旋回阶梯底形的动力地貌及其相关沉积物发育特征

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内容提要：旋回阶梯(Cyclic Step)是一种与斜坡相关的、向上迁移的、具有周期性水跃特征的底形，广义上还包括了冲槽与冲坑。基于迎流面沉积作用和背流面侵蚀作用的主导程度可将其划分为主沉积型和主侵蚀型两类。旋回阶梯具有长波长的特征，其波高比通常大于10。海(湖)底旋回阶梯的形成与坡度有很大的关系，其坡度范围通常为0.25°~2°，很少超过10°。与该种底形相关的沉积具有不对称透镜状或匙状纵切面形态，主要以块状或递变沉积及后积层发育为主要特征，其中以超临界浊流沉积和大规模向上迁移的沉积物波最为典型。旋回阶梯底形广泛分布于世界上绝大多数沉积环境中，其地貌动力学和相关沉积学研究对于“源—汇”系统、过程—产物具有重要意义。

关键词：旋回阶梯；水跃；超临界流；动力地貌；沉积特征

由于水力学条件的变化，沉积物在水流搬运过程中，底床松散的物质会呈现出不同的形态。当沉积物水流强度逐渐增大时，底床形态由无沉积物运动的平坦底床依次形成：沙纹、沙波、平坦底床、逆行沙丘以及冲槽与冲坑。沙波、沙纹底形的相关认识对牵引流沉积构造、水动力研究具有较强的实践意义(Ashley，1990)。然而，与超临界流所形成底形(如逆行沙丘、冲槽与冲坑底形)相关研究一直都很匮乏。随着床沙水槽实验技术日臻成熟，旋回阶梯(Cyclic Steps)作为一种新发现的高流态底形逐渐受到水利学家、沉积学家及地貌学家的重视。

在河流地貌研究中，地貌学家最早在山间河流的河床上发现了一系列似阶梯状的地貌现象(图1a)，并将其命名为“阶梯—深潭”系统(Step—pool system；Abrahams et al.，1995；倪晋仁，1998；Chin，1999；Zimmermann et al.，2001；余国安等，2011；徐江和王兆印，2004)。由于该系统具有稳定河床、消能减灾的功能，因此水利学家常将这种河床结构应用于山区河流的综合治理之中(Wang Zhaoyin et al.，2009；李文哲，2014)。该系统的“深潭”部分地貌在过去研究中常被称为“不连续的冲沟”(Discontinuous gullies；Reid，1989)，其成因属于壶穴的一种(吕洪波等，2008；吴忱等，2012；朱银奎，2014)。1995年，美国伊利诺伊州大学香槟分校土木工程系Parker教授及其研究生Ahern在冲积扇水槽实验中偶然发现了类似底形也存在周期性出现的现象，从而首次提出了“旋回阶梯”的概念(Parker，1996)，并逐渐得到大多数沉积学家、海洋地质学家的认同。实质上，“阶梯—深潭”系统与旋回阶梯同属一种底形结构，只是地质学家与地理学家、水利学家的研究方向有所差异。Kostic等(2010)对由这种超临界薄层流体形成的特殊底形进行系统性总结，并认为其发育环境涵盖从高山到深海的广阔地区(图1)。近年来，多位沉积学家分别通过物理模拟和数值模拟方法进一步论证了旋回阶梯的存在(Spinewine et al.，2009；Mulder，2010；Kostic，2011；Cartigny，2012；Balmforth和Vakil，2012；Normandeau et al.，2016)

水下声成像技术的发展使得沉积学家能够获取高清水下地貌资料，并在全球范围内多个海底峡谷—水道、湖盆内的异重流水道中发现了新月形底形的微地貌、大规模逆流迁移的沉积物波(图1c)，目前均被认为是旋回阶梯底形(Fildani et al.，2006；Lamb et al.，2008；Hughes Clark et al.，2012；Zhong Guangfa et al.，2015；Fricke et al.，2015；Turmel et al.，2015)。旋回阶梯实际上是超临界流与底床相互作用的产物，但其研究程度相对于低流态底形要低得多。所有发育超临界流环境(从源区

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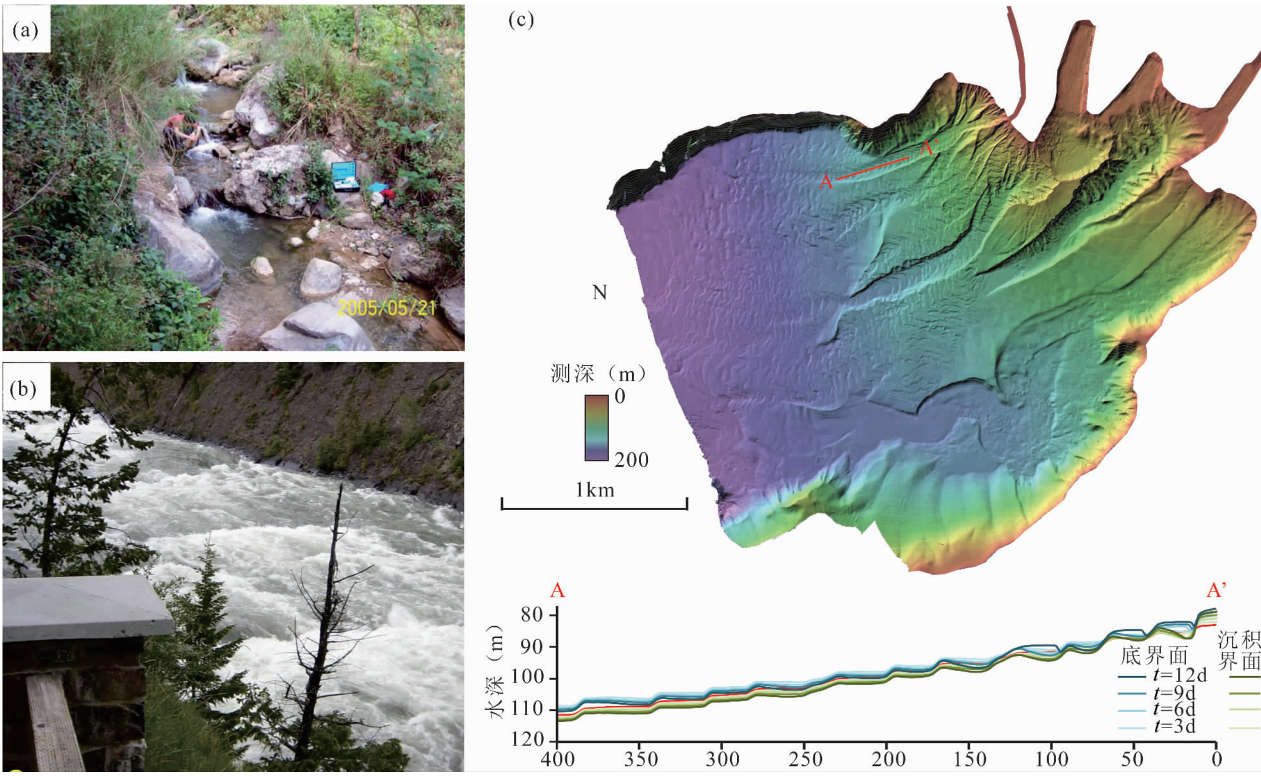

图 1 典型旋回阶梯地貌特征(据 Wang Zhaoyin et al. , 2009;MacDonald,2010; Covault et al.❶修改)

Fig. 1 Typical geomorphological characteristics of cyclic steps (modified from Wang Zhaoyin et al. , 2009; Kostic et al. , 2010; Covault et al.❶)

(a)云南省昆明市深沟溪“阶梯—深潭”系统;(b)加拿大 Banff 国家公园小型河流旋回阶梯;(c)加拿大不列颠哥伦比亚 Squamish 前三角洲内浊流水道旋回阶梯底形及剖面

(a)“Step—pool” system in the Shengou Creek of Kunming , Yunnan Province; (b)Small fluvial cyclic steps in the Banff National Park, Canada; (c)The cyclic step bedforms and cross section of turbidite channel in the Squamish prodelta of British Columbia, Canada

河流到深水扇体)均有可能出现这种特殊底形,因此旋回阶梯的水动力学定量表征对于“源—汇”系统研究具有重要的沉积学意义(Turmel et al. , 2015)。旋回阶梯的发现重新激发了沉积学家对于底床形态的探索,并在应用研究中将流态性质与沉积响应充分联系起来(Ventra et al. ,2015),弥补了高流态条件下底形演化及沉积物特征的空白,使得沉积学基础理论得到进一步完善。

目前,与旋回阶梯的相关研究仍然集中于地貌动力学模拟、相关底形识别两方面。Cartigny (2012)、Postma 和 Cartigny(2014)系统总结了与旋回阶梯相关沉积物的岩相发育特征,但是相关“过程—产物”研究仍需在未来几年内反复实验、不断验证(Talling et al. ,2015)。就我国东部中—新生代断陷湖盆而言,陡坡带、缓坡带坡折均具有形成旋回阶梯的坡度条件。在新理论指导下对近源粗粒沉积体系、深水重力流沉积物岩心进行重新解释,厘定超临界流和亚临界流沉积物差异,对于进一步恢复古水动力、沉积搬运过程具有重要的研究价值。

1　旋回阶梯的定义

旋回阶梯是与斜坡相关的、由超临界流水跃形成的、逆流迁移的底形。然而该概念的定义范围目前仍没有统一。Taki 和 Parker(2005)认为旋回阶梯是一系列周期性底形的总称,每一个完整波长均以一期水跃为界。广义上讲,冲槽与冲坑底形是旋回阶梯中的极端情况(福岡捷二,1982;Taki 和 Parker, 2005),因而属于旋回阶梯的一部分。

Cartigny 等(2009,2012)将旋回阶梯定义为波形逆流迁移且具有稳定性水跃特征的周期性底形。旋回阶梯由淹没水跃形成,而冲槽与冲坑则由正常水跃形成(图 2)。由于正常水跃的稳定性较差,因此在该定义下冲槽、冲坑底形并不纳入其中。为进一步突出水跃对床沙形态和相关沉积物的影响,本

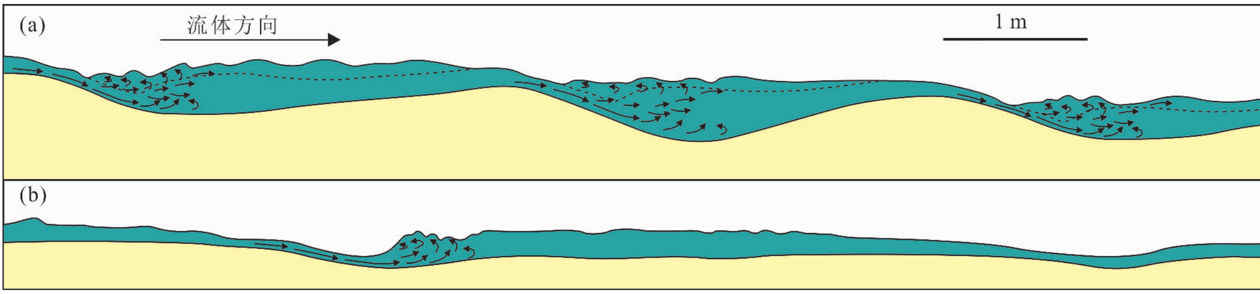

图 2 与旋回阶梯有关的水跃类型(据 Mulder,2010;Cartigny et al. ,2014 修改)

Fig. 2 The associated type of hydraulic jump with cyclic steps (modified from Mulder, 2010; Cartigny et al. , 2014)

(a)淹没水跃(动能<势能,即尾水深度小于跃后水深);(b)正常水跃(动能=势能,即尾水深度等于跃后水深)

(a) submerge hydraulic jump(kinetic energy < static energy, i. e. tailwater depth less than sequent depth);

(b) normal hydraulic jump (kinetic energy = static energy, i. e. tailwater depth equals to sequent depth)

文中所探讨的旋回阶梯沿用了 Taki 和 Parker (2005)提出的广义概念,即认为旋回阶梯存在正常水跃和淹没水跃两种成因,其发育环境涵盖了从源区到汇区绝大部分环境(Kositc et al. ,2010),无论是碎屑岩还碳酸盐沉积环境(Shitanishi et al. [1]),甚至在火星表面均有所发现(Smith et al. ,2013)。

2 旋回阶梯基本特征

2.1 分类方案

旋回阶梯依据发育环境分为海(湖)底、陆上两类。陆上旋回阶梯主要由明渠水流(如河流)形成,通常包含冲槽、冲坑底形。Kostic 等(2010)依据其基底岩性又将陆上部分进一步划分为冲积层、粘土层及基岩层三种。此外,冰层上也可形成该种底形(Yokokawa et al. , 2016)。其中,地貌学中的"阶梯—深潭"系统通常属于基岩层上发育的旋回阶梯(Shitanishi et al. [2])。海(湖)底旋回阶梯则主要由超临界浊流经过一系列淹没水跃形成,也是目前沉积认识较为成熟的部分。

前人依据沉积、侵蚀作用主导性将旋回阶梯分为主沉积型和主侵蚀型(Fildani et al. , 2006; Spinewine et al. ,2009)。该种分类方案在研究和论述中简单易用,因而被大多数学者所接受。在此基础上,Cartigny 等(2011)依据迎流面、背流面加积和侵蚀作用的程度又将其细分 3 类。其中,I 型旋回阶梯相当于主侵蚀型,III 型旋回阶梯(亦称为爬升型旋回阶梯)相当于主沉积型,而 II 型旋回阶梯为过渡型。

2.2 底床形态成因特征

主沉积型旋回阶梯形成坡度相对较小。当超临界流流经每个阶梯底部时,向亚临界流转化并产生水跃。水流继续沿着迎流面上倾方向流动时,流速逐渐减缓,水流能态进一步降低,因而以沉积作用为主。当水流经过阶梯顶点后开始沿背流面(坡度 > 40°)下倾方向不断加速,使得亚临界流向超临界流转化,因此以侵蚀作用为主(Kostic et al. , 2010; Kostic,2011)。主侵蚀型旋回阶梯形成坡度相对较大,主要表现为周期性冲刷特征,然而其背流面侵蚀作用远大于迎流面沉积作用程度。一般而言,迎流面沉积物保存程度比背流面更高,因此这种底形在垂向上表现出逆流迁移的特征(图 3)。

旋回阶梯的波长与流量、流深及坡度有关(Cartigny et al. ,2011; Kostic,2011),其波长通常可达几十米乃至几百米,波高比一般大于 10 (Kostic,

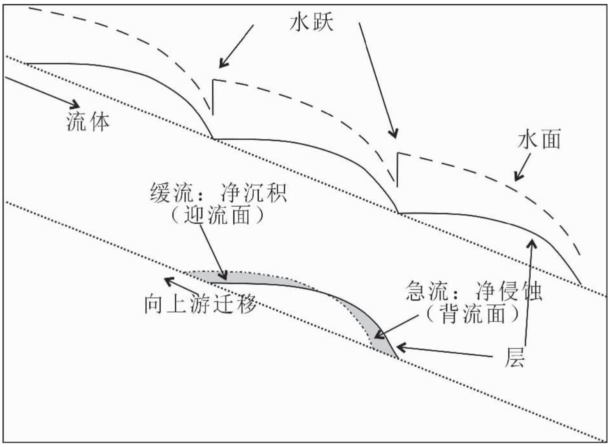

图 3 主沉积型旋回阶梯底形沉积作用及流体动力特征(据 Kostic et al. ,2010 修改)

Fig. 3 The flow dynamics and bed deposition of net-depositional cyclic steps (modified from Kostic et al. , 2010)

2011;图 4)。目前文献报道中规模最大的旋回阶梯发育于南海东北部台湾浅滩南、西澎湖峡谷水道中,其波长介于 1.2 ~10.0 km,波高比为 23 ~250,反映海底曾经存在强劲浊流活动(Zhong Guangfa et al.,2015)。

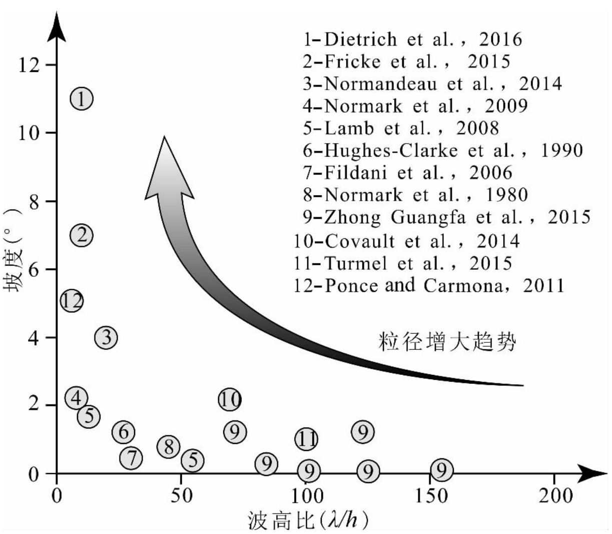

图 4 多种文献中所发育的旋回阶梯底形波高比与坡度关系(据 Dietrich et al.,2016 修改)

Fig. 4 The relationship between aspect ratios of cyclic steps and slope gradient reported in various publications(modified from Dietrich et al., 2016)

2.3　水动力学成因特征

旋回阶梯底形与超临界流产生水跃具有密切的联系(Cartigny,2012)。水跃是超临界流的一种特殊的自由表面现象(Alexander et al.,2001;Taki 和 Parker,2005),因此超临界流的水动力表征能够更好地理解该底形的水动力学成因机制。

对于水上环境而言,常用 Fr 指数来表征明渠水流的流态特征:

$$Fr = \frac{U}{\sqrt{gh}} \tag{1}$$

其中,U 为流速,g 为重力加速度,h 为流深。

对水下浊流而言,通常用 Fr_d 指数(密度弗劳德数)来表征其流态特征(Hand,1974; Kostic et al.,2010):

$$Fr_d = \frac{U}{\sqrt{RCgD}} \tag{2}$$

其中,R 为浊流中沉积物密度,C 为浊流中平均体积浓度,D 为浊流的流深。一般而言,当 $Fr(Fr_d)>1$ 时即可形成旋回阶梯。

为进一步分析高流态条件下流体的稳定性和均一性,Chow(1959)又提出了 Ve 指数:

$$Ve = xFr \tag{3}$$

其中,系数 x 表征流速对流深的依赖程度($x=2/3$,据曼宁公式)。当 $Ve<1$(即 $Fr<1.5$)时,流体稳定性较好,其界面上的自由表面波受到抑制。在紊流状态下继而进一步形成逆行沙丘底形。当 $Ve>1$(即 $Fr>1.5$)时,流体稳定性较差,自由表面波逐渐增大,在高流态下开始产生破浪。在紊流状态下继而出现旋回阶梯底形,包括冲坑、冲槽底形(图 5; Alexander et al., 2001; Spinewine et al., 2009; Cartigny et al.,2014)。

2.4　形成条件

徐江和王兆印(2004)结合水槽模拟成果提出河道比降是形成“阶梯—深潭”系统的关键因素。相关统计表明,形成这种特殊地貌的河道比降一般介于 0.02 ~ 0.25(即河道坡度 1.15° ~ 14.04°)(Chartrand et al.,2011),基本上可作为陆上旋回阶梯发育的重要条件。

对于海(湖)底旋回步而言,坡度也是形成这种超临界底形的主要外部条件(Kostic,2011;Zhong Guangfa et al.,2015)。一般而言,坡度越大,Fr_d 越大,越有利于旋回阶梯形成(Sequiros,2012;Zhong Guangfa et al.,2015)。

前人在数值模拟研究中常借助谢齐公式建立浊流流速与坡度的关系(Kneller 和 Buckee,2000)。

$$U = \sqrt{\frac{8RcgSD}{fb + fi}} \tag{4}$$

其中,S 为斜坡坡度,D 为流厚,fb 和 fi 分别为流体顶底的达西—魏斯巴赫摩擦系数, Hand(1974)的水槽实验表明该系数最大为 0.057。结合公式(2)和公式(3)可以建立 Fr_d 与坡度 S 的关系,即:

$$Fr_d = \sqrt{\frac{8S}{fb + fi}} \tag{5}$$

相关计算表明,就海(湖)底旋回阶梯($Fr_d>1.5$)而言,临界坡度仅为 0.016(即 0.92°)。若坡度过大,流体重力沿斜坡方向的分量也增大。该斜坡分力使得流体不断加速,从而抑制流体内产生水跃消能、并转化为亚临界流的可能性,因此坡度过大反而阻碍旋回阶梯的形成(Kostic,2011)。目前文献中报道的水下旋回阶梯坡度一般为 0.25° ~ 2.00°(Fildani et al.,2006;Lamb,2008;Normark et al.,2009;Covault et al.,2014),很少超过 10°(图 4;Dietrich et al.,2016;Normandeau et al.,2016)。

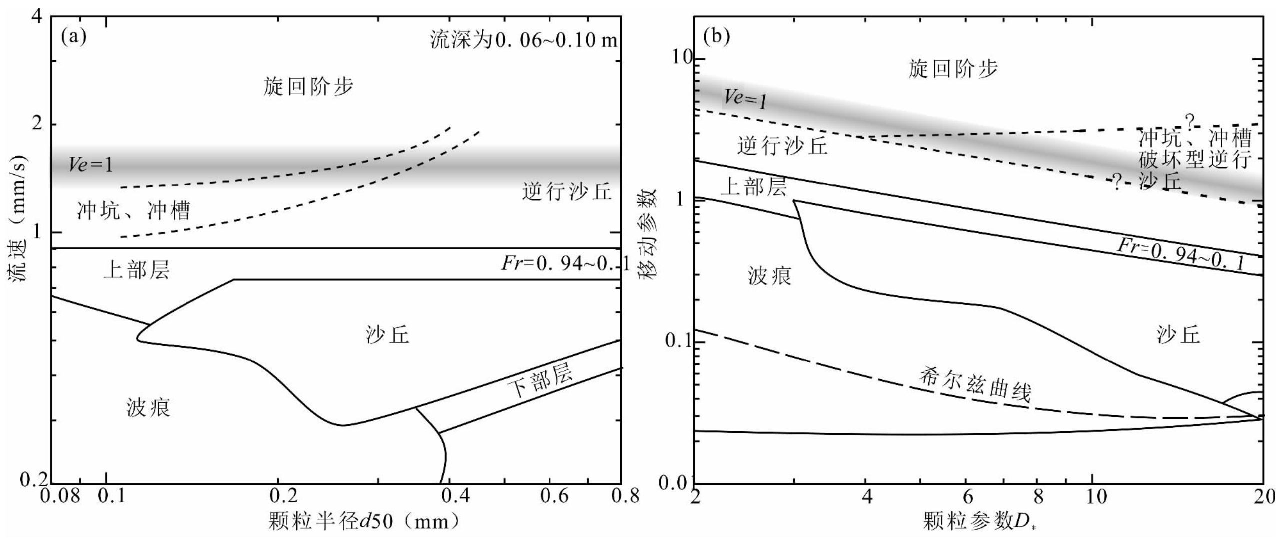

图 5 底床稳定性扩展性图解(据 Cartigny et al. ,2014 修改)

Fig. 5 Extended bedform stability diagrams (modified from Cartigny et al. , 2014)

(a)Southard 和 Boguchwal(1990)稳定性图解;(b)Van den Berg 和 Van Gelder(1988)稳定性图解。其中,希尔兹曲线为泥沙起动切应力的实验曲线

(a)Stability diagram from Southward and Boguchwal(1990);(b)Stability diagram from Van de Berge and Van Gelder(1988). The Shields Curve is an experimental curve for shear stress of sediment incipient

3 与旋回阶梯相关的沉积物

主侵蚀型旋回阶梯(如山间河流的“阶梯—深潭”系统、峡谷水道中的新月形底形等)以过路作用为主,沉积物很难保留下来,仅保留了周期性负向地貌形态(Spinewine et al. , 2009; Talling et al. , 2012;Covault et al. [1])。这种强侵蚀作用对于峡谷水道的初期演化具有重要的意义(Fildani et al. ,2013)。主要的沉积产物还是由主沉积型旋回阶梯形成的。以沉积作用为主的冲坑、冲槽形成的透镜状层系、类丘状交错层理的沉积构造复杂多变(Cartigny et al. ,2014),在本文中则不作过多介绍。

对于狭义上的旋回阶梯而言,单一旋回阶梯沉积体(或称为“水跃坝”)在纵切面上呈现不对称透镜状形态(MacDonald, 2010;Postma,2009),在横切面上表现为对称透镜状或匙状形态(图 6)。具体而言,以超临界浊流沉积和沉积物波最具代表性。

3.1 超临界浊积岩

Demko 等[3]在西班牙 Anisa、Ebro 及

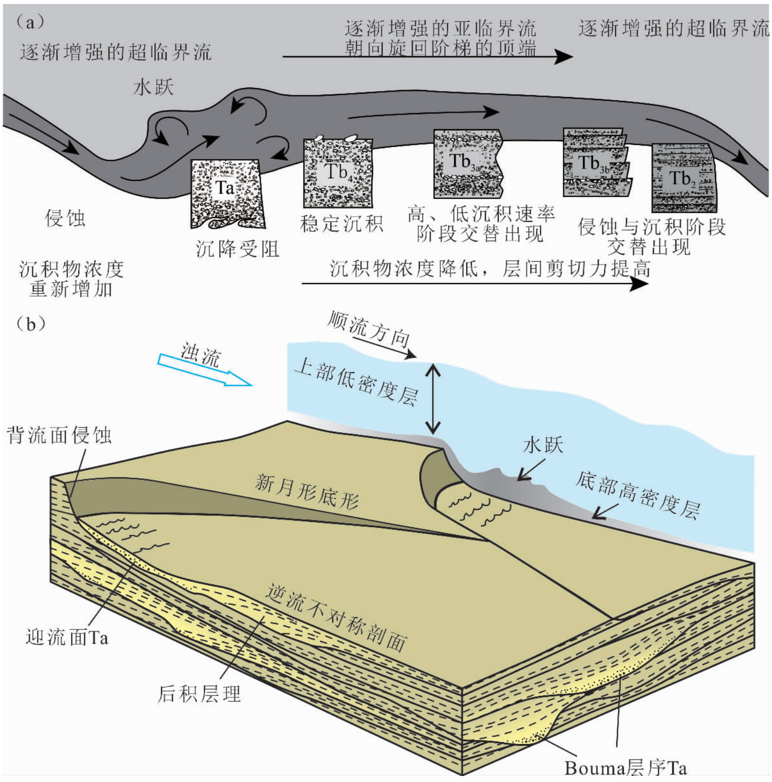

图 6 旋回阶梯空间岩相分布(a)及三维沉积发育模式(b)(据 Postma 和 Cartigny,2014;Postma et al. ,2014;Covault et al. [1]修改)

Fig. 6 The spatial distribution of litofacies (a) and three-dimension sedimentary model(b) of cyclic steps(modified from Postma and Cartigny, 2014; Postma et al. , 2014; Covault et al. [1])

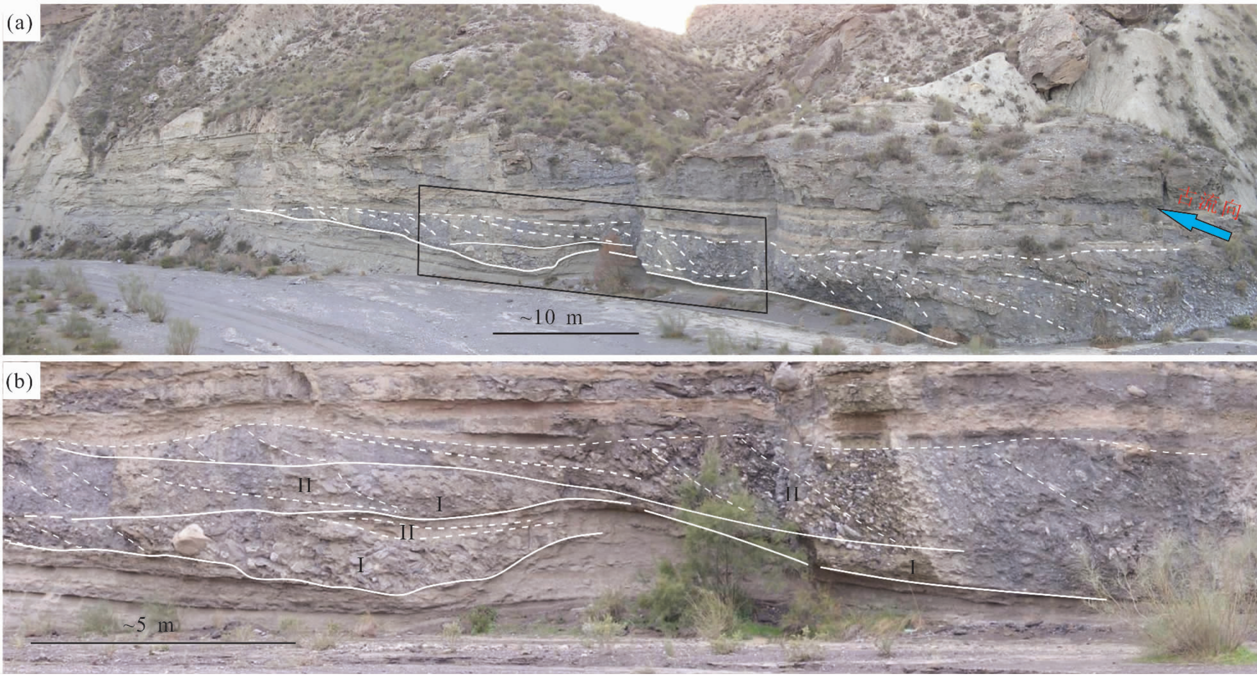

图 7 西班牙 Tabernas 盆地中新统 Donkey 露头逆流迁移的砾质旋回阶梯(据 Cartigny,2012 修改)

Fig. 7 Upstream migrating gravelly cyclic steps in the Miocene Donkey outcrop of the Tabernas Basin, Spain (modified from Cartigny,2012)

(a)多期逆流迁移的匙状砾质旋回阶梯全貌;(b)砾质旋回阶梯底形上依次为块状颗粒支撑砾岩(I)、后积层发育的中粗砂质砾岩(II)。其中,白色实线为冲刷面,白色虚线为层系面

(a) The general view of several upstream migrating spoon-shaped gravelly cyclic steps; (b) lower section are structureless clast-supported pebble conglomerates(I), and upper section are medium- to coarse-grained sandy conglomerates with backset beddings(II). The white solid lines are scouring surfaces, and the white dashed lines are the interfaces of bedsets

Tabernas 盆地海底扇和扇三角洲沉积序列中均发现了这种超临界浊积岩。Hoyal 等[4]甚至将与旋回阶梯、逆行沙丘等超临界底形相关的海底扇称之为"超临界扇"(Supercritical fan)。其中,与旋回阶梯相关的沉积主要发育于海底扇上倾水道、朵叶体以及天然堤部位。Cartigny(2012)结合水槽实验和露头研究,基于流态变化初步提出了浊积岩岩相综合发育模式。在此基础上,Postma 和 Cartigny(2014)将此模式不断完善,使其参考价值逐步增强。

当流体经过旋回阶梯底部开始水跃时,水流中高速部分与携带沉积物分离,形成显著的涡流和流体压力的巨大波动,使得底层沉积物液化变形,而此时水跃的中心部位沉积物则由于沉降受阻,从而形成底部高密度层(Postma, 2009; Postma et al., 2014)。因此,水跃区岩相主要为块状或粗尾递变砂岩,软沉积物变形(火焰状构造)较为发育,相当于 Bouma 层序递变层理(Ta)段(图 7;Postma et al., 2009)。

超临界流在水跃区沉积时,沉积物位置不断向源移动,表现为后积充填的现象(图 7;李思辰等[5])。值得注意的是,后积层的野外识别必须建立在古流向分析基础上,否则会得出错误的结论。在研究过程中首先充分结合盆地构造发育特征、上覆与下伏沉积地层的倾向变化及其他相关判别标志判定古水流的大致方向,之后再通过后积层精细对比确定该底形是否发育(Postma,2014)。

流体在迎流面上剪切力增强,高角度后积层不断向其顶端超覆,从而向低角度—近水平后积层过渡(图 6b;Postma 和 Cartigny,2014)。在后续多期水流冲刷作用下,迎流面顶端后积层的厚度一般较薄,甚至不发育。由于高密度浊流在该区域内以牵引毯沉积为主,故称为牵引毯区。基于 Sohn(1997)所提出的牵引毯流变域分类方案,牵引毯区相关沉积自下而上分别为摩擦性牵引毯段、碰撞性牵引毯段,属于 Bouma 层序平行层理段(Tb)。其中,摩擦性牵引毯段反映流体以高体积浓度(45% ~60%)、假层流为特征,其主要岩相 Tb_4 为厚层块状或反递变含砾

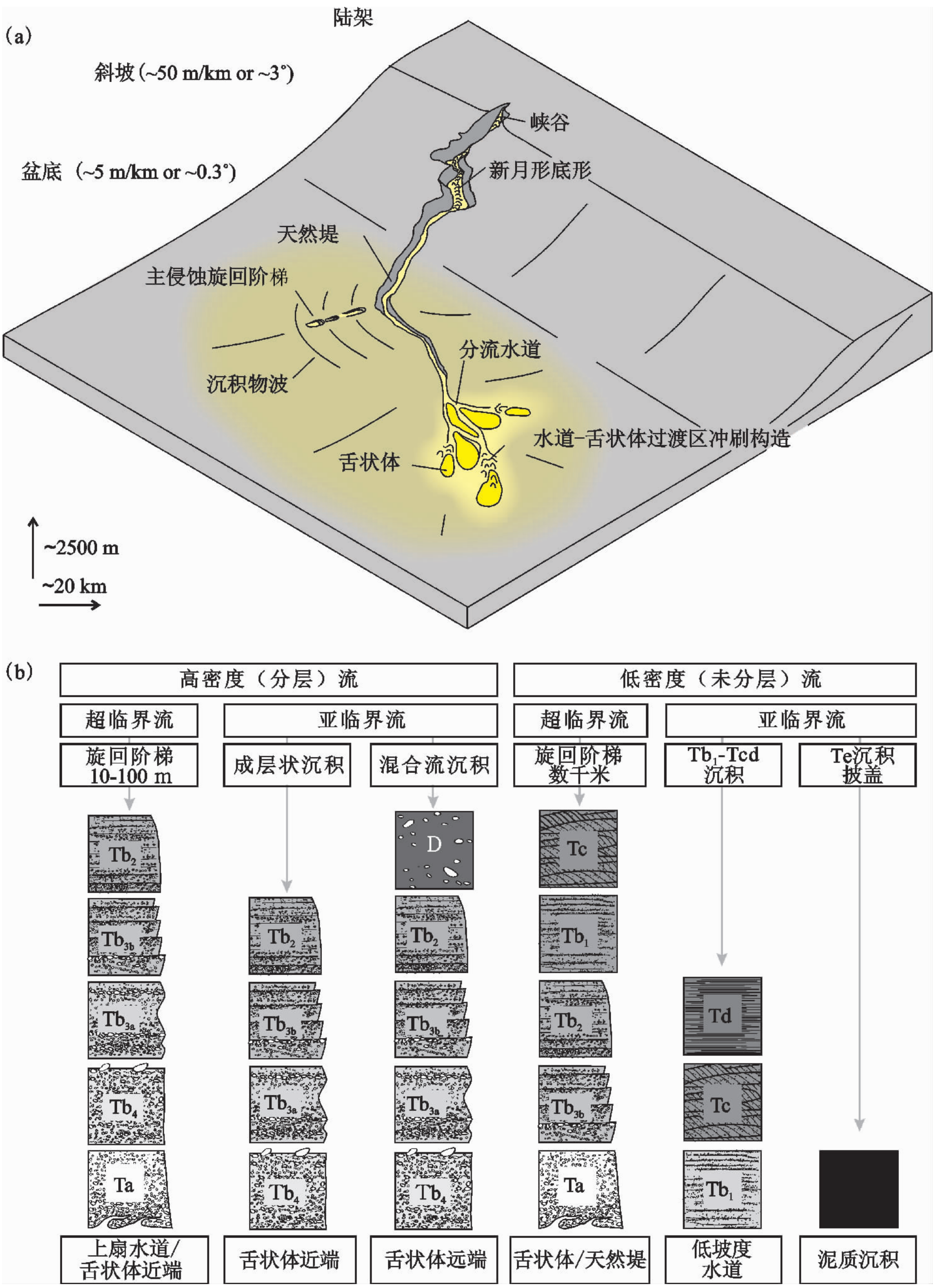

图 8 深水旋回阶梯底形发育环境(a)及相关沉积物岩相分布特征(b)

(据 Covault et al. ❶;Postma 和 Cartigny,2014 修改)

Fig. 8 Deep-water cyclic steps and lithofacies distribution of related deposits

(Modified from Covault et al. ❶; Postma and Cartigny, 2014)

砂岩。反递变层理的发育可能与层间剪切力和振动筛有关(Sohn,1997;Cartigny et al.,2013)。碰撞性牵引毯段反映流体体积浓度较低(9% ~45 %),其主要岩相为 Tb_{3a}、Tb_{3b}、Tb_2。其中,Tb_{3a} 岩相为含砾砂岩,砂、砾成层性相对差,层系界面粗略难以辨别。Tb_{3b} 和 Tb_2 岩相均为含砾砂岩,砾石层呈层状富集,与平行砂岩层间隔出现(图 6a;图 8b)。Hiscott (1994)将这种沉积构造称之为间隔性平行层理(Spaced Stratification)。与 Tb_{3b} 岩相相比,Tb_2 岩相平行含砾岩层与平行砂岩层间隔距离相对更小,间互出现较频繁(Postma et al.,2014)。

3.2 沉积物波

沉积物波是一种大型波状沉积底形,形成于海底流体下方,以逆流迁移为主,亦可顺流迁移(Migeon et al., 2000; Wynn et al., 2000; Normark et al.,2002;钟广法等,2007)。目前很多顺流迁移的沉积物波被解释为沙丘成因(Piper et al.,1988),而逆流迁移的沉积物波则被解释为逆行沙丘或内波成因(Normark et al., 1980)。实际上,沙丘和逆行沙丘底形均为短波长底形,单个波长、波高均十分有限,对于大规模(尤其是波长超过几百米,甚至上千米)沉积物波的成因解释非常牵强。近年来,Monterey 及 Eel 峡谷弯曲水道外侧发育的沉积物波均被认为是旋回阶梯成因(Lamb et al.,2008; Cartigny et al.,2011),并在之后的水槽实验中得到进一步验证(Spinewine et al.,2009)。

沉积物波迎流面上游方向粒度最粗,向下游方向粒度逐渐变细,而背流面粒度最细(Migeon et al.,2001)。迎流面以递变层理 Ta 段、水平层理 Tb_2 段、平行层理 Tb_1 段及波状层理 Tc 段。而其背流面则相对更细,以薄层粉砂岩和细砂岩间互为特征(图 8b)。

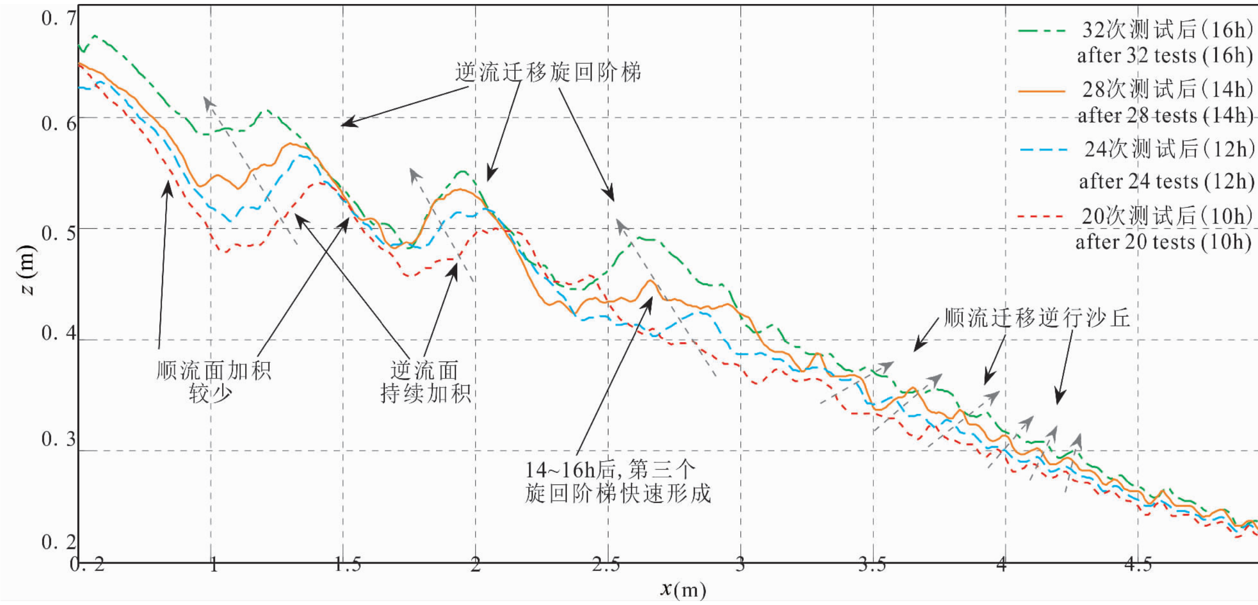

图 9 旋回阶梯与逆行沙丘演变过程水槽累计实验剖面(据 Spinewine et al. , 2009 修改)

Fig. 9 The cumulative flume experiment profiles recording the evolution of cyclic steps and anti-dunes (modified from Spinewine et al. , 2009)

对比两种典型沉积物的岩相特征不难发现，块状层理、粗尾递变层理及软沉积变形等沉积构造发育以及后积层的识别是水跃沉积、乃至与旋回阶梯相关沉积物的关键识别标志。

4 讨论

4.1 旋回阶梯与逆行沙丘的区别

虽然旋回阶梯与逆行沙丘同属超临界底形，在形态上也具有相似性(例如迎流面沉积、背流面侵蚀)，但是两者却存在本质区别。与旋回阶梯相比，逆行沙丘是一种不稳定底形(Ve < 1)。逆行沙丘的表面波稳定性差，既可逆流迁移，亦可顺流迁移，甚至可以原地停滞，偶有水跃现象(Yokokawa et al.[6])。因此，逆行沙丘底形并不能长距离稳定发育(Alexander et al. ,2011；Kostic et al. , 2010；Cartigny et al. ,2011)。旋回阶梯的表面波十分稳定，以逆流迁移为特征。周期性水跃使得水流动能骤降，流体稳定性随之增强(Kostic,2011)。就底形特征而言，逆行沙丘是短波长、对称底形，波高比一般小于 5，乃至更小。而旋回阶梯是长波长、不对称底形，波高比一般大于 10，甚至更大(Yokokawa et al.[6])。

在水槽模拟中可通过流速控制实现旋回阶梯与逆行沙丘转化。随着流速增强(*Fr* 指数增大)，逆行沙丘底形开始遭受破坏，并在局部区域重新表现为平坦底床特征，因而在先存逆行沙丘底形会继承性表现出微弱起伏的特殊地貌特征(图 8)。其中，部分规模较大的起伏底形则会逐步演变为旋回阶梯。在水槽累计实验剖面形象揭示了逆行沙丘向旋回阶梯的演化过程。最后一期阶梯下游仍以顺流迁移的逆行沙丘发育为特征，表明流速减缓，旋回阶梯与逆行沙丘同时发育(图 9)。

4.2 关于临界弗劳德数(Fr_{dc})的质疑

与明渠水流一样，水下浊流 Fr_{dc} 值在过去一直被认为是常量(即 $Fr_{dc} = 1$)。Huang Heqing 等(2009)在比能分析的基础上指出 Fr_{dc} 值并不是常量，临界值大小与沉积物浓度、流体卷吸、侵蚀作用与沉积速率等密切相关，有时甚至可以不存在。对于高沉积速率、高卷吸作用的浊流而言，Fr_{dc} 值并不存在，也就不存在流态变化的可能，因此很难形成旋回阶梯。对于强侵蚀作用的浊流而言，Fr_{dc} 值通常小于 1(Kneller et al.[7])。在这种低 Fr_{dc} 临界条件下，超临界浊流向亚临界流过渡是产生的水跃程度则相当显著，因而有利于旋回阶梯形成。因此，若在充分考虑周边水体和沉积物卷入程度，旋回阶梯的边界条件则会进一步复杂化，现存的水下底形稳定性图解局限性也相应突显出来。因此，与水下浊流流态相关的基础水动力研究仍有很长的路要走，才能更好地解决与水下浊流的流动过程及底形发育相

关的沉积地质问题。

5 结论

(1)旋回阶梯是与斜坡相关的、由超临界流水跃形成的、具有逆流迁移特征的底形,广义上包括了冲槽与冲坑底形。旋回阶梯通常具有长波长的特征,其波高比通常大于10;

(2)旋回阶梯可被划分为主沉积型和主侵蚀型。其中,主沉积型迎流面以沉积作用为主,背流面以侵蚀作用为主,而主侵蚀型旋回阶梯则表现为周期性冲刷特征;

(3)典型的旋回阶梯相关沉积在纵剖面上呈不对称透镜状或匙状形态,横剖面为对称透镜状形态,并以块状或粗尾递变沉积及后积层的发育为特征;

(4)旋回阶梯底形广泛分布于从源到汇绝大部分的沉积环境中。就海(湖)底旋回阶梯而言,深水水道、部分大规模逆流迁移的沉积物波是其最为重要组成部分。

注 释 / Notes

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The Morphodynamics of Cyclic Steps and Sedimentary Characteristics of Associated Deposits

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Abstract: Cyclic steps are upstream migrating bedforms associated with slopes and cyclic hydraulic jumps broadly including chutes and pools. It can be roughly classified into net-depositional or net-erosional one according to the predominance of aggradation at the stoss side or erosion at the lee side. Cyclic step is a long-wave bedform with the aspect ratio of wavelength to height over 10. Specially, the formation of submarine (sublacustrine) cyclic step is strongly linked with slope gradient. The forming slope gradient usually varies from 0.25° ~ 2°, while less would exceed 10°. Their associated deposits generally show asymmetrical lenticular or spoon-shape in the longitudinal section, and they are usually characterized by the occurrence of structureless or coarse-tail graded bedding and backset stratification. The supercritical turbidities and large-scale, upstream migrating sediment waves are most representative ones. This bedform is widely distributed in most worldwide depositional environments, thus morphdynamics and sedimentological study is very meaningful for source-to-sink system as well as process and product.

Keywords: cyclic step; hydraulic jump; supercritical flow; morphdynamics; depositional characteristics.

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