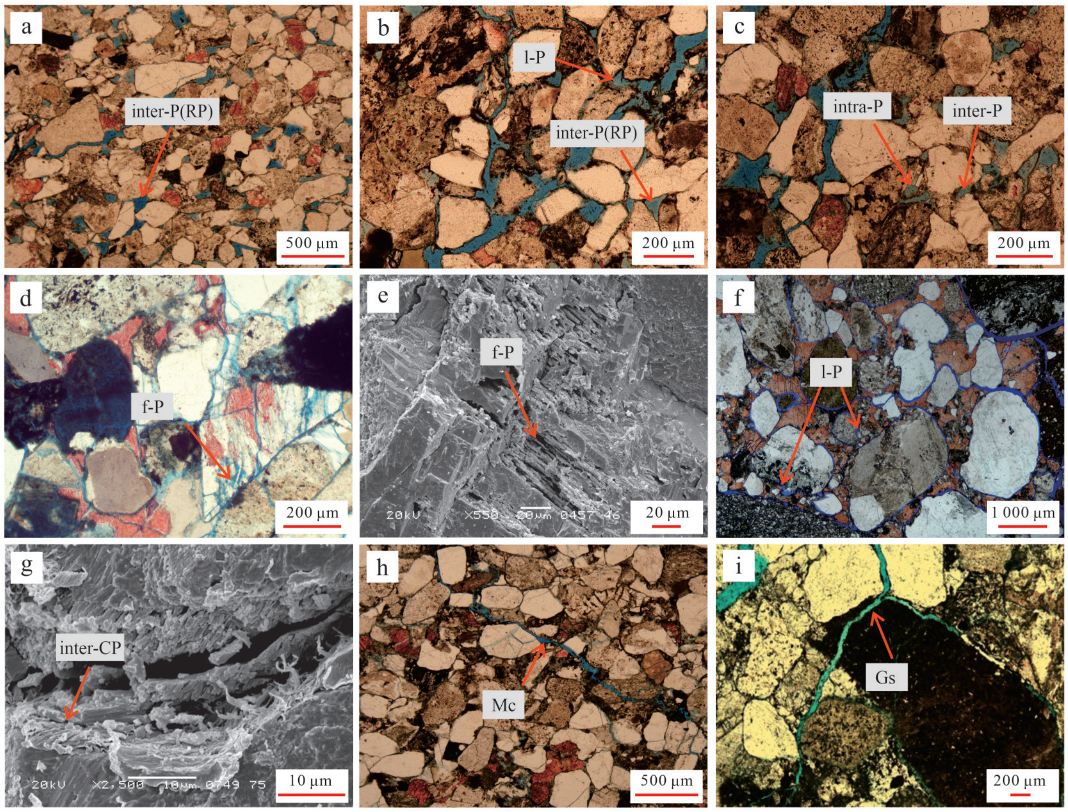

图4 鲁克沁地区上二叠统梧桐沟组深部储层孔隙特征

(a)剩余原生粒间孔，蓝色铸体，(−)，L23井，4 526.38 m，P_3w^1；(b)剩余原生粒间孔、岩屑溶孔，蓝色铸体，(−)，L23井，4 524.87 m，P_3w^1；(c)粒间溶孔和粒内溶孔，蓝色铸体，(−)，L23井，4 525.12 m，P_3w^1；(d)长石溶蚀孔，方解石胶结物，蓝色铸体，(−)，YT1井，6 048.50 m，P_3w^1；(e)长石溶蚀微孔发育，扫描电镜，YT1井，6 049.79 m，P_3w^1；(f)溶蚀孔发育，见方解石胶结，蓝色铸体，(−)，YT1井，5 827.78 m，P_3w^3；(g)方解石晶体溶蚀，可见粒间微缝，毛发状伊利石附着于碎屑颗粒表面，扫描电镜，L23井，4 524.32 m，P_3w^1；(h)微裂缝，蓝色铸体，(−)，YT1井，5 829.83 m，P_3w^3；(i)砂砾岩颗粒贴粒缝发育，YT1井，5 828.54 m，P_3w^3；inter-P(RP).剩余原生粒间孔；l-P.岩屑溶孔；inter-P.粒间孔；intra-P.粒内孔；f-P.长石溶孔；inter-CP.晶间孔；Mc.微裂缝；Gs.贴粒缝

Fig. 4 Pore characteristics of a deep reservoir from the Upper Permian Wutonggou Formation in the Lukeqin area

(a) remaining primary intergranular pores, blue cast, (−), well L23, 4 526.38 m, P_3w^1; (b) remaining primary intergranular pores, lithic dissolution pores, blue cast, (−), well L23, 4 524.87 m, P_3w^1; (c) intergranular and intragranular dissolution pores, blue cast, (−), well L23, 4 525.12 m, P_3w^1; (d) feldspar dissolution pores, calcite cements, blue cast, (−), well YT1, 6 048.50 m, P_3w^1; (e) development of feldspar dissolved micropores, scanning electron microscope (SEM), well YT1, 6 049.79 m, P_3w^1; (f) dissolution pores development, calcite cement, blue cast, (−), well YT1, 5 827.78 m, P_3w^3; (g) dissolution of calcite crystals, visible intergranular microfractures, hair-like illite attached to the surface of detrital grains, SEM, well L23, 4 524.32 m, P_3w^1; (h) microcrack, blue cast, (−), well YT1, 5 829.83 m, P_3w^3; and (i) sandy conglomerate particles attached to the granular seam development, well YT1, 5 828.54 m, P_3w^3; inter-P(RP). remaining primary intergranular pores; l-P. lithic dissolution pores; inter-P. intergranular pores; intra-P. intragranular pores; f-P. feldspar dissolution pores; inter-CP. crystal pores; Mc. microcrack; Gs. granular seam

因素。鲁克沁地区梧桐沟组深埋砂岩储集层的方解石胶结物含量与孔隙度整体上没有明显的相关性，表明其对储层质量的影响较为复杂。

根据薄片统计，方解石胶结物含量在1.0%~8.0%之间的储层孔隙度均值为7.7%，渗透率均值为1.5×10^{-3} μm²；胶结物含量大于8.0%时，大量孔隙被方解石充填，孔隙度均值小于6.2%，渗透率均值小于0.3×10^{-3} μm²；胶结物含量小于1.0%时，储层压实作用非常强，致密化严重，孔隙度均值小于6.3%，渗透率均值小于0.4×10^{-3} μm²。由此可见，胶结物含量介于1.0%~8.0%的储层物性相对较好，且含量在1.0%~8.0%之间的方解石胶结物含量与孔隙度呈正相关（图8）。过度胶结使原有孔隙完全占据（图9a），另一方面，因其埋藏较深，研究区储集砂岩经历了强烈的压实作用，胶结较弱的地方会因缺少胶结物的支撑而使碎屑颗粒压实的更加紧密（图9b），从而导致储层质量差，甚至为非储层。因此，梧桐沟组深埋储层的方解石胶结作用属于保持性成岩作用，既有建设性贡献，亦有破坏性作用。以往大量的研究表明，主压实作用前的早成岩阶段形成的方解石胶结物能保存砂岩中的原生孔隙，在后期成岩作用过程中，可能进一步溶蚀释放次生孔隙，改善储层质量[24-25]。

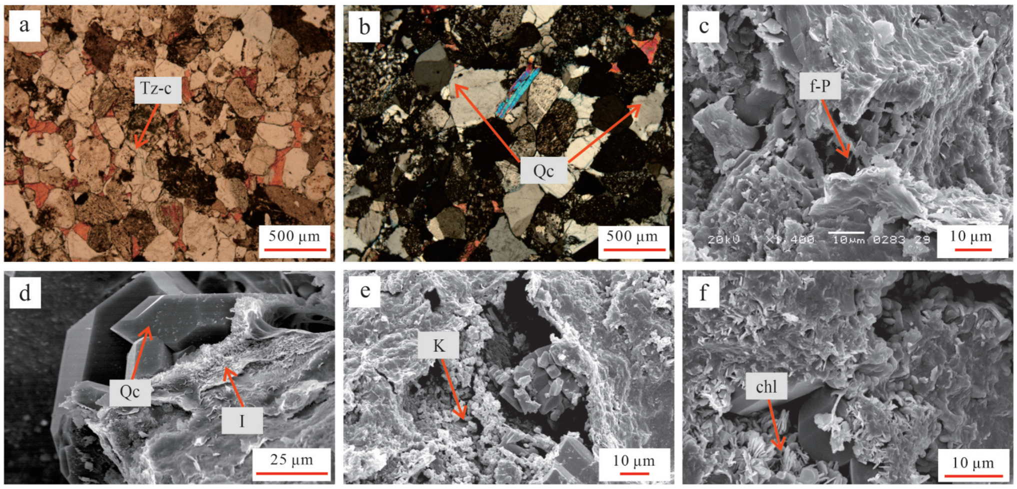

图5　鲁克沁地区梧桐沟组深部砂岩储层镜下成岩矿物特征

(a)粒间充填浊沸石,铸体薄片,(-),YT1井,6 048.59 m,P_3w^1;(b)石英次生加大,铸体薄片,(+),YT1井,6 048.70 m,P_3w^1;(c)长石颗粒沿解理被溶蚀,形成格架状长石溶蚀孔隙,扫描电镜,YT1井,5 970.98 m,P_3w^3;(d)针叶状伊利石附着于碎屑颗粒表面,自生石英晶体充填于碎屑颗粒之间,扫描电镜,L23井,4 525.17 m,P_3w^3;(e)溶蚀孔隙中见絮状高岭石集合体,扫描电镜,YT1井,5 828.93 m,P_3w^3;(f)片状绿泥石集合体充填于粒间孔隙中,扫描电镜,YT1井,6 054.64 m,P_3w^1;TZ-c.浊沸石胶结物;Qc.石英;f-P.长石溶蚀孔;I.伊利石;K.高岭石;chl.绿泥石

Fig. 5　Microscopic diagenetic mineral characteristics of a deep sandstone reservoir from the Wutonggou Formation in the Lukeqin area

(a) intergranular filling of turbid zeolite, cast sheet (−), well YT1, 6 048.59 m, P_3w^1; (b) secondary enlargement of quartz, cast sheet (+), well YT1, 6 048.70 m, P_3w^1; (c) feldspar particles are dissolved along the cleavage, forming lattice-like feldspar dissolution pores, SEM, well YT1, 5 970.98 m, P_3w^3; (d) coniferous illite is attached to the surface of the debris particles, and authigenic quartz crystals are filled between the debris particles, SEM, well L23, 4 525.17 m, P_3w^3; (e) flocculent kaolinite aggregates filled in the dissolution pores, SEM, well YT1, 5 828.93 m, P_3w^3; (f) flake chlorite aggregate filled in intergranular pores, SEM, well YT1, 6 054.64 m, P_3w^1; TZ-c. turbid zeolite cement; Qc. quartz; f-P. feldspar dissolution pores; I. illite; K. kaolinite; chl.chlorite

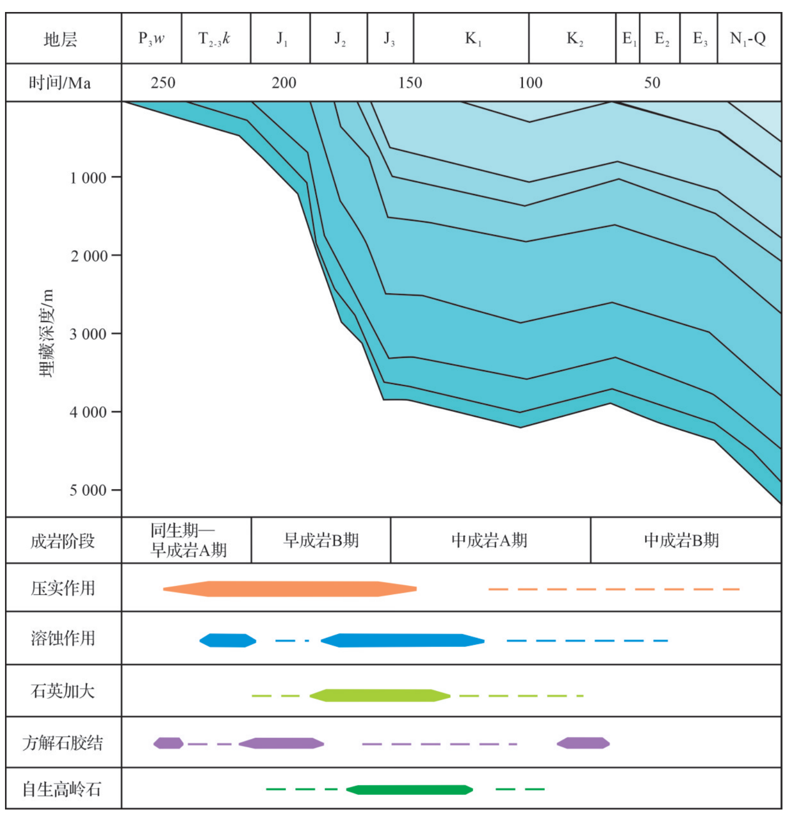

图6　鲁克沁地区梧桐沟组深部砂岩储层成岩作用演化

Fig. 6　Diagenetic evolution of a deep sandstone reservoir from the Wutonggou Formation in the Lukeqin area

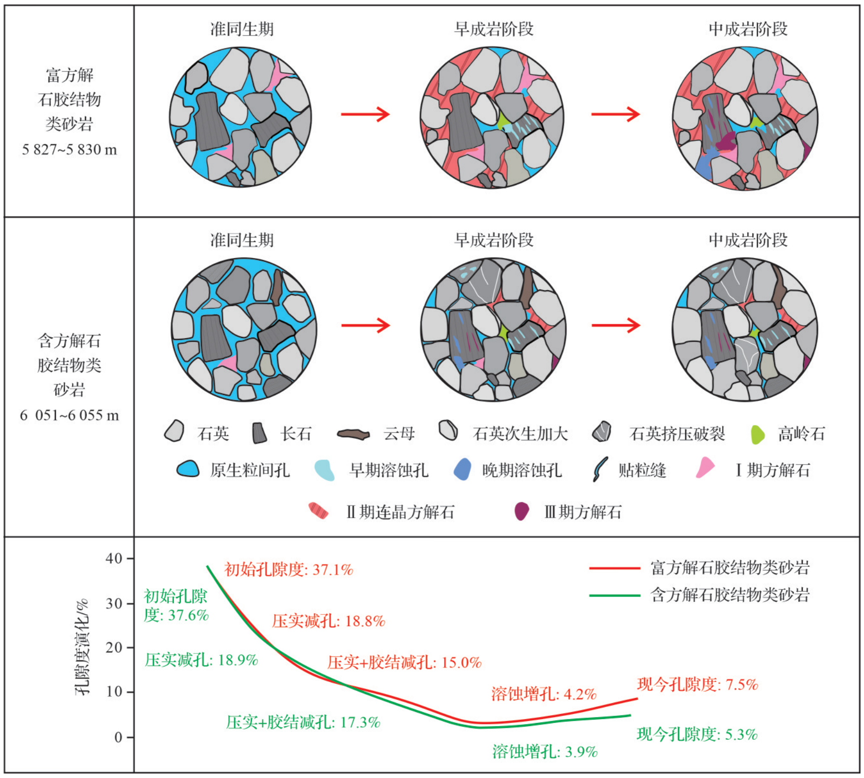

图7　梧桐沟组深部不同砂岩储层演化模式及孔隙变化

Fig. 7　Evolutionary pattern and pore space variation of different sandstone reservoirs in the deep part of the Wutonggou Formation

可见,方解石胶结物对储层的影响并不是一概而论,需要结合期次和成因具体分析当前环境下的影响。基于前文的分析,结合梧桐沟组方解石胶结物的成岩演化及孔隙演化过程,揭示其对储层演化的影响。Ⅰ期方解石含量较少,主要以充填原生粒间孔的形式出现,常呈包壳状裹挟碎屑颗粒,说明其较早就为岩石骨架起到了抗压支撑作用。Ⅱ期连晶方解石呈孔隙式充填颗粒间,碎屑颗粒呈点—线接触,即砂岩已遭受过一定程度的压实改造作用。通过对富方解石胶结物砂岩储层与含方解石胶结物砂岩储层的演化对比,前两期方解石胶结物相对发育的储层物性较好,此外,鲁克沁地区梧桐沟组深部储层超过4 500 m,但仍保存剩余原生粒间孔(图4a),表明其虽然阻碍了孔隙间的连通性,但也对颗粒起到了支撑作用,使得深埋藏下储层的原生孔隙得以保存,主要起抗压实作用;而Ⅲ期方解石胶结物充填在长石溶蚀产生的节理缝中,占据强压实作用下改善砂岩储层物性的次生溶孔之中,但Ⅲ期方解石的沉淀也通过促进长石溶蚀而提高了溶蚀孔隙。同时,前面提到埋藏期的酸性流体也会溶蚀早期方解石胶结物,并释放早期占据的粒间孔而提高储层物性。这一效应可以较好地解释部分深埋储层仍发育无颗粒支撑的连通孔隙,即早期通过方解石胶结物固结的砂岩通过胶结物溶蚀再释放有可能在深埋条件下发育该类粒间孔隙。

前文已述,连晶方解石胶结物主要在早成岩阶段形成,其对深埋优质储层形成具有关键作用。与之相关的砂岩储层与沉积期湖盆相带有关,主要为三角洲沉积环境的前缘水下分流河道[46]。这可能是因为三角洲前缘长期处于水下,从而相关的砂体在沉积期至浅埋藏期具有较活跃的孔隙水,有利于早期方解石胶结。综上,认为具有一定规模的水下分流河道沉积相与方解石成岩相耦合,有效保持了粒间孔,后期的方解石溶蚀作用释放了部分原生粒间孔,成为深埋条件下良好储层的重要因素。

4　结论

(1) 吐哈盆地鲁克沁地区梧桐沟组砂岩类型为岩屑砂岩和长石岩屑砂岩,分选中等—好,碎屑颗粒

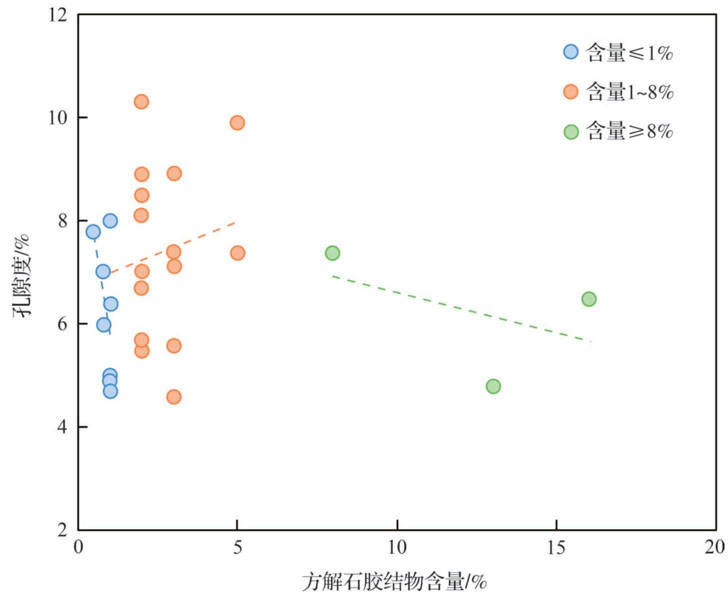

图8　梧桐沟组不同含量方解石胶结物与孔隙度关系图

Fig. 8　Relationship between calcite cement with different contents and porosity in the Wutonggou Formation

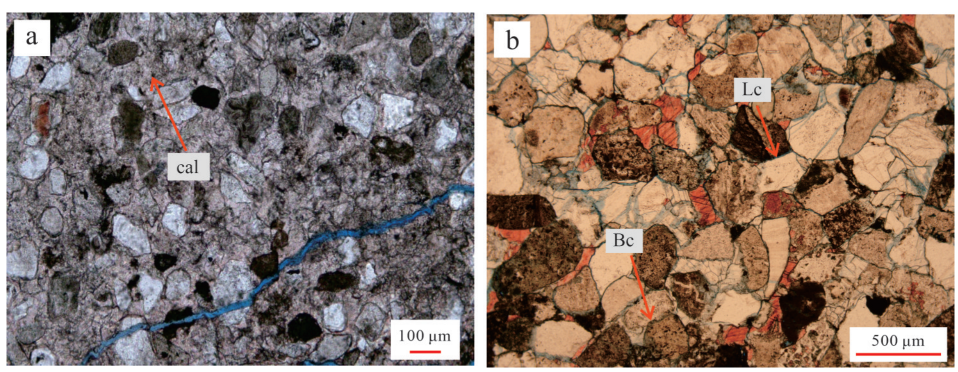

图9　不同含量方解石胶结物的储层特征

(a)方解石过度胶结和切穿颗粒的微裂缝,(−),YT1井,5 825.70 m,P_3w^3;(b)含方解石胶结物,颗粒间线—凹凸接触,(−),YT1井,6 049.68 m,P_3w^1;cal.方解石胶结物;Lc.线接触;Bc.凹凸接触

Fig. 9　Reservoir characteristics of calcite cements with different contents

(a) excessive calcite cementation and microfractures cutting through particles, (−), well YT1, 5 825.70 m, P_3w^3; (b) calcite-bearing cementation, line-convex contact between particles, (−), well YT1, 6 049.68 m, P_3w^1; cal. calcite; Lc. line contact; Bc. bumpy contact

呈次圆—次棱状,以点—线接触为主。孔隙类型以原生粒间孔、溶蚀孔和裂缝发育为主,孔隙度范围介于4.6%~11.4%,平均值为7.3%;渗透率范围介于(0.005~17.270)×10^{-3} μm^2,平均值为1.436×10^{-3} μm^2,孔隙度主要分布在7.0%~9.0%;渗透率主要集中在(0.100~1.000)×10^{-3} μm^2范围内,属于特低孔特低渗砂岩储层。

(2)根据矿物学特征,可将鲁克沁地区梧桐沟组方解石胶结物划分为3期。Ⅰ期方解石胶结物主要以孔隙式充填在颗粒间,与Ⅱ期连晶方解石共同起到了支撑颗粒的作用,提高了砂岩的抗压实能力;Ⅲ期方解石胶结物充填在次生溶孔中,导致储层物性较差。

(3)鲁克沁地区梧桐沟组深部砂岩储层具有显著的方解石胶结作用,占主导的Ⅱ期方解石胶结物含量与优质储层发育密切相关,含量在1%~8%的储层物性较好,过少或过多均会导致储层质量较差。三角洲前缘水下分流河道沉积相与方解石成岩相的耦合作用,控制着深埋条件下优质储层的发育。

致谢　感谢中国石油吐哈油田公司勘探开发研究院提供的宝贵资料,感谢三位审稿专家及编辑部老师提出的宝贵建设性修改意见。

参考文献(References)

[1] 吕成福,李小燕,陈国俊,等. 酒东坳陷下白垩统砂岩中碳酸盐胶结物特征与储层物性[J]. 沉积学报,2011,29(6):1138-1144. [Lü Chengfu, Li Xiaoyan, Chen Guojun, et al. Characteristics of carbonate cements and reservoiy quality of the Lower Cretaceous sandstone in Jiudong Sag[J]. Acta Sedimentologica Sinica, 2011, 29(6): 1138-1144.]

[2] Wang Q, He S, Wang F R, et al. Carbonate cementation-dissolution in deep-seated sandstones near the overpressure top in central Junggar Basin, Xinjiang, NW China[J]. Chinese Journal of Geochemistry, 2009, 28(1): 86-96.

[3] Wang J, Cao Y C, Liu K Y, et al. Pore fluid evolution, distribution and water-rock interactions of carbonate cements in red-bed sandstone reservoirs in the Dongying Depression, China[J]. Marine and Petroleum Geology, 2016, 72: 279-294.

[4] Liu Y F, Hu W X, Cao J, et al. Fluid–rock interaction and its effects on the Upper Triassic tight sandstones in the Sichuan Basin, China: Insights from petrographic and geochemical study of carbonate cements[J]. Sedimentary Geology, 2019, 383: 121-135.

[5] Taylor K G, Gawthorpe R L, Curtis C D, et al. Carbonate cementation in a sequence-stratigraphic framework: Upper Cretaceous sandstones, Book Cliffs, Utah-Colorado[J]. Journal of Sedimentary Research, 2000, 70(2): 360-372.

[6] Cui Y F, Jones S J, Saville C, et al. The role played by carbonate cementation in controlling reservoir quality of the Triassic Skagerrak Formation, Norway[J]. Marine and Petroleum Geology, 2017, 85: 316-331.

[7] 陈波,陈汾君,马进业,等. 冷湖地区上干柴沟组储层碳酸盐胶结物特征及地质意义[J]. 大庆石油地质与开发,2016,35(5):28-33. [Chen Bo, Chen Fenjun, Ma Jinye, et al. Characteristics and their geological significances of the carbonate cements in Shangganchaigou-Formation reservoirs of Lenghu area[J]. Petroleum Geology and Oilfield Development in Daqing, 2016, 35(5): 28-33.]

[8] Dutton S P. Calcite cement in Permian deep-water sandstones, Delaware Basin, west Texas: Origin, distribution, and effect on reservoir properties[J]. AAPG Bulletin, 2008, 92(6): 765-787.

[9] Lai J, Wang G W, Chen J, et al. Corrigendum to "origin and distribution of carbonate cement in tight sandstones: The Upper Triassic Yanchang Formation Chang 8 oil layer in west Ordos Basin, China"[J]. Geofluids, 2018, 2018: 8650963.

[10] 肖晓光,秦兰芝,张武,等. 西湖凹陷平湖组碳酸盐胶结物形成机制及其对储层的影响[J]. 地质科学,2021,56(4):1062-1076. [Xiao Xiaoguang, Qin Lanzhi, Zhang Wu, et al. The origin of carbonate cements and the influence on reservoir quality of Pinghu Formation in Xihu Sag[J]. Chinese Journal of Geology, 2021, 56(4): 1062-1076.]

[11] Mansour A S, Rifai R I, Shaaban M N. Geochemical constraint on the origin of the multi-mineralogic carbonate cements in the subsurface Middle Jurassic sandstones, Central Sinai, Egypt[J]. Journal of Geochemical Exploration, 2014, 143: 163-173.

[12] Liang H R, Xu F H, Xu G S, et al. Geochemical characteristics and origins of the diagenetic fluids of the Permian Changxing Formation calcites in the southeastern Sichuan Basin: Evidence from petrography, inclusions and Sr, C and O isotopes[J]. Marine and Petroleum Geology, 2019, 103: 564-580.

[13] 张庄,庞江,杨映涛,等. 川西坳陷中段须家河组四段砂岩中碳酸盐胶结物碳、氧同位素特征及成因探讨[J]. 地质学报,2022,96(6):2094-2106. [Zhang Zhuang, Pang Jiang, Yang Yingtao, et al. Carbon and oxygen isotope characteristics and genesis of carbonate cements in sandstone of the 4th member of the Xujiahe Formation in the central western Sichuan Depression, Sichuan Basin, China[J]. Acta Geologica Sinica, 2022, 96(6): 2094-2106.]

[14] Zhu S F, Yue H, Zhu X M, et al. Dolomitization of felsic volcaniclastic rocks in continental strata: A study from the Lower Cretaceous of the A'nan Sag in Er'lian Basin, China[J]. Sedimentary Geology, 2017, 353: 13-27.

[15] Schmid S, Worden R H, Fisher Q J, et al. Carbon isotope stratigraphy using carbonate cements in the triassic sherwood sandstone group: Corrib field, west of Ireland[J]. Chemical Geology, 2005, 225(1): 137-155.

[16] 王代富,罗静兰,陈淑慧,等. 珠江口盆地白云凹陷深层砂岩储层中碳酸盐胶结作用及成因探讨[J]. 地质学报,2017,91(9):2079-2090. [Wang Daifu, Luo Jinglan, Chen Shuhui, et al. Carbonate cementation and origin analysis of deep sandstone reservoirs in the Baiyun Sag, Pearl River Mouth Basin[J]. Acta Geologica Sinica, 2017, 91(9): 2079-2090.]

[17] 姚泾利,王琪,张瑞,等. 鄂尔多斯盆地中部延长组砂岩中碳酸盐胶结物成因与分布规律研究[J]. 天然气地球科学,2011,22(6):943-950. [Yao Jingli, Wang Qi, Zhang Rui, et al. Origin and spatial distribution of carbonate cements in Yanchang Fm. (Triassic) sandstones within the lacustrine center of Ordos Basin, NW China[J]. Natural Gas Geoscience, 2011, 22(6): 943-950.]

[18] 袁珍,李文厚. 鄂尔多斯盆地东南缘上三叠统延长组砂岩方解石胶结物成因[J]. 吉林大学学报(地球科学版),2011,41(增刊1):17-23. [Yuan Zhen, Li Wenhou. Origin of calcite cement in the sandstone reservoirs of the Upper Triassic Yanchang Formation in southeast of Ordos Basin[J]. Journal of Jilin University (Earth Science Edition), 2011, 41(Suppl. 1): 17-23.]

[19] 王琪,郝乐伟,陈国俊,等. 白云凹陷珠海组砂岩中碳酸盐胶结物的形成机理[J]. 石油学报,2010,31(4):553-558. [Wang Qi, Hao Lewei, Chen Guojun, et al. Forming mechanism of carbonate cements in siliciclastic sandstone of Zhuhai Formation in Baiyun Sag[J]. Acta Petrolei Sinica, 2010, 31(4): 553-558.]

［20］ Mcbride E F M, Milliken K L. Giant calcite-cemented concretions, Dakota Formation, central Kansas, USA[J]. Sedimentology, 2006, 53(5): 1161-1179.

［21］ 郭鹏戈，屈红军，杨欢，等. 鄂尔多斯盆地东部山西组山2段胶结物特征及其对储层物性的影响[J]. 地质科技情报，2017，36（2）：51-57.［Guo Pengge, Qu Hongjun, Yang Huan, et al. Characteristics of cement and its influence on reservoir physical property of Shan-2 member of Shanxi Formation in the eastern Ordos Basin[J]. Geological Science and Technology Information, 2017, 36(2): 51-57.］

［22］ Taylor T R, Giles M R, Hathon L A, et al. Sandstone diagenesis and reservoir quality prediction: models, myths, and reality [J]. AAPG Bulletin. 2010, 94(8): 1093-1132.

［23］ Liu Y F, Hu W X, Cao J, et al. Diagenetic constraints on the heterogeneity of tight sandstone reservoirs: A case study on the Upper Triassic Xujiahe Formation in the Sichuan Basin, southwest China[J]. Marine and Petroleum Geology, 2018, 92: 650-669.

［24］ Luo L, Gao X, Meng W, et al. The origin and alteration of calcite cement in tight sandstones of the Jurassic Shishugou Group, Fukang Sag, Junggar Basin, NW China: Implications for fluid-rock interactions and porosity evolution[J]. Australian Journal of Earth Sciences, 2018, 65(3): 427-445.

［25］ 盛军，孙卫，解腾云，等. 苏里格气田东南部盒8段储层成岩作用研究及其孔隙演化模式定量分析[J]. 地质科技情报，2015，34（1）：20-27.［Sheng Jun, Sun Wei, Xie Tengyun, et al. Diagenesis of He-8 reservoir and its quantitative analysis of porosity evolution model in southeast Sulige gas field[J]. Geological Science and Technology Information, 2015, 34(1): 20-27.］

［26］ Xie D L, Yao S P, Cao J, et al. Origin of calcite cements and their impact on reservoir heterogeneity in the Triassic Yanchang Formation, Ordos Basin, China: A combined petrological and geochemical study[J]. Marine and Petroleum Geology, 2020, 117: 104376.

［27］ Yang T, Cao Y C, Friis H, et al. Genesis and distribution pattern of carbonate cements in lacustrine deep-water gravity-flow sandstone reservoirs in the third member of the Shahejie Formation in the Dongying Sag, Jiyang Depression, eastern China[J]. Marine and Petroleum Geology, 2018, 92, 547-564.

［28］ 李思辰，刘俊田，卿忠，等. 鲁克沁构造带二叠系稠油油藏特征与主控因素[J]. 石油地质与工程，2015，29（4）：19-22，26.［Li Sichen, Liu Juntian, Qing Zhong, et al. Characteristics and main controlling factors of Permian heavy oil reservoirs in Lukeqin structure zone[J]. Petroleum Geology and Engineering, 2015, 29(4): 19-22, 26.］

［29］ 吴昊. 鲁克沁地区二叠系梧桐沟组沉积体系研究[D]. 青岛：中国石油大学（华东），2016.［Wu Hao. Study on sedimentary system of Permian Wutonggou Formation in Lukeqin area[D]. Qingdao: China University of Petroleum (East China), 2016.］

［30］ 武超，李宏伟，盛双占，等. 吐哈盆地鲁克沁构造带二叠系：三叠系油气成藏特征与主控因素[J]. 中国石油勘探，2021，26（4）：137-148.［Wu Chao, Li Hongwei, Sheng Shuangzhan, et al. Characteristics and main controlling factors of hydrocarbon accumulation of Permian-Triassic in Lukeqin structural zone, Tuha Basin[J]. China Petroleum Exploration, 2021, 26 (4): 137-148.］

［31］ 苟红光. 吐哈盆地鲁克沁—玉北地区二叠系油气成藏规律研究[J]. 石油天然气学报，2015，37（5）：1-5.［Gou Hongguang. Study on hydrocarbon accumulation law of Permian in Lukeqin-Yubei area, Turpan-Hami Basin[J]. Journal of Oil and Gas Technology, 2015, 37(5): 1-5.］

［32］ 程金婷. 吐哈盆地台北凹陷二叠系梧桐沟组储层特征[D]. 北京：中国石油大学（北京），2021.［Cheng Jinting. Reservoir characteristics of Wutonggou Formation in Permian, Taipei Sag, Turpan-Hami Basin[D]. Beijing: China University of Petroleum (Beijing), 2021.］

［33］ 司学强，李亚哲，王少霞，等. 新疆吐哈盆地鲁克沁地区二叠系梧桐沟组沉积特征及沉积模式[J]. 古地理学报，2018，20（5）：803-814.［Si Xueqiang, Li Yazhe, Wang Shaoxia, et al. Sedimentary characteristics and models of the Permian Wutonggou Formation in Lükqün area, Turpan-Hami Basin, Xinjiang[J]. Journal of Palaeogeography, 2018, 20(5): 803-814.］

［34］ 李伟，梁世君，姜均伟，等. 吐鲁番坳陷鲁克沁稠油油藏形成及演化特征[J]. 石油学报，2006，27（6）：14-18.［Li Wei, Liang Shijun, Jiang Junwei, et al. Special migration and accumulation of heavy oil reservoir in Lukeqin area of Turpan Depression[J]. Acta Petrolei Sinica, 2006, 27(6): 14-18.］

［35］ 苟红光，张品，佘家朝，等. 吐哈盆地石油地质条件、资源潜力及勘探方向[J]. 海相油气地质，2019，24（2）：85-96.［Gou Hongguang, Zhang Pin, She Jiachao, et al. Petroleum geological conditions, resource potential and exploration direction in Turpan-Hami Basin[J]. Marine Origin Petroleum Geology, 2019, 24(2): 85-96.］

［36］ 陈旋，胡前泽. 鲁克沁地区稀油成藏规律研究[J]. 吐哈油气，2009，14（4）：307-310.［Chen Xuan, Hu Qianze. Study on accumulation rule of thin oil in Lukeqin area[J]. Tuha Oil & Gas, 2009, 14(4): 307-310.］

［37］ 李逸群，鞠传学，张宪国. 吐哈盆地鲁克沁中西区侏罗系沉积特征[J]. 中国石油大学胜利学院学报，2016，30（1）：19-21，28.［Li Yiqun, Ju Chuanxue, Zhang Xianguo. Sedimentary characteristics of Jurassic in the Middle and western part of Lukeqin, Turpan-Hami Basin[J]. Journal of Shengli College China University of Petroleum, 2016, 30(1): 19-21, 28.］

［38］ 李建忠. 第四次油气资源评价[M]. 北京：石油工业出版社，2019.［Li Jianzhong. Fourth assessment for oil and gas resource[J]. Beijing: Petroleum Industry Press, 2019.］

［39］ 宋玉旺. 鲁克沁稠油富集带油气分布规律及勘探潜力[J]. 石油地质与工程，2009，23（4）：1-5.［Song Yuwang. Hydrocarbon distribution and exploration potential of heavy oil in Lukeqing oilfield[J]. Petroleum Geology and Engineering, 2009, 23(4): 1-5.]

[40] 赵文智，李伟，张研. 吐哈盆地鲁克沁稠油藏成藏过程初探与勘探意义[J]. 石油勘探与开发，1998，25(2)：1-3. [Zhao Wenzhi, Li Wei, Zhang Yan. A preliminary study on the forming process of Lükqün heavy oil pool and its exploratory significance to Turpan-Hami Basin[J]. Petroleum Exploration and Development, 1998, 25(2): 1-3.]

[41] 金爱民，楼章华，朱蓉，等. 吐哈盆地鲁克沁构造带稠油成藏机理[J]. 浙江大学学报(理学版)，2006，33(4)：464-468. [Jin Aimin, Lou Zhanghua, Zhu Rong, et al. Formation mechanism of heavy oil reservoirs in Lukeqin structure belt, the Turpan-Hami Basin[J]. Journal of Zhejiang University(Science Edition), 2006, 33(4): 464-468.]

[42] 任敏华，杨少春，宋璠，等. 鲁克沁油田梧桐沟组砂砾岩储层夹层特征及分布[J]. 河南科学，2016，34(5)：792-797. [Ren Minhua, Yang Shaochun, Song Fan, et al. Interlayer characteristics and distribution of sand-conglomerate reservoirs of Wutonggou Formation in Lukeqin oilfield[J]. Henan Science, 2016, 34(5): 792-797.]

[43] Brigaud B, Durlet C, Deconinck J F, et al. The origin and timing of multiphase cementation in carbonates: Impact of regional scale geodynamic events on the Middle Jurassic Limestones diagenesis (Paris Basin, France) [J]. Sedimentary Geology, 2009, 222(3/4): 161-180.

[44] Liu G Z, Hu G C, Shi X Z, et al. Carbonate cementation patterns and diagenetic reservoir facies of the Triassic Yanchang Formation deep-water sandstone in the Huangling area of the Ordos Basin, northwest China[J]. Journal of Petroleum Science and Engineering, 2021, 203: 108608.

[45] 国家经济贸易委员会. SY/T 5477—2003 碎屑岩成岩阶段划分[S]. 北京：石油工业出版社，2003. [Oil and Gas Industry Standard of the People's Republic of China. SY/T 5477-2003 the division of diagenetic stages in clastic rocks[S]. Beijing: Petroleum Industry Press, 2003.]

[46] 王永超. 吐哈盆地台北凹陷二叠系梧桐沟组沉积相研究[D]. 青岛：中国石油大学(华东)，2020. [Wang Yongchao. Study on sedimentary facies of the Permian Wutonggou Formation in Taibei Depression, Tuha Basin[D]. Qingdao: China University of Petroleum (East China), 2020.]

Calcite Cementation of Deep Sandstone and Its Reservoir Formation Effect in the Turpan-Hami Basin

XU Hui[1,2], CHENG Tian[3], CHEN AnQing[1], XU ShengLin[1], CHEN Xuan[3], WU Chao[3], YANG Shuai[1], LI FuXiang[1], ZHOU Gang[1]

1. Key Laboratory of Deep-time Geography & Environment Reconstruction and Applications, MNR & Institute of Sedimentary Geology, Chengdu University of Technology, Chengdu 610059, China

2. Geological Exploration Technology Institute of Anhui Province, Hefei 230031, China

3. PetroChina Tuha Oilfield Company, Hami, Xinjiang 839009, China

Abstract: [**Objective**] The Upper Permian Wutonggou Formation in the Lukeqin area of the Turpan-Hami Basin has good oil and gas exploration potential, making it a key deep exploration target in the Turpan-Hami Basin. Diagenetic analysis shows that calcite cement is one of the main authigenic minerals developed in the reservoir of the Wutonggou Formation in this area, but more work on the precise analysis is still recommended to improve our understanding of its diagenetic period and how it affects the reservoir quality. [**Methods**] Because the calcite cement is an abundant authigenic cements in most clastic rocks, it is also the product of fluid rock interaction during diagenesis, during which its relative content, occurrence type, occurrence, state and formation mechanism would likely exert huge impacts on reservoir quality. Combined with the previous study that concluded that mechanical compaction and cementation under deep burial conditions are the two main factors affecting the quality of the Wutonggou Formation sandstone reservoir in the Lukeqin area, we present the thin section identification, physical property analysis, scanning electron microscopy, cathodoluminescence, and other testing methods of the Wutonggou Formation in the Lukeqin area, Turpan-Hami Basin. We systematically investigated the period and diagenetic evolution of common calcite cements in the deep sandstone reservoir of this period and discussed the influence of calcite cement on reservoir quality. [**Results**] The photomicrographs and statistics show a clear positive correlation between the porosity and permeability, indicating that the sandstone reservoir of the Wutonggou Formation is porous. The calcite cement content most favorable for reservoir development of the Wutonggou Formation reservoir in Lukeqin area is 1%-8%. More than 8.0% samples show that the primary pores are almost filled with calcite, while less than 1.0% samples indicate that the compaction is too strong and unfavorable for reservoir development; Photomicrographs also exhibit a filling relationship that indicates three stages of calcite cement; the first stage is argillaceous calcite with 25%; the second stage is calcite cemented by continuous crystal with 60%; and stage Ⅲ is calcite filled with feldspar and other intragranular solution pores with 15%. There is no distinct positive or negative correlation between calcite cement and physical properties, which indicates that it belongs to ret entive diagenesis in the form of pore filling, which could occupy the remaining intergranular pores while enhancing their ability to resist compaction of the clastic particle skeleton. This is also consistent with a large number of earlier studies that the calcite cement formed in the early diagenetic stage before the main compaction can preserve the primary pores in the sandstone, which may further dissolve and release the secondary pores to improve the reservoir quality in the later diagenetic process. [**Conclusions**] Therefore, we suggest that the calcite cement is the key factor for the development of deep sandstone reservoirs of the Wutonggou Formation in the Lukeqin area.

Key words: calcite cement; cementation; deep sandstone reservoir; Wutonggou Formation; Turpan-Hami Basin