

# 深水砂质碎屑流沉积:概念、沉积过程与沉积特征

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**内容提要:** 在总结国内外相关文献的基础上,对砂质碎屑流的相关概念、沉积动力学过程及沉积特征进行系统梳理,并对争议问题进行了讨论。砂质碎屑流是一种富砂质具塑性流变性质的宾汉塑性流体,代表一个从黏性至非黏性碎屑流连续系列,具有中—高碎屑浓度(体积浓度25%~95%)、较低的泥质含量(体积浓度可低至0.5%)、湍流不发育。其沉积物以块状砂岩、含碎屑逆粒序砂岩沉积为代表,局部可见滑动剪切构造和液化漩涡构造。砂质碎屑流的形成多经历滑动—滑塌—砂质碎屑流—浊流的有序演化过程;滑水作用和基底剪切润湿作用是克服砂质碎屑流与基底剪切摩擦拖拽的重要机制,流体强度则是克服上覆环境水体混入稀释的重要原因;砂质碎屑流头部和边部优先固结沉积,进而控制流体整体沉降。砂质碎屑流是形成深水块状砂岩的主要原因之一,砂质碎屑流在相对低流体效率的深水重力流沉积环境广泛发育。

**关键词:** 砂质碎屑流;高密度浊流;沉积动力学;沉积特征;深水块状砂岩

Kuenen 和 Migliorini (1950) 提出的浊流形成正粒序层理的浊流理论将事件沉积作用的思想引入沉积地球科学,标志着现代沉积学的诞生;尔后 Middleton 和 Hampton (1973) 将浊流理论扩展为重力流沉积理论。作为沉积学研究的经典问题之一,深水重力流沉积相关研究受到海洋地球物理学家、沉积学家的持续关注。近年来,伴随科学技术的不断进步,关于深水重力流流体类型、成因机制、演化过程及沉积模式的研究取得了丰硕的成果:围绕砂质碎屑流 (Sandy debris flow) (Shanmugam, 2013; Postma and Cartigny, 2014)、异重流 (Hyperpycnal flow) (Mulder and Syvitski, 1995; Zavala and Arcuri, 2016)、混合重力流 (Hybrid gravity flow) (Haughton et al., 2009)、超临界重力流 (Supercritical gravity flow) (Postma and Cartigny, 2014) 的对比研究加深了对重力流搬运及沉积动力机制的理解;多种触发机制作用下的沉积物再搬运和沉积物持续供给的重力流成因机制研究揭示了重力流沉积广泛发育的本质 (方爱民, 1998; Mutti et al., 2009; Piper and Normark, 2009; Clare et al., 2016); 沉积物浓度控制下的碎屑

流与浊流相互转化过程阐述了重力流砂体分布复杂的原因 (Haughton et al., 2009; Talling, 2013; 李存磊, 2012; 操应长等, 2017a, b); 重力流水道形成过程控制下的重力流砂体沉积模式研究为重力流砂体的准确预测提供了可能 (Fildani et al., 2013; Covault et al., 2014; Talling et al., 2015; De Leeuw et al., 2016)。其中,砂质碎屑流沉积的相关研究在中国以陆相湖盆为主的深水重力流沉积研究中产生了广泛影响,围绕砂质碎屑流沉积特征、演化过程及分布规律等系列研究取得了丰硕的成果 (李相博等, 2009, 2011, 2013, 2014; 鲜本忠等, 2012, 2013, 2014; 高红灿等, 2012)。

砂质碎屑流的大量研究始于 Shanmugam (1996) 对 Lowe (1982) 提出的高密度浊流概念的质疑与批判,并提出使用砂质碎屑流替代高密度浊流概念的认识,以合理解释深水重力流沉积中块状砂岩成因这一历史难题 (操应长等, 2017b)。砂质碎屑流沉积在中国湖盆沉积中的广泛研究始于鄂尔多斯盆地 (邹才能等, 2009; 李相博等, 2009; Li Xiangbo et al., 2011; Zou et al., 2012), 尔后迅速席卷全国,

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相关沉积在全国各大陆相含油气盆地陆续被报道(耳闯等,2010;鲜本忠等,2012;潘树新等,2013;杨田等,2015;袁静等,2016;Li Xiangbo et al.,2016,2018;Xu et al.,2016;Liu et al.,2017;Xian Benzong et al.,2018),砂质碎屑流沉积一时成为湖相重力流沉积的主要代名词。实际上,王德坪和刘守义(1987),王德坪(1991)是国内最早开始砂质碎屑流沉积研究的先行者,他们以东营凹陷沙三段的深水重力流沉积研究为主要对象,提出了三角洲前缘广泛发育砂质碎屑流沉积(内成碎屑流)的新认识。但是,除了中国沉积学者广泛接受砂质碎屑流概念及沉积解释湖相深水块状砂岩成因外,欧洲和美国的深水重力流沉积主流研究学者对砂质碎屑流的概念、沉积过程及其沉积产物的相关认识都存在诸多不同意见(Talling et al.,2012,2013)。因而,有必要重新审视砂质碎屑流概念、沉积过程及其沉积产物,以求更加客观的来认识深水重力流沉积,解决深水重力流沉积认识争议,从而为合理的指导中国深水重力流沉积油气勘探提供理论指导。

## 1 砂质碎屑流相关概念

### 1.1 砂质碎屑流内涵

砂质碎屑流是一种富砂质具塑性流变性质的宾汉塑性流体,代表一个从黏性至非黏性碎屑流连续过程系列,以中—高碎屑浓度(体积浓度25%~95%)、较低的泥质含量(体积浓度可低至0.5%)、湍流不发育为特征,沉积物整体停止流动,块状固结,其沉积物支撑机制主要是基质强度、颗粒间的摩擦强度和浮力(Shanmugam,1996,2013),以块状砂岩、含碎屑逆粒序砂岩沉积为代表。Talling等(2012)进一步强调超孔隙流体压力是砂质碎屑流沉积物颗粒重要的支撑机制。砂质碎屑流沉积物一般基质含量较低,仅在颗粒接触处存在的黏土—水基质起成分意义上的基质作用,表现为凝聚强度,可由公式 $F=2\gamma_L V/X^2$ 体现。式中, $F$ 为颗粒受到的毛细管力, $X$ 表示两颗粒间的距离, $V$ 是两颗粒间液滴的体积, $\gamma_L$ 是液体的界面张力(王德坪,1991);颗粒接触处存在的黏土—水基质使颗粒间受到毛细管力作用,产生很大的黏附力,使得流体具有塑性流变性质。试验表明,颗粒支撑的碎屑流沉积中的黏土重量含量低至1.5%甚至更低(Hampton,1975);或泥基(黏土+水基质)体积含量低至5%,足以起到润滑碎屑流中的颗粒以防止摩擦锁定的作用,并能提供碎屑流自身的流体强度(Rodine and Johnson,

1976)。塑性流变性质使得流体在搬运过程中能够保持整体搬运,由于流体底部存在滑水现象(Hydroplaning)和基底润湿(Basal shear wetting)现象(Talling,2013),因而砂质碎屑流能够整体在水下搬运较长距离,在平坦的湖底平原发生整体卸载,块状冻结,形成以块状层理为主的深水砂体,砂质碎屑流沉积多具有底部层流段、顶部塞流段的韵律结构(Rodine and Johnson,1976;Shanmugam and Moiola,1995)。

### 1.2 滑水作用

在实验条件下,当碎屑流自身渗透性较差时能够有效抵抗环境水体对流体的稀释,如果碎屑流的动压力超过了其自身重力沿斜坡向下的分量,碎屑流的头部和基底接触部位会侵入一层液体,从而使碎屑流的头部与基底分离,减少了头部流体与基底剪切拖拽,从而使碎屑流能够发生快速搬运,这种现象被称为碎屑流的滑水作用(Hydroplaning;图1)(Mohrig et al.,1998;Harbitz et al.,2003;De Blasio et al.,2004;Talling,2013)。Mohrig等(1998)的水槽模拟实验证实碎屑流的流体弗洛德数大于0.4,是其发生滑水作用的临界条件。滑水作用能够使得碎屑流的头部脱离原有流体,快速向前搬运,形成孤立的碎屑流块体沉积;并且能加快碎屑流头部向浊流的转化(Hampton,1972;Mohrig et al.,1998)。虽然滑水作用导致的碎屑流底部的润滑作用是碎屑流在低坡度角条件下长距离搬运的可能解释(Mohrig et al.,1998;Talling,2013);但是,滑水作用并不能保证碎屑流整体发生长距离的搬运。事实上,滑水作用仅在碎屑流头部起作用,Mordrig等(1998)的实验中滑水作用范围仅为几十厘米,因而仅能对碎屑流的头部搬运起到润滑作用(Talling,2013)。

### 1.3 基底剪切润湿作用(Basal shear wetting)

Ilstad等(2004)通过水槽模拟实验证实滑水作用在碎屑流头部限制的环境水体由于碎屑流的快速剪切作用,会与碎屑流的体部混合,在碎屑流的底部形成一层由水和碎屑流底部沉积物共同组成的薄层剪切沉积层,对碎屑流起到明显的润滑作用,该过程被称为剪切润湿作用(图2)(Talling,2003;Ilstad et al.,2004)。该剪切润湿层分布范围要远大于滑水作用范围,从而对碎屑流在相对低坡度条件下的快速、远距离搬运起到明显的控制作用(Talling,2003;Ilstad et al.,2004)。碎屑流自身的物质组成控制的流体强度可能是控制滑水作用及剪切润湿层分布的重要原因(Ilstad et al.,2004);现阶段,碎屑流剪切

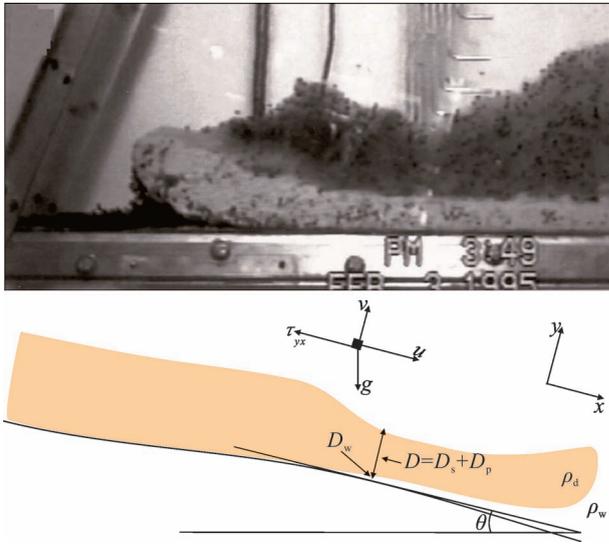


图 1 碎屑流滑水作用现象和原理(据 Mohrig et al., 1998; De Blasio et al., 2004)

Fig. 1 Phenomenon and mechanism of debris flow hydroplaning (from Mohrig et al., 1998; De Blasio et al., 2004)

$\rho_w$ —环境水体密度,  $\rho_d$ —碎屑流密度,  $D$ —碎屑流厚度,  $D_s$ —剪切层厚度,  $D_p$ —层塞流厚度,  $D_w$ —滑水层厚度,  $u$ —沿  $x$  方向速度,  $v$ —沿  $y$  方向速度,  $\tau_{yx}$ —应力张量的剪切分量,  $g$ —重力加速度,  $\theta$ —坡角

$\rho_w$ —density of water,  $\rho_d$ —Density of debris flow,  $D$ —total thickness of debris flow,  $D_s$ —thickness of the shear layer,  $D_p$ —thickness of the plug layer,  $D_w$ —thickness of water layer,  $u$ —longitudinal velocities,  $v$ —transverse velocities,  $\tau_{yx}$ —shear component of the stress tensor,  $g$ —gravitational acceleration,  $\theta$ —slope angle of bed

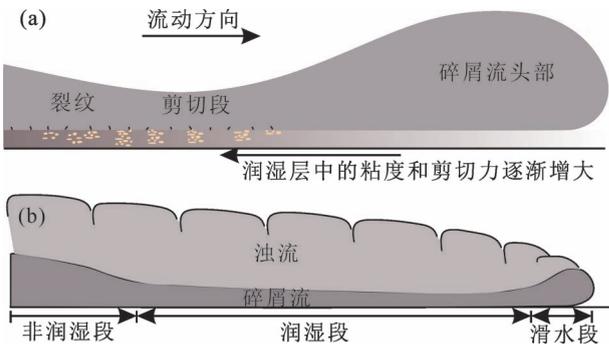


图 2 碎屑流基底润湿作用原理(据 Ilstad et al., 2004)

Fig. 2 Mechanism of debris flow basal shear wetting (from Ilstad et al., 2004)

润湿作用的的控制因素还有待深入研究。

## 2 砂质碎屑流沉积动力学过程

### 2.1 触发机制

Shanmugam(2013)强调砂质碎屑流沉积是深水沉积物垮塌再搬运形成重力流的主要流体类型,因而砂质碎屑流的触发机制与沉积物垮塌再搬运触发机制一致。深水沉积物垮塌再搬运的触发机制包括长期事件、中期事件和短期事件三种类型,长期事件主要为海平面升降控制的低位域条件;中期事件主要为构造过陡、冰川负载、盐运动、沉积负载、静液压负载、海洋底流、生物侵蚀、天然气水合物分解;短期事件主要包括地震、陨石撞击、火山活动、海啸波、魔鬼波、气旋波、季风降雨、落潮流、野火等(Shanmugam, 2012; 李相博等, 2011)。地震活动是引发沉积物垮塌再搬运最为明显的触发机制,1929年发生在加拿大纽芬兰岛东南的大浅滩地震引发陆坡沉积物垮塌再搬运,导致震中附近铺设在海底的电缆向海沿着沉积物搬运方向发生多处折断(Shanmugam, 2012; Talling et al., 2012); 2006年中国台湾屏东县发生地震,地震过后沿海底铺设的电缆向海沿沉积物搬运方向依次折断(Talling et al., 2012),这些海底电缆稍的折断多为地震作用导致的沉积物垮塌和沉积物垮塌演化形成的快速搬运的碎屑流和浊流所引起,Shanmugam(2012)认为上述现象是地震触发形成砂质碎屑流的良好佐证。但是,洪水触发形成的异重流同样具有搬运粗碎屑的能力(Mutti et al., 2003),其所形成的双层流体的底部密集层与砂质碎屑流具有相似的流体性质(Mutti et al., 2003),同时部分学者提出的底床载荷主导的异重流沉积也应该与砂质碎屑流具有相似的流体性质(Mulder and Chapron, 2011),因而洪水触发形成的异重流同样可以形成砂质碎屑流沉积(Girard et al., 2012)。例如,在陆相断陷湖盆的陡坡带发育的近岸水下扇扇裙,主要为洪水搬运沉积物直接入湖形成,属于典型的底床载荷主导的粗粒异重流沉积,其沉积特征具有砂质碎屑流的特征(Cao Yingchang et al., 2018)。因而,砂质碎屑流沉积并不专属沉积物垮塌再搬运成因的重力流沉积,笔者以为既然砂质碎屑流代表一个从黏性至非黏性碎屑流连续系列,在黏性碎屑流发育的情况下,通过流体的稀释演化就有可能形成砂质碎屑流沉积,从沉积演化过程来理解砂质碎屑流的触发机制更为合理。

### 2.2 搬运过程

砂质碎屑流的搬运过程主要涉及其在自身重力驱动下沿斜坡向下搬运而不与环境水体混合而解散转化为浊流的过程;在搬运的过程中,流体下部需要

克服与下伏底床的剪切摩擦,流体上部需要克服上覆环境水体的稀释混入(Mohrig et al.,1998;Ilstad et al.,2004)。前文已述,滑水作用和基底剪切润湿作用是克服流体下部与基底剪切摩擦拖拽的重要机制,而流体自身强度则是克服上覆环境水体稀释混入的重要原因(Ilstad et al.,2004)。因而,杂基类型及含量多少控制的流体自身强度强弱控制了砂质碎屑流的搬运过程(Marr et al.,2001;Ilstad et al.,2004)。需要指出,泥质杂基含量较高流体、强度较大的碎屑流易于发生滑水作用和基底剪切润湿作用(Marr et al.,2001;Ilstad et al.,2004);砂质碎屑流是泥质含量较低、强度相对较弱的碎屑流,其发生滑水作用和基底剪切润湿作用的可能性大大减小(Marr et al.,2001;Ilstad et al.,2004)。虽然部分学者指出砂质碎屑流中的黏土—水基质起到成分意义上的基质作用,表现为黏附强度,使得流体具有塑性流变性质,并且泥基(黏土+水基质)体积含量低至5%,足以起到润滑碎屑流中的颗粒以防止摩擦锁定的作用,但是这种流体能否发生长距离的搬运而不向浊流发生转化还不得而知(Hampton,1975;王德坪,1991)。Marr等(2001)和Ilstad等(2004)的水槽实验结果均表明低黏土含量的砂质碎屑流易于向浊流发生转化。虽然Talling等(2007,2013)报道了低杂基含量的砂质碎屑流可以向深海盆地发生长距离搬运而形成厚层砂岩的研究实例,但是将这种砂质碎屑流的成因解释为高密度浊流侵蚀泥质基底,使得流体湍动发生抑制从而转化为该种砂质碎屑流沉积(Talling et al.,2007,2013);或者为砂质碎屑流发生长距离搬运未发生离散而沉积,并且认为对其长距离搬运过程的理解仍然还是摆在沉积学家面前的难题(Talling et al.,2012)。陆相湖盆也存在上述问题,例如鄂尔多斯盆地延长组长6段—长7段广泛发育于半深湖—深湖环境的厚层块状砂质碎屑流沉积,泥质杂基含量一般小于10%,最低可至4.8%(李相博等,2015),因而这些流体如何向深水盆地搬运还存在较多争议。李相博等(2015)借鉴(王德坪,1991)的解释,认为少量的黏土—水基质在颗粒间呈薄膜状时,产生很强的黏附力,并以广泛发育在碎屑颗粒表面的绿泥石黏土薄膜为佐证材料,认为该等厚薄膜层在颗粒之间必然充当了“黏附剂”的角色,使得颗粒相互之间存在着巨大吸引作用,从而使低黏土含量的砂质碎屑流发生长距离搬运而未发生解散。作者以为将流体的强度等同于泥质杂基含量未必完全合理(Hampton,1975),如东营凹陷发

育的大量砂质碎屑流沉积中未见广泛发育的黏土包壳现象(Yang Tian et al.,2016,2019);而黏土包壳的发育可能与微生物作用形成的胞外多聚物(EPS)构成的生物膜之间存在密切的关系(Wooldridge et al.,2017),这种广泛发育的微生物膜是否为控制砂质碎屑流流体强度的主控因素有待后续的深入研究(Malarkey et al.,2015;van de Lageweg et al.,2018)。

### 2.3 沉降机制

碎屑流由于具有塑性流变学特征,当孔隙流体超压减小,沉积物颗粒不足以被超孔隙流体压力支撑,导致流体内部的抗剪强度(或摩擦阻力)超过了自身重力的分量,沉积物会发生整体固结沉降停止搬运,沉积物颗粒不会按照粒径大小发生分异,沉积物的厚度与流体的厚度相当(Shanmugam,1996;Talling et al.,2012)。但是,沉积物的固结并非瞬间完成,多为流体头部和边部优先沉积固结,形成内部流体的运动阻碍,流体整体停止运动,尔后内部流体的超孔隙流体压力再逐渐消散(Iverson,1997;Major and Iverson,1999),而并非前人认为的超孔隙流体压力的均匀消散导致流体整体固结沉降(Hutchinson,1986)。同时,碎屑流在滑水作用发育的情况下,脱离流体主体的碎屑流块体可以对后部流体起到阻挡作用,而迫使其减速沉降;在滑水作用不发育的情况下,由于动力筛选形成的位于碎屑流前部的粗碎屑同样对后部流体的搬运起到遮挡作用,而迫使其减速沉降,因而碎屑流头部和边部的沉积动力学特征是控制碎屑流沉降的重要原因(Johnson,1970;Sohn,2000)。此外,Ilstad等(2004)和Breien等(2010)的水槽模拟实验进一步证实,薄层状超孔隙流体压力支撑的砂质流体在垂向上的逐层叠加沉积是形成块状砂岩的重要原因,从流体性质来看,这种流体属于砂质碎屑流(Talling et al.,2012),这种液化层的逐层叠加沉降可能是砂质碎屑流除块状固结以外的重要沉降机制。砂质碎屑流整体沉降固结机制导致砂体外部形态的突然尖灭,是识别砂质碎屑流沉积最为重要的识别标志(Talling et al.,2012,2013)。沉积坡折带是控制砂质碎屑流沉降的重要控制因素,在坡折带之下地形坡度急剧降低,导致自生重力向下的分量减少;坡折带控制的水力跳跃作用使得超孔隙流体压力进一步降低,导致砂质碎屑流的块状固结沉降(Felix and Peakall,2006;李相博等,2011)。

### 2.4 演化过程

深水重力流事件由于流体类型多样,不同的流

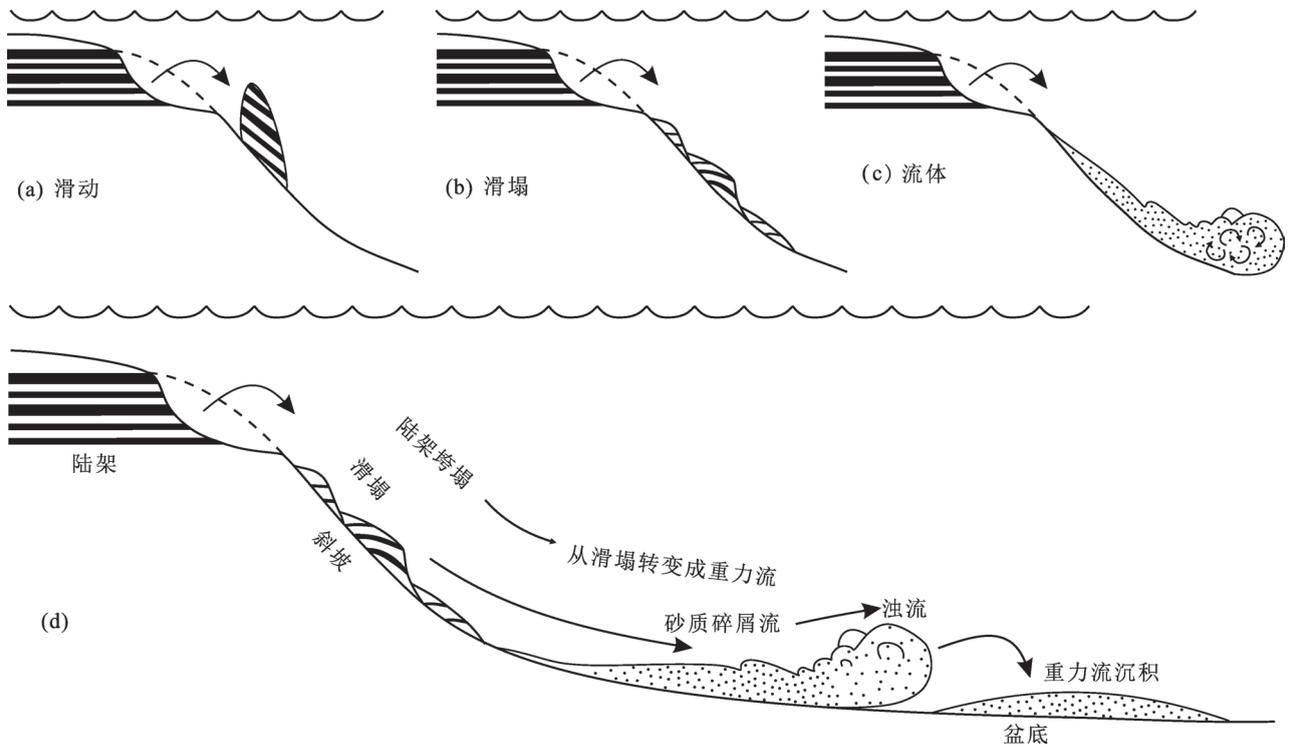


图 3 砂质碎屑流形成演化过程(据 Covault, 2011)

Fig. 3 Formation and evolution processes of sandy debris flow (from Covault, 2011)

体之间可以相互转化,因而可以将重力流事件触发到沉积过程中发生的不同的流体之间转化的综合过程称为流体演化过程(Haughton et al., 2009; Talling et al., 2012)。已有的大量实例证实先存沉积物在外界触发机制作用下会发生垮塌再搬运,搬运过程中伴随环境水体的卷入稀释,会依次发生滑动→滑塌→碎屑流→浊流的有序演化过程(图 3)(Shanmugam, 2013; Talling et al., 2012, 2013)。早期对重力流的流体转化认识主要包含四种形式:体转化、重力转化、面转化、淘洗转化(Fisher, 1983),体转化主要是层流与紊流之间的流体变化,填隙流体未发生明显变化;重力转化主要指重力作用下高密度沉积物在流体底部优先聚集造成流体转化;面转化即环境水体在流体表面的混合稀释作用造成流体转化,淘洗转化主要指沉积颗粒受流体内部孔隙流体向上运动的淘洗造成流体转化(Fisher, 1983)。后期的进一步深入研究认为液化作用、沉积物破碎、流体顶部剪切侵蚀、接触面不稳定性及波浪破碎、水力跳跃、流体头部与环境水体混合和多种机制作用下均可发生高浓度的碎屑流向低浓度的浊流转化(Felix and Peakall, 2006)。高浓度层流在流体稀释机制作用下向低浓度紊流的转化现象已被沉积学者

广泛接受(Waltham, 2004; Felix and Peakall, 2006),即砂质碎屑流向浊流的转化;但是重力转化指示了低浓度紊流向高浓度层流转化的可能性(Fisher, 1983),大量沉积实例证实了低浓度浊流向高浓度碎屑流转化的可能性,成为目前深水重力流沉积研究的热点问题(Haughton, 2003, 2009; Talling et al., 2004, 2012; Talling, 2013; Yang Tian et al., 2018; 操应长等, 2017b)。Talling 等(2012, 2013)对意大利亚平宁山脉 Marnoso-arenacea 深水重力流沉积的研究证实存在高密度浊流向砂质碎屑流转化的现象。作者赞同 Talling 等(2013)将高密度浊流与砂质碎屑流两个概念区别对待的做法,两种流体在自然界均存在(裴羽等, 2015);此外,需要指出 Talling 等(2013)砂质碎屑流的概念更加强调超孔隙流体压力对沉积物颗粒的支撑作用。但是,如何理解砂质碎屑流与高密度浊流之间的相互转化还有待深入的研究,何种因素(地形坡度、物质组成、粒度分选等)如何控制演化的方向?重力流的流态、浓度、流变学特征之间存在相互依存的关系,能否将这些参数结合起来理解其综合演化过程(Waltham, 2004),例如超临界流与亚临界流之间可以相互转化,高密度浊流与砂质碎屑流之间的相互转化是否遵从相似的规律

(Postma and Cartigny, 2014; Symons et al., 2016; 操应长等, 2017)。此外, 大量研究关注了碎屑流与浊流之间的相互转化, 而沉积物连续块体向重力流流体转化的研究并未引起足够的重视, 物质组成、固结程度和地形坡度是否为控制其发生滑动、滑塌转化为碎屑流的主要因素, 块体物质能否完全转化为重力流流体, 这种搬运过程能否在沉积产物中保存; 与重力流沉积相伴生的滑动剪切和滑塌变形构造是否为块体搬运作用的可靠标志, 特别是在岩心尺度上, 这些构造与近原地的软沉积物变形构造如何有效区分 (Shanmugam, 2017)。

### 3 砂质碎屑流沉积特征

砂质碎屑流沉积的典型识别标志包括: ①底部具有剪切构造的块状砂岩; ②砂岩层顶部泥质碎屑集中发育; ③泥质碎屑表现出逆粒序特征; ④分散和漂浮状的大碎屑颗粒; ⑤泥质碎屑成层平行于层面分布; ⑥页岩碎屑/泥岩撕裂屑发育; ⑦不规则的上接触面和侧向突然尖灭的几何形态; ⑧相对高的泥质杂基含量以产生一定的屈服强度和塑性流变学特征 (图 4) (Shanmugam and Moiola, 1995; Shanmugam, 1996, 1997)。除了上述沉积特征以外, 由液化作用产生的漩涡构造、砂岩顶部的突变接触、混杂分布的泥质碎屑也是砂质碎屑流沉积的典型识别标志 (Talling et al., 2012, 2013)。

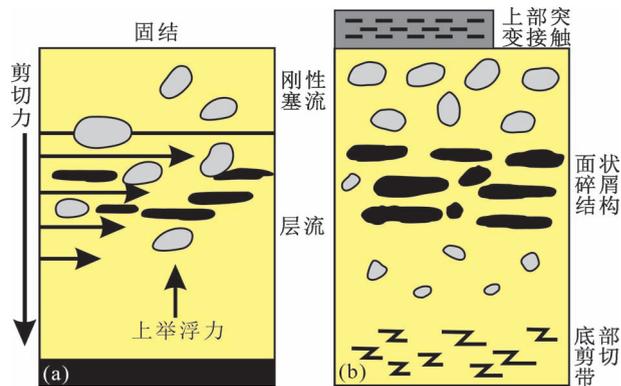


图 4 砂质碎屑流典型识别标志

(据 Shanmugam and Moiola, 1995)

Fig. 4 Typical diagnose criterial of sandy debris flow deposits (from Shanmugam and Moiola, 1995)

#### 3.1 块状构造

砂质碎屑流成因的块状构造以砂岩与底部和顶部泥岩突变接触为典型特征, 砂岩层内部不含任何沉积构造及垂向的粒度变化; 同一块状砂岩厚度稳

定, 不同块状砂岩厚度变化较大, 厘米到米级尺度均可发育, 以厚层更为常见; 岩性以中细砂岩最为常见, 多为泥质杂基含量相对较低的砂质碎屑流整体块状固结形成, 块状构造结合块状砂岩的侧向突变尖灭是识别砂质碎屑流沉积最为可靠的标志 (Talling et al., 2012; 李磊, 2012)。

#### 3.2 漂浮碎屑

漂浮碎屑是砂质碎屑流沉积的典型识别标志, 指示了其较强的屈服强度和塑性流变学特征 (裴羽等, 2015), 根据漂浮碎屑的成分, 可以进一步划分为漂浮泥质碎屑、漂浮镶边泥球、漂浮砾石等 (Shanmugam, 1996, 1997); 泥质碎屑根据其外部形状进一步可划分为磨圆泥质碎屑和不规则泥岩碎屑; 根据其分布可进一步划分为平行排列泥质碎屑和杂乱分布泥质碎屑等 (Li Xiangbo et al., 2017)。泥质碎屑的形状和分布对指示流体的搬运和形成过程具有重要意义: 漂浮镶边泥球外围的砾石粒径多大于周围砂岩, 指示了相对粗粒径、高能量的流体侵蚀形成镶边泥球, 尔后搬运过程中, 在浮力作用下上浮且整体固结沉积形成 (Shanmugam, 2012); 磨圆的泥质碎屑多指示了长距离搬运, 具有撕裂茬的泥质碎屑多指示了块体搬运中的拉张作用 (廖纪佳等, 2013; 杨田等, 2015); 平行排列的泥质碎屑多指示了碎屑流下部层流段的剪切改造作用, 杂乱分布的泥质碎屑则多指示了碎屑流上部“刚性”筏流段的块状固结作用 (高红灿等, 2012; 杨田等, 2015)。漂浮碎屑根据其成因和形成时间的差异, 可以分布在砂体的任何部位, 但由于受浮力作用大于周围沉积物颗粒, 趋于在砂体中上部集中分布并表现出逆粒序的特征。

#### 3.3 剪切构造

剪切构造主要发育在块状砂岩的底部, 受流体自身屈服强度和塑性流变性质的控制, 在滑水作用和基底剪切润湿作用发育的情况下, 在厚层流体的底部会形成薄层剪切沉积层, 使得下部流体表现出层流特征, 其沉积物在垂向上的叠加会形成部分显示剪切作用的液化或似平行层理的断续剪切面 (Marr et al. 2001; Ilstad et al. 2004)。此外, 薄层状平行排列的泥质碎屑多为剪切改造成因, 其垂向上的叠加也指示剪切作用的存在 (高红灿等, 2012)。在流体自身屈服强度较弱的情况下剪切构造一般不发育, 由于砂质碎屑流泥质杂基含量低, Talling et al. (2012, 2013) 认为其块状砂岩底部的剪切构造可能并不发育; 但是, 砂质碎屑流与底部泥质基底

互作用可能会导致流体底部泥质含量增加,剪切作用增强。

### 3.4 沉积序列

砂质碎屑流的沉积序列主要受其自身物质组成及搬运演化过程的控制,在其底部剪切作用发育的情况下多形成下部层流段上部刚性筏流段的两段式沉积序列(王德坪,1991;高红灿等,2012)。层流段以剪切构造及拉长状平行排列泥岩撕裂屑为典型特征,可显示逆粒序特征(Talling et al.,2012);刚性筏流段以块状层理和漂浮碎屑为典型特征(王德坪,1991;高红灿等,2012)。此外,砂质碎屑流由于自身抗剪强度较弱,其流体顶部与环境水体也会发生剪切拖拽,从而在顶部形成部分牵引构造发育或显示微弱正粒序的薄层,指示上部流体的转化过程,这种下部碎屑流沉积,上部浊流沉积序列也可称为碎屑流—浊流沉积组合或密集段(Gani,2004;Felix et al.,2009)。与之相反,部分学者认为碎屑流沉积顶部的剪切作用会形成分选差、漂浮碎屑富集的逆粒序剪切层(Xian Benzong et al.,2017)。

## 4 讨论

### 4.1 砂质碎屑流沉积争论焦点

Hampton(1975)首次通过水槽模拟实验证实,流体中高岭石质量分数为1.5%就能产生足够的流体强度支持细颗粒砂质沉积物形成细粒碎屑流。考虑到高岭石颗粒较大且离子交换能力较弱,相同含量的高岭石产生的流体强度要小于蒙脱石等黏土矿物,因而当含有蒙脱石等黏土矿物时,实际流体中杂基含量小于1.5%即可形成细粒碎屑流(Hampton,1975)。尔后,Shanmugam(1995)基于Sanders(1965)提出的浊流底部的流动颗粒层/惯性流层的认识和细粒碎屑流的认识,首次提出了砂质碎屑流的概念,并且将砂质碎屑流和高密度浊流的概念和内涵进行了系统对比(Shanmugam,1996),认为Lowe(1982)提出的沉积物颗粒由颗粒碰撞分散压力、浮力、基质强度、受阻沉降综合作用支撑的高密度浊流实际上是砂质碎屑流(Lowe,1982;Shanmugam,1996)。砂质碎屑流和高密度浊流的争论及深水块状砂岩的成因成为近20年深水重力流沉积研究的热点问题(Shanmugam,2000,2013;Stow and Mayall,2000a,b;Baas,2004;Talling et al.,2007,2012,2013;Breien et al.,2010)。现阶段关于深水块状砂岩的成因有高密度浊流底部受阻沉降导致的整体卸载(Stow and Johansson,2000)、高密度浊流底部

的牵引毯垂向叠加(Cartigny et al.,2013)、高密度浊流底部的持续液化层卸载(Kneller and Branney,1995)、不同强度黏性碎屑流的块状固结(Shanmugam,2000;Talling et al.,2013b)、细粒沉积物的淘洗漂浮(Stevenson and Peakall,2010;Breien et al.,2010)、异重流沉积(Zavala and Arcuri,2016;Zavala and Pan shuxin,2018)等多种认识。作者认为高密度浊流是上部流体拖拽下部沉积物搬运,与基质强度、超孔隙流体压力和颗粒分散压力混合支撑的砂质碎屑流之间存在显著差异(Mutti et al.,2009;Talling et al.,2012,2013),如牵引毯构造发育的块状砂岩显然属于高密度浊流成因,高密度浊流仍然是形成块状砂岩的主要机制,大多数块状砂岩都包含一定的粒序,尽管这种粒序可能十分微弱(Talling et al.,2012);当然,如何准确识别砂质碎屑流整体固结形成的块状砂岩和稳定的高密度浊流垂向叠加形成的块状砂岩仍然是摆在沉积学家面前的难题(Ilstad et al.,2004;Breien et al.,2010;Talling et al.,2012)。此外,顶部富含泥质碎屑的砂质碎屑流沉积与下部浊流沉积与上部碎屑流沉积的混合事件层之间就形成过程而言存在较大差异,但沉积产物十分相近(图5);虽然野外露头尺度混合事件层与砂质碎屑流沉积之间能够被有效区分(图5a),但是在岩心尺度要准确区分上述两种沉积还存在一定困难(图5b—c)(Haughton et al.,2003,2009;Talling et al.,2004;Talling,2013;Shanmugam,2012)。在重力流沉积岩心分析中沉积界面的拟定对沉积作用类型及其产物的确定起到十分关键的作用,并不是所有的岩性界面都代表了不同的重力流沉积事件(谈明轩等,2016)。

研究尺度和研究对象的差异也可能是造成砂质碎屑流沉积与高密度浊流沉积争议的重要原因。Shanmugam(2006,2012)对砂质碎屑流沉积的研究多源于岩心分析,受其侧向连续性制约,并不能很好的展示侧向分布特征;因而,可能会遗漏部分的重要沉积学信息,如Talling等(2012,2013)指出砂体的侧向突然尖灭是砂质碎屑流沉积最为重要的识别标志。高密度浊流沉积的研究则主要源于野外露头的分析,在精细的沉积构造及垂向和侧向地层对比的基础上升华为理论认识(Mutti et al.,2009)。此外,研究对象的差异也可能会形成较多的误解,Shanmugam(2006,2012)强调沉积物垮塌再搬运是深水重力流沉积的唯一成因来源,信仰沉积物垮塌再搬运经历滑动滑塌,转化为砂质碎屑流再转化为



图 5 重力流混合事件层或砂质碎屑流沉积

Fig. 5 Gravity flow hybrid event beds or sandy debris flow deposits

浊流,这种认识在陆相湖盆三角洲供给成因的相对细粒深水重力流沉积中普遍适用(邹才能等,2009;李相博等,2011;鲜本忠等,2012;杨仁超等,2014)。但是,在陆相湖盆中广泛发育洪水成因的深水重力流沉积,如近岸水下扇、扇三角洲、湖底扇沉积等,这些深水重力流沉积粒度普遍偏粗,沉积构造和沉积序列上与Lowe(1982)提出的高密度沉积基本一致。近期,深水重力流沉积海底监测表明在浊流底部发育的高密度流动颗粒层能够快速向上游方向迁移,是形成深水旋回坎及沉积物波的主要动力机制,也称为超临界浊流(Hughes Clarke,2016);同时,在野外露头中,大量的粗碎屑沉积物波和旋回坎沉积构造被相继发现(Ito and Saito,2006;Ito,2010;Postma et al.,2014),进一步指示了这种超临界高密度浊流沉积的广泛发育。如此看来,高密度浊流沉积显然存在,盲目的采用砂质碎屑流替代高密度浊流是狭隘的(Postma et al.,2009;Talling et al.,2012,2013;操应长等,2017b),砂质碎屑流沉积不应该是深水重力流沉积中的块状砂岩成因的唯一解释(Mutti et al.,1999)。

#### 4.2 砂质碎屑流沉积的存在性

水槽模拟实验、现代沉积和古代露头的研究均证实深水环境可以发育砂质碎屑流沉积(Hampton,1975;Shanmugam et al.,1995;Marr et al.,2001;Ilstad et al.,2004;Talling et al.,2007,2013),以低泥质杂基含量的块状砂岩沉积为典型特征,顶底部与上下泥岩突变接触,内部泄水和漩涡构造发育(Shanmugam et al.,1995;Talling et al.,2007,2013)。

深水重力流沉积中高密度碎屑流向低密度浊流的转化已被大量研究证实(Hampton,1972;Mohrig et al.,1998;Talling et al.,2012),从沉积作用的连续性和有序性出发,在高密度碎屑流与低密度浊流之间显然存在过渡流体类型(Gani,2004),高泥质杂基含量的碎屑流在搬运过程中随着环境水体的卷入,泥质杂基的淘洗溢出(Fisher,1983;Breien et al.,2010),可能会向低泥质杂基含量的碎屑流转化即砂质碎屑流沉积,随着泥质杂基含量的逐渐变化,形成一个从黏性至非黏性的碎屑流序列。这一转化过程受到流速和泥质杂基含量的共同控制,低泥质杂基含量沉积物高速再搬运,易于转化为砂质碎屑流;高泥质杂基含量沉积物低速再搬运则相反(Mohrig et al.,1998;Marr et al.,2001;Ilstad et al.,2004)。因此,砂质碎屑流与高密度浊流应为不同的流体类型,并且二者之间可能存在相互转化,砂质碎屑流的进一步稀释转化可以形成高密度浊流,而高密度浊流对泥质基底的侵蚀混合则可能转化为砂质碎屑流(Talling et al.,2007,2012,2013)。

#### 4.3 砂质碎屑流沉积的普遍性

深水重力流沉积中砂质碎屑流的存在成为不争的事实(Ilstad et al.,2004;Talling et al.,2007,2013),深水重力流砂体的形成是一个包含深水重力流“触发—搬运—沉降”的综合作用过程,也称为重力流事件(Talling et al.,2012);伴随沉积物向盆地方向搬运距离的增加,流体按照沉积物颗粒大小分异,形成不同岩相类型的能力称为流体效率,流体效率是决定重力流沉积类型及其分布的主要因素

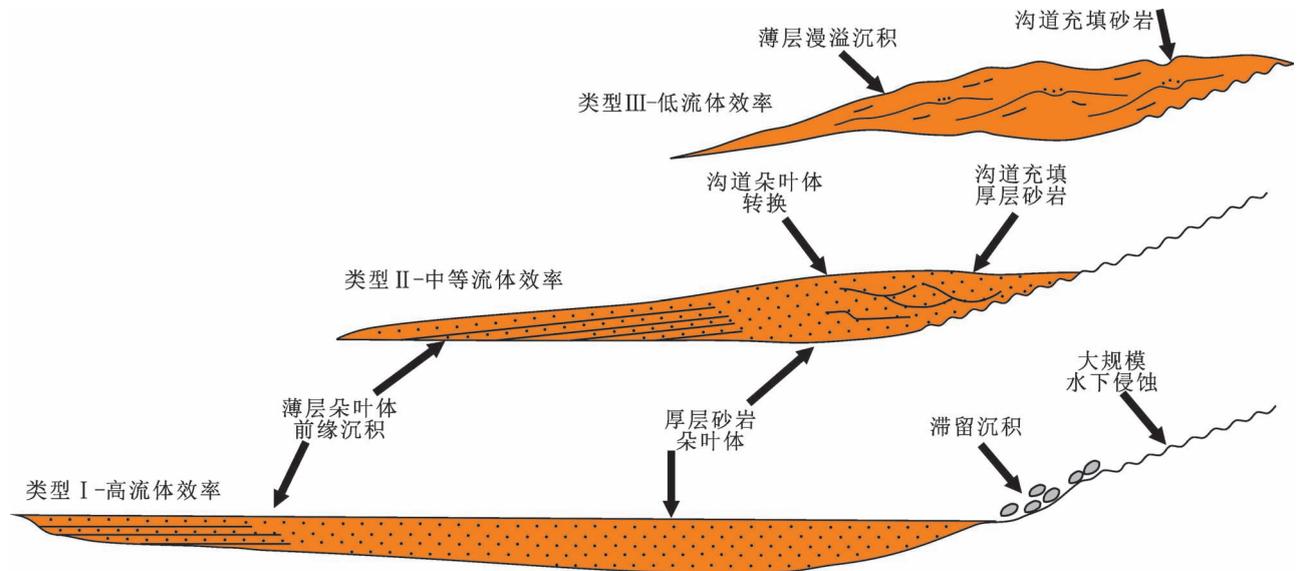


图6 不同流体效率的深水重力流沉积类型(据 Mutti, 1992)

Fig. 6 Deep water gravity flow deposits of different flow efficiency(from Mutti, 1992)

(Mutti et al., 1999, 2009)。流体效率主要受自生携带的细粒沉积物和流体侵蚀加入的细粒沉积物含量控制,一方面细粒沉积物能够阻止超孔隙流体压力的释放,促使粗粒沉积物发生长距离搬运,另一方面细粒沉积物能够增加流体湍动的动力,促使细粒沉积物发生长距离搬运(Mutti et al., 1999, 2009)。高流体效率的重力流一般搬运距离远,沉积物供给充分,沉积物分异彻底,流体演化充分,分布范围大,以浊流沉积为主;低流体效率的重力流一般搬运距离较近,沉积物供给少,沉积物分异不彻底,流体演化不充分,分布范围小,以碎屑流沉积为主(Mutti et al., 1999)(图6)。因而,低流体效率的重力流沉积环境砂质碎屑流沉积可能广泛发育,如陆相湖盆三角洲前缘沉积物垮塌形成的深水重力流沉积,相较海相盆地,陆相湖盆中的砂质碎屑流沉积可能更为发育。当然,正如 Mutti (1992) 指出的“自然界并不存在两处完全相同的深水重力流沉积”一样,针对重力流沉积类型及分布的问题需要结合实际的沉积构造背景进行具体分析,试图建立统一的沉积作用类型及沉积分布模式的努力是徒劳地,这样的历史教训已然深刻(Normark, 1978; Walker, 1978)。

## 5 结论

(1) 砂质碎屑流是一种富砂质具塑性流变性质的宾汉塑性流体,其沉积物支撑机制主要是基质强度、颗粒间的摩擦强度、浮力以及超孔隙流体压力,

以块状砂岩、含碎屑逆粒序砂岩沉积为代表。滑水作用和基底剪切润湿作用是克服砂质碎屑流与基底剪切摩擦拖拽的重要机制,而流体自身强度则是克服上覆环境水体混入稀释的主要原因。

(2) 沉积物垮塌再搬运和洪水重力流均可形成砂质碎屑流沉积,砂质碎屑流的搬运过程主要涉及其在自身重力驱动下沿斜坡向下搬运而不与环境水体混合解散转化的过程。泥质杂基类型及含量控制的流体自身强度强弱决定了砂质碎屑流的搬运过程;当流体内部的抗剪强度超过了自身重力的分量,流体由边部向中心整体固结沉降。

(3) 砂质碎屑流沉积的典型识别标志包括:①底部具有剪切构造的块状砂岩;②砂岩层顶部泥质碎屑集中发育;③泥质碎屑表现出逆粒序特征;④分散和漂浮状的大碎屑颗粒;⑤泥质碎屑成层平行于层面分布;⑥页岩碎屑/泥岩撕裂屑发育;⑦砂岩顶部不规则的上接触面和侧向突然尖灭的几何形态;⑧相对高的泥质杂基含量以产生一定的屈服强度和塑性流变学特征。此外,液化作用产生的漩涡构造、砂岩顶部的突变接触、混杂分布的泥质碎屑也是砂质碎屑流沉积的典型识别标志。

(4) 砂质碎屑流是深水块状砂岩形成的原因之一,深水环境发育砂质碎屑流沉积已成为不争的事实。砂质碎屑流可能为高密度碎屑流向高密度浊流转化的过渡类型,在低流体效率重力流沉积环境广泛发育。

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## Deep-water sandy debris flow deposits: concepts, sedimentary processes and characteristics

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**Abstract:** On the basis of summarizing relevant literatures at home and abroad, the related concepts, sedimentary dynamics and sedimentary characteristics of sandy debris flow are systematically sorted out, and the controversial issues are discussed. Sandy debris flow is a kind of Bingham plastic fluid with medium to high detrital concentration (volume concentration ranges from 25% to 95%) and low mud matrix content (minimum volume concentration 0.5%). It represents a series of debris flow from cohesive to non-cohesive flow without obvious turbulence. Sandy debris flow deposits are represented by massive sandstone, sandstone with inverse floating mud clasts. Slump shear structures and liquefied swirly patchy texture can be observed occasionally. The formation of sandy debris flow mostly undergoes the orderly evolution process of sliding → slipping → sand debris flow → turbidity flow. Hydroplaning and basal shear wetting are the main mechanisms to overcome shear friction between sandy debris flow and the base. Fluid strength is an important reason to overcome the dilution of the overlying ambient water. Debris flow has the characteristics of preferential deposition and consolidation of the head and the edge, thus controlling the overall settlement of the fluid. Sandy debris flow is one of the main reasons for the formation of deep-water massive sandstone, which is widely developed in a relatively low fluid efficiency deep water gravity flow deposition environment.

**Keywords:** sandy debris flows; high-density turbidity; sediment dynamics; sediment characteristics; deep-water massive sandstone

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