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细粒沉积物搬运机理研究进展

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摘　要　【意义】细粒沉积物搬运机理研究是细粒沉积物“源—汇”系统理论中的重要一环，对恢复沉积环境、理解细粒沉积物分布和预测非常规油气资源等方面具有重要意义。由于细粒沉积物粒度细小，不便观察，且搬运方式多样，不同搬运方式对应多种沉积构造，因此，细粒沉积物搬运机理的研究进展缓慢。纵观国内外现有的研究成果，目前还缺乏针对细粒沉积物搬运机理研究成果的梳理和总结。【进展】综合当前的研究成果，系统梳理了细粒沉积物的搬运方式及沉积特征，将细粒沉积物搬运方式分为物理搬运、化学搬运和生物搬运三大类。物理搬运包括河水、大气、底流、异轻流和六种重力流搬运，河水和大气搬运依靠流水或风的动力，克服细粒物质的重力作用，实现对细粒物质的搬运，搬运的驱动力主要是推移力和载荷力；底流、异轻流和重力流搬运由潮汐、风力、地震、洪水、风暴、火山喷发等方式触发，搬运的驱动力主要是重力。黏土矿物、溶解有机碳、碳酸盐类矿物、铁质矿物等呈胶体溶液或真溶液被搬运；溶解物质受环境的 pH 值、Eh 值、温度、压力、离子浓度或电荷等影响，能够通过化学方式搬运。生物吸收富集、生物活动引起环境改变和生物扰动均能影响细粒物质的形成和搬运。【结论与展望】物理搬运方式以推移力、载荷力和重力等作用为驱动力，可形成丰富的沉积构造；化学搬运主要涉及溶解物质，受 pH 值、温度等环境因素影响；生物搬运通过吸收富集、改变环境和生物扰动等方式影响细粒物质搬运。未来应聚焦于细粒沉积物搬运机制间的相互作用，提高沉积构造识别精度，重视模拟实验研究，加强化学作用和生物作用定量化分析，以提升对细粒沉积物搬运过程的认识，推动细粒沉积学理论向前发展。

关键词　细粒沉积物；搬运机理；触发机制；沉积特征

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0　引言

细粒沉积物在岩石学中是指粒径小于 62.5 μm 的泥级和粉砂级沉积物[1-2]，成分主要包括黏土矿物、长英质矿物、碳酸盐矿物、有机质等[3]。2007 年 Schieber *et al.*[4]利用水槽实验，证明了黏土矿物能够在高能水体中搬运沉积，颠覆了人们在细粒沉积方面的传统认识，标志着细粒沉积学研究进入了新阶段。之后，研究人员又利用水槽实验，证明了细粉砂和细粒碳酸盐矿物能够像砂粒一样被搬运并沉积[5-6]。随着研究的不断深入，细粒沉积物通过底流、异轻流、风暴流、异重流、波浪增强重力流[7-12]等流体搬运的证据不断被发现，印证了细粒沉积岩能够在高能水动力环境中形成的观点。此外，众多学者[13-16]也指出，化学作用和生物

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作用在细粒沉积物的搬运过程中同样扮演着重要角色，这些认识极大地促进了细粒沉积学的发展。尽管对细粒沉积物搬运方式的研究已取得了显著进展，但相较于细粒沉积学其他领域进展仍然缓慢，目前国内外学者还没有对细粒沉积物的不同搬运方式开展系统性总结。基于此，本文收集和整理了前人的研究成果，结合东营凹陷沙河街组三段—四段细粒沉积岩、川北及川东北侏罗系千佛崖组（凉高山组）二段泥页岩的研究成果，对细粒沉积物搬运方式的特征、触发条件以及形成的沉积构造等特征进行了系统性的梳理和总结，以期为细粒沉积物搬运机理的后续深入研究和细粒沉积物沉积机理的研究提供参考，从而促进细粒沉积学理论的发展，同时为非常规油气资源分布预测提供理论支撑。

1 物理搬运

细粒沉积物有多种物理搬运方式，包括河水搬运、风力搬运、底流搬运、异轻流搬运和重力流搬运[17-20]。

1.1 河水搬运

黏土和粉砂级的长英质矿物能够以悬浮载荷方式在河水中搬运[21]，水流速度、粒径大小[22-23]等是影响河流中沉积物悬浮载荷的关键因素，例如河床底部的细粒沉积物能够被强烈的水流冲刷，重新悬浮起来[22]；较小的粒径需要较低的流速来克服重力，因此更易在水流中悬浮，从而搬运更远的距离[23]。Lamb *et al.*[24]通过研究 8 条低洼沙质河道中 180 个沉积物浓度剖面，认为河水中的细粒沉积物多以絮凝体形式进行悬浮搬运。Maroulis *et al.*[25]研究发现，土壤中粉—细砂长英质矿物和富含蒙脱石的黏土物质，在干旱和潮湿交替的环境中能够形成细砂大小、密度低于石英颗粒的絮凝体。土壤成因的絮凝体主要以类似石英颗粒的滚动或跳跃形式底载荷搬运[25]，絮凝体的底载荷搬运在现代和古代的河流记录中是一个普遍现象[26]。水槽实验表明，这些絮凝体处于不同流速下，在床底能够形成低、过渡和高流态的不同床面形态[25]。由于黏土片层之间存在静电作用，絮凝体具有良好的稳定性[27]。一般情况下，当水流条件发生变化时，絮凝体能保持其形态，尺寸不会明显减小[26-28]，不过，在持续的洪水事件中，这些絮凝体会发生解聚[29]，解聚后的物质呈悬浮态，在床底形成具有黏性、抗搬运的表面，这种表面在之后的干旱和潮湿周期中可以再次形成泥质絮凝体[25]。

水体碳库中包括颗粒无机碳（PIC）、溶解无机碳（DIC）、颗粒有机碳（POC）和溶解有机碳（DOC）[30]。研究表明，河水将 POC 和 DOC 从陆地搬运到水体是全球碳循环中的重要环节[31]，其中每年全球河水向海洋物理搬运的 POC 达 110~230 亿吨[32]。水体中的 POC 是不能通过亚微米级孔径过滤器的有机物，主要由河水中的陆源输入物、水体中的自生浮游

植物和大型水生植物碎片组成[33-35]，河水中的陆源输入物主要是陆地植物碎片和土壤有机物混合物[33]。季节变化、洪水、风暴等是影响河水向盆地水体搬运 POC 的重要因素[31,33,35-39]。通常认为，河水中的 POC 随着细粒悬浮沉积物一起悬浮搬运[39]，但最近的研究表明，粒径较大或密度较高的植物碎屑、木屑等粗颗粒有机物能够在（近）河床表面被搬运[31]，颗粒有机质所占比例受颗粒大小和形状、难降解性、沉积物负荷、湍流程度[31]、靠近河床的流速及二次流运动等条件的控制[40-42]。搬运过程中，（近）河床表面的颗粒有机质与其他碎屑颗粒之间的相互作用会导致有机质的磨损[40,43-44]，磨损后的颗粒有机质在河水中将转变为悬浮搬运[31]。在川北地区千二段和东营凹陷沙四上亚段的部分细粒沉积岩中，近圆形、长条形或不规则形状的黑色炭屑与长英质或碳酸盐矿物颗粒均匀分布，利用扫描电镜分析，川北地区千二段细粒沉积岩中破碎的镜屑体、惰屑体等陆源有机质碎屑较为发育，夹杂于石英、黏土等陆源碎屑矿物之间（图 1a），反映了颗粒有机质在河流的输运作用下，与其他物质组分相互磨损、破碎，共同搬运入湖悬浮沉降的特征。

1.2 大气搬运

大气搬运的细粒沉积物主要为沙尘和火山灰[15,17-18,45]。现代沙尘暴观测结果表明，粒径在 0.1~0.5 mm 的颗粒以跳跃方式运动，0.5~2 mm 的颗粒通过蠕动方式前进，小于 0.1 mm 的颗粒以悬浮方式运移[46]，沙尘主要由粉砂粒径的石英构成，这些细粒物质借助风力可以输送到距离源区数千公里的位置沉积下来[47]，例如撒哈拉沙漠产生的沙尘影响范围远至美国东南部、加勒比海等地区[48-49]，O’Brien[50]认为风力搬运到盆地中的粉砂和黏土悬浮沉降，是形成细粒沉积岩中水平连续、层内无粒度分级、界面突变接触的粉砂和黏土薄层的机制之一（图 1b）。火山喷发时产生的大量细小火山灰（粒径小于 2 mm）可通过风力等自然作用进行长距离搬运，研究表明粒径小于 10 μm 的火山灰颗粒在大气中停留时间可能超过 10 天[51]，甚至数月[52]，例如 7 万年前印尼的多巴超级火山喷发，3 000 km^{3}的火山灰迅速扩散，3 天后遮蔽了半个地球，距离火山口 2 000 km 外的印度沉积了 5 m 厚的火山灰[53]。

1.3 底流搬运

底流通常指深水沉积环境中长期或持续作用于水体底部，能够造成搬运、侵蚀和沉积的半永久性水流[54-56]，等深积岩是底流活动直接作用的沉积产物[57-59]。底流的形成与温盐驱动、风、潮汐、上升流和下降流等多种因素有关[54]。根据底流的驱动机制，底流分为风驱底流、温盐底流、深水潮汐底流和内波/内潮汐驱动的斜压流四类[59-60]。

研究表明，底流是水体中细粒沉积物的重要搬运机制[61]。Smith *et al.*[62]分析了美国东部阿巴拉契亚盆地中—上泥盆统富有机质黑色页岩后，认为底流的搬运作用是形成该套细粒沉

积地层的重要因素，证明了富有机质页岩可以形成于具有一定水动力的含氧环境；Schieber *et al*.[7]研究了罗马尼亚的沥青质灰泥岩地层后，提出其中的细粒复合颗粒是由同时期的海底底流侵蚀，之后以底床载荷方式运输后沉积而成，丰富了人们对细粒沉积物搬运机制的认识；Paz *et al*.[63]在阿根廷 Neuquén 盆地侏罗纪晚期—白垩纪早期的细粒沉积地层中，发现了大量底流搬运形成的平行层理、波状交错层理等牵引构造，扩展了学界对细粒沉积物运输过程的理解。

牵引构造是底流搬运最常见的沉积构造[60,64]（图 1c），平行层理、波状层理、压扁层理、透镜状层理、双黏土层、羽状交错层理、低角度交错层理、双向交错层理、爬升波痕交错层理、波状交错层理、脉状层理、逆粒序层理等沉积构造能够在底流沉积物中识别出来[64-66]，这些沉积构造往往单独出现，并非形成一个完整递变的序列，从而可以与浊流等流体类型进行区分[66]，但四类底流均能形成类似的牵引构造，如何利用这些沉积构造区分不同类型的底流是目前面临的挑战[64]。东营凹陷沙河街组三段—四段的灰质泥岩或泥质灰岩中，常见泥晶方解石颗粒构成的透镜体（图 1d），透镜体长轴多水平排列，成层性较好，附近沉积物未见风暴作用造成的扰动构造，说明搬运流体为水平运动的层流，且沉积时水体能量较低。透镜体纵向上不具有粒序特征，可能为多期流体运动所致。综合上述推断，东营凹陷沙河街组三段—四段灰质泥岩或泥质灰岩中的透镜体主要为多期底流成因，底流冲刷破碎均质灰质泥纹层，破碎后的泥晶方解石纹层被底流搬运沉积，在压实作用下形成泥晶方解石透镜体。川北地区千二段的粉砂质泥岩或泥质粉砂岩中，纹层之间的接触面常为不平整冲刷面，内部偶见反映底流牵引作用的微波状断续纹层，部分上覆沉积构造中可见下覆沉积构造的撕裂碎片，部分纹层可组成交错层理等多样的沉积构造类型（图 1e），指示了沉积时期底流频繁发育。

1.4　异轻流搬运

异轻流是河水流入湖（海）盆后，由于盐度和密度差异，漂浮在湖（海）面的浮力水体[67]，风力是主要驱动力[68]，常形成水平层理、块状层理等沉积构造，其中常见植物碎屑[69]。Kineke *et al*.[70]通过分析 Sepik 河口附近水体中的悬浮沉积物和盐度的分布，结合地震剖面观测等技术，证明了河水形成的异轻流可以将细粒沉积物搬运到大陆架和斜坡上沉积。随后，Curran *et al*.[8]提出异轻流中的悬浮沉积物的聚集和沉降速率与风速、风向以及潮汐有关，证实了黏土絮凝体与长英质颗粒是河水异轻流的重要组成部分，这些沉积物能够被搬运到湖盆水体较深的位置沉积。实验研究表明，异轻流中的沉积物通量主要受湍流产生的对流过程控制，而与沉积物的颗粒特性关系较小[71]。最近研究发现，河流携带的细粒沉积物入海形成的异轻流，在大潮混合作用下，是造成深水重力流的重要机制[72-73]。盐度差异是两者发生转

化的关键因素，盐度差越小，越容易发生转化[74-75]，沉积物常形成云雾状构造、砂质团块和液化构造[76]（图 1f）。

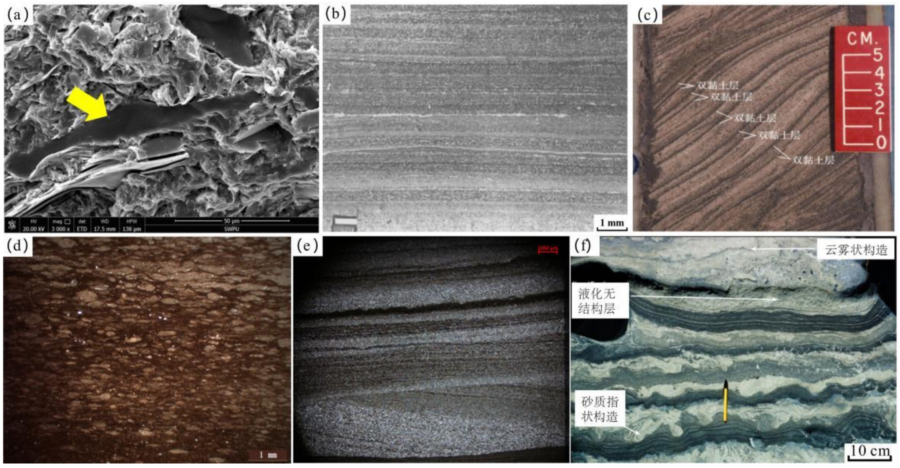

图 1 不同物理搬运机制形成的沉积特征

（a）陆源有机质碎屑，YY2 井，千二段，3 725.64 m，3 000x；（b）页岩中水平连续的粉砂纹层和黏土纹层互层，阿巴拉契亚盆地，泥盆系[50]；（c）双黏土层，尼日利亚近海 Edop 油田，上新统[64]；（d）泥晶方解石颗粒构成的透镜体，FY1 井，沙三段，3 127.90 m，1x（-）；（e）交错层理，YY3 井，千二段，3 554.10 m，1x（-）；（f）异轻流形成的沉积构造，喀麦隆，白垩系[77]

Fig.1 Deposition structures formed by different physical transport mechanisms

(a) terrestrial organic detritus, Well YY2, Jq^2, 3725.64 m, 3000 x; (b) horizontally continuous silt laminations and clay laminations interbedded in shale, Appalachian Basin, Devonian[50]; (c) double clay layers, Edop oil field offshore Nigeria, Pliocene[64]; (d) lens made of micrite calcite grains, Well FY1, Es^3, 3 127.90 m, 1 x (-); (e) cross-bedding, Well YY3, Jq^2, 3 554.10 m, 1 x (-); (f) deposition structures formed by plumes, Cameroon, Cretaceous[77]

1.5 重力流搬运

重力流作为一种高效的搬运机制，对细粒沉积物的分布具有深远意义。细粒沉积物中的重力流搬运有多种类型，包括滑动—滑塌、浊流、异重流、泥质碎屑流、风暴流和波浪增强重力流等[9-10,77-82]。

1.5.1 滑动—滑塌

滑动—滑塌沉积是在一定触发机制下，由于自身重力作用，沉积物上的重力沿斜面向下的分力不足以克服沉积物内部的内聚力，斜坡高部位先存的沉积物发生再搬运，沿斜坡以连续或不连续块体（刚性固体）形式向斜坡底部运动，在斜坡下部平缓地带堆积形成的沉积体[83-84]。

滑动—滑塌触发机制多样，包括沉积颗粒自重、波浪震荡、地震、火山、海啸等多种成因[77,85-86]，常形成底部剪切面、逆冲断层、褶皱、包卷层理、交叉切割的碎屑岩脉、矿化劈理面、不规则塑性变形泥砾等构造[77,83,87-92]（图 2）。根据滑动—滑塌中变形构造，能够判断沉积物的受力情况和移动方向[93]，从而帮助人们认识当时的沉积环境、古地形和古地震事件[94]，并对现今的地质灾害研究和油气勘探有重要指导意义[73,95-96]，而变形构造种类较多，

成因和触发机制复杂，特别是在滑塌褶皱形成时的沉积环境、构造背景、变形机理等方面[97-102]，众多学者还存在较大争议，使得滑塌褶皱研究成为目前变形构造研究中最具争议的课题[85]。

国内外学者在西班牙东南部 Prebetic 地区、加拿大西北部 Bowser 盆地、鄂尔多斯盆地镇原地区、渤海湾盆地东营凹陷、海拉尔盆地东明凹陷、滦平盆地、共和盆地等地区的细粒沉积地层中识别出了大量滑动—滑塌构造[84,90,103-108]，表明滑动—滑塌在细粒沉积物的搬运中起到了重要作用。东营凹陷沙四上亚段滑动—滑塌较为常见，在樊页 1 井、牛页 1 井、官 17-斜 10 井、牛斜 55 井等取心井中发育较多包卷层理、纹层强烈变形等滑动—滑塌作用形成的变形构造。

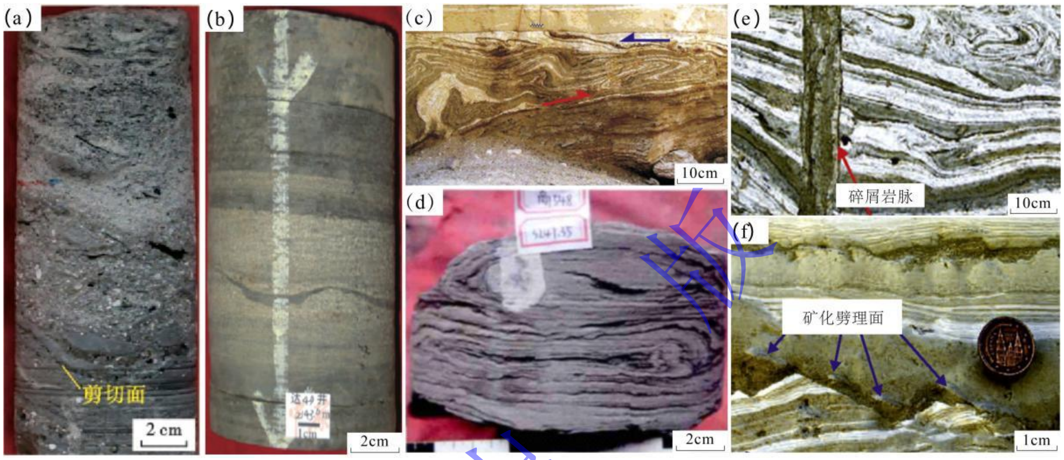

图 2　滑动—滑塌沉积特征

（a）底部剪切面，MD2 井，白垩系，522.13 m[90]；（b）灰黑色拉长状不规则泥砾，D41 井，白垩系，2 143.60 m[92]；（c）逆冲断层和褶皱，死海盆地，上更新统[87]；（d）包卷层理，S548 井，沙三段，3 247.35 m[83]；（e）碎屑岩脉，死海盆地，上更新统[91]；（f）矿化劈理面，死海盆地，上更新统[91]

Fig.2　Sliding and slumping sedimentary characteristics

(a) Bottom shear surface, Well MD2, Cretaceous, 522.13 m [90]; (b) dark gray elongated irregular mud clasts, Well D41, Cretaceous, 2 143.60 m [92]; (c) reverse faults and folds, Dead Sea Basin, Upper Pleistocene [87]; (d) convergent bedding, Well S548, Es^3, 3 247.35 m [83]; (e) clastic dykes, Dead Sea Basin, Upper Pleistocene [91]; (f) mineralized cleavage surfaces, Dead Sea Basin, Upper Pleistocene [91]

1.5.2　浊流

浊流是一种在水体底部形成的高速紊流状态的混浊流体，由水和大量自悬浮物质混合而成，是重力流的一种[109-110]。研究表明，浊流是将陆地上的陆源碎屑物质及其他颗粒类型，搬运至深海或者深湖地区的最重要搬运方式[110-112]，浊流能够将大量泥砂带入海洋或湖泊深处，形成浊积岩。季节性洪水、地震、海啸、风暴、火山喷发等地质事件都能够触发浊流[113-117]。

浊流内部的颗粒主要受流体扰动支撑，当浊流速度降低，能量逐渐衰减而不足以搬运沉积物时，浊流中的沉积物按其颗粒的大小依次沉降，从而形成了具有递变沉积特征的正粒序层理[92,118-119]。需要注意的是，一次浊流形成的单层总是呈向上变细的正粒序[120-121]，即正粒序的概念只是针对单一浊流事件沉积[118,122-123]，将正粒序应用于由多个层组成的、代表多个

沉积事件的混合单元是错误的[124-125]。浊流搬运机制表现为沉积物重力流—牵引搬运—悬浮沉积的变化特征[63]，能够形成包含 5 个纹层组的垂向变化序列[126]（图 3a），所以浊积岩不仅发育鲍马序列，在搬运过程中，浊流可能会侵蚀下覆沉积物，形成冲刷面、印模和槽模[84,92,127]（图 3b~d），随着较粗颗粒的卸载，流体的密度和悬浮物的沉降速度降低，水流的牵引作用增加[121]，其沉积物就会发育主要由上覆流体牵引驱动形成的纹层构造[128]。笔者在东营凹陷樊页 1 井、利页 1 井、牛页 1 井和通 41 井等取心井的沙三下—沙四上亚段地层和川北地区元页 2 井、元页 3 井和川石 60 井等取心井的千二段地层中识别出了正粒序构造、重荷模构造等浊流搬运的证据。

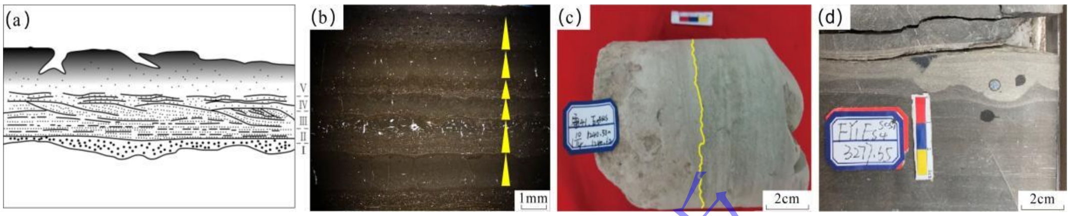

图 3　浊流沉积特征

（a）浊流沉积序列示意图[126]，底面：侵蚀面；Ⅰ.均质纹层组，粒度最粗；Ⅱ.连续平行的纹层组，粒度相对较粗；III.不连续、弯曲、不平行的纹层组，粒度相对较粗；Ⅳ.连续—不连续的平行纹层组；Ⅴ.层理模糊的递变纹层组，粒度最细；（b）多期正粒序，NY1 井，沙四段，3 438.58 m，1x（-）；（c）冲刷面，T41 井，沙四段，1 240.50~1 240.62 m；（d）印模，FY1 井，沙四段，3 277.35 m

Fig.3　Turbidity current sedimentary characteristics

(a) schematic diagram of turbidity current sedimentary sequence[126], Base: erosional surface: I. homogenous laminae set, with coarsest grain size; II. continuous parallel laminae set, with relatively coarse grain size; III. discontinuous, curved, non-parallel laminae set, with relatively coarse grain size; IV. continuous-discontinuous parallel laminae set; V. gradational laminae set with indistinct bedding, with finest grain size; (b) multiple normal grading sequences, Well NY1, Es^4, 3438.58 m, 1x(-); (c) erosional surface, Well T41, Es^4, 1 240.50–1 240.62 m; (d) cast, Well FY1, Es^4, 3 277.35 m

1.5.3　异重流

异重流作为一种近年来提出的沉积物输送机制[129]，是携带沉积物颗粒导致流体密度大于稳定环境水体的密度，流体受浮力影响小，沿盆地底部流动的高密度流体[130]。大量研究表明，异重流由洪水期河口直接注入，不需要沉积物的早期积累、再搬运及地震、火山、风暴、海啸等触发机制，由大范围降雨、冰雪融水、火山泥流等事件形成的包含大量沉积物的洪水是异重流形成的主要触发机制[10,131-134]。

异重流颗粒间的支撑机制为流体湍动支撑[135]，近端多为中—细砂岩，中部以细砂岩、粉砂岩为主，远端则主要为粉砂岩、泥质粉砂岩和泥岩等细粒沉积岩[134]，因此异重流被认为是将大量细粒沉积物搬运至深水盆地的重要流体类型[81]。异重流由近源到远源流动过程中，能量亏损，流速降低，单期异重岩沉积过程与异重流能量演化过程密切相关，因此异重岩垂向上形成了记录异重流能量增强和减弱的逆—正粒序[135]。由于异重流存在悬浮载荷、

底床载荷和漂浮载荷[131,136-139]，异重岩中还可能发育爬升沙纹层理、平行层理、波状层理、交错层理、层内微侵蚀面、植物碎片等沉积特征[84,140-141]。异重流在川北地区千二段较少发育，但在东营凹陷沙四上亚段较多，例如东营凹陷樊页 1 井、通 29 井、王 7 井、王 31 井、王 129 井等取心井中存在大量异重流搬运的证据（图 4）。

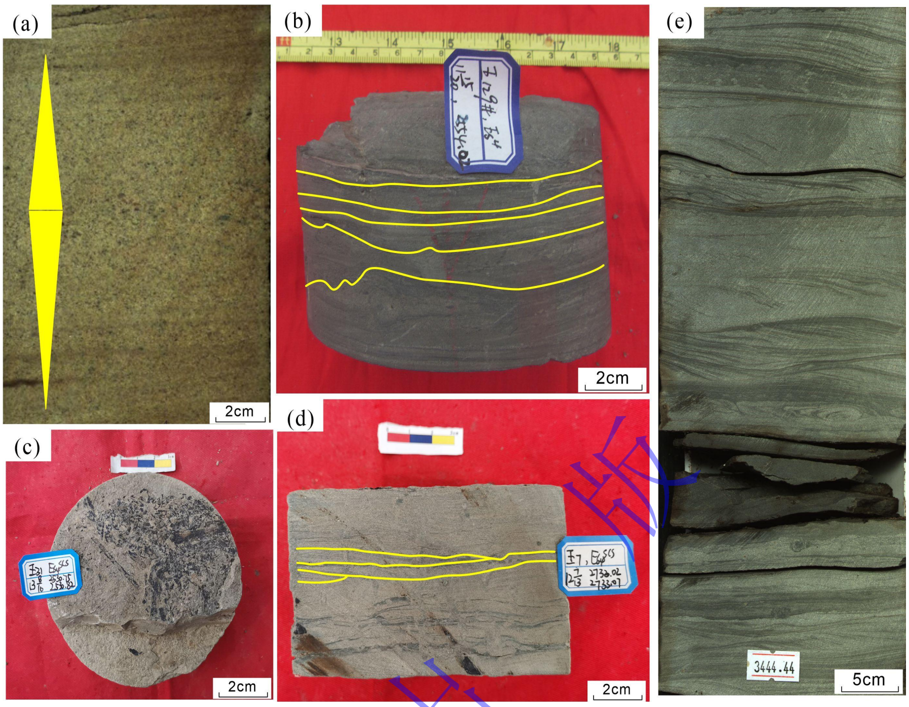

图 4　异重流沉积特征

（a）逆正粒序构造，W1 井，古近系[141]；（b）波状纹层，W129 井，沙四段，2 554.02 m；（c）碳质碎屑，W31 井，沙四段，2 530.80 m；（d）低角度交错层理，W7 井，沙四段，2 733.50 m；（e）爬升沙纹层理，FY1 井，沙四段，3 444.24~3 444.44 m

Fig.4　Gravity flow sedimentary characteristics

(a) reverse grading structure, Well W1, Paleogene[141]; (b) wavy laminations, Well W129, Es^4, 2 554.02 m; (c) carbonaceous detritus, Well W31, Es^4, 2 530.80 m; (d) low-angle cross-stratification, Well W7, Es^4, 2 733.50 m; (e) climbing ripple lamination, Well FY1, Es^4, 3 444.24–3 444.44 m

1.5.4　风暴流

风暴流沉积作为一种较特殊的沉积体，一般发育在正常浪基面与风暴浪基面之间，风暴浪破坏了原始的水温和水动力条件，并冲击和改造了异地和原地沉积，同时将浅水的粗粒碎屑带到深水，形成低能条件下的高能沉积[99]。风暴流的产生与风暴息息相关，气温、水温、湿度、地形、气压、季节等因素控制着风暴的形成[142-151]。Xu *et al.*[84]利用天文旋回研究了东营凹陷沙四段细粒沉积地层中的风暴事件后，发现长偏心率较大时期，水体和陆地之间较大的热力差与暖湿的气候促进了季风的形成，进而为风暴流的发生创造了良好条件。

风暴事件可划分为风暴高峰期、风暴晚期和风暴后期三个阶段[152]。在风暴流作用初期，水底沉积物开始受到扰动，随着风暴高峰到来，风暴流能量骤增，大量沉积物冲刷水底沉积物，形成风暴侵蚀面等构造。当风暴高峰期过后，能量逐渐衰减，水体由高流态向低流态过

渡，风暴流搬运的物质依次堆积，沉积物粒度逐渐变细，显示了水动力由弱突然变强，再逐渐减弱的沉积过程。一次风暴流形成的完整风暴岩沉积序列，自下而上包括粒序层理段（砾岩—含砾砂岩）、块状层理段（粉砂岩—含砾砂岩）、丘状交错层理与平行层理段（粉砂岩—细砂岩）、波状纹层段（粉砂岩—泥岩）和泥岩段[153]（图 5a）。此外，底面侵蚀构造（图 5b）、粗粒滞流沉积、生物逃逸迹、浪成交错层理等构造也是风暴岩的识别标志[84,155-157]。上述风暴流搬运形成的沉积构造在东营凹陷沙四上亚段的细粒沉积岩中广泛发育（图 5c~e）。

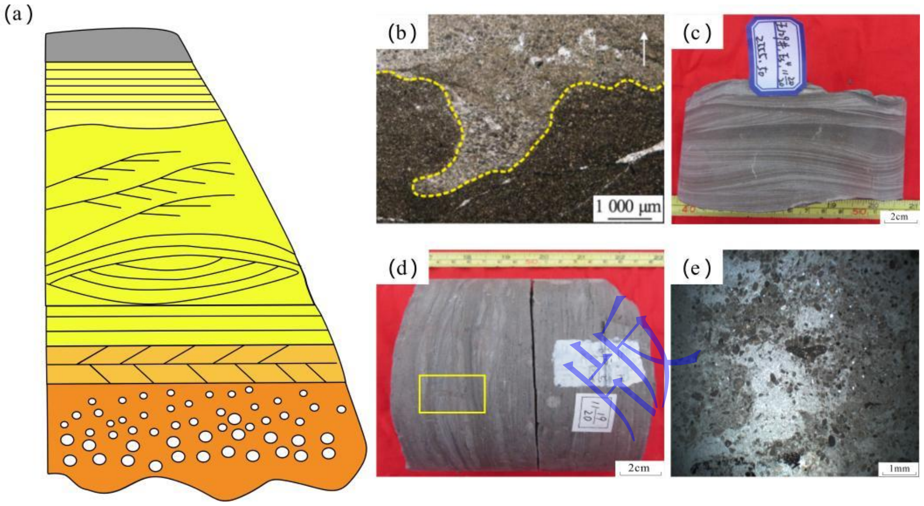

图 5　风暴沉积特征

（a）风暴岩沉积序列；（b）冲刷面，城口地区剖面，上寒武统[154]；（c）浪成交错层理，W129 井，沙四段，2 555.50 m；（d）生物逃逸迹，W129 井，沙四段，2 555.40 m；（e）粗粒滞流沉积，FY1 井，沙四段，3 436.94 m，1x（-）

Fig.5　Storm deposition characteristics

(a) storm rock sedimentary sequence; (b) erosional surface, Chengkou section, Upper Cambrian Series[154]; (c) wave-formed cross-stratification, Well W129, Es^4, 2 555.50 m; (d) bioturbation traces, Well W129, Es^4, 2 555.40 m; (e) coarse-grained lags, Well FY1, Es^4, 3 436.94 m, 1x(-)

1.5.5　泥质碎屑流

Shanmugam[158]在 1996 年提出了泥质碎屑流的术语，泥质碎屑流是一种以泥质沉积为主的塑性流体，以层流态方式运移，其沉积物支撑机制包括基质强度、分散压力和浮力，内部混杂少量砂质颗粒和砂质团块，黏土含量高，黏结性强[158]。该流体在一定的触发机制下，通过自身重力驱动沿斜坡向下运动，由于基质内聚力较强，环境水体难以对流体稀释，并且被限制在流体底部，产生滑水现象，使得流体能够在水体中搬运较长距离，最后由于能量逐渐降低而沉积在斜坡下部和湖盆的平坦部位[139,159]。

洪水和滑塌作用都能够形成泥质碎屑流[139,160]，沉积物以块状为主，与底部和顶部泥岩呈突变接触，反映了块状冻结的特征，内部常见砂质团块以及平行排列、两端拉长变细的漂浮状泥岩撕裂屑[161-163]（图 6a，b），反映了层流流动特征，表明其经过了较长的搬运和调整。

泥质碎屑流在搬运过程中，常伴随着流体类型之间的转化[165-167]，这主要与流体在流动时，沉积物中黏土矿物、有机质等颗粒含量的变化有关[78,168]。研究发现，泥质碎屑流与浊流、砂质碎屑流之间的演变是常见的转化形式[80,166,169-172]。李聪等[173]研究了南堡凹陷陆相重力流沉积岩后，认为内部具有大量泥岩撕裂屑和砂岩透镜体的泥质碎屑流沉积，是由后端的浊流转化而成；王冠民等[171]分析了辽中凹陷东三段重力流沉积，认为砂质碎屑流转化成泥质碎屑流后，泥质含量升高，会导致形成的储层物性变差。

泥质碎屑流搬运在川北地区千二段少量发育，本次分别在元页 2 井、元页 3 井、阆页 1 井和川石 60 井等取心井的块状泥质粉砂岩或粉砂质泥岩岩心上，识别出了少量泥质碎屑流形成的沉积构造，例如在元页 2 井 3 743.36 m 和元页 3 井 3 548.17 m 附近识别出了大小在 4 cm 左右的孤立粉砂质团块（图 6d）。

1.5.6　波浪增强重力流

波浪增强重力流的概念由 Macquaker *et al.*[11]在 2010 年提出，这是一种在波浪作用下，将沉积物以流体泥的形式沿低角度大陆架向坡下运输的流体。国内外学者在现代陆架泥质沉积物、英国克利夫兰铁矿组、美国 Mowry 页岩、加拿大阿尔伯塔省 Smoky 河附近的白垩纪泥岩、中国雅布赖盆地新河组和渤海湾盆地古近系等细粒沉积岩地层中识别出了该类流体[11-12,174-175]。

波浪增强重力流形成的沉积构造由三部分构成（图 6c）：（1）由粉砂或细砂粒级的石英和黏土聚合体形成的底层，内部可能发育波状纹层和内碎屑，表明沉积物是在波浪影响的湍流条件下，受到牵引分量形成[11]；（2）当流体中悬浮泥质含量逐渐升高，流体流动结构发生改变[11,176-177]，湍流逐渐转变为过渡性流体[12]，形成了平行互层的粉砂和泥质纹层，向上泥质比例增加；（3）晚期流体能量减弱，流速降低，泥质含量增高，湍流受阻，颗粒凝聚发生凝胶化作用，整体快速沉积形成泥质层[177-178]。

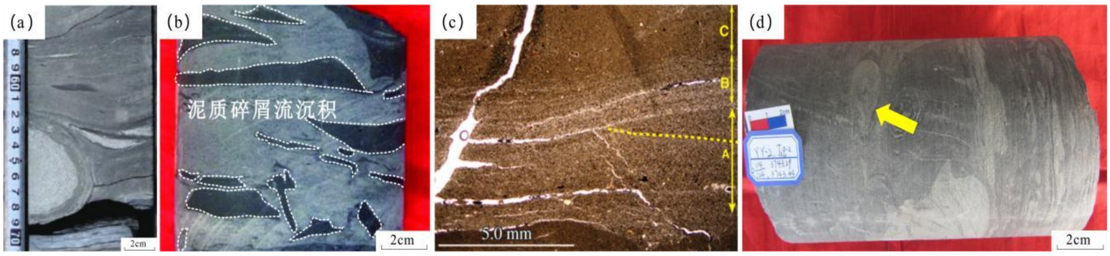

图 6　泥质碎屑流和波浪增强重力流沉积特征

（a）砂质团块，X4 井，白垩系，1 130.66 m[162]；（b）泥质撕裂屑，L57 井，长 7 段，2 356.49 m[164]；（c）现代沉积物中波浪增强重力流的三层沉积构造，Eel 陆架[11]；（d）粉砂质团块，YY2 井，千二段，3 743.36 m

Fig.6　Muddy debris flow and wave-enhanced gravity current sedimentary characteristics

(a) sandy clasts, Well X4, Cretaceous, 1 130.66 m[162]; (b) muddy rip-up clasts, Well L57, Chang 7 section, 2 356.49 m[164]; (c) three-layered sedimentary structures of wave-enhanced gravity flows in modern sediments, Eel Shelf[11]; (d) silty clumps, Well YY2, 3 743.36 m

2　化学搬运

细粒沉积物中的溶解物质，可以呈胶体溶液或真溶液被搬运。当环境的 pH 值、Eh 值、温度、压力、离子浓度或电荷等发生改变时，溶解物质就可能从溶液中絮凝或沉淀出来[15]。

黏土矿物在水体中能够以胶体质点形式搬运[16,179]。带同种电荷的胶体质点之间存在的相互排斥力，是引起胶体质点搬运的主要因素，也是胶体质点在重力作用下难以沉积的根本原因[180]。研究人员利用高岭石、蒙脱石胶体溶液，探讨了黏土矿物在水溶液中的电化学行为，发现改变无机盐种类、无机盐浓度、pH 值等环境条件，能够影响黏土矿物的双电层特性，进而影响颗粒间的相互作用，最后控制胶体悬浮液的稳定性[181-183]。

研究显示，当溶液中 Na^+浓度增加到一定程度时，黏土颗粒间产生静电排斥力的扩散离子层厚度被压缩，范德华力开始占据主导，黏土颗粒之间的相互作用力变为引力，导致颗粒聚集，形成絮凝体沉降[184]，随着无机盐浓度的增加，颗粒间碰撞频率增加，絮凝速率加快，絮凝体尺寸逐渐变小[185]，也有学者通过探讨不同盐度条件下高岭石的絮凝沉积作用，认为盐度不是决定高岭石临界沉积速度的主要因素，但是能够促进絮凝效率[186]。不同无机盐含有价态各异的离子，在黏土絮凝过程中会造成不同的影响，有研究指出，二价阳离子（如 Ca^{2+}和 Mg^{2+}）相较于单价阳离子（Na^+和 K^+）电荷更高，能更有效中和黏土颗粒表面的负电荷，减少颗粒间排斥力，从而促进黏土颗粒的絮凝[187]。相同价态的不同阳离子对黏土颗粒的絮凝作用也有所差异，例如，相同条件下 Ca^{2+}比 Mg^{2+}能够更有效促进黏土颗粒的絮凝[188]（图 8），Xu *et al*.[189]利用 $NaNO_3$ 和 KNO_3 溶液探究了蒙脱石的絮凝作用，结果显示，K^+更有助于黏土颗粒的絮凝，K^+在黏土颗粒表面发生的强烈非经典极化现象是造成这一差异的原因。有机化合物也能够促进黏土颗粒的絮凝[190]，与无机盐离子略有不同，有机化合物除了可以通过影响黏土矿物表面的电荷，影响黏土矿物的絮凝沉积，还可以通过桥接作用使黏土物质结合到一起，形成絮凝物[24,191]。众多研究表明，pH 值对黏土矿物的絮凝作用有重要影响，pH 值较小时，有利于黏土矿物的絮凝[191-194]，其原因是质子（H^+）与黏土矿物边缘的羟基（OH^-）反应，影响黏土矿物边缘电荷密度，进而影响絮凝行为[194]。Mietta *et al*.[193]运用多种实验手段研究了蒙脱石和高岭石的絮凝行为后，发现 pH 值为 4 时，蒙脱石和高岭石颗粒边缘带正电荷，导致其快速絮凝并形成较大絮凝体，而 pH 值为 8 时，黏土颗粒边缘带负电荷，不利于发生絮凝。此外，颗粒大小、颗粒浓度、水动力条件和沉降速度同样影响着黏土矿物的絮凝[185,195-196]，进而影响黏土矿物在水体中的搬运。不过，颗粒预处理的影响、

颗粒尺寸对表面性质的影响，以及天然矿物与实验室纯矿物之间表面性质的差异，使得实验室得出的结果，能否用来解释自然水体中黏土胶体质点的电化学行为还存在很大的不确定性[197]。

自然环境中，河流将带负电荷的黏土矿物以胶体形式搬运至河口时，湖（海）水中 Ca^{2+} 和 Mg^{2+} 等带正电的离子能够与黏土矿物表面的负电荷中和，消除黏土矿物之间的相互排斥力，从而使得黏土胶体质点发生凝聚，下沉形成胶体沉积物[179]。本次对川北地区千二段和东营凹陷沙三下亚段—沙四上亚段细粒沉积岩进行扫描电镜观察，发现两地区黏土矿物粒径较小，普遍小于 10 μm，有利于黏土矿物间发生絮凝作用。在川石 60 井、阆页 1 井、元页 2 井、牛页 1 井、利页 1 井等多口取心井的部分深度段可见黏土矿物絮凝作用形成的絮凝孔（图 7a），指示了化学作用促进了两地区黏土矿物的搬运和沉积。

前文提到，水体碳库中包括颗粒无机碳（PIC）、溶解无机碳（DIC）、颗粒有机碳（POC）和溶解有机碳（DOC）[30]，其中 DOC 是水生系统中重要碳源，也是水体中微生物生命活动的重要物质来源[198-199]。河水是将 DOC 输入到海洋碳库的主要途径[200]，当海平面快速上升或远洋深层水上涌时，深水中的 DOC 能够被运输到浅水区域[30]。由于黏土矿物粒径小，比表面积大，层间域有较大胀缩性，且表面裸露化学官能团，因此黏土矿物具有吸附水中 DOC 的特性[201-202]。水体中的 DOC 通过离子交换、阳离子桥、水桥和离子偶极力等多种机制，被吸附在黏土矿物的外表面和层间域中[203]，形成结构复杂的有机碳—黏土絮凝体，所吸附有机碳按赋存空间分为表面与絮凝孔隙吸附的有机碳、结构边缘孔隙吸附的有机碳和内部层间域吸附的有机碳[204]，被黏土矿物吸附的 DOC，特别是吸附在黏土矿物层间域的有机碳很难被降解或被微生物利用[201-205]。因此，认为有机碳—黏土絮凝体的形成促进了有机碳的富集，有利于 DOC 在水体中保存，增加了 DOC 向盆地更远位置运输的可能性。

碳酸盐类矿物是细粒沉积物中的重要组分。很多湖泊中的碳酸盐矿物是由湖泊周围地区岩石风化剥蚀，输送到水体中沉积形成的[13]，但是在钙质基岩区，水、CO_2 和含钙矿物之间发生反应，大量 Ca^{2+}、HCO_3^- 或 CO_3^{2-} 随地表径流或地下水搬运入湖，使得湖水中含有较高浓度的 Ca^{2+}、HCO_3^- 或 CO_3^{2-}，当水体中的 CO_2 浓度、温度或 pH 等环境条件发生变化时，碳酸盐类矿物便会沉淀析出，例如东营凹陷沙四上亚段广泛发育的泥晶方解石纹层（图 7b），就是由于古气候和古盐度变化，导致湖水中 $CaCO_3$ 溶解度发生改变沉积而成的[15]。

铁是湖相细粒沉积物中的常见元素，有时也可呈离子状态在水中被搬运。影响铁搬运的主要因素是 Eh 和 pH 值。Fe^{3+} 只有在 pH 小于 2~3 的水体环境中，才能做长距离搬运，当 Eh 值降至 200 mV 以下，pH 值显中性特征时，Fe^{3+} 转化为 Fe^{2+}，Fe^{2+} 可以聚集在沉积物孔隙

水中或以离子形式作长距离搬运，因此 Fe^{2+}远较 Fe^{3+}易于搬运，若 Eh 值继续降低，Fe^{2+}则会以难溶解的硫化铁化合物沉淀下来[13,180]。

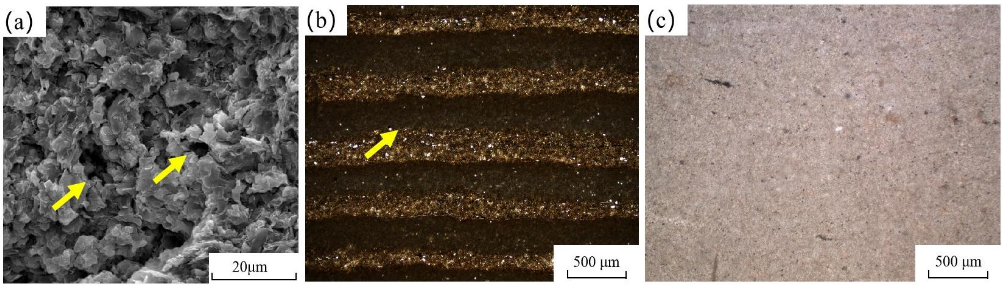

图 7　细粒沉积岩中黏土矿物絮凝孔及泥晶碳酸盐矿物特征

（a）黏土矿物絮凝孔，NY1 井，沙四段，3 473.96 m；（b）泥晶方解石纹层，FY1 井，沙四段，3 326.00 m，5x（-）；（c）块状泥晶灰岩，FY1 井，沙四段，3 437.54 m，5x（-）

Fig.7　Characteristics of micritic carbonate minerals in fine-grained sedimentary rocks

(a) flocculated pores in clay minerals, Well NY1, Es^4, 3 473.96 m; (b) micritic calcite laminae, Well FY1, Es^4, 3 326.00 m, 5 x (-); (c) massive micritic limestone, Well FY1, Es^4, 3 437.54 m, 5 x (-)

3　生物搬运

一般认为，生物搬运有两种方式[180]：一种是生物在生活过程中，不断从周围介质吸收物质成分，从而将一些元素富集起来，当生物死亡后，其遗体堆积物就可以形成特定的岩石或矿产；另一种是生物通过生命活动引起周围环境改变，影响物质的搬运。

细粒沉积物中，钙质矿物、硅质矿物、有机质等物质成分可以通过上述第一种方式进行生物搬运，其中钙质矿物和硅质矿物受生物矿化作用控制。碳酸钙是自然界中最丰富的生物成因矿物，存在方解石、文石、球文石等多种变体[206-208]，其中方解石和文石最为稳定且常见[209]。碳酸钙矿物能够形成轮藻、颗石藻、软体动物贝壳以及珊瑚等众多生物的壳体。研究人员在巴西 Araripe 盆地 Romualdo 组、美国堪萨斯州下二叠统、中国四川盆地千佛崖组、渤海湾盆地沙河街组、准噶尔盆地芦草沟组、松辽盆地青山口组等地区及层位中的海相或陆相细粒沉积岩中识别出了广泛发育的钙质有孔虫、介形虫、轮藻及其他钙藻等钙质生物化石[210-218]，例如在东营凹陷沙四段和川北地区千二段细粒沉积岩中，发育较多成层或零散分布的介壳碎屑（图 8a）。生物体内的硅多以微小的非晶态二氧化硅形式存在，具有良好的塑性和强度[219]。细粒沉积物中常见的硅质生物包括放射虫、海绵骨针和硅藻[220-223]。放射虫和海绵对海洋硅循环至关重要，它们的生活和保存受海洋上升流和火山活动影响[224-225]，生物死亡后，骨骼沉积形成硅质软泥[224,226]。硅藻在自然水体中广泛分布[227]，晚冬早春时，随着水温上升和营养物质上移，小型硅藻大量繁殖，夏季被绿藻或蓝藻取代[228-230]，大型硅藻则从早夏生长至晚秋，秋末冬初时大量死亡并沉降到海底[228,231]。硅质外壳因难以降解，得以

在沉积物中保存[232]。藻类勃发不仅可以搬运沉积大量钙质或硅质骨骼，而且藻类死亡后可以分解产生大量有机质，形成有机质纹层，这是优质烃源岩形成的重要机制[213,233-234]。例如，鄂尔多斯盆地中元古界、松辽盆地青山口组、济阳拗陷古近系、准噶尔盆地芦草沟组等地区及层位中的烃源岩成烃母质，皆主要来源于藻类等低等水生生物[235-238]。气候、季节变化、火山喷发、热液活动等都能够导致藻类勃发，提高古生产力，促进有机质纹层形成[228,239-244]。微生物及其分泌的微生物细胞外聚合物（EPS）形成生物膜，这些生物膜在有利环境下，进一步发展成有机质厚层，称为微生物席[245]，微生物死亡残体、释放的代谢产物及其捕获的有机质颗粒是微生物席向沉积物贡献的有机质类型[246]。

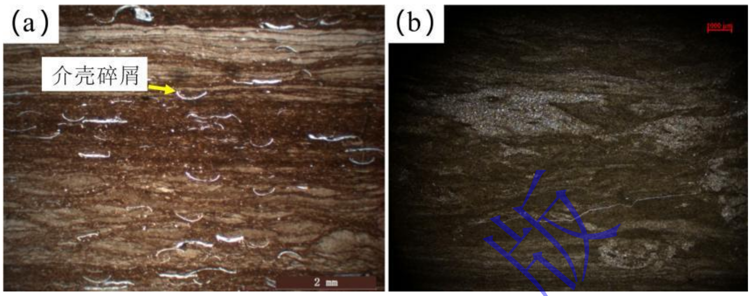

图 8　细粒沉积岩中介壳及生物扰动构造特征

（a）零散分布的介壳碎屑，FY1 井，沙四段，3 425.70 m，1x（-）；（b）生物扰动构造，元页 2 井，千二段，3 739.55m，1x（-）

Fig.8　Characteristics of shell debris and bioturbation structures in fine-grained sedimentary rocks

(a) scattered shell debris, Well FY1, Es^4, 3 425.70 m, 1 x (-); (b) bioturbation structures, Well YY2, Jq^2, 3 739.55 m, 1 x (-)

第二种生物搬运方式中，生物作用能够改变沉积物的稳定性，从而控制物质的搬运。微生物席上的 EPS 通常具有黏性，在吸附水体中碎屑物质的同时[247-251]，能够增强沉积物的稳定性及抗侵蚀能力[247,252-253]，进而影响沉积物的搬运。Malarkey *et al*.[254]利用水槽实验研究发现，非常少量但广泛分布的 EPS，足以显著影响底形的形成，这是由于 EPS 的黏性远比细粒沉积物物中各物质之间的物理黏性强，极大抑制了细粒物质的移动。之后，Parsons *et al*.[255]同样利用水槽实验，量化了 EPS 对底形形态的影响，证明了 EPS 通过增强细粒沉积物颗粒之间的黏合力，控制了底形的形态。另外，生物还能够通过生命活动引起周围微环境（如 pH、离子浓度等）改变、为矿物提供结晶位点、进行还原作用等方式，促进细粒沉积物中碳酸盐矿物、黏土矿物、石英、黄铁矿、有机质等物质的形成和搬运。例如，藻类能促使湖水中碳酸盐矿物的形成和搬运：夏季水温升高，日照较强，使藻类勃发，同时光合作用增强，不断消耗水体中的 CO_2，促使表层水中碳酸盐矿物形成[256-257]，最终在湖底形成浅色钙质泥晶纹层；水体中微生物细胞（即细菌、古菌和微型真核生物）分泌的 EPS 有助于微生物附着于表面，形成“生物膜群落”[248]，并能够通过影响周围环境条件[258]、提供成核点[259]、物理吸附[249]等方式控制碳酸盐矿物、硅酸盐矿物、长英质矿物、有机质等物质的形成和搬

运[247,258-263]；细菌硫酸盐还原作用（BSR）是细粒沉积物中黄铁矿形成的重要途径，该作用由细菌介导，硫酸盐还原细菌将 SO_4^{2-}还原成 H_2S（式 1），再与 Fe^{2+}结合形成铁硫化物，形成粒度较小的草莓状黄铁矿[264-265]。

$$2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^{-} + H_2S\uparrow \qquad \text{式（1）}$$

此外，生物扰动对沉积物搬运也有重要作用[266]。生物扰动是指充氧环境下，鱼类或其他动物群对湖（海）底沉积物造成的机械混合作用[13]。底栖生物通过摄食、掘穴和建造钻孔，扰动水底沉积物，影响颗粒物质的运输[14,267-269]。与物理搬运不同，生物扰动引起的沉积物运输，不存在于极低或极高能量的水体环境，而在中等能量的水体环境中最为活跃[270]。

生物扰动会在细粒沉积岩中形成丰富的遗迹化石，Lobza *et al.*[271]利用模拟实验还原了美国田纳西州中部上泥盆统页岩中生物扰动构造的形成过程，认为基质黏度、生物形态以及生物运动类型是控制不同形态生物扰动遗迹发展的关键因素。不同类型的生物在扰动过程中，会造成不同类型的生物搬运，Hakanson 和 Jansson 根据生物种类的不同，将湖泊沉积物中生物对物质的搬运作用分为垂直向上搬运（图 9a）、沉积物—水界面附近的搬运（图 9b）和多类型生物综合搬运（图 9c）三种类型，同时指出生物搬运作用会随着季节变化而变化[13]。不同生物的摄食模式不同，可能是影响沉积物内颗粒或溶解质运输的关键，例如头朝下进食的 *Heteromastus* 蠕虫将作为粪便团的颗粒从深部沉积物搬运到表层沉积物，表面底栖生物 *Marenzelleria* 蠕虫通过在沉积物表面附近挖掘寻找食物，搬运、混合了沉积物颗粒，研究人员利用发光体作为示踪剂，评估了二者对颗粒物质运输的影响后，发现 *Marenzelleria* 的颗粒混合率比 *Heteromastus* 高出 1.5 到 2.2 倍，说明不同类型生物对沉积物的运输条件与摄食模式紧密相关[14]。为了满足氧气的代谢，洞穴中的底栖生物通常会进行灌溉作用，这一过程是孔隙水运输最重要的生物机制[267]。川北地区千二段细粒沉积岩中，发育大量生物扰动构造，这些生物扰动构造在沉积过程中显示出较好的持续性和普遍性，最常见的是发育在沉积物—水界面附近的斑驳状、边界模糊的生物扰动构造，将原始沉积构造搅混、破坏（图 8b）。

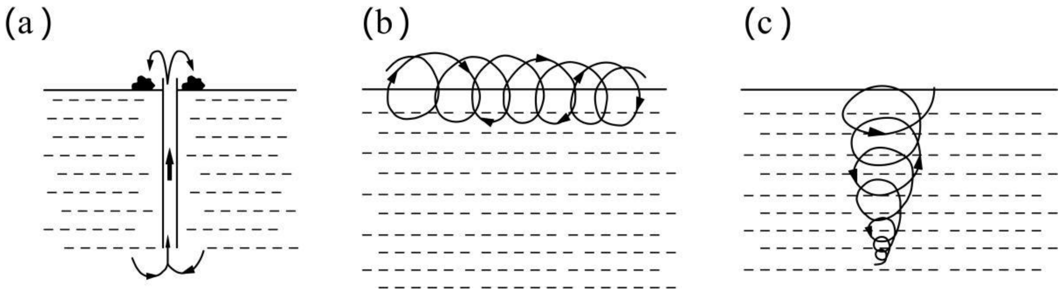

图 9　三种不同的生物搬运方式示意图[13]

Fig.9 Schematic diagram of three different types of biological transport mechanisms [13]

生物扰动可以改变沉积物的粒径、稳定性、孔隙度、渗透率等性质，并显著影响水—沉积界面处营养物质的通量。研究人员利用示踪剂，在东太平洋圣卡塔利娜盆地探究了不同颗粒大小与生物扰动之间的关系，发现细颗粒比粗颗粒更深入地渗透到沉积物中，细颗粒的生物扩散速率是粗颗粒生物扩散速率的 10 倍，原因可能是生物优先摄食细颗粒，并将其向下运输[272]。生活在潟湖潮间带泥滩中的多毛类蠕虫通过摄食和排泄，对底层沉积物进行搬运，它们的搬运活动使得表层沉积物具有更好的颗粒分选性，排出的粪便富含有机质，增加了沉积物的凝聚力，有助于沉积物的稳定[273]。但底栖生物的掘穴、爬行等活动能够将沉积物混合，避免细粒物质在沉积物表面形成保护层[274]，同时使沉积物表面处于松散或未压实状态，从而降低沉积物的抗侵蚀能力[275]。研究显示，生物搬运到水—沉积界面处富含有机质的粪便，能够在沉积物中创造还原条件[276-277]，促进微生物在沉积物表面吸收氧气[278]，并增加水—沉积物界面处的营养物质通量[266,279-280]；有研究表明，生物灌溉作用能够将黏土大小的颗粒运输到生物洞穴周围的孔隙空间中，降低原始孔隙度和渗透率，从而影响沉积物的性质[278]。然而，另外的关于潮间带蠕虫生物活动的实验发现，蠕虫更倾向吞食沉积物中较小的泥质颗粒，并通过排泄将其搬运到沉积物表面，之后这些细颗粒会在波浪作用下重新悬浮，并从沉积物中移除，这一过程使潮间带沉积物颗粒变粗，渗透率升高，同时也为沉积物中蠕虫的生命活动提供了足够的氧气[281-282]。生物搬运对生态系统也有一定影响，有研究认为，底栖生物通过在泥质沉积物中摄食沉积物的搬运作用，减少了浮游生物的密度[267]。

4　结论与展望

与传统搬运理论更侧重于单一的搬运方式不同，本文将细粒沉积物的搬运方式分为物理搬运、化学搬运和生物搬运三大类（表 1），并将传统搬运理论中分析较为薄弱的化学搬运和生物搬运进行了更加深入的探讨：

（1）物理搬运方式多样，包括河水搬运、大气搬运、底流搬运、异轻流搬运和重力流搬运，重力流搬运又分为滑动—滑塌、浊流、异重流、泥质碎屑流、风暴流和波浪增强重力流六种类型。推移力、载荷力和重力是物理搬运方式的驱动力，风力、潮汐、地震、洪水、风暴、火山喷发等是不同物理搬运方式的触发机制，这些搬运方式能够形成平行层理、交错层理、透镜状层理、粒序层理、褶皱构造、底面侵蚀构造、砂质团块等丰富的沉积构造。（2）化学搬运主要涉及呈胶体溶液或真溶液被搬运的溶解物质，例如黏土矿物、溶解有机碳、碳酸盐类矿物、铁质矿物等，这些物质受环境的 pH 值、Eh 值、温度、压力、离子浓度或电

荷等影响，能够从水体中絮凝或沉淀形成细粒沉积物。（3）生物能够通过吸收富集、生物活动引起环境改变和生物扰动影响物质的搬运。钙质矿物、硅质矿物、有机质等物质成分可以通过生物吸收富集的方式形成和搬运；生物活动引起环境改变可以影响沉积物的稳定性，进而控制细粒沉积物的搬运，同时可以结合为矿物提供结晶位点、进行还原作用等方式，促进细粒沉积物中碳酸盐矿物、石英、黄铁矿等物质的形成和搬运；生物扰动主要是底栖生物通过摄食、掘穴等活动对细粒物质进行运输，搬运作用分为垂直向上搬运、沉积物—水界面附近的搬运和多类型生物综合搬运。生物搬运可以改变沉积物的性质，显著影响水—沉积界面处营养物质的通量，并对生态系统也有一定影响。

表 1　细粒沉积物搬运机理类型及特点总结

Table 1　Summary of fine-grained sediment transport mechanism types and characteristics

搬运方式		搬运沉积特征	触发机制或影响因素
物理搬运	河水	低、过渡和高流态的不同床面形态	水流速度、粒径大小等
	大气	水平连续、层内无粒度分级、界面突变接触的粉砂和黏土薄层	粒径大小
	底流	平行层理、波状层理、压扁层理、透镜状层理、羽状交错层理、低角度交错层理等牵引构造	温盐驱动、风、潮汐、上升流和下降流等
	异轻流	水平纹层、块状构造、植物碎屑等	盐度和密度差异
	滑动—滑塌	底部剪切面、逆冲断层、包卷层理、不规则塑性变形泥砾等	沉积颗粒自重、波浪震荡、地震、火山、海啸等
	浊流	冲刷面、印模、槽模、正粒序等	洪水、地震、海啸、风暴、火山喷发
	异重流	逆—正粒序、爬升沙纹层理、平行层理、波状层理、交错层理、层内微侵蚀面、植物碎片等	洪水
	风暴流	底面侵蚀构造、粗粒滞流沉积、生物逃逸迹、浪成交错层理等	气温、水温、湿度、地形、气压、季节
	泥质碎屑流	块状构造、砂质团块、漂浮状泥岩撕裂屑等	洪水、滑塌作用
	波浪增强重力流	波状纹层、内碎屑、平行互层的粉砂和泥质纹层等	波浪作用
化学搬运		块状构造、纹层状构造	pH 值、Eh 值、温度、压力、离子浓度、电荷等
生物搬运		纹层状构造、硅质或钙质生物化石、遗迹化石	含氧量、气候、季节、火山、热液等

细粒沉积物搬运方式的研究近年来已取得显著进展，但由于细粒沉积物难以直观观测、搬运方式间相互作用与转换具有复杂性、搬运介质和沉积环境具有多样性，以及化学和生物搬运过程存在多重影响因素，并且在实际沉积环境中，多种搬运机制可能会同时发生。例如，生物活动过程中可能会改变沉积物的物理特性，从而影响其化学稳定性和物理搬运能力；化学沉积过程可能会为生物提供附着基质，进而影响生物搬运；浊流等物理搬运机制运输黏土矿物时，可能会促进黏土矿物的絮凝等化学沉积过程；风暴流、底流等物理搬运机制运输沉积物时，引起的生物搬运会进一步混合沉积物，两种搬运机制共同决定了沉积产物的性质。以上问题导致当前对细粒沉积物搬运方式的识别仍具有多解性和不确定性。

未来的研究应集中于以下几个方面：首先，深入探究不同细粒沉积物搬运机制之间的相

互作用和转换规律，进一步重视和加强水槽实验、数值模拟在细粒沉积物搬运机理研究中的作用，采用多学科交叉的方法，全面分析不同搬运机制之间的相互作用和转换规律；其次，利用先进的技术手段，提高对沉积构造的识别精度和分析深度，例如，研究经历了成岩作用改造后的细粒沉积岩时，能否利用先进技术手段，判断岩石中代表不同搬运机制的沉积构造是否受到了成岩作用改造等；第三，加强对化学作用和生物活动对细粒沉积物物理化学性质影响的定量研究，揭示其在搬运过程中的具体作用机理。这些研究方向的深入探索，有助于厘清不同类型搬运机制如何共同影响细粒沉积物的搬运和沉积，有望进一步减少细粒沉积物搬运方式研究中的不确定性，推动该领域的理论发展和实际应用。

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Current Research Status on the Transportation of Fine-grained Sediments

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Abstract: The study of fine-grained sediment transport mechanisms is an important part of the “source-to-sink” system theory of fine-grained sediments, and it is significant for the restoration of sedimentary environments, understanding the distribution of fine-grained sediments and predicting the distribution of unconventional oil and gas resources. Due to the fine grain size, which makes them difficult to observe, and the diversity of transport modes, each transport mode corresponds to particular sedimentary structures. Therefore, research on the transport mechanisms of fine-grained sediments has progressed slowly. From a review of the existing research reported in China and elsewhere, it is evident that there is still a lack of sorting and summarizing research findings regarding the transport mechanisms of fine-grained sediments. This study synthesizes current research, systematically sorts the transport modes and sedimentary characteristics of fine-grained sediments and classifies the transport modes of fine-grained sediments into three major categories: physical transport, chemical transport, and biological transport. Physical transport includes river water, atmosphere, bottom current, density underflow, and six types of gravity-flow transport. River water and atmospheric transport rely on the forces exerted by water flow and/or wind to overcome the gravitational force on fine-grained materials. These are mainly traction force and load force. Bottom current, density underflow, and gravity flow transport are triggered by tides, wind, earthquakes, floods, storms, volcanic eruptions and other means, with gravity being the main driving force. Clay minerals, dissolved organic carbon, carbonate minerals, iron minerals and others are transported as colloids or as true solutions. Dissolved substances are affected by environmental factors such as pH, Eh, temperature, pressure, and ion concentration or charge, and are transported by chemical means. Biological absorption and enrichment, environmental changes caused by biological activities and bioturbation all affect the formation and transport of fine-grained materials. The transport mechanisms of fine-grained sediments can be divided into three major categories: physical transport, chemical transport, and biological transport. Physical transport has diverse modes. With driving forces such as traction force, carrying capacity, and gravity, it can form a rich variety of sedimentary structures. Chemical transport mainly involves dissolved substances and is affected by environmental factors such as pH values and temperature. Biological transport influences the transport of fine-grained substances through absorption and enrichment, alteration of the environment, and bioturbation. In the future, attention should be focused on the interactions among the transport mechanisms of fine-grained sediments, the accuracy of identifying sedimentary structures should be improved, importance should be attached to simulation experiment research, and the quantitative analysis of chemical and biological effects should be strengthened, so as to enhance the understanding of the transport processes of fine-grained sediments and promote the development of the theory of fine-grained sedimentology.

Key words: Fine-grained sediments; transport mechanisms; triggering mechanisms; sedimentary characteristics