



钙华的形成环境与特征及在油气储集方向的探讨

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钙华的形成环境与特征及在油气储集方向的探讨

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摘要 钙华是一种特殊的化学或生物化学沉积, 它们在大陆内部广泛地分布且含有重要的地质信息, 是一种特殊的油气储集体。影响钙华沉积的因素复杂多样, 在调研钙华的形成过程及分类的基础上, 从气候环境、水文地质条件、水体物理化学条件、生物活动及构造活动五个方面讨论钙华形成的控制因素; 并从沉积环境与模式、沉积速率等方面将新疆塔北地区的钙华与国外钙华沉积体进行类比, 发现塔北钙华沉积体在温暖湿润的环境下表现出良好的季节性分层, 五道班地区钙华在沉积时汇入了大量的陆源碎屑, 受生物活动影响较大; 硫磺沟地区的钙华沉积则是伴随断裂活动所形成热液上涌的产物。通过对比发现, 塔北露头缝洞内充填的钙华内部孔隙发达、连通性较好, 并有良好的含油显示, 故钙华具备一定的储集能力。

关键词 沉积环境; 沉积模式; 沉积速率; 影响因素; 油气储集; 钙华

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0 引言

岩溶是在地表水与地下水的化学和物理过程的共同作用下, 对可溶性岩石的破坏和改造作用及其形成的水文现象和地貌现象^[1]。在岩溶发育地区, 钙华作为一种淡水碳酸盐沉积物普遍存在^[2], 常常形成十分瑰丽的自然景观, 如我国四川的九寨沟、日本的Nagano-yu、土耳其的Pamukkale。钙华沉积体含大量孔隙, 与形成环境、气候、水文地质条件、水体物理化学条件、生物活动和构造运动等有着密切的联系^[2]。国内外众多学者对钙华沉积等方面做了一系列的研究, 认为钙华在指示古气候、古环境、区域构造、地热活动历史^[3-4]、研究地球演化^[5]和保护环境^[6]等方面有着重要的应用价值。由于钙华的形态、成因类型多样, 沉积受控制的因素复杂, 且钙华作为多孔碳酸盐岩对于油气储集亦有一定的作用。因此, 本文在调研了国内外近年相关文献的基础上, 总结了钙华的类型、形成环境及模式、钙华形成的影响因素, 并讨论了塔北地区钙华的孔渗特征。

1 钙华的形成及分类

钙华形成于富含CO₂和CaCO₃的淡水中^[7-8], 通常是一种多孔、具微层的易碎碳酸盐岩^[9]。常温常压下CO₂以1:1溶于水, 当温度越低, 压强越大时CO₂在水中溶解的越多; 当水中的CO₂分压高于周围大气的分压时, 则会使CO₂从水中逸出, 水中的碳酸钙过饱和并发生沉淀^[10]。因此, 钙华的形成包括放气、沉淀两个阶段^[9], 其化学反应式为:



式中的正向反应为吸热反应, 可得出温度的升高将促进钙华的形成^[10]。同时, 在引起钙华沉积的水溶液中, 其pH值也对钙华的形成有一定影响。据郭卫星^[11]对川西北钙华的研究中发现, 在酸性介质中易于溶解, 而在碱性介质中比较稳定易沉淀。钙华的主要矿物为方解石和文石, 因文石不稳定, 可向方解石转变, 故可以根据主要矿物的组成判断钙华形成时间的早晚^[12]。

从钙华的成因上看, 可将钙华分为大气成因类钙

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华(meteogene travertine)和热成因类钙华(thermogene travertine),即对应表生钙华(Tufa)和内生钙华(Travertine)^[13]。划分以上两种钙华的依据是引起表生钙华沉积的水溶液中,有来源于大气和土壤成因(或来自高寒冷成因的)的CO₂气源对碳酸盐岩进行溶解和再沉积,多孔性强、层理较差、含有丰富的微生物和大型植物、无脊椎动物和细菌的遗迹^[14]。而引起内生钙华沉积的水溶液中,其CO₂气源产生于非大气和非土壤成因(如来自地球深部的变质成因或地幔成因),从而引起对碳酸盐岩的溶解和再沉积^[13,15],主要是坚硬的结晶沉淀物(有些易碎),通常含有薄层或灌木状细菌的生长^[16],形成具有规则层理和精細层理、低孔隙度、低渗透率和无机结晶无光泽的矿床^[14]。因此,关于钙华的成因机制亦分为有机(生物—化学)沉淀与无机沉淀。

从钙华的沉积形态上看,Pedley^[17]将钙华分为原地钙华和碎屑钙华,其中原地钙华又分为光合植物骨架钙华与光合植物黏结灰岩。Pentecost^[18]主张将其分为原地沉积和异地沉积,并将原地钙华依照形态分为八类(图1)。Vázquez-Urbez *et al.*^[19]将Tufa分为致密层状(叠层石)、致密—多孔块状、多孔(含苔藓、藻类的粗糙层状)状、致密—坚硬—层状沉积物(洞穴中)四种类型;Porta *et al.*^[20]将Travertine根据其岩相分为原地沉积类、生长部位被沉淀碳酸盐包覆的大型植物类、热水析出的颗粒类及碎屑类(内碎屑和底物外碎屑)四种类型。

在国内,前人在大量野外实践的基础上,将钙华沉积体的形态主要分为层状/似层状钙华、海绵状钙华、钟乳石状钙华、钙质包壳钙华、豆荚状/长条状钙华、砂糖状钙华等^[12]。新疆塔北硫磺沟古钙华主要分布于硫磺沟古溶洞的上部或裂缝中,大多含油颜色为黄褐色和灰白色间互、部分饱含沥青颜色为黑色和灰色间互,产出形式大多呈纹层状,少部分呈块状或环状包裹砾石,单层厚度受沉降环境和沉淀速度的影响,从1 mm~1.5 cm不等。五道班地区见多个钟乳石成群出现,大小不一,层界面内侧孔隙内含油;也可见分布于砾岩层顶部、层厚约0.1~1.5 m的砂糖状钙华,粒度上与碎屑岩中的粗砂岩相当,晶间孔隙发育,总体呈“缝网状”^[21]。

2 钙华的沉积特征

2.1 沉积环境和沉积模式

钙华广泛地分布岩溶区等多种沉积环境,如洞穴、岩溶泉、河流、湖泊、沼泽或温泉周围^[22-24]。在气候和构造区域的控制下^[16,23-24],不同成因机制的钙华其沉积环境表现出明显的差异。大气成因钙华(Tufa)一般形成于淡水环境,在快速流动的水域形成层状相,伴有快速相变化,在遇异常洪水时,其沉积体系会产生强烈的侵蚀,不连贯,因此保存潜力低,厚度差异大^[25-26];热成因钙华(Travertine)的沉积环境一般以缓坡为主,局部可演化为台地体系^[27],常出现于局部地形

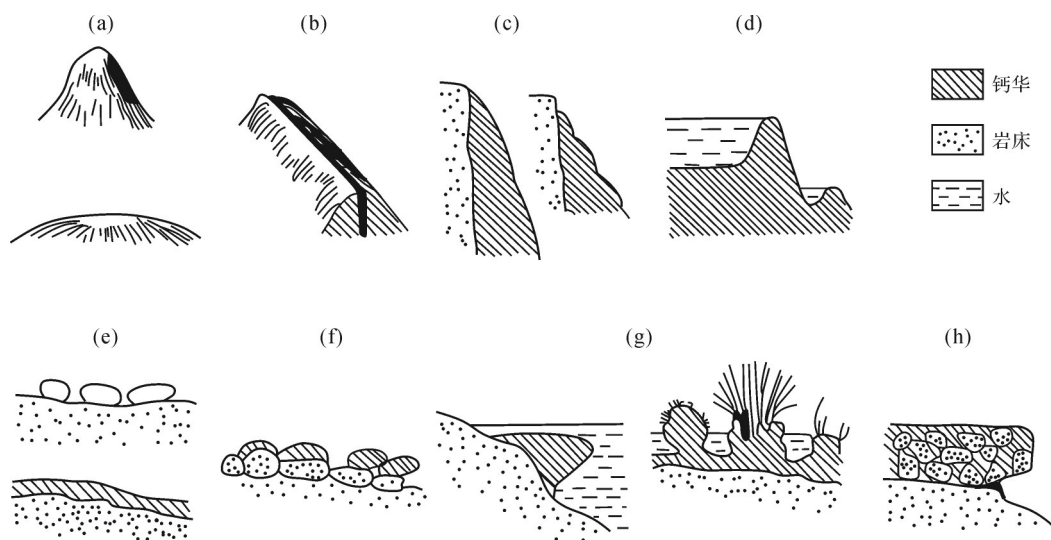


图1 钙华的沉积形态^[18]

(a) 泉华丘; (b) 泉华脊; (c) 瀑布; (d) 泉华坝; (e) 河流结壳; (f) 湖相结壳; (g) 沼泽沉积; (h) 表面胶结砾屑

Fig.1 The sedimentary morphology of travertine^[18]

(a) mounds; (b) fissure ridge; (c) cascades; (d) dam; (e) stream crust with oncoids; (f) lake crust with oncoids; (g) paludal deposit; (h) cemented rudite

有火山口的位置,在其几何形状、断层活动、水文、物理化学性质、热流率和碳酸盐沉淀率控制下致使沉积下来的钙华有厘米级的变化,因而其更易沉积在光滑的斜坡、阶地斜坡和次水平的斜坡环境中^[20]。

钙华的沉积模式与沉积环境有着密切的联系。Pedley^[17]将钙华沉积模式主要分为四种:泉水沉积、河流沉积、湖泊沉积和沼泽沉积(图2a~d);然而在岩溶发育地区,普遍存在着溶洞中沉积钙华的现象,因此作者补充了溶洞钙华沉积模式(图2e)。不同的沉积模式中,钙华在沉积过程中也表现出了明显的差异:泉水钙华多沿斜坡、急滩或陡崖沉积,形成滩华、坝华和瀑华,也可见钟乳石状钙华和石灰华洞;河流系统中形成的钙华坝在暖热地区下易形成较高的坝,在温凉环境下易形成较厚的障碍湖,在干热环境中由于坝高而易形成较大的湖;在生物群落更为完整的湖泊中,可在边界透光性良好的区域形成叠层状钙华,而在深水区则更易沉积碎屑状钙华;沼泽环境中一般为碎屑沉积,常形成厚度较大的疏松层状钙华沉积体,也常在动植物体上见碳酸钙结壳^[28];而在溶洞模式中,受流水控制,常在洞顶、洞壁形成石钟乳、石柱,在洞底见石笋、石枕等。

在曹乐等^[29]对巴丹吉林沙漠湖泊钙华的研究以及 Yeşilova *et al.*^[30]对土耳其 Anatolia 东部地区的大型钙华的研究中发现富钙的地下水进入湖泊产生的密度差支持了富钙水的运移,形成了柱状钙华的沉积体(图3f)。但有一种罕见的现象, Pellicer *et al.*^[31]在西班牙 Pyrenees 地区对钙华进行研究时发现此处湖泊是在钙华丘内部凹陷处形成的,并且将湖泊的演化过阶段划分出了五种沉积相:在强水文季节性时期形成的富碳酸盐的古陆沉积相、大量高等生物扰动的有机软泥相、与区域有效水分增加相关的富碳酸盐有机质带状相、细粒富石英风成/坡积物相和高海拔湖泊干涸后沉积的塌积相。

对于河流环境中的钙华, Toker^[32]将第四纪钙华分为苔藓、溶瘤、叠层石、植物碎屑、内碎屑、外碎屑、腐泥质、古泥质八种相和辫状河、堤坝、点砂坝三个沉积体系。 Nicoll *et al.*^[33]以埃及南部的尼罗河为例,研究了与古潜山相关的、绿洲和河谷附近的岩溶排水系统中的钙华,其内部具亚平行、交织的开放空间、局部的“蜂窝状(honeycomb)”结构,因孔隙体积、胶结程度不同表现出硬化—脆性的特征。 Wanas *et al.*^[34]认为河流环境中所呈现出的层状、块状、粒状等

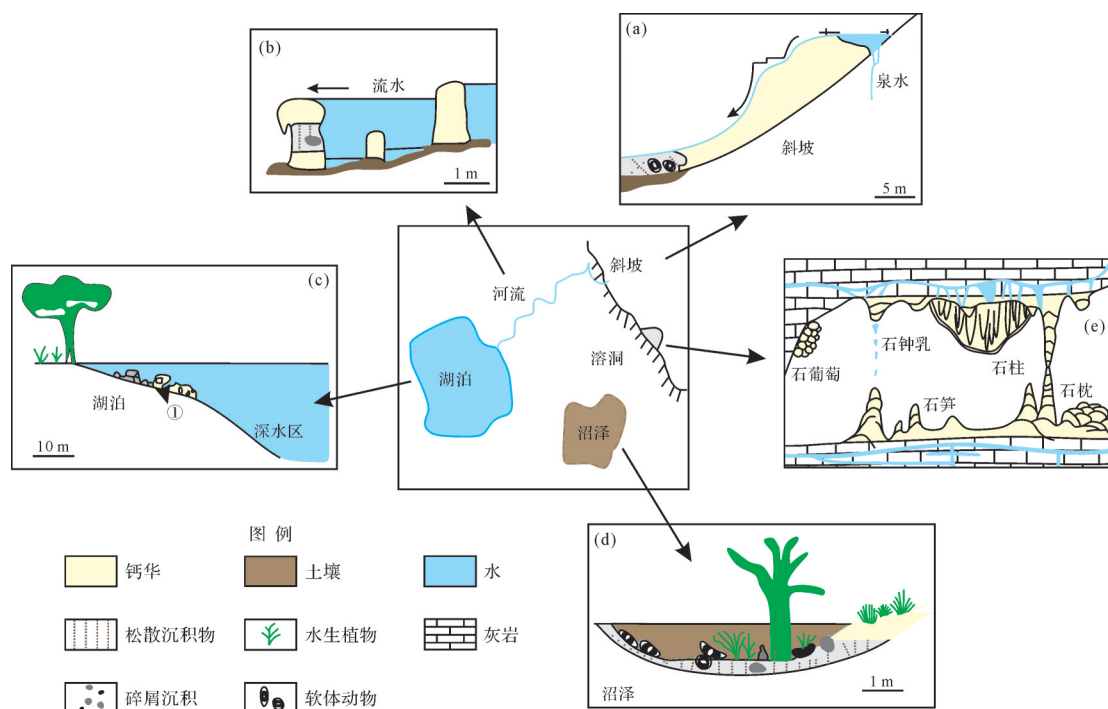


图2 钙华的沉积模式^[17]

(a)泉水钙华沉积;(b)河流沉积系统;(c)湖泊环境:其中①为叠层状钙华和碎屑沉积;(d)沼泽沉积模式;(e)溶洞沉积模式

Fig.2 The sedimentary model of travertine^[17]

(a) perched springline travertine model; (b) fluvial travertine model; (c) generalized lacustrine travertine model, ① the shallower areas promote stromatolitic developments associated with oblate oncoids and phytoclastic sediments; (d) generalized paludal modal; (e) karst cave deposition model

不同形态的钙华是大气降水与土壤中不同 C_3 植物作用下的结果, C_3 植物则是指光合作用时能将 CO_2 中的C直接转移到 C_3 里的植物,多为温带植物。

在塔北五道班和硫磺沟地区,钙华的沉积环境较为复杂。受沉积相带的控制,沉积模式为泉水、河流沉积;经历长期的岩溶作用后,溶洞发育,又在地下暗河的影响下,表现为溶洞沉积与河流沉积的双重模式,因此发育了具不同沉积形态的钙华。例如,五道班地区一处断裂系统中,钙华呈带状充填其中(图3a),在溶洞系统中以团块状沉积在地下暗河道中(图3d),在河流系统中沉积的包壳钙华外部壳体表现为叠层状(图3e);而硫磺沟地区的溶洞系统中则形成了同心圆状钙华的沉积(图3b),在河流环境中形成层状、马牙状钙华的沉积体(图3g)。

2.2 沉积速率

钙华一般具有极其明显的纹层结构(图4),纹层与温度、季节、生物和年份密切相关,因此可以通过纹层结构、厚度及现代钙华的沉积观察实验来探讨其沉积速率^[19,26,35-37]。Gradziński^[38]发现钙华在15~18

个月间沉积厚度可达1~2 cm, Pentecost *et al.*^[39]和 Nishikawa *et al.*^[40]研究发现钙华的平均沉积速率可高达1.75 mm/年与30.9 mg/cm²/天,胥良等^[41]基于钙均衡估算出黄龙钙华在整个现代堆积区内的平均沉积速率为2.51 mm/年,可见钙华的沉积速度相当之快。Vázquez-Urbez *et al.*^[19]在现代钙华观察实验中发现温暖气候环境沉积速率较大,每年可达5.26 mm和0.86 g/cm²,而寒冷气候则每年2.26 mm和0.13 g/cm²;并在快速流动且活动的瀑布中钙华沉积表现出高速率,在缓流或不流动的河流中表现出明显的低沉积速率,表现出明显的气候分异规律^[41]。Kawai *et al.*^[35,42]对日本西南地区河流相钙华进行研究过程中,发现此处的钙华沉积普遍发育夏季致密层和冬季疏松层的双年叠合,同时发现热带钙华与温带钙华相比,呈现较少的清晰分层和更密集的钙化纹理(图5)。

前人实验表明,大气成因的钙华在温暖或高能环境下沉积1 cm厚度平均需要2年,在寒冷或低能环境中则需要4年。而热成因钙华沉积速率明显低于大气成因的钙华,热成因钙华块状沉积体至少

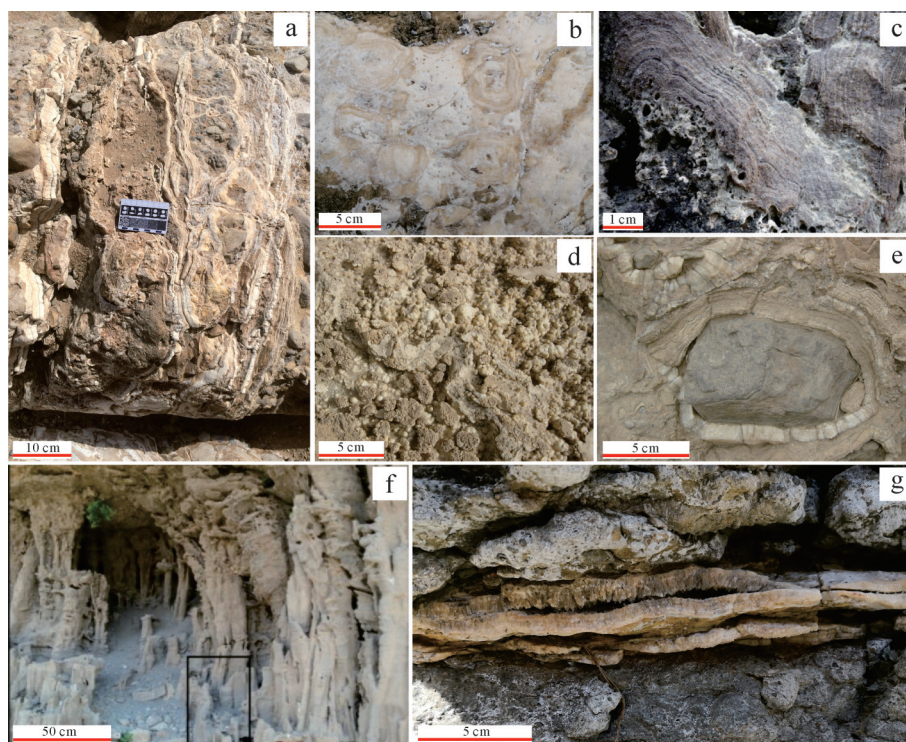


图3 钙华的沉积形态

(a)五道班脉状钙华;(b)硫磺2号沟同心圆状钙华;(c)肯尼亚南部叠层状钙华(Lee Ray *et al.*^[24]);(d)五道班地区团块状钙华;(e)五道班包壳砾岩(壳体呈叠层状);(f)土耳其Anatolia东部柱状钙华(Yeşilova *et al.*^[30]);(g)硫磺3号沟层状、马牙状钙华

Fig.3 The sedimentary morphology of travertine

(a) vein travertine in Wudaoban; (b) concentric round travertine in Liuhuanguo No.2 groove; (c) stromatolite travertine in southern Kenya (Lee Ray *et al.*^[24]); (d) massive travertine in Wudaoban; (e) encapsulated conglomerate in Wudaoban (with laminated shells); (f) columnar travertine in eastern Anatolia, Turkey (Yeşilova *et al.*^[30]); (g) stratified horsetooth travertine in Liuhuanguo No. 3 groove

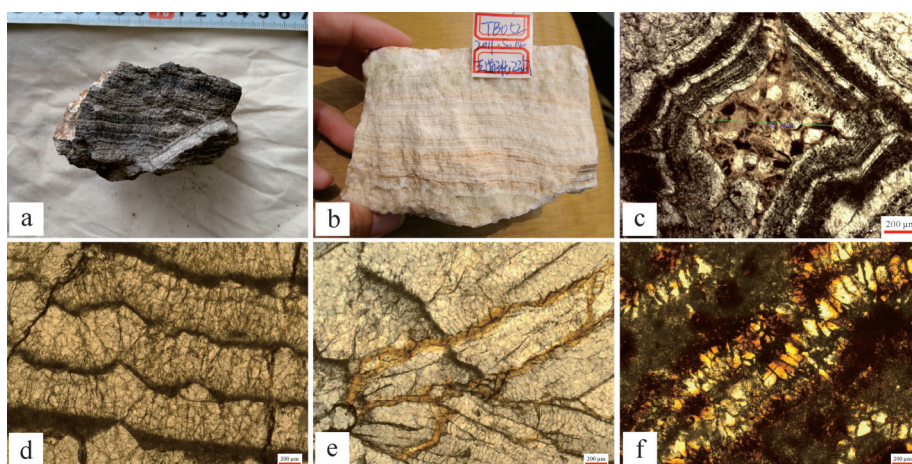


图4 层状钙华及镜下特征

(a)黑色含油钙华;(b)黄色含油钙华;(c)钙华包层间缝,单偏光,50×;(d)图(b)的镜下照片,纹层清晰,裂隙发育,单偏光,50×;(e)图(d)的镜下照片,裂缝发育且见油气充注,单偏光,50×;(f)层状含油钙华镜下照片,层间以马牙状颗粒分布排放,单偏光,50×

Fig.4 Stratified travertine and its microscopic characteristics

(a) black oily travertine; (b) yellow oily travertine; (c) travertine interlamellar fractures, plane-polarized light, 50×; (d) the microscopic characteristics of (b), it has clear laminae and developed cracks; (e) the microscopic characteristics of (d), fractures are developed and hydrocarbon charging is observed, plane-polarized light, 50×; (f) microscopic characteristics of a stratified oil-bearing travertine, horse tooth particles are distributed between layers, plane-polarized light, 50×

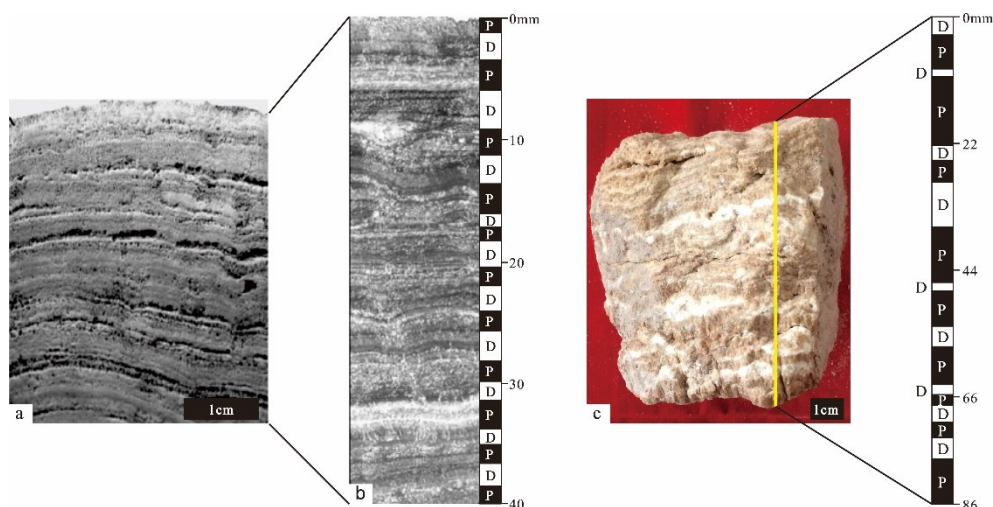


图5 钙华沉积的纹层特征

(a)层状钙华,日本西南Shimokuraida地区(据Kawai *et al.* [42]);(b)叠片结构,可见致密与多孔的重复(据Kawai *et al.* [42]);(c)层状含油钙华,可见致密与多孔的重复,新疆柯坪硫磺沟

Fig.5 Laminar characteristics of travertine deposition

(a) stratified tufa, Shimokuraida, SW-Japan(after Kawai *et al.* [42]); (b) lamination structure, there are repetitions of dense (D) and porous (P) (after Kawai *et al.* [42]); (c) stratified oily travertine, there are repetitions of dense (D) and porous (P), Liuhuanggou, Keping, Xinjiang

5~10年才可沉积1 cm,层状沉积体则需要更长的时间,平均在20年以上^[18]。在我国塔北硫磺沟地区先是地表抬升被剥蚀,再经历了一系列的岩溶作用,后期由岩浆活动分异而出的一部分岩浆热液流体沿断裂、裂缝或不整合面活动^[43-44],从而迅速成矿,其证据为该地区发现了大量钙华与热液成因的硫磺、石膏所伴生的现象。因此在硫磺2号沟所发现的纹层状古钙华属热成因型^[45],并且表现出了疏密互层沉积的

特征,在多孔层有含油显示,如图2中c样品厚度约为8.8 cm,推测其沉积时间需要180年左右。

3 钙华形成的影响因素

钙华作为一种化学沉积物,常出现在岩溶地区,经历着反复的侵蚀与堆积,在气候、地质地貌、水文、水体物理化学性质和生物的多重影响下形成了独一

无二的沉积体。从钙华的形成过程来看,主要受以下几个方面的控制。

3.1 气候

钙华可在寒温带到半干旱气候区形成^[16],但温暖潮湿的温带气候更有利于大气成因钙华的形成^[17]。气候是影响钙华形成的重要因素,由钙华生成的化学反应式可知, CaCO_3 的结晶沉淀是吸热反应,温度的升高有利于此反应的进行。此外,水中 CO_2 的平衡浓度对 CaCO_3 的饱和度有直接影响, CO_2 的溶解量随着温度的增高而降低^[28]。另外,有学者在对日本西南部钙华的研究中,水与方解石的分配率系数随温度的变化而变化;同时,钙华的沉积也与降水量有着密切联系,在雨季时具有明显的负相关关系,在旱季则为正相关^[37],当降水减弱时,在一定程度上也降低了钙华中矿物的析出率^[42]。另外,张红敏等^[46]在对诺日朗大坝钙华的研究中发现气候的变化影响钙华的颜色,在多雨季节,蓝藻依附钙华表面生长使其呈现出浅绿黄色,相反在旱季,蓝藻因缺水死亡,致使钙华含有的有机质在长期暴露环境中被氧化而呈黑色。

3.2 水文地质条件

不同的水文地质条件也影响着钙华的形成,如受深部岩溶动力系统(白水台)与表层岩溶动力系统(桂林长流水)控制形成的钙华就显著不同,长流水钙华沉积孔隙较大,较难观察到层面,而白水台钙华具有良好的季节性分层,其碳氧同位素较长流水钙华相比具明显季节性变化规律,且 $\delta^{13}\text{C}$ 值较高^[47]。而且,在一些含蒸发岩的碳酸盐岩(如鄂尔多斯盆地的中奥陶统灰岩、贵州三叠系灰岩)分布区,其泉水和地表河水中含有较高的硫酸钙,同离子效应也会引起钙华的沉积^[28]。另外,Okumura *et al.*^[48]对叠层状钙华的研究中发现,不同的水文条件会形成各种类型的分层,进而影响到叠层石灰岩的地质微生物学过程。

3.3 地形地貌条件

复杂的地质构造运动形成了不同的地形地貌,进一步影响了钙华的沉积。例如,山西介休洪山泉钙华沉积于洪积扇发育的山前倾斜冲洪积平原,NE向断裂阻挡了南东侧的岩溶水并形成断层溢流泉,使钙华沉积在了断裂北西侧的扇形台地上,剖面上呈楔状^[49];四川黄龙地区,受控于高寒区以冰川沟为主的地貌条件,在沟口洪积扇处形成了石坝、滩华、

瀑华等钙华景观,单体以鲕状钙华包壳粒为主^[50];新疆塔北地区,钙华多充填于断裂带发育处,或在有地下暗河发育的溶洞系统中。

3.4 水体物理化学条件

水体中存在压力效应,水中溶解的 CO_2 和大气中的 CO_2 分压有一定的平衡关系,当大气中的 CO_2 分压降低时,水中溶解的 CO_2 含量也将随之相应降低,有利于钙华的形成^[28]。同时,水化学的稳定性也对钙华的结构和化学成分有着重要影响,水中微量元素的浓度决定了所形成的钙华中微量元素的浓度,进而影响Mg/Ca、Mg/Sr或碳氧同位素等^[42,51]。国外学者还提出人类活动(森林砍伐等)影响了水化学成分的变化和地表径流的加剧,从而影响了钙华的化学和物理降解,因此对其沉积具有抑制作用^[8,52-61]。

水位与水动力效应(水力状态和流速)也会对钙华沉积造成影响^[62-66]。Bisse *et al.*^[63]根据Bongongo hot springs水位波动和气候变化特征建立了三种温泉碳酸盐岩沉淀推断过程和控制模型(图6)。干旱环境中水量减少致使地表水水位下降,热流体沸腾区于更深的地方形成,同时增加了上升流体的 CO_2 浓度,而上升液体在沸腾过程中产生脱气,pH值的升高使 CaCO_3 沉淀在通道上,表面水域因 Ca^{2+} 浓度较低故沉淀物较少;潮湿环境下易在距离地表较近处形成浅沸腾区,上升的热流体与冷却密集的地表水混合,有利于迅速消除 CO_2 导到浅层表面、并在沸腾点附近的喷口析出 CaCO_3 ,又由于降水增多会稀释沼泽中的水,因此可能会进一步导致钙华的沉淀减少;在由潮湿转为干旱的正常环境下,沼泽水位的下降,稀释了碱性补给和热液混合,促使径流补给也相应减少,此可降低沸水带的形成,从而增加了浅层方解石析出,剩余排出的液体则可能会沉淀陆生方解石,于地表形成钙华。

一些学者将钙华沉积速率的水动力控制归结为固液界面间存在的扩散边界层效应,即流速越快、扩散边界层越薄、沉积速率越大,反之亦然^[23,63-64,67]。比如在瀑布处因水流飞溅使水中的 CO_2 脱气产生沉淀^[13],四川黄龙地区快速流动的水体中 CaCO_3 的沉积速率是慢速流动水体中的2~5倍^[64],并且在流速较快的滩流、边石坝或跌水处,藻类易在钙华表层形成藻席,在季节变化中形成钙华纹层,而在水动力较弱的池子中央则易形成粗大的球粒状集合体^[68]。

3.5 生物条件

生物活动对钙华沉积有着不可忽视的影响,尤其是微生物。众所周知,蓝藻细菌和藻类的代谢作用可以改变沉积水体水化学,能够诱导方解石/文石沉淀,从而形成含有大量藻类植物的微生物碳酸盐^[25,68-69]。

生物成因的钙华影响着钙华沉积的颜色、结构、形态、沉积速率等^[35-36,70-72]。在四川九寨沟地区沉积的钙华则可明显观察到生物活动参与钙华沉积的现象,位于诺日朗瀑布形成的大坝钙华以黑灰色为主,结构疏松、层次性差,内部多孔洞,多种植物残余以及生物骨架发育;其顶部夹杂褐色至黄色的杂色碎屑钙华层,多为藻类和微生物残骸,在风化后表现出

成层性^[46]。其钙华结构受藻类的生长及季节变化常形成生物结构纹层,与物理化学成因为主的亮晶方解石纹层互层^[68]。另外,生物分布与环境的相互作用也会使钙华在水平和垂直方向上都表现出快速地相变化且不连贯,呈由小到大的洞穴状结构且厚度差异明显(图7)^[6,69,73]。

3.6 构造活动

断裂活动会促进热液流动,表现为快速的碳酸盐沉淀(图8)^[74-76]。近年来,在裂缝—山脊(断层)地带发现了石灰华(钙华)矿床,且多数地区发生过历史性的地震,故强调了地震事件、流体循环和钙华沉积之间的强烈关系,认为地震活动可重新激活热液流体和诱发钙华沉积,从而产生协同/震后效应^[77]。

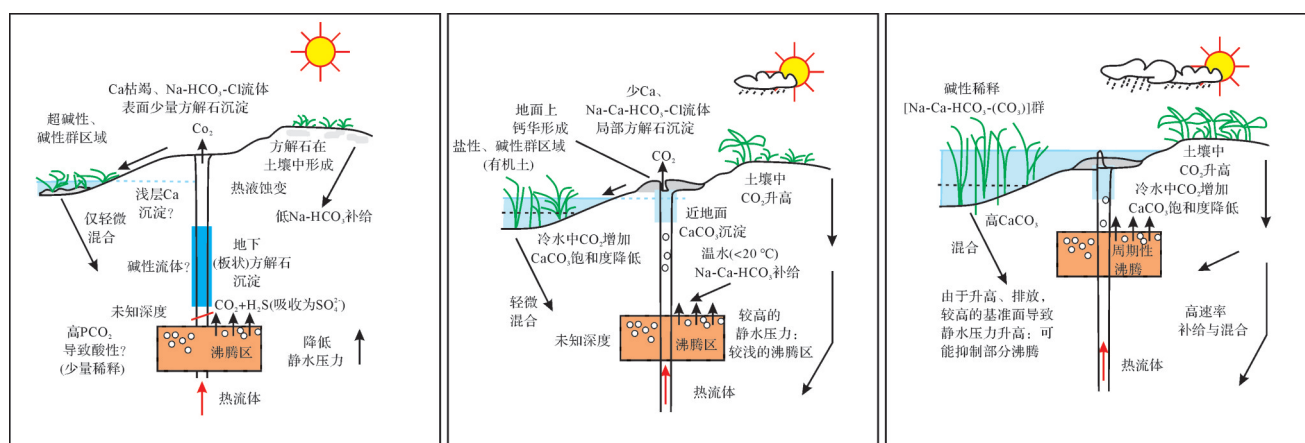
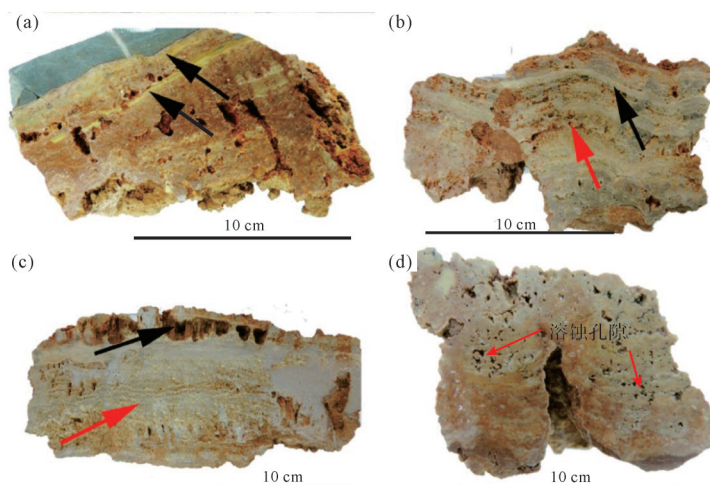


图6 温泉碳酸盐岩沉淀推断过程和控制模型(据 Bisse *et al.*^[63]修改)

(a)干旱环境;(b)正常环境;(c)潮湿环境

Fig.6 Inference process and control model of carbonate precipitation in a hot spring (modified from Bisse *et al.*^[63])

(a) Arid condition; (b) Intermediate condition; (c) Humid condition



↑ 叠层状: 形成于微生物膜内, 经连续的生物与非生物成因方解石沉淀而成
↑ 柱状: 柱间腔内残留红土的堆积破坏了生物介导的方解石沉淀而成

图7 受生物影响的层状与柱状(钟乳石状)钙华(据 Khalaf^[69]修改)

Fig.7 Stratiform and columnar (stalactite) travertine under biological influence (modified from Khalaf^[69])

例如,裂脊受到构造控制导致热泉排放,造成热液沉积,其母岩富含碳酸氢盐的热液流体沿相互连通的裂缝分布,从而形成层状或带状的钙华^[4,78-81]。由此可见,研究钙华沉积的机理也可作为重建古地震、分析断裂和地震活动的重要工具^[77,82-83]。

综合上述影响钙华沉积的各种因素,在塔北地区,钙华是在温暖湿润的亚热带环境中形成的,由于冬夏气温和降水的差异,钙华在夏季沉积厚度较大^[15,45,84-85]。据地球化学特征显示(表1),该地区的泉

水、河流中具较高的硫酸钙,在同离子效应下沉积了一定的钙华;另外,Mg/Ca 比较小说明钙华在沉积时,在大气降水的影响下汇入大量的陆源碎屑。微生物的活动有利于方解石或文石沉淀,故而在泉口附近的河流中见大量的钙华沉积体,同时对钙华沉积的纹层特征产生一定的影响。而在塔北硫磺沟、大湾沟地区的断裂带处所见到的钙华沉积体,深受构造活动的影响,在此处热液流体上涌后形成呈带状或层状的钙华充填于裂缝。

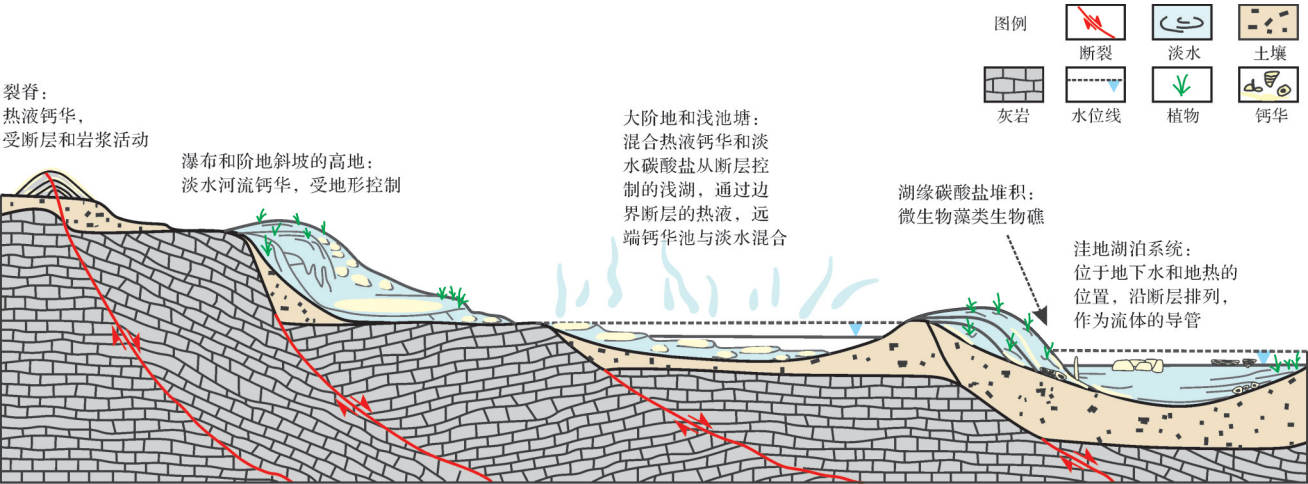


图8 裂脊与钙华沉积 (据 Török *et al.*^[74]修改)
Fig.8 Fissure ridge and travertine deposition (modified from Török *et al.*^[74])

表1 新疆塔北钙华Ca、Mg、S元素含量表(%)

Table 1 Ca/Mg/S contents in the travertine from Tabei, Xinjiang (%)

样品编号	采样地	岩性	CaO/×10 ⁻²	MgO/×10 ⁻²	S/×10 ⁻²
TB040	硫磺沟1	缝洞钙华	55.97	0.272	0.027
TB005-3	硫磺沟2	含硫层状钙华	50.98	0.282	6.80
TB008	硫磺沟2	含硫钙华	44.20	0.205	17.97
TB023	硫磺沟2	方解石晶簇	55.73	0.312	0.133
TB013	硫磺沟2	含油钙华	56.06	0.343	0.352
TB006	硫磺沟2	表层含硫层状钙华	56.30	0.322	0.203
TB024	硫磺沟2	方解石晶簇	55.20	0.308	0.046
TB080	硫磺沟2	包壳砾岩	55.89	0.313	0.064
TB081	硫磺沟2	包壳砾岩	53.04	0.338	1.65
TB028	五道班1	砂糖状钙华	53.92	1.81	0.026
TB066	五道班1	钙华	12.38	7.89	0.014
TB067	五道班1	方解石	54.72	1.39	0.128
TB089	五道班2	砾石钙质胶结	35.43	6.96	0.034
TB051	五道班4	方解石	38.88	12.72	0.014
YJF07	一间房	灰岩夹薄层石膏	39.211	0.832	17.852
YJF09	一间房	含硫灰岩	32.017	0.247	16.905
YJF11	一间房	含硫灰岩	41.266	0.693	18.71

4 钙华的孔渗特征

国外的许多学者在研究钙华时发现,钙华具有多孔、疏松、孔隙度高的物性特点,可作为良好油气储集体,孔隙度可达4%~30%^[27],特别是受生物活动影响强烈的钙华沉积体,由于其良好的层状结构及外部包壳使其内部存在大量连通的孔隙。在 Freytet *et al.*^[70]对巴黎盆地钙华的研究中发现近现代正在沉积的钙华其孔隙率可高达40%~50%。在大陆性的碳酸盐岩沉积台地,不同的相序由于沉积环境的变化,钙华沉积常出现多孔与致密的互层现象,孔隙度相对较好(平均值大于10%),渗透率在露头、岩溶系统和裂缝网络发达的地方有显著提高^[4,27,74,83]。在活跃的构造环境中,活动断裂影响着水热循环,基底沉降、重力塌陷在一定程度上会促进和控制钙华裂隙的发育,从而改善断层的渗透率^[86-87]。

在国内,学者普遍认为钙华作为缝洞化学充填物,基本不具有储渗能力,难以构成有效储集空间^[88]。缝洞充填方解石可将缝洞储层完全封闭,导致连通洞穴隔绝,对储层作用是破坏性的^[89-90]。然而少数学者如牛永斌等^[15]、钟建华等^[45]、Zhong *et al.*^[84]、毛毳等^[85]在研究塔北奥陶系含油古溶洞时则发现钙华沉积,疏松多孔,局部见油气充注或过油现象(图9);汪智军等^[6]也证实大气成因的钙华中的动植物残体在被埋藏后快速分解,从而形成大量生物成因的孔隙。

通过对新疆塔北地区钙华沉积体的进一步研究发现,钙华内部的储集空间多为裂缝及溶蚀孔隙

(图10)。对该地区钙华沉积物进行孔渗测试后得到孔隙度分布在3.1%~32.2%之间,主要集中在2%~10%之间,均值为8.03%;渗透率从 $0.10 \times 10^{-3} \mu\text{m}^2$ 到 $113 \times 10^{-3} \mu\text{m}^2$ 不等,均值为 $22.24 \times 10^{-3} \mu\text{m}^2$,集中分布在 $(1 \sim 20) \times 10^{-3} \mu\text{m}^2$ 区间内,渗透率较好(表2)。由于钙华中的小裂隙、晶间孔、缝非常发育,良好的孔渗特征使其具备了很好的储集能力。并且在新疆的硫磺沟和五道班的古溶洞中常见此类的黄褐色和黑色古钙华,具有硫化氢和沥青气味,含有油质或沥青质,基于上述现象认为钙华可以作为碳酸盐岩油藏的潜力储层。然而在塔河油田岩心中,溶洞中少见钙华,而是常被结晶方解石充填,受成岩作用的影响储集物性整体较差。因此,钙华虽具有一定的油气储集意义,但其沉积体形成大型油气储集的能力有限。

5 结论

(1) 在以气候和地质构造运动为主的控制下,水体性质、生物活动及断裂系统也发生着相应变化,进而影响到钙华沉积时的速率和分布,也使得钙华沉积体在颜色、形态、结构等方面表现出明显的差异性。总体而言,塔北五道班和硫磺沟,钙华表现出以黑灰色或浅黄色纹层状为主的沉积特征,多在温暖潮湿的气候环境中,沉积于斜坡环境中并伴有快速的相变化,同一地区的钙华生成不拘于同一沉积模式,沉积速率的变化使钙华展现出致密与疏松交互的纹层特

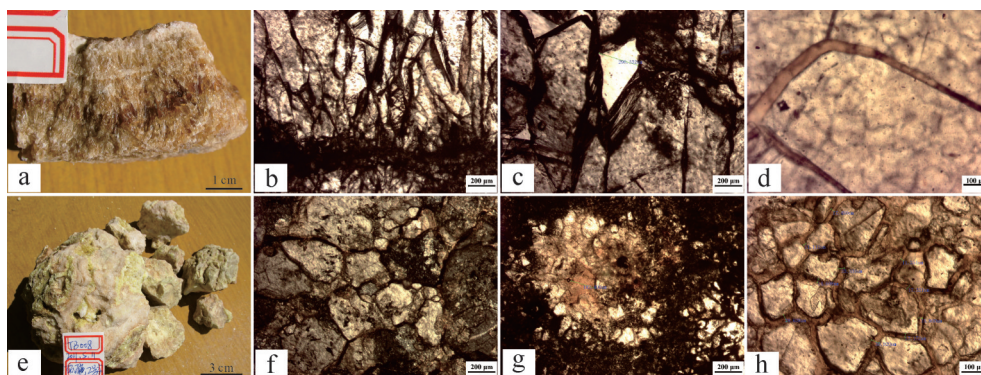


图9 钙华样品及镜下特征^[85]

晶簇状含油钙华(新疆塔北):(a)截面;(b)钙华孔隙,单偏光,50×(据毛毳等^[85]);(c)溶蚀孔,单偏光,50×;(d)油类充注,单偏光,100×;包壳状钙华(新疆柯坪硫磺沟):(e)钙华样品;(f)钙华及晶间缝,正交光,50×;(g)溶孔钙华胶结及残余孔,单偏光,50×;(h)晶间缝及油类充注,单偏光,100×(据毛毳等^[85])

Fig.9 Travertine samples and microscopic characteristics^[85]

crystalline clusters of an oil-bearing travertine (Tabei, Xinjiang): (a) travertine section; (b) travertine pore, plane-polarized light, 50× (after Mao *et al.*^[85]); (c) erosion pore, plane-polarized light, 50×; (d) oil filling, plane-polarized light, 100×. encrusted travertine (Liuhuanguo, Keping, Xinjiang) (e) travertine samples; (f) intercrystalline calcification, orthogonal light, 50×; (g) dissolution pore travertine cementation and residual pore, plane-polarized light, 50×; (h) intergranular joints and oil filling, plane-polarized light, 100× (after Mao *et al.*^[85])

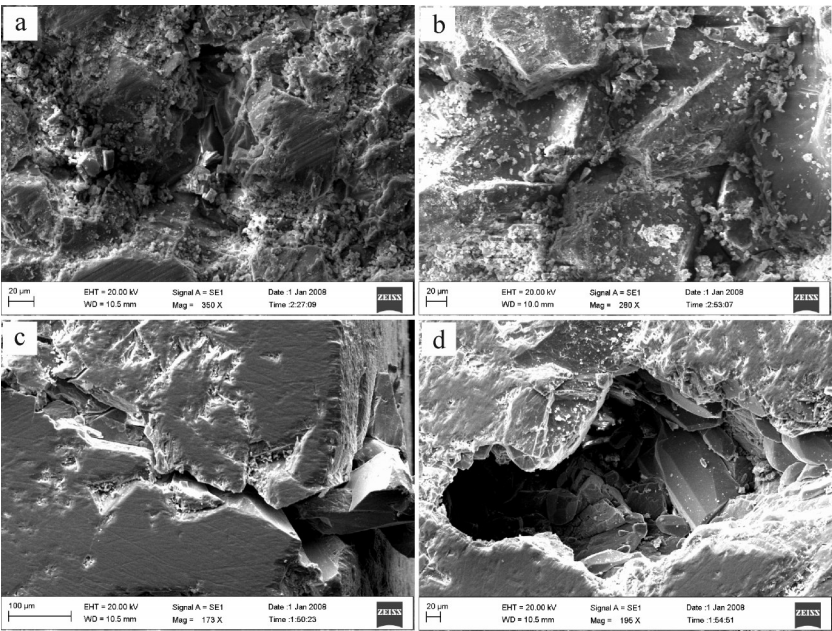


图 10 新疆塔北钙华镜下孔隙特征^[82]

(a)黄色含油钙华内部孔隙,SEM,350×;(b)黄色含油钙华内部孔隙,SEM,280×;(c)黑色含油钙华,裂缝及溶蚀孔,SEM,173×;(d)黑色含油钙华,溶蚀孔,SEM,285×

Fig.10 Microscopic pore characteristics of the travertine in Tabei, Xinjiang^[82]

(a) yellow oil-bearing travertine internal pore, SEM, 350×; (b) yellow oil-bearing travertine internal pore, SEM, 280×; (c) black oily travertine, cracks and dissolution pores, SEM, 173×; (d) black oily travertine, dissolution pores, SEM, 285×

表 2 新疆塔北钙华孔渗数据表

Table 2 Data sheet of travertine porosity and permeability in Tabei, Xinjiang

序号	井号/地区	岩性	密度/(g/cm ³)	孔隙度/%	渗透率/×10 ⁻³ μm ²
1	柯坪	黄色纹层状钙华	2.50	7.2	0.191
2	柯坪	黄色含油钙华	2.53	6.1	8.780
3	柯坪	白色砂糖状灰岩	2.60	3.1	113
4	柯坪	包壳砾岩	2.59	3.8	0.649
5	柯坪	钟乳石	2.58	4.7	5.40
6	柯坪	白色钙华、钟乳石	2.50	6.8	106
7	五道班	砾岩胶结物	2.52	7	32.90
8	五道班	钟乳石	2.56	9.5	18.200
9	五道班	黄褐色铁质胶结方解石	2.94	4.1	0.102
10	硫磺2号沟	包壳砾岩	2.34	13.3	8.040
11	硫磺沟	砂糖状钙华	1.75	32.2	6.570
12	硫磺2号沟	白黄色细纹层状钙华	2.60	3.5	1.720
13	五道班	砖红色铁质胶结方解石	3.01	4.9	0.520
14	硫磺2号沟	硅质砾石胶结物、包壳砾岩	2.53	5.1	17.400
15	硫磺沟521	含油钙华	2.44	9.2	14.100
平均值			2.53	8.03	22.24

征,指示了不同的古气候条件;另外,母岩富含碳酸氢盐的热液流体在相互连通的裂缝和断裂带处所形成的钙华沉积体,可以推测断裂活动期及活动强弱。

(2) 钙华具有良好的孔隙结构,渗透率也较高,广泛发育在岩溶地区。特别是在新疆塔北地区,钙华作为一种充填物充填在缝洞型碳酸盐岩储集层中,裂缝及溶洞充填物里所发育的残余粒间孔、溶

蚀孔为油气的储集提供了相对充裕的空间,且含油显示良好。这对于从精细角度研究缝洞型碳酸盐岩成储控储机理及油气资源评价具有一定的参考价值。

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Overview of the Formation Environment and Characteristics of Travertines and Discussion on the Direction of Oil and Gas Reservoir

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Abstract: A travertine is a special chemical or biochemical deposition. They are widely distributed in the interior of the continent and contain important geological information and are special reservoirs of oil and gas. The factors that affect the deposition of travertines are complex and diverse. Based on the investigation of the formation process and classification of travertines, this article discusses the controlling factors of travertine formation from five aspects: climate environment, hydrogeological conditions, physical and chemical conditions of water bodies, biological activities, and structural activities. Then, the travertine in the Tabei area of Xinjiang province is compared with foreign travertine deposits in terms of depositional environment, model, and deposition rate. The travertine deposits show good seasonal stratification under a warm and humid environment in north Tarim. The travertine in Wudaopan area was deposited into a large amount of terrigenous debris and greatly affected by biological activities. In Liuhuanggou, travertines are a product of hydrothermal upwellings resulting from fault activity. By comparing and summarizing the findings, the travertine that filled in the fractured caves in Tabei has well-developed internal pores, good connectivity, and good oil content display. Therefore, the travertine has a certain storage capacity.

Key words: depositional environment; depositional model; deposition rate; influence factor; oil and gas reservoir; travertine