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## 渤海湾盆地东营凹陷碎屑流主控型深水体系沉积过程及模式

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**提要:**【研究目的】碎屑流是深水环境沉积物搬运和分散的重要机制,其相关的砂岩储层是含油气盆地重要的勘探目标,然而,与经典浊流及浊积系统相比,对碎屑流主控型深水体系的发育规律目前仍知之甚少。【研究方法】本文基于岩心、测井及全三维地震资料,通过系统的岩心观察描述、测井及地震资料解释,对渤海湾盆地东营凹陷始新统沙三中亚段深水体系沉积过程及模式开展研究。【研究结果】结果表明,沙三中深水体系发育九种异地搬运岩相,可概括为四大成因类型,反映了块体及流体两种搬运过程。岩相定量统计表明,该深水体系主要由碎屑流沉积构成,浊流沉积很少,碎屑流中又以砂质碎屑流为主。重力流在搬运过程中经历了滑动、滑塌、砂质碎屑流、泥质碎屑流及浊流等5个阶段演变,发育5类主要的深水沉积单元,包括滑动体、滑塌体、碎屑流水道、碎屑流朵体及浊积薄层砂。从发育规模及储层物性上,砂质碎屑流水道、朵体及砂质滑动体构成了本区最重要的深水储层类型。【结论】认为沙三中时期充足的物源供给、三角洲前缘高沉积速率、断陷期频繁的断层活动以及较短的搬运距离是碎屑流主控型深水体系形成及演化的主控因素,最终基于沉积过程、沉积样式及盆地地貌特征综合建立了碎屑流主控型深水体系沉积模式。本研究将进一步丰富深水沉积理论,为陆相深水储层预测提供借鉴。

**关键词:**深水沉积;碎屑流;浊流;油气储层;断陷湖盆;油气勘查工程;渤海湾盆地

**创 新 点:**(1)明确了陆相断陷湖盆碎屑流主控型深水体系的存在,对其成因流体类型进行了定量研究;(2)揭示了碎屑流主控型深水体系的沉积动力过程、沉积结构单元特征及发育控制机理。

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## Depositional process and model of debris dominated deep–water system in the Dongying Depression, Bohai Bay Basin

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**Abstract:** This paper is the result of oil and gas exploration engineering.

**[Objective]** Debris flow represents an important mechanism of sediment transport and dispersal in deep–water environment, the related sandstone reservoir constitute one of the important targets for petroleum exploration in petroliferous basins, while deep–water systems dominated by debris flows are still poorly understand compared to well–studied turbidity currents and turbidite systems. **[Methods]** The depositional process and model of gravity flows which developed in the Middle Sub–member of the 3rd Member of the Eocene Shahejie Formation, Dongying Depression, Bohai Bay Basin have been studied through the integration of core data examination, well logging data and 3D seismic data interpretation. **[Results]** It is suggested that nine base types of lithofacies can be recognized in slump–derived gravity flow deposits, which can be summarized into four main origin types, which indicate mass transport and flow transport processes, respectively. Quantitative lithofacies analysis suggests that the slump–derived gravity flow depositional system is dominated by debris flows, while turbidity currents are less important, and sandy debris flows represent the most important debris flow type. The slump–derived gravity flows undergo five evolution stages including slide, slump, sandy debris flow, muddy debris flow and turbidity currents, which correspondingly develop five types of deep–water depositional elements during transportation and evolution, including slide, slump, debris channel, debris lobe and turbidite sheet. Sandy debris channels, lobes and sandy slides constitute the most important deep–water reservoirs in the study area according to their wide distribution and reservoir property. **[Conclusions]** It is proposed that adequate sediment supply, high depositional rate on delta–front, frequent tectonic activities and short transport distance are the main controlling factors. Accordingly, a depositional model is proposed to depict slump–derived gravity flow systems based on depositional processes, sedimentary patterns and basin morphology. This study seeks to improve deep–water sedimentary theories and provide guidance for petroleum exploration of deep–water sands in deep–lacustrine basins.

**Key words:** deep–water deposition; debris flow; turbidity current; reservoir; lacustrine rift basin; oil and gas exploration engineering; Bohai Bay Basin

**Highlights:** (1) The development of debris dominated deep–water system in lacustrine rift basin has been demonstrated and the sediment gravity flow types have been quantified. (2) Depositional process, sedimentary architecture and controlling factors of debris dominated deep–water system have been revealed.

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## 1 引言

重力流是深水盆地最重要的沉积动力之一(Middleton and Hampton, 1976; Mulder and Alexander, 2001; Mutti et al., 2009; Talling et al., 2012; Zavala and Arcuri, 2016),也是形成深水储层的主要成因(Stow and Johansson, 2000; Piper and Normark, 2001)。自20世纪50年代“浊积岩”概念被首次提出以来(Kuenen and Migliorini, 1950),重力流便成为沉积学界的一大热点而被持续关注(Steel and Milliken, 2013)。近年来,随着深水沉积理论及深水油气勘探的不断发展,“砂质碎屑流”(Shanmugam, 1996)、“混合事件层”(Haughton et al., 2009)、“过渡型流体”(Kane and Ponten, 2012)、“异重流”(Mulder et al., 2003)、“超临界流”(Posta and Cartigny, 2014)等概念的建立、推广或重新认识,揭示了深水沉积过程的多样性和复杂性,掀起了新的重力流研究热潮。

重力流沉积在世界深水盆地中被广泛报道(Shanmugam, 2000, 2013; Talling et al., 2007; Clare et al., 2014),在中国松辽(王尉等, 2018)、鄂尔多斯(李相博等, 2009; 邹才能等, 2009; 杨仁超等, 2014)、渤海湾(鲜本忠等, 2013; 杨田等, 2015; 刘建平, 2016; 操应长等, 2021)、苏北(袁静等, 2016)等大、中型湖相含油气盆地及南海陆缘(雷振宇等, 2017; 高红芳等, 2020; 邢作昌等, 2020)等地区也广泛发育。现代海底监测表明,在洪水、滑塌、冰川融水、火山爆发等多成因重力流中,综合考虑沉积规模及触发频率,滑塌成因的重力流占据主导地位(Talling, 2014)。随着滑塌重力流理论(Shanmugam et al., 1994)的引入并在中国湖相深水油气勘探中取得重要发现突破(李相博等, 2009; Zou et al., 2012; Shanmugam, 2013),进一步明确了滑塌触发的碎屑流砂岩是中国湖相深水勘探的重要目标,碎屑流因此成为中国湖相重力流研究的一大热点(邹才能等,

2009; Zou et al., 2012; 鲜本忠等, 2013, 2014, 2016; 杨仁超等, 2014; 操应长等, 2021)。当前,国内外学者基于野外露头、地下资料或模拟实验开展了众多的滑塌重力流沉积过程及流体性质的讨论(Shanmugam et al., 1994; Mohrig et al., 1998; Felix et al., 2009; Zou et al., 2012; 鲜本忠等, 2014, 2016; Zhang et al., 2016; 谈明轩等, 2017; 王星星等, 2018; 王家豪等, 2020; 操应长等, 2021),然而,其不同沉积阶段的沉积响应规律,即沉积要素或结构单元特征,尚不明确。此外,研究表明,与经典浊积系统相比(Normark, 1970),在深海斜坡或盆底环境中也发现存在由碎屑流主导的深水体系(Shanmugam, 2000),对此类深水体系的成因、岩相构成、沉积结构及发育分布规律开展深入研究及定量评估对于深化重力流沉积理论、拓宽深水油气勘探领域具有重要的意义。本文基于研究区大量的取心、测井及全覆盖三维地震资料,开展系统的岩相分析统计、测井及地震沉积学研究,对渤海湾盆地东营凹陷始新统沙河街组沙三段中亚段( $Es_3^m$ )碎屑流主导的深水体系岩相特征、沉积过程、结构要素、控制因素及沉积模式和油气储层意义开展综合研究,以期进一步揭示和完善湖相深水沉积规律,为中国陆相湖盆深水砂岩油气勘探提供参考。

## 2 地质背景

东营凹陷是发育于渤海湾盆地东南隅的一个中—新生代断—坳复合盆地,宽65 km,长90 km,面积约5700 km<sup>2</sup>,呈NEE走向,具北断南超、北陡南缓的箕状凹陷特征。其四周凸起环绕,但又与济阳拗陷内其他凹陷相连,其东与青坨子凸起相邻,西以平南断层和高青断层为界;北邻陈家庄凸起,以陈南断层为界;南邻鲁西隆起及广饶凸起,以齐河—广饶断裂为界。东营凹陷内部可进一步划分为北部陡坡带、中央隆起带、南部缓坡带及牛庄、民丰、利津、博兴洼陷等7个二级构造单元(邱桂强等, 2001)(图1)。

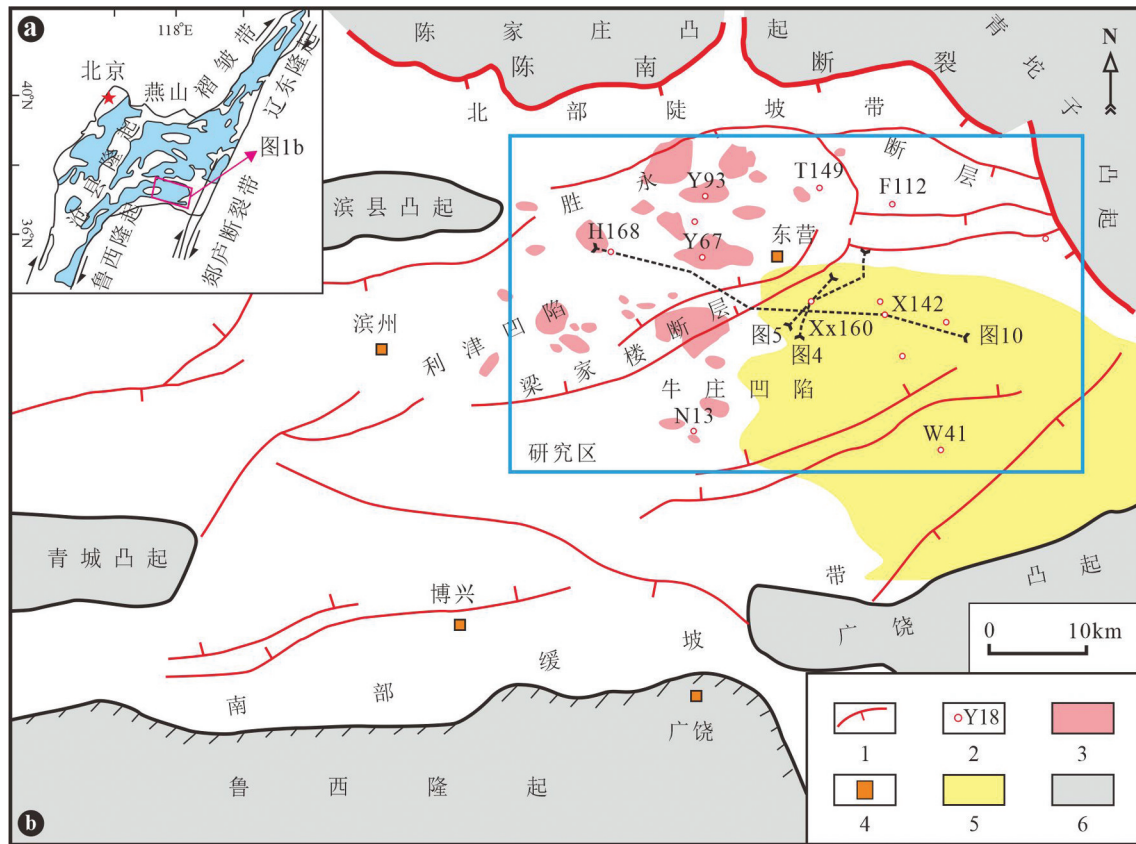


图1 渤海湾盆地东营凹陷构造位置及沙三中亚段沉积体系分布图

1—断层;2—取心井;3—重力流;4—城市;5—三角洲;6—隆起/凸起

Fig.1 Tectonic location of the Dongying Depression and depositional systems of the Es<sub>3</sub><sup>m</sup>

1—Fault ; 2—Cored well ; 3—Gravity flow ; 4—City ; 5—Delta ; 6—Uplift/rise

东营凹陷经历了两期构造演化,古近纪同裂谷期及新近纪以来的裂后热沉降期。始新统沙河街组沙三段处于裂陷鼎盛阶段,盆地沉降速率大,分布广泛的半深湖—深湖区。沙三段中亚段(沙三中)沉积时期,东营凹陷南部发育多个三角洲体系,其中发育于湖盆东南端的东营三角洲沉积时间最长,规模最大,对地貌格局的影响最深远。自其由东南向西北推进过程中,沉积范围持续扩大至利津和民丰凹陷(范代读等,2000)。这一时期,伴随着东营三角洲的推进,在三角洲前端斜坡及深水区发育大量的重力流沉积(图1)。本次研究区位于凹陷中东部,东营三角洲主要沉积区,范围主要包括利津、牛庄凹陷,以东营三角洲快速推进背景下的沙三中为目的层,利用本区38口取心井、968 m取心资料及大量的测井、全三维地震资料,开展东营三角洲相关的滑塌深水体系的沉积过程及响应规律研究。

### 3 重力流沉积特征及成因

#### 3.1 岩相特征及解释

基于沙三中亚段968 m岩心资料,依据岩性、粒度、沉积结构、构造等特征,开展了研究区重力流沉积岩相类型的识别,共划分出9种异地搬运岩相,可概括为4大成因类型,包括滑动、滑塌、碎屑流及浊流(表1)。可进一步根据Dott对重力驱动过程的力学机制划分(Dott, 1963),将滑动、滑塌及碎屑流划分为弹—塑性流或塑性流(MTDs),而将浊流划分为黏性流体(viscous fluid)两大类型。

##### 3.1.1 滑动

原始沉积物处于未固结状态,受到外界因素触发,在重力沿下坡分力的作用下,沿着滑动面向下产生位移的初始过程便形成滑动。在三角洲环境,滑动多发生在前缘河口等高沉积速率的位置,由于

表1 东营凹陷始新统沙三中亚段重力流岩相类型划分  
Table 1 Lithofacies classification of gravity flow deposits of the Es<sub>3</sub><sup>m</sup> in the Eocene Dongying Depression

成因类型	典型岩相	代码	沉积特征	搬运过程	力学特性	流体类型
滑动	交错层理砂岩	S1	交错层理,夹于暗色泥岩中	滑动	弹性块体	砂质滑动
滑塌	变形层理砂岩	S2	变形	滑塌	弹-塑性块体	砂质滑塌
	变形层理泥岩	M1	变形、包卷层理,发育滑塌异粒岩相	滑塌	弹-塑性块体	泥质滑塌
碎屑流	洁净块状砂岩	S3	无韵律细砂岩,块状构造,低黏土含量	冻结式沉积	塑性流变学	砂质碎屑流
	含漂砾块状砂岩	S4	无韵律的砂质基质,见泥岩撕裂屑、砂质或者泥质团块,通常呈杂乱结构	冻结式沉积	塑性流变学	砂质碎屑流
	含漂砾块状泥质砂岩	MS	块状构造,含较多泥质,见泥岩撕裂屑或漂浮状砂、泥团块,通常呈杂乱结构	冻结式沉积	塑性流变学	泥质碎屑流
	含漂砾块状泥岩	M2	块状构造,见砂质或泥质碎屑,通常呈杂乱结构	冻结式沉积	塑性流变学	泥流
浊流	正递变砂岩	S5	正递变层理,底部弱侵蚀或无侵蚀	悬浮沉降	牛顿流变学	浊流,鲍玛序列A段
	波纹交错层理砂岩	S6	细、粉砂岩,发育波纹交错层理	悬浮沉降及底床牵引	牛顿流变学	浊流,鲍玛序列C段

这一阶段沉积物尚未和周围水体充分混合和液化,滑动体内部层系、颗粒之间相对位置未发生明显变化,因此能够保留原始沉积构造,可以反映再搬运之前的沉积环境。在研究区,滑动沉积典型的岩相为交错层理砂岩(S1),其内部层理结构清晰,基本未发生形变,底部以较平整的滑动面与湖相暗色泥岩突变接触,夹有泥质纹层,反映了动荡的三角洲前缘河口环境(图2a)。随着滑动块体中泥质含量增高,含水量增加,刚性减弱,块体更容易液化,内部结构往往遭受破坏,因此在地质记录中泥质滑动一般不易保存,本区岩心观察表明滑动沉积主要以砂质滑动为主(表1)。

### 3.1.2 滑塌

滑动块体通过与周围水体进一步混合、液化,增加含水体积,颗粒质点产生相对位移,发生塑性变形,不再完全保留弹性块体特性,具有部分塑性流体特性,形成滑塌。研究区滑塌沉积的识别特征包括滑塌异粒岩相(砂、泥混杂),包卷、揉皱变形层理,层内高角度小断层,有时可见底部暗色泥岩中注入的砂岩脉等。根据砂、泥含量的差异,进一步将滑塌沉积细分为砂质滑塌和泥质滑塌两种类型,分别发育变形层理砂岩相(S2)(图2b)和变形层理泥岩相(M1)(图2c)(表1)。

### 3.1.3 碎屑流

碎屑流属于非牛顿流体,具塑性流变学特性,具有一定的屈服强度以及触变特性。当重力沿下

坡分力提供的外部剪切力超过流体屈服强度将发生塑性流动,以块体形式搬运,当剪切力小于屈服强度将发生“冻结式”沉积(Shanmugam et al., 1994)。根据泥质基质含量的差异,在研究区可识别出砂质碎屑流、泥质碎屑流和泥流三种碎屑流沉积(表1)。砂质碎屑流发育洁净块状砂岩(S3)(图2d)和含漂砾块状砂岩(S4)(图2e)两种岩相,而泥质碎屑流和泥流则分别形成含漂砾块状泥质砂岩(MS)(图2f)和含漂砾块状泥岩相(M2)(图2g)(表1)。

砂质碎屑流泥质含量低,其屈服强度主要来自颗粒碰撞摩擦强度以及一部分黏土基质提供的黏性强度,其发生“冻结式”沉积主要是由于摩擦颗粒受阻(Middleton and Hampton, 1973),洁净块状砂岩整体缺乏分异、块状无韵律构造反映了塑性流体的“冻结式”沉积过程(图2d)。含漂砾块状砂岩中随机杂乱分布的漂砾反映了发生“冻结式”沉积时砾屑的最后位置,而平行层面分布的碎屑反映了流体搬运过程中的沿层剪切应力(图2e)(Enos, 1977)。分布于层上部,呈“反韵律”特征的漂浮碎屑指示了流体前部的弱剪切作用或者动力筛以及上浮力的作用(图2e)(Iverson, 1997)。

泥质碎屑流及泥流的泥质含量更高(体积百分比>>5%),其屈服强度主要来自黏性基质提供的黏性强度。泥质碎屑流整体上为泥质砂岩,而泥流主体为泥岩沉积。含漂砾块状砂岩(图2f)或含漂砾块状泥岩(图2g)中近于垂直或斜交的漂浮砾屑反映了塑性流



图2 东营凹陷沙三中亚段重力流沉积岩相特征

a—交错层理; b—砂岩中的变形层理, 见泥质纹层扭曲; c—泥岩中的变形构造, 见砂质条带扭曲; d—洁净块状砂岩; e—块状砂岩中的漂浮泥砾; f—洁净块状砂岩与上覆含漂砾块状砂岩直接接触; g—块状泥岩中漂浮砾石; h—砂岩中的垂向多期正韵律; i—波纹交错层理

Fig.2 Sedimentary facies of gravity flow deposits in the Es<sub>3</sub><sup>m</sup> in the Dongying Depression

a—Cross bedding; b—Deformed bedding and contorted mud layers in sandstones; c—Deformed structure and contorted sand layers in mudstones; d—Clean massive sandstones; e—Floating mud clasts in massive sandstones; f—Clean massive sandstones immediately contacted with overlying massive sandstones with floating clasts; g—Floating clasts in massive mudstones; h—Multiple fining-upwards rhythm in sandstones; i—Sand ripples

体的触变特性和“冻结式”沉积过程,有时可见砂质碎屑沿层拉伸变形,能够指示流体内部黏性基质和未固结砂岩之间的界面剪切力和层流状态(表1)。

### 3.1.4 浊流

浊流是典型的牛顿流体,无屈服强度,碎屑颗粒以紊流形式进行搬运。在研究区发育两类浊积岩相,呈不完整浊积序列,分别是正递变砂岩(S5)(图2h)及波纹交错层理砂岩(S6)(图2i,表1),砂岩粒度以粉细砂为主。正递变砂岩表现为垂向上粒度旋回的多期叠置,每期旋回垂向变细的粒径剖面指示了浊流能量衰减和逐级悬浮沉降过程,代表了浊积岩“鲍玛序列”的Ta层段。波纹交错层理砂岩响应于低密度浊流能量衰减的末期,向牵引流的转变过程,对应“鲍玛序列”的Tc层段。

### 3.1.5 岩相组合特征

垂向岩相组合特征一定程度上记录了更完整的重力流事件。以冲刷面、深湖暗色泥岩或岩相转化面为界,识别出7种岩相组合类型。具体包括(a)巨厚层(1~3 m)砂质碎屑流,垂向上以单一的S3岩相或S4岩相或两者的组合S3-S4为特征;(b)厚层(0.3~1 m)复合层,垂向上以S3-S6或S4-S6或S4-MS组合为特征,反映了流体搬运过程中下部碎屑流向浊流或砂质碎屑流向泥质碎屑流的逐渐转化;(c)厚层—巨厚层(0.5~5 m)泥质碎屑流,垂向上以单一的MS岩相为特征;(d)巨厚层(1~3 m)泥流,垂向上以单一的M2岩相为特征;(e)巨厚层(1~1.5 m)砂质滑动,垂

向上以单一的S1岩相为特征;(f)厚层—巨厚层(0.5~3 m)砂质或泥质滑塌,垂向上以单一的S2岩相或M1岩相为特征;以及(g)薄层—厚层(0.1~0.5 m)浊积岩,垂向上以单一的S6岩相为特征,反映了沉积后期流体末端,多期低密度浊流的活动。

### 3.2 岩相定量统计

为进一步明确研究区重力流的成因分布特征,在岩相分析的基础上(表1),开展了岩相定量统计。对单期厚度>0.1 m的岩相单元进行成因统计,对不同成因重力流沉积的钻遇频次、钻遇厚度及不同类型碎屑流沉积的钻遇厚度开展了定量分析。

结果表明,在钻遇频次上,砂质碎屑流与泥质碎屑流沉积钻遇最多,分别占比52.55%和17.33%;其次是泥流及砂质滑塌沉积,分别占10.04%和7.56%,浊流沉积相对较少,仅占8.46%,滑动和泥质滑塌沉积最少,都不足3%(图3a)。在钻遇厚度上,砂质碎屑流、泥流及泥质碎屑流沉积钻遇厚度最大,分别占42.5%、21.46%和17.77%;浊流沉积钻遇厚度很小,仅占4.55%(图3b)。仅针对碎屑流沉积钻遇厚度开展分析,表明本区主要为砂质碎屑流沉积,占比高达52%;其次是泥流和泥质碎屑流沉积,分别为26%和22%(图3c)。

## 4 深水沉积结构单元

### 4.1 沉积单元类型

通过岩心相、地震相、测井相及地震沉积学综

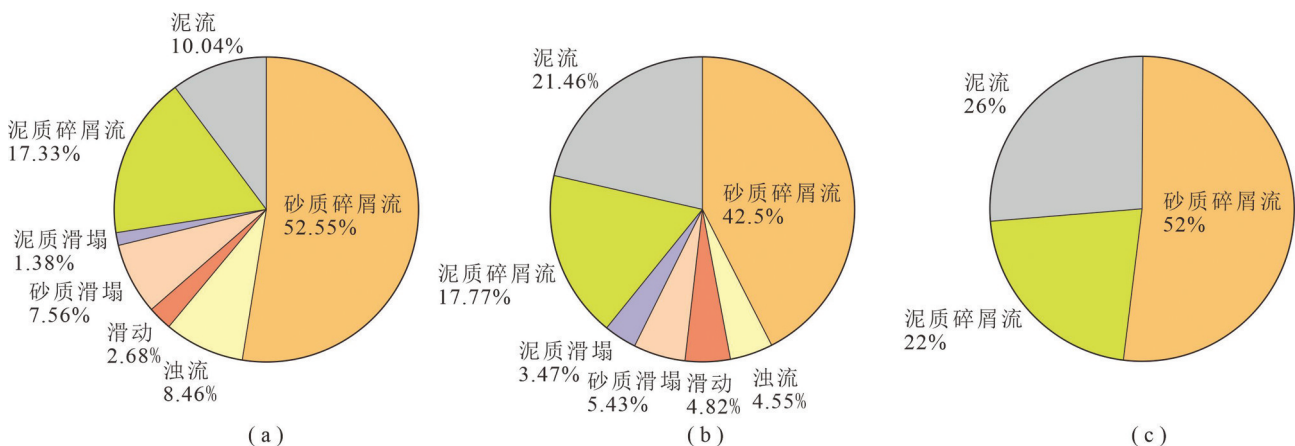


图3 沙三中亚段重力流沉积岩相定量分析

a—不同成因类型的重力流沉积钻遇频次饼状图;b—不同成因类型的重力流沉积钻遇厚度饼状图;c—碎屑流沉积钻遇厚度饼状图

Fig.3 Quantification of lithofacies in gravity flow deposits in the Es<sub>3</sub><sup>m</sup>

a—Pie chart of frequency distribution of different gravity flow deposits; b— Pie chart of thickness distribution of different gravity flow deposits;

c— Pie chart of thickness distribution of different debris flow deposits

合分析,开展了沙三中亚段深水沉积结构单元研究,共识别出5类深水沉积单元,分别是滑动体、滑塌体、碎屑流水道、碎屑流朵体及浊积薄层砂。

### 4.2 沉积单元发育特征

#### 4.2.1 滑动体

滑动体主要由滑动砂岩构成,发育在三角洲前端深湖环境。研究区滑动体以透镜状、强振幅地震反射为特征,横向连续性较差,宽度一般不超过6

km;GR测井曲线可见典型漏斗状形态,指示了原始三角洲河口坝的反韵律特征。滑动体单期厚度一般不超过30 m,多期叠置可达近150 m;岩心上表现为灰白色、灰色细砂岩与暗色泥页岩互层(图4)。粒度累计概率曲线以两段式或三段式为主,跳跃次总体含量高,约70%,悬浮组分含量低,一般小于20%,表明原始沉积物为推移负载,细截点 $\phi$ 值较大,介于3~4,悬浮组分多为极细砂—泥级颗粒。在

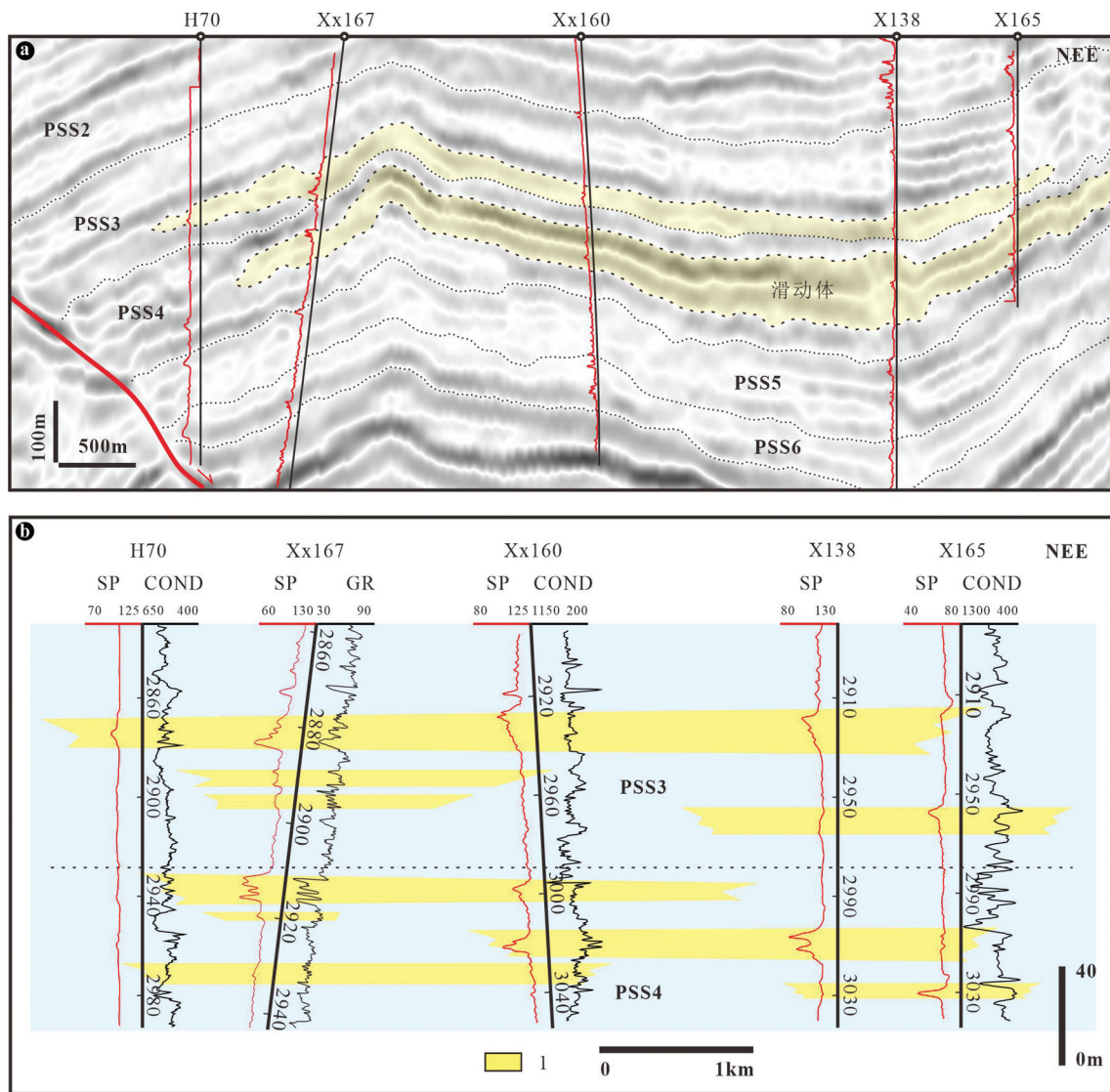


图4 东营凹陷沙三中亚段滑动体垂直物源地震剖面解释及砂岩分布(剖面位置见图1)

图a中钻井旁红色曲线为自然电位测井曲线;SP—自然电位测井;GR—伽马测井;COND—感应测井;PSS—准层序组;1—砂质滑动体  
Fig.4 Seismic facies of slide in the vertical direction of source and sand distribution in the Es<sub>3</sub><sup>m</sup> in the Dongying Depression (see location in Fig.1)

Logging curves (red) in Fig.4a indicate spontaneous potential well-logs; SP- spontaneous potential logging; GR-Gamma ray logging; COND- Induction-conductivity logging; PSS-Parasequence set; 1-Sand slides



均方根平面振幅属性图中表现为深湖弱振幅背景下的局部强振幅区域,与泥岩边界较为清晰,其分布往往受到断层控制,出现在活动断层的下降盘,单个滑动体面积一般不超过20 km<sup>2</sup>。

#### 4.2.2 滑塌体

滑动体继续搬运,液化变形,原始沉积结构遭受破坏,形成滑塌体。在研究区发育砂质滑塌体和泥质滑塌体两种类型,它们具有相似的形成机制,区别在于发生失稳滑塌的初始沉积物粒度不同。滑塌体地震剖面为中等—弱振幅反射强度,呈丘状外形、内部杂乱或空白反射,垂向多期叠置可厚达近200 m;岩相构成主要以变形层理砂岩或变形层理泥岩为主,发育变形层理、包卷层理等同沉积变形构造;GR测井曲线响应类型多样,可呈漏斗形、钟形或齿状(图5);平面均方根振幅属性图中,滑塌体与周围弱振幅湖相泥岩边界较清楚,平面上分布在生长断层下降盘,其面积不等,一般为数平方米至小于25 km<sup>2</sup>。

#### 4.2.3 碎屑流水道

碎屑流水道是本区深水体系沉积物搬运的重要通道,同时也是重要的深水沉积单元和储层发育类型。研究区碎屑流水道主体由碎屑流沉积构成,

平面上呈弯曲条带状形态,依据水道内部充填类型又可进一步划分为砂质碎屑流水道和泥质碎屑流水道。砂质碎屑流水道内部岩相类型主要包括洁净块状砂岩和含漂砾块状砂岩(图2d、e),泥质碎屑流水道岩相类型主要为含漂砾泥质砂岩(图2f);在地震剖面上,水道呈近于顶平底凸状反射,水道带宽度一般小于3 km,厚度小于40 m,延伸可超过10 km;自然电位曲线上,砂质碎屑流水道以钟形或箱形为主,泥质碎屑流水道多呈齿状或指状特征;水道内部多期碎屑流往往相互切割叠置,常见砂岩融合界面(图6)。总体上,同一时期,靠近三角洲前缘的斜坡带,水道由砂质碎屑流主导,随着向湖盆中心推进,水道中的泥质含量逐渐增多,发育泥质碎屑流水道。

地震均方根振幅属性切片及钻井标定表明,碎屑流水道内砂岩的分布并不均匀,水道内发育“分散状”砂体,这一特征可作为碎屑流水道的典型标志。根据前人的碎屑流沉积模拟实验(Mohrig et al., 1998),具有一定基质强度的碎屑流在搬运过程中易于产生“滑水”效应,导致碎屑流流体头部抬高,与底部水体之间形成一层水膜,有效地减小了底床摩擦阻力,碎屑流便在重力的作用下在这层水

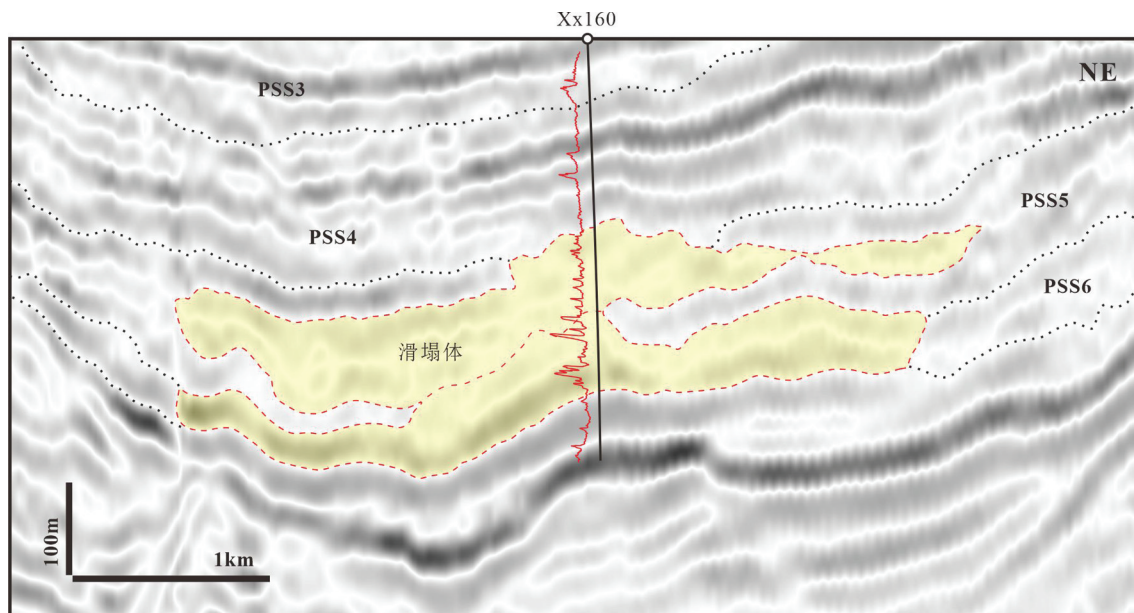


图5 东营凹陷沙三中亚段滑塌体地震反射剖面解释(剖面位置见图1)

注:井旁为自然电位测井曲线;PSS—准层序组

Fig.5 Seismic facies of slump in the Es<sub>3</sub><sup>m</sup> (see location in Fig. 1)

Note that logging curves in Fig.5 indicate spontaneous potential well-logs; PSS—Parasequence set

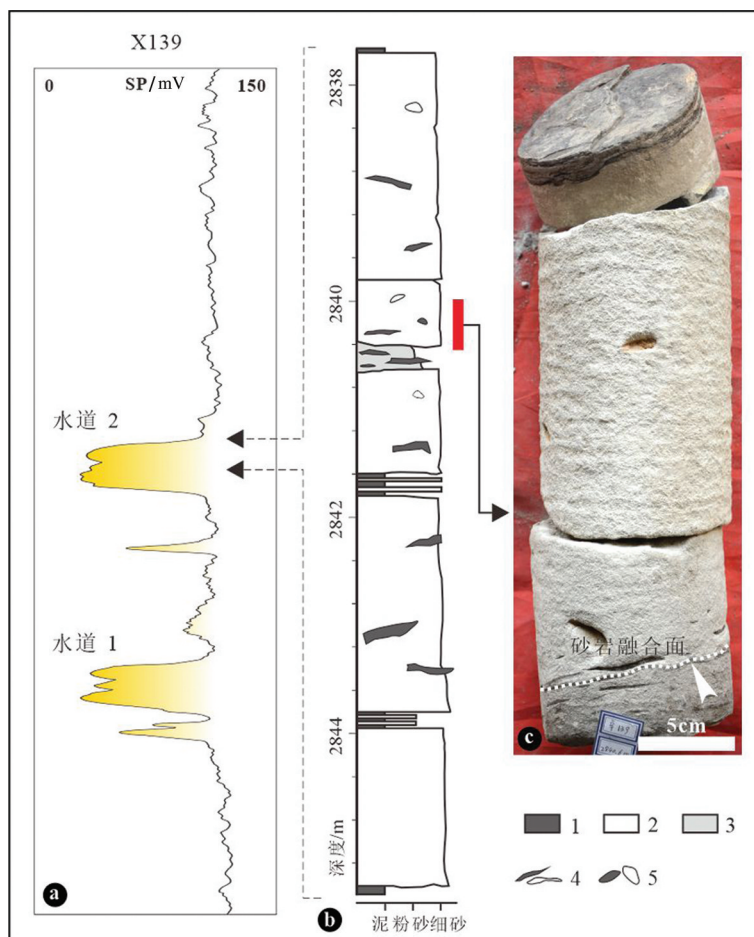


图6 X139井沙中亚段砂质碎屑流水道沉积特征

a—X139井碎屑流水道自然电位测井曲线特征,SP—自然电位测井;b—水道岩心柱状图;c—水道中块状砂岩沉积  
1—泥岩;2—砂岩;3—泥质砂岩;4—泥/砂撕裂屑;5—泥/砂砾石

Fig.6 Depositional characteristics of sandy debris flow channel in Well X139 in the Es<sub>3</sub><sup>m</sup>

a—Spontaneous potential well-log of debris flow channel in Well X139, SP—Spontaneous potential logging; b—Core description of debris flow channel; c—Massive sandstones in debris flow channel; 1—Mudstone; 2—Sandstone; 3—Muddy sandstone; 4—Mud/sand rip ups; 5—Mud/sand pebbles

膜之上加速流动。由于流体头部速度最大,因而流体头部往往易与流体尾部分离,从而导致流体裂解,分离的头部继续搬运一段距离发生沉积,新的流体头部持续形成,不断裂解。因此在碎屑流水道中,随着碎屑流向前搬运,经过“滑水”(Mohrig et al., 1998)、加速、流体头部裂解、“冻结式”沉积,新的流体头部再次形成,如此反复,最终形成“分散状”砂体(Ilstad et al., 2004)。

#### 4.2.4 碎屑流朵体

碎屑流朵体是另一类碎屑流沉积单元,在碎屑流水道末端,由于流体能量消耗和衰减,碎屑流发生整体卸载,形成朵状体。在研究区,碎屑流朵体沉积规模不等,其面积一般为数平方千米至小于30

km<sup>2</sup>,单个朵体厚度可达35 m左右,宽度及长度可达5 km及7 km,长宽比1.2~1.5。测得碎屑流朵体的纵横比较低,一般约150:1(宽度/最大厚度),这一数值仅相当于前人统计的海底浊积朵体纵横比(约1000:1)(Prelat et al., 2010; Koo et al., 2016)的1/6,指示了碎屑流的块体搬运和“冻结式”沉积过程,可作为碎屑流朵体的辨别参数之一。基于取心、测井和地震综合分析,可将碎屑流朵体进一步细分为砂质碎屑流朵体和泥质碎屑流朵体。碎屑流朵体的岩相类型主要包括洁净块状砂岩、含漂砾块状砂岩、含漂砾泥质砂岩以及少量浊流或泥流成因的正递变砂岩、波纹交错层理砂岩或含漂砾块状泥岩;单个朵体由多期碎屑流叠置而成,每期碎屑流沉积

厚约0.5 m,不同期次之间通过弱冲刷接触;在测井响应上,朵体一般呈反韵律或箱状特征;在振幅剖面上,由于地震垂向分辨率限制,碎屑流朵体一般包含在单个强振幅反射同相轴内部,难以识别典型的丘状反射特征(图7,图8)。

4.2.5 浊积薄层砂

浊积薄层砂分布于深水体系的最末端,一般发育在碎屑流朵体前端、侧缘或水道两侧,主要由水道末端碎屑流逐步稀释,形成低密度浊流沉积形成,或是水道拐弯处上部低浓度流体溢岸而成。浊积薄层

砂地震振幅表现为中等—强振幅,其平面范围可与同期碎屑流朵体相当(图8),主要由低密度浊流成因的灰白色、灰色薄层正递变(粉细)砂岩与深湖暗色泥岩反复互层,构成韵律层;测井齿化特征明显,垂向厚度很薄,单期一般小于20 cm(图2h)。

4.3 深水沉积展布及演化

基于地震切片平面属性分析,结合三角洲—深水沉积体系连井精细对比,对沙三中亚段滑塌重力流沉积的平面展布、结构组合及演化过程开展研究。均方根振幅切片显示,沙三中亚段各深水结构

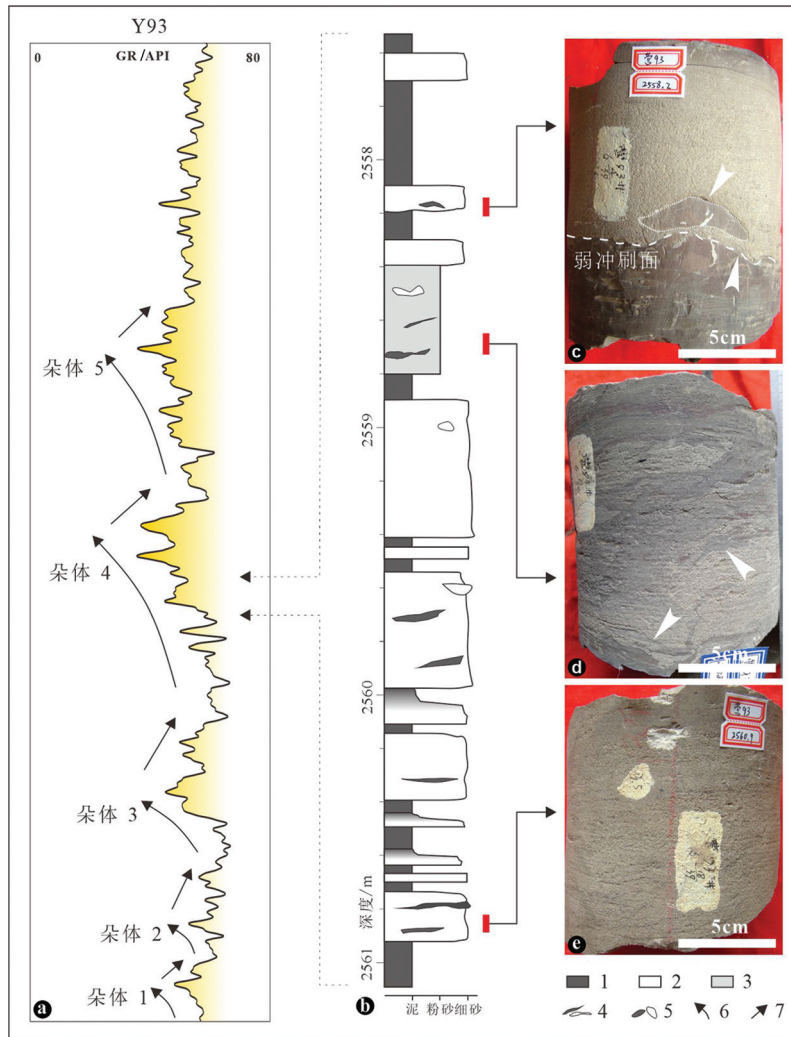


图7 Y93井沙三中亚段碎屑流朵体沉积特征

a—Y93井碎屑流朵体伽马测井曲线特征,GR—伽马测井;b—朵体岩心柱状图;c—朵体中冲刷面及含漂砾块状砂岩沉积;d—朵体中含漂砾块状泥质砂岩沉积;e—朵体中洁净块状砂岩沉积;1—泥岩;2—砂岩;3—泥质砂岩;4—泥/砂撕裂屑;5—泥/砂砾石;6—朵体前积;7—朵体退积

Fig.7 Depositional characteristics of sandy debris flow lobe in Well Y93 in the Es<sub>3</sub><sup>m</sup>

a—GR logging responses of debris flow lobe in Well Y93, GR—Gamma ray logging; b—Core description of debris flow lobe; c—Erosive surface and sandstones with floating clasts in debris flow lobe; d—Massive muddy sandstones with floating clasts in debris flow lobe; e—Clean massive sandstones in debris flow lobe;1—Mudstone; 2—Sandstone; 3—Muddy sandstone; 4—Mud/sand rip ups; 5—Mud/sand pebbles; 6—Lobe progradation; 7—Lobe retrogradation

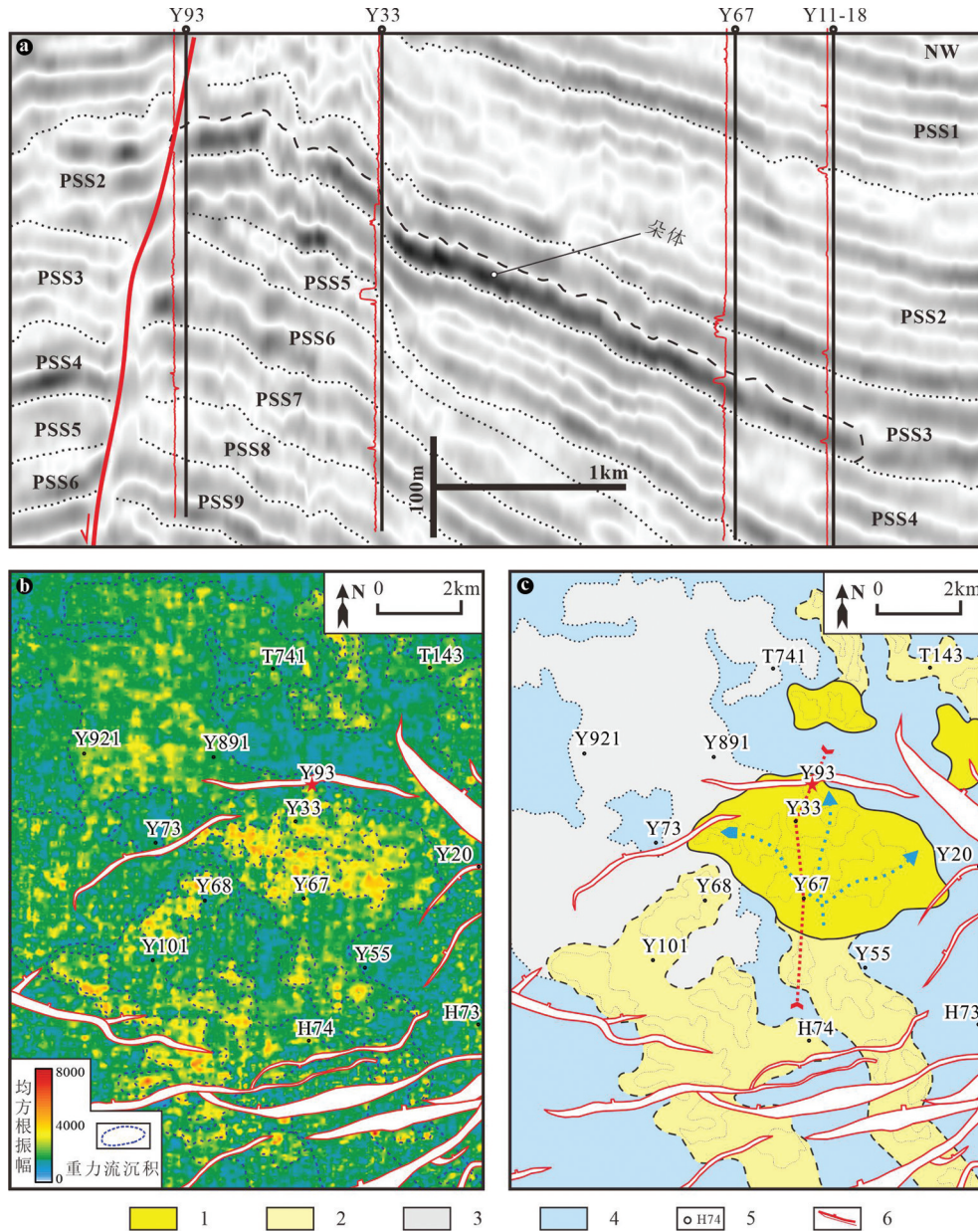


图8 沙三中亚段碎屑流朵体沉积特征

a—朵体地震反射剖面;b—碎屑流朵体地震均方根振幅属性切片;c—沉积解释;  
1—碎屑流朵体;2—碎屑流水道;3—浊积薄层砂;4—深湖;5—井位;6—断层;PSS—准层序组

Fig.8 Depositional characteristics of sandy debris flow lobe in the Es<sub>3</sub><sup>m</sup>

a—Seismic profile of debris flow lobe; b—RMS seismic amplitude slice of debris flow lobe; c—Sedimentary interpretation;  
1—Debrite lobe; 2—Debrite channel; 3—Turbidite sheet; 4—Deep lake; 5—Well location; 6—Fault; PSS—Parasequence set

单元在平面上呈现有规律的组合,且很大程度上受断层活动控制。滑动、滑塌等块体分布于靠近物源一侧,平面上主要分布在断层的下降盘;碎屑流水道向前延伸,平面上断层的结合部位或断距减小部位往往成为碎屑流搬运的优势通道;水道末端发育强振幅、分布较广的碎屑流朵体;朵体边缘,发育低

密度浊流沉积,形成中、强振幅,薄层状的浊积砂岩,此外,在水道侧缘拐弯处,由于流体漫溢也容易形成浊积薄层砂沉积(图9)。

前人研究表明,沙三中亚段为一个三级层序,以高位域大规模三角洲进积为特征(邱桂强等, 2001)。连井剖面揭示沙三中亚段滑塌重力流沉积

体系的空间分布主要受控于东营三角洲的逐期前积。沙三中亚段可划分出六期主要的三角洲-重力流前积单元,分别对应于6个准层序组(十万年尺度),伴随着东营三角洲自东南向西北快速推进以及沙三中湖盆的充填萎缩,深水重力流水道-朵体的分布范围也由牛庄凹陷向西北逐渐延伸至利津凹陷(图10)。

## 5 深水沉积动力过程及沉积模式

### 5.1 深水沉积主控因素

自然环境中,滑塌重力流的形成需要具备两个前提条件,首先是充足的原始沉积物,其次需要存在导致原始沉积物产生失稳滑塌的触发因素。在研究区,东营三角洲是重力流发育的主要物源供给,前人研究表明,东营三角洲在4 Myr时间里向西北方向推进了80 km,平均前积速率达200 m/万年,而垂向加积速率仅3 m/万年,在三角洲的发育过程中,沉积物通量达到了 $1.59 \times 10^{11} \text{ m}^3$ (Li, 2005),在沙三中亚段不到2 Myr的时间跨度中,三角洲推进了

约40 km(邱桂强等,2001)。充足的沉积物供给、较低的加积速率和快速的前积速率,导致了三角洲前缘极高的堆积速率,为滑塌重力流的形成奠定了物质基础。此外,过高的堆积速率不利于沉积物的充分压实,增加了沉积物失稳的可能。构造活动被认为是促进重力流形成的第二个重要因素。东营凹陷沙三中时期处于裂陷鼎盛阶段,盆地构造沉降速率高达300~500 m/a(Feng et al., 2013)。平面上,重力流沉积与断层的良好匹配关系指示了断层相关的构造活动对重力流分布的影响。活动断层除了改变局部地貌,形成新的沉积物输送优势通道及可容纳空间(Gawthorpe and Leeder, 2000; 林畅松等, 2000),还是触发斜坡失稳垮塌的直接因素。因此三角洲前缘的高沉积速率及活跃的构造运动被认为是这一时期重力流形成发育的主要机制。

### 5.2 沉积搬运动力过程

由于深水环境实地观测及实验模拟的困难,深水沉积流体过程一直是重力流领域讨论的热点(Shanmugam et al., 1994; Shanmugam, 1996; Mohrig

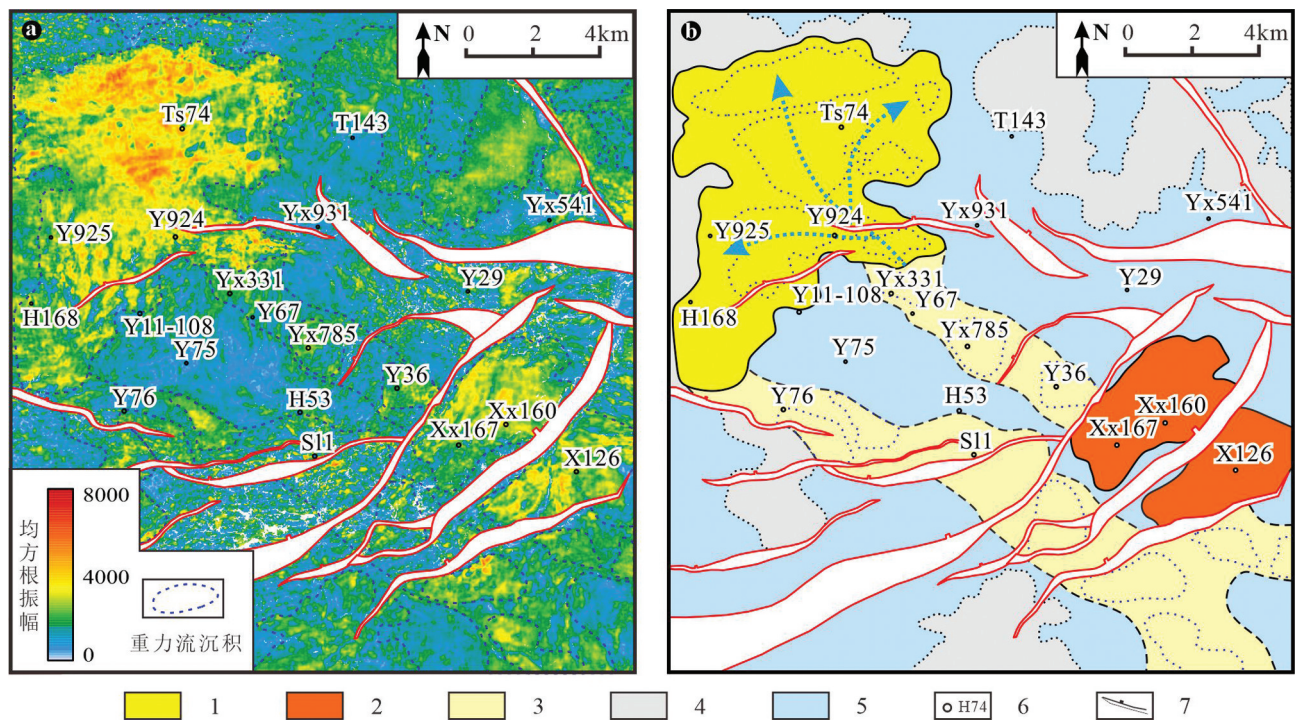


图9 东营凹陷沙三中亚段重力流沉积地震切片及相解释

a—地震均方根振幅属性切片;b—沉积解释;1—碎屑流朵体;2—滑动物体;3—碎屑流水道;4—浊积薄层砂;5—深湖;6—井位;7—断层

Fig.9 Seismic slicing and facies interpretation of gravity flow deposits in the Es<sub>3</sub><sup>m</sup> in the Dongying Depression

a—RMS amplitude seismic slice; b—Sedimentary interpretation; 1—Debrite lobe; 2—Slides; 3—Debrite channel; 4—Turbidite sheet; 5—Deep lake; 6—Well location; 7—Fault

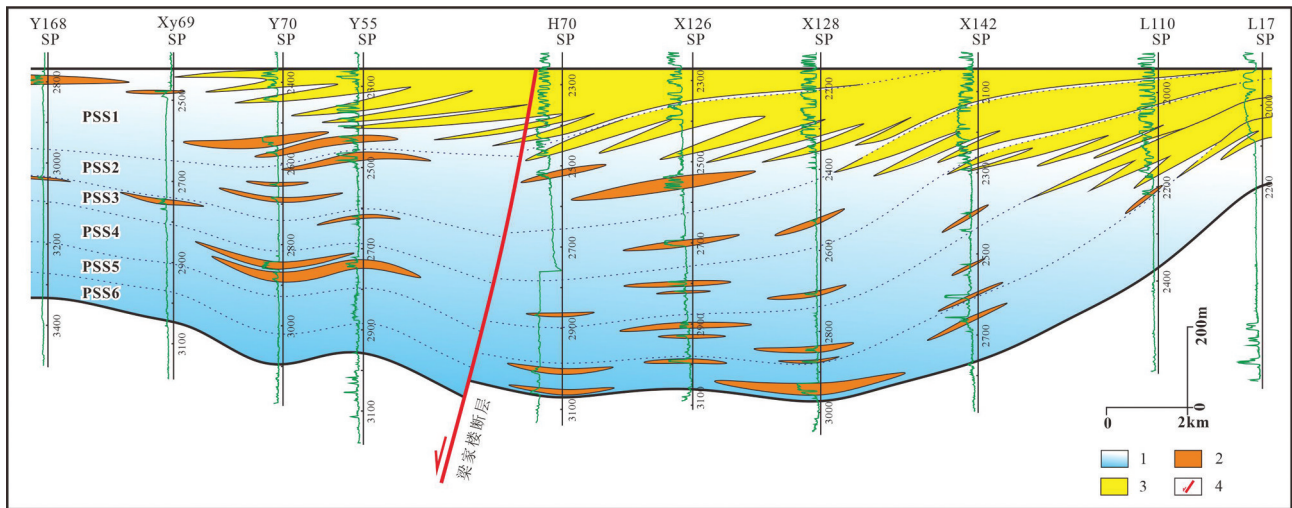


图 10 东营凹陷沙三中亚段连井对比及重力流沉积分布特征

井旁为自然电位测井曲线,SP-自然电位测井;1-湖相;2-重力流沉积;3-三角洲;4-断层

Fig. 10 Correlation section along the supply direction and gravity flow deposits distribution in the Es<sub>3</sub><sup>m</sup> in the Dongying Depression Logging curves in Fig.10 indicate spontaneous potential well-logs, SP-Spontaneous potential logging;1-Lake; 2-Gravity flow deposits; 3-Delta; 4-Fault

et al., 1998; Haughton et al., 2009; Felix et al., 2009; Kane and Ponten, 2012; Zou et al., 2012; 鲜本忠等, 2014, 2016; 李华等, 2022)。基于岩心观察及描述, 研究区发育 4 种沉积类型, 分别是滑动、滑塌、碎屑流及浊流沉积。前人基于现代、古代沉积记录 (Shanmugam et al., 1994; Piper et al., 1999; Sohn et al., 2002; Talling et al., 2012; 鲜本忠等, 2016; Yang et al., 2019; 操应长等, 2021) 及实验模拟 (Mohrig et al., 1998; Felix et al., 2009), 认为在滑塌型重力流沉积过程中, 随着搬运距离增加和流体稀释, 存在滑动、滑塌向碎屑流和浊流的流态转变。进一步, 对本区重力流沉积过程开展分析, 认为存在以下两大特点: 首先, 岩相定量统计表明 (图 3), 研究区重力流主要以碎屑流为主导, 而浊流很少。这可能受控于研究区重力流有限的搬运距离。在研究区, 从三角洲前缘至深水沉积区, 距离一般不超过 20 km, 很可能导致碎屑流向浊流的转化并不充分。这与中国东部断陷湖盆的地貌结构有关, 多级断裂控制了多个沉积中心和深水区的发育, 重力流很难跨过不同深水区分进行长距离搬运, 而在海相盆地或坳陷型盆地中, 重力流普遍经过数百至上千千米的搬运 (Talling et al., 2007)。此外, 碎屑流向浊流的转换过程可能存在更细微的流态变化。前人研究表明, 海底高密度浊流在搬运过程中可以通过增大自身黏

土含量, 向泥质碎屑流转化 (Haughton et al., 2009; Kane and Ponten, 2012)。在研究区, 块状砂岩的无粒序结构及漂浮的大块砾石、泥岩碎屑, 难以解释为能量逐级递减的浊流沉积, 更能够代表碎屑流的块体搬运与“冻结式”沉积 (Enos, 1977; Shanmugam et al., 1994), 在本文中解释为砂质碎屑流。砂质碎屑流由于具有较低的泥质含量和较高的渗透性, 在搬运过程中, 难以在流体底部形成有效的隔水层 (Mulder and Alexander, 2001; Sohn et al., 2002), 更容易侵蚀并破坏底床, 从而捕获泥质, 增大自身泥质含量。含漂砾块状砂岩中的暗色泥岩基质、泥砾或泥岩撕裂屑是捕获底床泥质的有力证据 (图 2e、f)。随着泥质含量增高, 形成的泥质碎屑流具有更高的基质强度, 降低了流体-底床界面的摩擦阻力, 其侵蚀能力减弱, 向前“滑水”加速过程中, 流体头部流速过大, 将快速裂解、稀释向浊流转化。当三角洲斜坡失稳物质主要为泥质沉积物时, 由于泥质的高含水性, 不易形成并保存泥质滑动, 主要发育泥质滑塌, 泥质滑塌向前搬运、液化, 最终向泥流转化。

### 5.3 沉积模式与油气意义

基于东营凹陷沙三中亚段重力流沉积岩相特征、沉积成因、流体过程、沉积结构及储层特点分析, 综合建立了碎屑流主控型深水体系的沉积模式 (图 11)。该模式强调了流体过程、物源供给及构造

活动对沉积响应及油气储层分布的控制作用。在高沉积速率和构造活动背景下、滑塌作用主导的三角洲前缘斜坡环境中,重力流的发育过程主要经过了滑动、滑塌、砂质碎屑流、泥质碎屑流等块体搬运过程及浊流等流体搬运过程,可概括为3种主要的沉积响应模型(a~c)。第一种代表了三角洲斜坡上的泥质失稳,形成泥质滑塌和泥流沉积(a)。由于泥质块体的高含水特性,将很难保存初始结构并形成泥质滑动体。其余两种代表砂质滑塌体系,重力流既可以长距离完整搬运,发育砂质滑动体、滑塌体、砂质碎屑流水道、泥质碎屑流水道及泥质碎屑流朵体(b);也可短距离搬运发育砂质滑动体、滑塌体、砂质碎屑流水道及砂质碎屑流朵体(c)。在研究区,有限的搬运距离使得砂质碎屑流向泥质碎屑流和浊流的转化并不充分,形成整体上以砂质碎屑流为主导的深水体系;断层活动导致的微地貌改变,控制了重力流沉积的平面分布,活动断层下降盘,断层转换斜坡及断距减小部位是重力流沉积储层的有利发育区(图11)。

从发育规模和储集物性上,砂质碎屑流成因的块状砂岩分选好、泥质杂基含量低、发育广泛,构成了研究区重力流的主导沉积类型和优质的深水储层类型,滑动砂岩由于基本保存了三角洲前缘砂的

结构特征,也具有较好的储集性能。这些深水砂岩上、下均被深水暗色泥岩包裹,成藏条件优越,易形成自生自储油气藏,因此砂质碎屑流水道-朵体及砂质滑动体很可能构成了碎屑流主控型深水体系油气勘探的主要目标。值得注意的是,砂质碎屑流由于其典型的“冻结式”沉积特征,其朵体相较于海底浊积朵体往往具有更低的横纵比,其砂体侧向相变或尖灭快,易形成单个面积较小,但厚度相对较大、较均质的油气储集体。泥质碎屑流水道-朵体、泥质滑塌体、泥流及浊积薄层砂由于储集物性差或者规模小,难以形成优质的油气储层。

## 6 结 论

(1)湖相深水盆地可发育碎屑流主控型深水体系。东营凹陷碎屑流主控型深水体系发育4种异地搬运沉积类型,分别是滑动沉积、滑塌沉积、碎屑流沉积及浊积岩,其中滑塌沉积包括砂质和泥质滑塌沉积,碎屑流沉积包括砂质碎屑流、泥质碎屑流和泥流沉积。识别出9种具体的岩相类型,岩相厚度定量统计表明,沙三中亚段重力流沉积以碎屑流为主导,约占82%,且碎屑流中以砂质碎屑流为主,占比约52%。

(2)碎屑流主控型深水体系的沉积过程经过滑

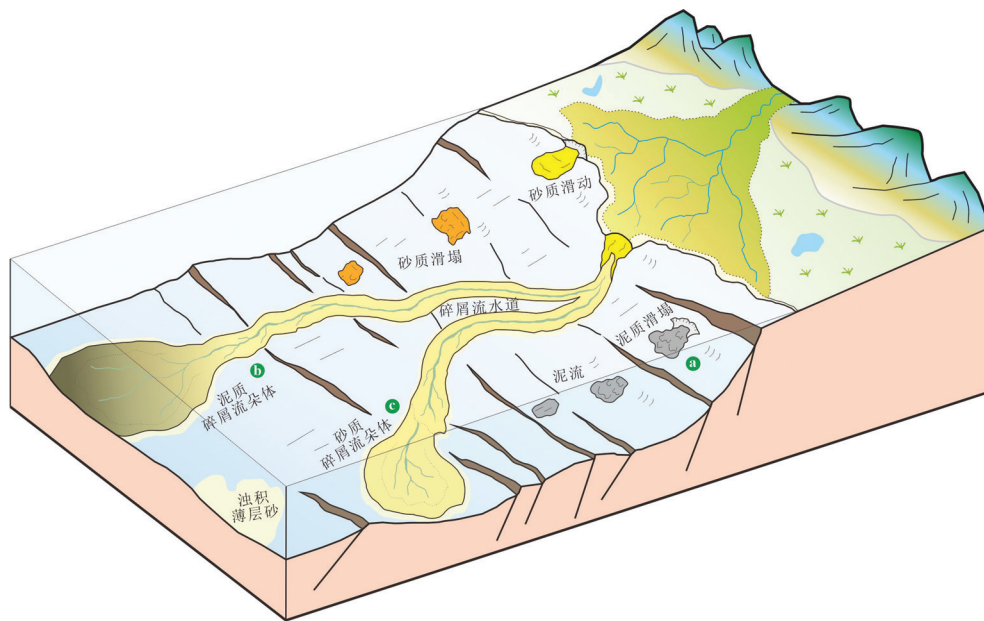


图11 东营凹陷始新统沙三中亚段碎屑流主控型深水体系沉积模式

Fig.11 Depositional model of debris dominated deep-water system in the Es<sub>3</sub><sup>m</sup> of the Eocene Dongying Depression

动、滑塌、砂质碎屑流、泥质碎屑流、浊流等5大流体演变。强调碎屑流向浊流转换过程中存在由砂质碎屑流向泥质碎屑流、最终再向浊流的逐步转化。对湖底/海底底床泥质的侵蚀、捕获及掺混,是砂质碎屑流向泥质碎屑流转化的重要机制。当原始滑坡物质以泥质为主时,则主要发生泥质滑塌向泥流的转化。

(3)碎屑流主控型深水体系发育滑动体、滑塌体、碎屑流水道、碎屑流朵体及浊积薄层砂等5类深水沉积单元。其中滑塌体包括砂质或泥质滑塌体,水道和朵体可分别划分出砂质碎屑流或泥质碎屑流为主导的类型。综合储集性能和发育规模,砂质碎屑流水道、朵体及砂质滑动体是优质的深水储层发育类型。

(4)沉积物供给、构造活动及搬运距离共同控制了碎屑流主控型深水体系的发育及演化。多期三角洲快速前积背景下三角洲前缘的高沉积速率为重力流形成提供了物质条件,裂隙期频繁的断层活动是三角洲斜坡沉积物垮塌的重要触发因素及砂体分布的主控因素,较短的搬运距离是流体转换不充分的主要原因。

## References

- Cao Yingchang, Jin Jiehua, Liu Haining, Yang Tian, Liu Keyu, Wang Yanzhong, Wang Jian, Liang Chao. 2021. Deep-water gravity flow deposits in a lacustrine rift basin and their oil and gas geological significance in eastern China[J]. *Petroleum Exploration and Development*, 48(2): 247–257(in Chinese with English abstract).
- Cao Yingchang, Zhang Qingqing, Wang Yanzhong, Yang Tian, Wang Xinyi, Xue Xiujie. 2017. Delta front gravity flow deposits in the middle submember of the third member of the Shahejie Formation in the Dongying depression: Lithofacies and lithofacies association types and their distribution[J]. *Sedimentary Geology and Tethyan Geology*, 37(1): 9–17.
- Clare M A, Talling P J, Challenor P, Malgesini G, Hunt J. 2014. Distal turbidites reveal a common distribution for large (>0.1 km<sup>3</sup>) submarine landslide recurrence[J]. *Geology*, 42(3): 263–266.
- Dott Jr R H. 1963. Dynamics of subaqueous gravity depositional processes[J]. *AAPG Bulletin*, 47(1): 104–128.
- Enos P. 1977. Flow regimes in debris flow[J]. *Sedimentology*, 24(1): 133–142.
- Fan Daidu, Qiu Guiqiang, Li Congxian, Cong Youzi, Yang Jizeng. 2000. Paleocurrent properties of Dongying Delta in Bohai Bay Basin[J]. *Acta Petrolei Sinica*, 21(1): 29–33 (in Chinese with English abstract).
- Felix M, Leszczynski S, Slaczka A, Uchman A, Amy L, Peakall J. 2009. Field expressions of the transformation of debris flows into turbidity currents, with examples from the Polish Carpathians and the French Maritime Alps[J]. *Marine and Petroleum Geology*, 26(10): 2011–2020.
- Feng Youliang, Li Sitian, Lu Yongchao. 2013. Sequence stratigraphy and architectural variability in late Eocene lacustrine strata of the Dongying Depression, Bohai Bay Basin, eastern China[J]. *Sedimentary Geology*, 295: 1–26.
- Gao Hongfang, Zhong Hexian, Sun Meijing, Nie Xin, Jiang Tao, Huang Wenkai, Du Wenbo, Chen Jiale. 2020. The large deep-water turbidity fan system in southeastern South China Sea Basin: Formation and tectonic constraint[J]. *Geology in China*, 47(5): 1395–1406(in Chinese with English abstract).
- Gawthorpe R L, Leeder M R. 2000. Tectono-sedimentary evolution of active extensional basins[J]. *Basin Research*, 12(3/4): 195–218.
- Houghton P, Davis C, Mccaffrey W, Barker, S. 2009. Hybrid sediment gravity flow deposits— Classification, origin and significance[J]. *Marine and Petroleum Geology*, 26(10): 1900–1918.
- Ilstad T, Elverhøi A, Issler D. 2004. Subaqueous debris flow behaviour and its dependence on the sand/clay ratio: a laboratory study using particle tracking[J]. *Marine Geology*, 213(1/4): 415–438.
- Iverson R M. 1997. The physics of debris flows[J]. *Reviews of Geophysics*, 35(3): 245–296.
- Kane I A, Ponten A S. 2012. Submarine transitional flow deposits in the Paleogene Gulf of Mexico[J]. *Geology*, 40(12): 1119–1122.
- Koo W M, Olariu C, Steel R J, Olariu M I, Carvajal C R, Kim W. 2016. Coupling between shelf-edge architecture and submarine-fan growth style in a supply dominated margin[J]. *Journal of Sedimentary Research*, 86(6): 613–628.
- Kuenen P H, Migliorini C I. 1950. Turbidity currents as a cause of graded bedding[J]. *Journal of Geology*, 58(2): 91–127.
- Lei Zhenyu, Zhang Li, Su Ming, Luo Shuaibing, Qian Xing, Shuai Qingwei, Zhang Boda. 2017. Middle Miocene deep-water sediments in the Beikang Basin, Southern South China Sea: Types, characteristics and implications[J]. *Marine Geology & Quaternary Geology*, 37(6): 110–118(in Chinese with English abstract).
- Li Chenyi. 2005. Study on the Forming Mechanism of the Slumped Turbidite and the Controlling Sandbody Model of High Frequency Base-Level Cycle of Dongying Deltas[D]. Beijing: China University of Geoscience (Beijing), 1–126.
- Li Hua, He Mingwei, Qiu ChunGuang, Wang Yingmin, He Youbin, Xu Yanxia, He Ruiwu. 2022. Research processes on deep-water interaction between contour current and gravity flow deposits, 2000 to 2022[J/OL]. *Acta Sedimentologica Sinica*. DOI:10.14027/j.issn.1000-0550.2022.027.
- Li Xiangbo, Liu Huaqing, Wanyan Rong, Wei Lihua, Liao Jianbo, Ma Yuhu. 2009. First discovery of the sandy debris flow from the



- Triassic Yanchang Formation, Ordos Basin[J]. *Lithologic Reservoirs*, 21(4): 19–21 (in Chinese with English abstract).
- Lin Changsong, Pan Yuanlin, Xiao Jianxin, Kong Fanxian, Liu Jingyan, Zhen Herong. 2000. Structural slope\_break zone: Key concept for stratigraphic sequence analysis and petroleum forecasting in fault subsidence basins[J]. *Earth Science—Journal of China University of Geosciences*, 25(3): 42–48 (in Chinese with English abstract).
- Liu Jianping, Xian Benzong, Wang Lu, Lu Zhiyong, Li Yuzhi, Liu Saijun, Jiang Jian. 2016. Seismic sedimentology of delta-fed turbidites of the Eocene in Dongying Sag, Bohai Bay Basin[J]. *Journal of Palaeogeography*, 18(6): 961–975 (in Chinese with English abstract).
- Middleton G V, Hampton M A. 1976. Subaqueous sediment transport and deposition by sediment gravity flows[C]//Stanley DJ, Swift D J P(eds.). *Marine Sediment Transport and Environmental Management*. New York: Wiley, 197–218.
- Middleton G V, Hampton M A. 1977. Sediment gravity flows: Mechanics of flow and deposition[C]// Middleton G V, Bouma A H. *Turbidites and Deep-Water Sedimentation*. Anaheim: SEPM, California Short Course Notes, 1973: 38.
- Mohrig D, Ellis C, Parker G, Whipple K X, Hondzo M. 1998. Hydroplaning of subaqueous debris flows[J]. *Geological Society of America Bulletin*, 110(3): 387–394.
- Mulder T, Alexander A. 2001. The physical character of subaqueous sedimentary density flows and their deposits[J]. *Sedimentology*, 48(2): 269–299.
- Mulder T, Syvitski J P, Migeon S, Faugères J C, Savoye B. 2003. Marine hyperpycnal flows: Initiation, behavior and related deposits. A review[J]. *Marine and Petroleum Geology*, 20(6/8): 861–882.
- Mutti E, Bernoulli D, Lucchi F R, Tinterri R. 2009. Turbidites and turbidity currents from Alpine ‘flysch’ to the exploration of continental margins[J]. *Sedimentology*, 56(1): 267–318.
- Normark W R. 1970. Growth patterns of deep-sea fans[J]. *AAPG Bulletin*, 54(11): 2170–2195.
- Piper D J W, Cochonat P, Morrison M L. 1999. The sequence of events around the epicentre of the 1929 Grand Banks earthquake: Initiation of debris flows and turbidity current inferred from sidescan sonar[J]. *Sedimentology*, 46(1): 79–97.
- Piper D J W, Normark W R. 2001. Sandy fans— from Amazon to Hueneme and beyond[J]. *AAPG Bulletin*, 85(8): 1407–1438.
- Postma G, Cartigny M J. 2014. Supercritical and subcritical turbidity currents and their deposits—A synthesis[J]. *Geology*, 42(11): 987–990.
- Prelat A, Covault J A, Hodgson D M, Fildani A, Flint S S. 2010. Intrinsic controls on the range of volumes, morphologies, and dimensions of submarine lobes[J]. *Sedimentary Geology*, 232(1/2): 66–76.
- Qiu Guiqiang, Wang Jufeng, Zhang Xin, Li Congxian. 2001. Preliminary study on stratigraphic architecture of middle-Shasan Dongying Delta and its significance to hydrocarbon exploration[J]. *Acta Sedimentologica Sinica*, 19(4): 569–574 (in Chinese with English abstract).
- Shanmugam G. 1996. High-density turbidity currents: Are they sandy debris flows?[J]. *Journal of Sedimentary Research*, 66(1): 2–10.
- Shanmugam G. 2000. 50 years of the turbidite paradigm (1950s–1990s): Deep-water processes and facies models— a critical perspective[J]. *Marine and Petroleum Geology*, 17(2): 285–342.
- Shanmugam G. 2013. New perspectives on deep-water sandstones: Implications[J]. *Petroleum Exploration and Development*, 40(3): 294–301.
- Shanmugam G, Lehtonen L R, Straume T, Syvertsen S E, Hodgkinson R J, Skibeli M. 1994. Slump and debris-flow dominated upper slope facies in the Cretaceous of the Norwegian and northern North Seas (61–67 N): Implications for sand distribution[J]. *AAPG Bulletin*, 78(6): 910–937.
- Sohn Y K, Choe M Y, Jo H R. 2002. Transition from debris flow to hyperconcentrated flow in a submarine channel (the Cretaceous Cerro Toro Formation, southern Chile) [J]. *Terra Nova*, 14(5): 405–415.
- Song Mingshui, Xiang Kui, Zhang Yu, Cai Pan, Liu Jianlei, Yang Renchao. 2017. Research progresses on muddy gravity flow deposits and their significances on shale oil and gas: A case study from the 3<sup>rd</sup> oil-member of the Paleogene Shahejie Formation in the Dongying Sag[J]. *Acta Sedimentologica Sinica*, 35(4): 740–751.
- Steel R J, Milliken K L. 2013. Major advances in siliciclastic sedimentary geology, 1960–2012[J]. *The Web of Geological Sciences: Advances, Impacts, and Interactions*. Geological Society of America, Special Papers 500: 121–166.
- Stow D A V, Johansson M. 2000. Deep-water massive sands: Nature, origin and hydrocarbon implications[J]. *Marine and Petroleum Geology*, 17(2): 145–174.
- Talling P J, Masson D G, Sumner E J, Malgesini G. 2012. Subaqueous sediment density flows: Depositional processes and deposit types[J]. *Sedimentology*, 59(7): 1937–2003.
- Talling P J, Wynn R B, Masson D G, Frenz M, Cronin B T, Schiebel R, Akhmetzhanov A M, Dallmeier-Tiessen S, Benetti S, Weaver P P E, Georgiopoulou A, Zühlsdorff C, Amy L A. 2007. Onset of submarine debris flow deposition far from original giant landslide[J]. *Nature*, 450(7169): 541–544.
- Talling P J. 2014. On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings[J]. *Marine Geology*, 352: 155–182.
- Tan Mingxuan, Zhu Xiaomin, Liu Wei, Shi Ruisheng. 2017. The morphodynamics of cyclic steps and sedimentary characteristics of associated deposits[J]. *Geological Review*, 63(06): 1512–1522(in

- Chinese with English abstract).
- Wang Jiahao, Wang Hua, Xiao Dunqing, Pu Xiugang, Han Wenzhong, Zhang Wei. 2020. Differentiation between hyperpycnal flow deposition and slump-induced gravity flow deposition in terrestrial rifted lacustrine basin[J]. *Acta Petroli Sinica*, 41(04): 392–402,411 (in Chinese with English abstract).
- Wang Xingxing, Wang Yingmin, Gao Shengmei, Mao Peixiao, Zhuo Haiteng, Wang Minghan, Zhou Jiawei. 2018. Advancements of the deep-water gravity flow simulations and their implications for exploitation of marine petroleum [J]. *Journal of China University of Mining & Technology*, 47(3): 588–602(in Chinese with English abstract).
- Wang Wei, Jiang Youlu, Li Ruilei, Zhu Jianfeng, Zhao Honghao. 2018. Genetic types and characteristic research on deep-water gravity flows of Yingcheng Formation in Longfengshan subsag, Changling Depression[J]. *Journal of China University of Petroleum (Edition of Natural Science)*, 42(5): 23–34 (in Chinese with English abstract).
- Xian Benzong, An Siqi, Shi Wenhua. 2014. Subaqueous debris flow: Hotspots and advances of deep-water sedimentation[J]. *Geological Review*, 60(1): 39–51 (in Chinese with English abstract).
- Xian Benzong, Wan Jinfeng, Dong Yanlei, Ma Qian, Zhang Jianguo. 2013. Sedimentary characteristics, origin and model of lacustrine deep-water massive sandstone: An example from Dongying Formation in Nanpu depression[J]. *Acta Petrologica Sinica*, 29(9): 3287–3299 (in Chinese with English abstract).
- Xian Benzong, Wang Lu, Liu Jianping, Lu Zhiyong, Li Yuzhi, Niu Shuanwen, Zhu Yongfei, Hong Fanghao. 2016. Sedimentary characteristics and model of delta-fed turbidites in Eocene eastern Dongying Depression[J]. *Journal of China University of Petroleum*, 40(5):10–21 (in Chinese with English abstract).
- Xing Zuochang, Zhang Zhongtao, Lin Changsong, Zhang Bo, Hong Fanghao, Zhang Zhengtao. 2020. Provenance feature of Upper Oligocene to Early Miocene in Liwan Sag, Pearl River Mouth Basin and its influence on depositional filling[J]. *Geology in China*, 47(5): 1577–1588(in Chinese with English abstract).
- Yang Renchao, He Zhiliang, Qiu Guiqiang, Jin Zhijun, Sun Dongsheng, Jin Xiaohui. 2014. Late Triassic gravity flow depositional systems in the southern Ordos Basin[J]. *Petroleum Exploration and Development*, 41(6): 661–670 (in Chinese with English abstract).
- Yang Tian, Cao Yingchang, Liu Keyu, Wang Yanzhong, Carlos Zavala, Henrik Friis, Song Mingshui, Yuan Guanghui, Liang Chao, Xi Kelai, Wang Jian. 2019. Genesis and depositional model of subaqueous sediment gravity-flow deposits in a lacustrine rift basin as exemplified by the Eocene Shahejie Formation in the Jiyang Depression, Eastern China[J]. *Marine and Petroleum Geology*, 102: 231–257.
- Yang Tian, Cao Yingchang, Wang Yanzhong, Zhang Shaomin. 2015. Types, sedimentary characteristics and genetic mechanisms of deep-water gravity flows: a case study of the middle submember in Member 3 of Shahejie Formation in Jiyang depression[J]. *Acta Petroli Sinica*, 36(9): 1048–1059(in Chinese with English abstract).
- Yuan Jing, Liang Huiyuan, Liang Bing, Dong Daotao, Min Wei, Song Pan, Li Heyong. 2016. Sedimentary characteristics and development model of lacustrine gravity flow: A case study of Dainan Formation in deep sag belt of Gaoyou depression, Northern Jiangsu Basin[J]. *Acta Petroli Sinica*, 37(3): 348–359 (in Chinese with English abstract).
- Zavala C, Arcuri M. 2016. Intrabasinal and extrabasinal turbidites: Origin and distinctive characteristics[J]. *Sedimentary Geology*, 337: 36–54.
- Zhang Jianguo, Jiang Zaixing, Liang Chao, Wu Jing, Xian Benzong, Li Qing. 2016. Lacustrine massive mudrock in the Eocene Jiyang Depression, Bohai Bay Basin, China: Nature, origin and significance[J]. *Marine and Petroleum Geology*, 77: 1042–1055.
- Zou Caineng, Wang Lan, Li Ying, Tao Shizhen, Hou Lianhua. 2012. Deep-lacustrine transformation of sandy debrites into turbidites, Upper Triassic, Central China[J]. *Sedimentary Geology*, 265: 143–155.
- Zou Caineng, Zhao Zhengzhang, Yang Hua, Fu Jinhua, Zhu Rukai, Yuan Xuanjun, Wang Lan. 2009. Genetic mechanism and distribution of sandy debris flows in terrestrial lacustrine basin[J]. *Acta Sedimentologica Sinica*, 27(6): 1065–1075(in Chinese with English abstract).

## 附中文参考文献

- 操应长, 金杰华, 刘海宁, 杨田, 刘可禹, 王艳忠, 王健, 梁超. 2021. 中国东部断陷湖盆深水重力流沉积及其油气地质意义[J]. *石油勘探与开发*, 48(2): 247–257.
- 范代读, 邱桂强, 李丛先, 丛友滋, 杨积增. 2000. 东营三角洲的古流向研究[J]. *石油学报*, 21(1): 29–33.
- 高红芳, 钟和贤, 孙美静, 聂鑫, 姜涛, 黄文凯, 杜文波, 陈家乐. 2020. 南海海盆东南部大型深水浊积扇体系及其成因的构造控制[J]. *中国地质*, 47(5): 1395–1406.
- 雷振宇, 张莉, 苏明, 骆帅兵, 钱星, 帅庆伟, 张伯达. 2017. 南海南部北康盆地中新世深水沉积体类型、特征及意义[J]. *海洋地质与第四纪地质*, 37(6): 110–118.
- 李趁义. 2005. 东营三角洲滑塌浊积岩形成机制与高频基准面旋回控砂模式研究[D]. 博士学位论文, 中国地质大学(北京), 1-126.
- 李相博, 刘化清, 完颜容, 魏立花, 廖建波, 马玉虎. 2009. 鄂尔多斯盆地三叠系延长组砂质碎屑流储集体的首次发现[J]. *岩性油气藏*, 21(4): 19–21.
- 林畅松, 潘元林, 肖建新, 孔凡仙, 刘景彦, 郑和荣. 2000. “构造坡折带”——断陷盆地层序分析和油气预测的重要概念[J]. *地球科学*, 25(3): 42–48.

- 刘建平, 鲜本忠, 王璐, 路智勇, 李宇志, 刘赛君, 蒋健. 2016. 渤海湾盆地东营凹陷始新世三角洲供给型重力流地震沉积学研究[J]. 古地理学报, 18(6): 961-975.
- 李华, 何明薇, 邱春光, 王英民, 何幼斌, 徐艳霞, 何瑞武. 2022. 深水等深流与重力流交互作用沉积(2000—2022年)研究进展[J/OL]. 沉积学报. DOI:10.14027/j.issn.1000-0550.2022.027.
- 邱桂强, 王居峰, 张昕, 李从先. 2001. 东营三角洲沙河街组三段中亚段地层格架初步研究及油气勘探意义[J]. 沉积学报, 19(4): 569-574.
- 谈明轩, 朱筱敏, 刘伟, 施瑞生. 2017. 旋回阶梯底形的动力地貌及其相关沉积物发育特征[J]. 地质论评, 63(6): 1512-1522.
- 王尉, 蒋有录, 李瑞磊, 朱建峰, 赵鸿皓. 2018. 长岭断陷龙凤山次凹营城组重力流成因类型及沉积特征[J]. 中国石油大学学报(自然科学版), 42(5): 23-34.
- 王家豪, 王华, 肖敦清, 蒲秀刚, 韩文忠, 张伟. 2020. 陆相断陷湖盆异重流与滑塌型重力流沉积判别[J]. 石油学报, 41(4): 392-402, 411.
- 王星星, 王英民, 高胜美, 毛佩筱, 卓海腾, 王明晗, 周家伟. 2018. 深水重力流模拟研究进展及对海洋油气开发的启示[J]. 中国矿业大学学报, 47(3): 588-602.
- 鲜本忠, 万锦峰, 董艳蕾, 马乾, 张建国. 2013. 湖相深水块状砂岩特征、成因及发育模式——以南堡凹陷东营组为例[J]. 岩石学报, 29(9): 3287-3299.
- 鲜本忠, 安思奇, 施文华. 2014. 水下碎屑流沉积: 深水沉积研究热点与进展[J]. 地质论评, 60(1): 39-51.
- 鲜本忠, 王璐, 刘建平, 路智勇, 李宇志, 牛栓文, 朱永飞, 洪方浩. 2016. 东营凹陷东部始新世三角洲供给型重力流沉积特征与模式[J]. 中国石油大学学报(自然科学版), 40(5): 10-21.
- 邢作昌, 张忠涛, 林畅松, 张博, 洪方浩, 张正涛. 2020. 珠江口盆地荔湾凹陷上渐新统一早中新统物源特征及其对沉积充填的影响[J]. 中国地质, 47(5): 1577-1588.
- 杨仁超, 何治亮, 邱桂强, 金之钧, 孙冬胜, 金晓辉. 2014. 鄂尔多斯盆地南部晚三叠世重力流沉积体系[J]. 石油勘探与开发, 41(6): 661-670.
- 杨田, 操应长, 王艳忠, 张少敏. 2015. 深水重力流类型、沉积特征及成因机制——以济阳坳陷沙河街组三段中亚段为例[J]. 石油学报, 36(9): 1048-1059.
- 袁静, 梁绘媛, 梁兵, 董道涛, 闵伟, 宋璠, 李鹤永. 2016. 湖相重力流沉积特征及发育模式——以苏北盆地高邮凹陷深凹带戴南组为例[J]. 石油学报, 37(3): 348-359.
- 邹才能, 赵政璋, 杨华, 付金华, 朱如凯, 袁选俊, 王岚. 2009. 陆相湖盆深水砂质碎屑流成因机制与分布特征——以鄂尔多斯盆地为例[J]. 沉积学报, 27(6): 1065-1075.