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末次盛冰期以来青藏高原-孟加拉湾"源-汇"系统研究进展

石学法[1,2], 李景瑞[2], 乔淑卿[1,2], 刘升发[1,2], 万世明[2,3], 杨守业[2,4]

1. 自然资源部第一海洋研究所海洋地质与成矿作用重点实验室, 青岛 266061
2. 崂山实验室海洋地质过程与环境功能实验室/深海多学科交叉研究中心, 青岛 266237
3. 中国科学院海洋研究所海洋地质与环境重点实验室, 青岛 266071
4. 同济大学海洋地质国家重点实验室, 上海 200092

摘要: 近 20 年来, 国际上对末次盛冰期以来青藏高原-孟加拉湾"源-汇"系统的研究取得了重要进展。为及时跟踪研究前沿, 并进一步为地球系统科学思想指导下东北印度洋源汇过程研究提供新思路, 本文按照从源到汇的思路, 从流域风化侵蚀、海洋沉积物来源、沉积模式、源汇系统响应等几个方面总结了目前国内外最新研究进展, 并指出了未来的主要突破方向。概括起来, 主要取得如下认识: 恒河-布拉马普特拉河流域尺度的物理侵蚀过程主要受控于季风气候变化, 而化学风化过程与季风气候关系复杂, 温度、降水、植被和冰川等因子在特定时期均可能起着重要的控制作用。孟加拉湾沉积物主要来自周边河流输入的流域风化产物, 以恒河-布拉马普特拉河输入的青藏高原物质为主, 同时也有部分来自印度半岛和缅甸的物质; 末次盛冰期以来青藏高原源区物质贡献占据绝对优势（>70%）, 且整体变化不大, 但各物源端元贡献比例在千年尺度上出现明显波动变化。孟加拉湾陆架发育典型的风暴控制型三角洲-陆架沉积, 而底层浊流和表层环流作为孟加拉湾最重要的两个输运动力, 对孟加拉湾深海扇沉积物组成和分布起着重要的控制作用。总体看来, 末次盛冰期以来青藏高原-孟加拉湾"源-汇"系统演化主要受印度夏季风和海平面变化控制。未来的研究应以地球系统科学思想为指导, 加强海陆结合的现代沉积过程的长期连续观测, 聚焦沉积记录中环境替代指标的精确解译, 揭示流域风化过程对季风气候变化的响应机制; 结合数值模拟和海洋大数据分析, 预测快速全球变化背景下青藏高原-孟加拉湾"源-汇"系统的演化趋势及环境效应, 同时加强与世界大陆边缘其他典型源汇系统的比较研究。

关键词: 风化侵蚀; 沉积模式; 印度季风; 海平面; 源-汇系统; 青藏高原-孟加拉湾

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Research progress of the Tibetan Plateau - Bay of Bengal "source-sink" system since the Last Glacial Maximum

SHI Xuefa[1,2], LI Jingrui[2], QIAO Shuqing[1,2], LIU Shengfa[1,2], WAN Shiming[2,3], YANG Shouye[2,4]

1. Key Laboratory of Marine Geology and Metallogeny, Ministry of Natural Resources, First Institute of Oceanography, Qingdao 266061, China
2. Laboratory for Marine Geology/Deep-sea Multidisciplinary Research Center, Laoshan Laboratory, Qingdao 266237, China
3. Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
4. State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

Abstract: In the last two decades, significant approach has been made in the study on the Tibetan Plateau (TP) - Bay of Bengal (BoB) "source-sink" system since the Last Glacial Maximum (LGM). To track the research frontiers and provide new ideas on the source-sink process of the Northeast Indian Ocean under the guidance of the thought of the earth system science, we summarized the latest progress in several aspects such as weathering and erosion, sediment provenance, sedimentary patterns, and source-sink system responses, and pointed out the breakthrough directions in the future. The physical erosion process in the Ganges-Brahmaputra (G-B) basin is primarily influenced by monsoon climate change, while the chemical weathering process exhibits a complex relationship with the monsoon climate. Temperature, precipitation, vegetation, and glaciers may all play significant roles in controlling these processes in specific times. The sediments in the BoB are mostly

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作者简介: 石学法（1965—）, 男, 博士, 研究员, 研究方向为海洋沉积学与海底成矿作用, E-mail: xfshi@ fio.org.cn

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weathered products transported by surrounding rivers, particularly from the Ganges-Brahmaputra (G-B) River that transports great amounts of materials from the TP, and partially from Myanmar and Indian Peninsula. The TP has consistently contributed >70% terrigenous materials to the BoB with little changes since the LGM. However, contributions from each provenance varied significantly on a millennial scale. The BoB shelf developed typical storm-controlled delta-shelf deposits. As two most-significant regional transport driving forces, the bottom turbidity current and surface circulation had a crucial impact on the composition and distribution of deep-sea fan sediments. In general, the evolution of the TP - BoB “source-sink” system since the LGM is mainly controlled by the Indian Summer Monsoon (ISM) and sea level changes. In the future, more attention shall be paid to develop the joint land-sea long-term observation of modern deposition processes, and focus on the accurate interpretation of environmental signals in sedimentary records and response mechanism of weathering processes to monsoon climate change. With numerical simulation technology and marine big data, the evolution and environmental impacts of TP - BoB “source-sink” system under the fast global changes deserve more investigations. Meanwhile, comparative studies on other typical source-sink systems in the continental margins of the world shall be strengthened.

Key words: weathering and erosion; sedimentary pattern; Indian monsoon; sea level; source-sink system; Tibetan Plateau - Bay of Bengal

青藏高原的隆升与边缘海的形成是亚洲中新生代地质发展历史上的重大事件，它们构成了地球历史上一对独特的构造格局[1]，同时塑造了亚洲大河“同源异命”的源汇格局[2]，巨量侵蚀物质被搬运至边缘海形成各具特色的沉积体系[3]。孟加拉湾作为青藏高原侵蚀物质向印度洋的主要聚集地之一，发育了世界级的三角洲和深海扇，形成了巨大的沉积物源-汇系统，同时记录了高原-山脉隆升及相关的气候和环境变化历史，被誉为“高原监视器”[4]。活跃的山地构造活动、典型的印度季风气候、发达的河流搬运体系、巨厚的海洋沉积地层，吸引了众多研究计划及研究者聚焦孟加拉湾，如 DSDP 22 航次（1974 年）、ODP 116（1987 年）和 121 航次（1988 年）、IODP 353（2014 年）和 354 航次（2015 年）均选址于此区域。另外，法国 Marion Dufresne 系列调查航次（20 世纪 70 年代）、德国 Sonne 系列航次（20 世纪 90 年代至 21 世纪初）、印度 RV-Akademik Boris Petrov、ORV Sagar Kanya 及天然气水合物系列调查航次（20 世纪 80 年代至 21 世纪 20 年代）、中国-泰国系列联合调查航次（2014—2018 年）、中国-孟加拉国联合调查航次（2019 年）等在孟加拉湾进行了较为系统的沉积学调查研究，取得了丰硕的资料和成果。

末次盛冰期以来，地球上的气候和环境发生了剧烈变化，这在陆海相互作用强烈的大陆边缘表现尤其明显，从流域风化侵蚀到海洋沉积过程对此都有敏感的响应。恒河-布拉马普特拉河等世界级大河，是孟加拉湾沉积物的主要来源[5-7]，其流域的风化侵蚀过程及向孟加拉湾的物质输运，被认为对地质历史上的气候变化和物质能量收支产生显著影响[8-9]。恒河-布拉马普特拉河流域风化侵蚀模式对印度季风气候变化的响应机制、巨量陆源物质入海后的扩散和沉积模式、海平面和季风气候在区域源-汇模式中的角色等，都是青藏高原-孟加拉湾源汇系统研究中的关键问题，本文将简要介绍其相关研究进展。

1　流域风化侵蚀

1.1　流域现代风化侵蚀

作为孟加拉湾最主要的物质来源，恒河-布拉马普特拉河流域经度范围跨度大，其地形、岩性、温度、降水、径流、冰川、植被等空间分布不均匀，导致了流域风化侵蚀作用存在空间异质性。受地势落差大、降水量及径流量大等因素控制，东喜马拉雅侵蚀速率显著高于西部[10-14]（图 1），Namche Barwa-Gyala Peri 山区以占布拉马普特拉河 2% 的流域面积贡献了 50% 的侵蚀物质产量[15]。Nd 同位素数据揭示高喜马拉雅基岩对恒河-布拉马普特拉河沉积物的贡献可达 70% 甚至更高，而小喜马拉雅基

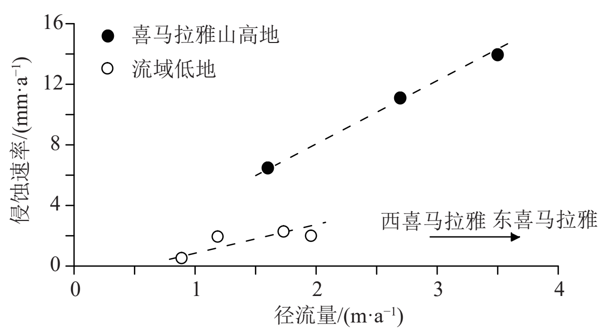

图 1　恒河-布拉马普特拉河流域侵蚀速率随径流量变化空间分布

数据引自文献 [10, 12-13]。

Fig.1　Spatial distribution of erosion rate with runoff in the Ganges-Brahmaputra River basin

Data are cited from [10,12-13].

岩贡献约 10% ～ 30%[16]。由于山区物理侵蚀速率快(图 1),导致新鲜矿物不断暴露,化学风化速率较快,但又由于快速搬运导致风化时间缩短,风化强度较弱 (初始风化),黏土矿物组成以伊利石和绿泥石为主[17],易迁移元素/不易迁移元素比值偏高[11],以动力限制型风化机制为主[18]。而洪泛平原物理侵蚀速率慢,新鲜矿物供应不足,化学风化速率慢,但由于滞留时间长[19-20]导致风化强度较大(再风化),沉积物黏土矿物中蒙皂石和高岭石含量显著高于山区[21-22],易迁移元素/不易迁移元素比值偏低[11],以供应限制型风化机制为主[23-24]。值得注意的是,恒河-布拉马普特拉河流域风化机制不仅在空间上存在差异,而且同一地点不同季风气候状态下也存在风化机制的季节性转换现象[25]。流域风化侵蚀过程和机制的多样性使该区成为研究气候-风化侵蚀关系的理想地点,几十年来热度不减,但仍存在若干迫切需要解决的科学问题,如量化不同岩性风化侵蚀过程对气候的响应差异,对准确理解气候-风化侵蚀关系及评估流域尺度的风化碳汇至关重要[4]。但目前依据水文观测、元素地球化学和同位素地球化学组成数据估算的结果之间存在很大差异,模型精度也亟待提高。

1.2 末次盛冰期以来的流域风化侵蚀

由于恒河-布拉马普特拉河流域风化侵蚀过程的复杂性,其控制机制一直存在争议。目前一般认为流域尺度的物理侵蚀过程主要受控于季风气候变化,但化学风化过程则存在多种不同的解释机制,分别强调不同因子的控制作用。

恒河-布拉马普特拉河流域物理侵蚀过程显著响应于印度季风气候的演化。在冰期-间冰期尺度上,全新世印度夏季风强度明显高于末次盛冰期,降水和径流量的增加强化了河流-洪泛平原之间的交互作用,这导致更多来自洪泛平原的物质输入孟加拉湾,如蒙皂石含量增加明显[26-28];而在千年尺度上,受印度季风气候影响,流域物理侵蚀呈现基本同步变化的特征[29-34];降水及与之相关的径流量、高地冰川动态控制了流域侵蚀过程,包括河流上游峡谷水道与冲积扇的地层侵蚀堆积、洪泛平原与三角洲建造过程及深海扇陆源输入量变化等均有所记录[35-40]。

恒河-布拉马普特拉河流域化学风化与季风气候之间的联系十分密切,但相较物理侵蚀要更为复杂。目前的认识主要强调温度、降水、植被和冰川等 4 种不同因子的控制作用。认为温度为主的研究者认为,温度通过影响矿物风化反应的典型活化能而控制化学风化的反应速率,这一机制导致自末次盛冰期以来流域尺度的化学风化逐渐增强,同时也强调了洪泛平原风化的控制作用,因为洪泛平原相比山区具有更高的温度及更强的再风化过程[16,33,41]。主张降水(及径流量)为主要控制因素的研究者认为,季风加强导致径流量增加,滑坡和河流刻蚀加剧,从而提高了侵蚀速率[21,42],泥沙输运能力增强减少了土壤和沉积物在流域内的平均滞留时间,从而限制了化学风化作用,这导致末次盛冰期末期以来喜马拉雅山化学风化速率下降[43],强调了径流和物理侵蚀是控制喜马拉雅山末次盛冰期以来化学风化的主要因素,气候变暖在这个时间尺度上起次要作用;喜马拉雅山河流阶地 Li 同位素风化记录同样揭示了其千年尺度的硅酸盐风化主要受控于径流和物理侵蚀,温度次之[44]。强调冰川作用的学者认为,喜马拉雅山冰川规模、进退速率等控制了山地侵蚀过程[29,45-50],冰川动态影响硅酸盐中阳离子从冰下新鲜矿物表面的释放,进而影响化学风化过程[51]。除此之外,还有研究者强调,与气候或人类活动密切相关的植被覆盖变化也是影响流域风化侵蚀的重要因素,末次盛冰期以来恒河-布拉马普特拉河流域尺度的植被演化受控于季风气候,呈现 C4 植物逐渐减少的趋势[52],植被覆盖类型的变化对土壤的稳定性造成影响,从而可能影响其侵蚀发育过程。

总体看来,恒河-布拉马普特拉河流域风化过程,尤其是化学风化控制因素众多,其过程存在多解性。单一指标带来的偏差以及缺乏较长时间的现代过程观测是引起各研究结果矛盾的重要原因。因此,需寻找精确有效的替代指标构建示踪体系对风化侵蚀历史的重建结果进行联合约束。这就提示我们需要结合区域背景从河流沉积物组成构建系统的示踪指标体系,并把“将今论古”和“从源到汇”的思路运用于风化沉积记录的科学解译。对于化学风化控制机制的深入研究,应该加强现代过程观测,将沉积记录与模型结果相结合,定量约束替代指标的环境示踪意义。

2 物质来源

孟加拉湾沉积物主要来自周边河流输入,除浅海陆架区物源比较明确外,深海区(主要为孟加拉扇)沉积物往往为多河流输入物质的混合。以往对孟加拉扇沉积物来源主要强调青藏高原侵蚀物质的贡献,针对印度半岛和缅甸物质贡献的研究近些

年也开始受到重视[34-35,53-61]。研究者基于孟加拉扇表层沉积物样品的黏土矿物组合、元素地球化学组成及磁学特征研究，提供了空间上高分辨率物源混合的信息[49-50,54-55,62]。但由于缺乏可靠的缅甸端元组成数据，主要研究了喜马拉雅源区和印度半岛河流物质对孟加拉扇表层沉积物的贡献，结果显示印度半岛物质主要沉积于孟加拉扇西部，贡献约为17%～45%[49-50,54-55]。沉积柱样 Sr-Nd 同位素研究结果显示，缅甸物质对孟加拉湾东部沉积物组成影响较大[23,51,63-65]。总体来看，孟加拉扇沉积物组成呈现三端元混合模式，即青藏高原物质、缅甸物质和印度半岛物质的混合，其中青藏高原物质占据绝对优势，在全海域均有分布，而印度半岛物质主要影响孟加拉扇西部沉积物组成，缅甸物质则主要沉积在孟加拉扇东部海域，中部为 3 个源区物质的交汇区，此即孟加拉扇物源分布的“2-3-2”混合模式[52]。

在时间演变规律上，孟加拉湾末次盛冰期以来青藏高原源区物质贡献占据绝对优势（平均值＞70%），且整体变化不大[48,52]。但值得注意的是，各物源端元贡献比例在千年尺度上呈现出明显的波动变化 (图 2)，主要体现在末次盛冰期、海因里希事件 1 期 (H1)、早全新世气候最适宜期和中晚全新世等时期[48,52]，与印度夏季风降水几乎同步变化，并受到冰期-间冰期尺度海平面变化的调控。考虑到 3 个源区的径向位置和降水量差异，端元贡献比例的变化可能反映了副热带辐合带 (ITCZ) 在千年尺度的径向迁移，这与季风降水息息相关，可能对风化侵蚀-气候耦合关系具有指示意义。亦有研究认为，特定时期喜马拉雅山高处冰川动态对物理侵蚀产量影响较大，可能成为主控因素[46,48,66]。总体来看，孟加拉湾物质来源的控制机制十分复杂，在分析时要特别注意研究的时空尺度问题。

3　沉积模式

3.1　风暴控制型三角洲-陆架沉积模式

恒河-布拉马普特拉河 95% 的输沙量发生在夏季风期间[67]，这决定了入海物质通量及近河口沉积动态具有季节性变化[68]。受强潮汐作用影响，恒河-布拉马普特拉河汇流段的下游河水-海水混合作用强烈，入海后堆积于近岸区的沉积层常表现出周期性变化[69]。除受季节性河流输沙量差异及近岸潮汐作用影响外，孟加拉陆架沉积动力过程的另一特征是频发的风暴活动。孟加拉湾是全球八大易发风暴的海域之一，频繁的风暴活动对海洋水动力条件及海底沉积特征造成显著影响，在孟加拉湾北部陆架区形成典型的风暴沉积层[70-71]。由风暴涌动产生的砂与粉砂/黏土互层沉积，在三角洲前积层经常出现[65]。沿陆架方向，“无底大峡谷”是恒河-布拉马普特拉河沉积物向西南输运的汇，头部沉积速率可达 50 cm/a[65,72]，峡谷东部地层沉积较厚，而峡谷西部则处于沉积“饥饿”状态[67]。跨陆架方向，风暴作用及偶发地震导致峡谷头部频繁发生滑塌可引起

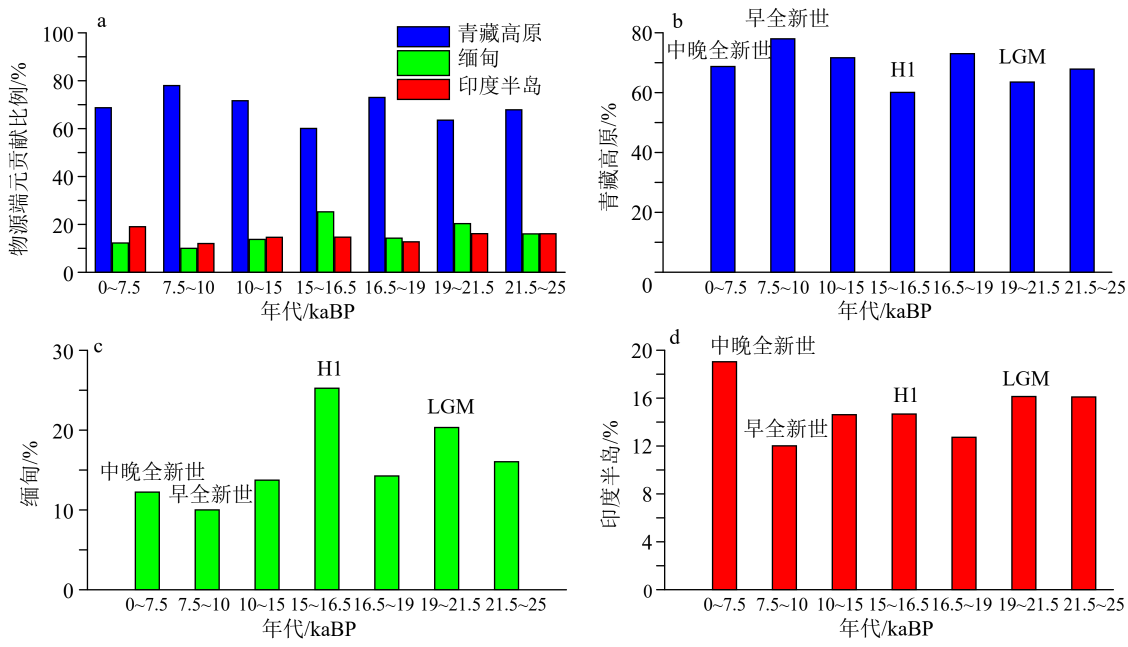

图 2　孟加拉湾周边物源端元贡献比例[57]

Fig.2　Provenance end-members contribution percentage during different stages [57]

重力流的发生，从而导致沉积物由海底峡谷向深海输运[73]；风暴或地震也会破坏三角洲前积层的稳定性，从而引发局部重力流的发生（图 3）；但在外陆架，由于风暴作用，使得细颗粒物质再悬浮，水深超过 80 m 后几乎没有全新世沉积物出现[67,74]，但有鲕粒沙脊和贝壳等发育[69]，说明其为低海面时期的残留沉积。

需要指出的是，高频而广泛的风暴沉积发育带来的一个难题是陆架地层年代格架的建立十分困难：地层垂向混合强烈导致 ^{210}Pb、^{137}Cs、^{228}Ra 等放射性核素失效[65]，而有孔虫又保存很少，至今尚无可靠的陆架地层年代框架发表。有研究者选取峡谷头部地层，利用粗颗粒砂层与风暴事件历史记录进行比对定年[75-77]，取得了不错的效果，但尚未有向陆架成功推广应用的先例。

3.2 浊流-环流双动力型深海扇沉积模式

孟加拉湾巨量物质输入与发达的浊流系统造就了孟加拉扇这一世界第一大深海扇，同时表层季节性环流也将不同河流入海物质源源不断地向海搬运扩散。底层浊流和表层环流作为孟加拉湾最重要的两个输运动力，对深海扇沉积物组成和分布起着重要的控制作用（图 3）。深海浊流沉积主要来自北部陆坡区“无底大峡谷”搬运的陆架和水下三

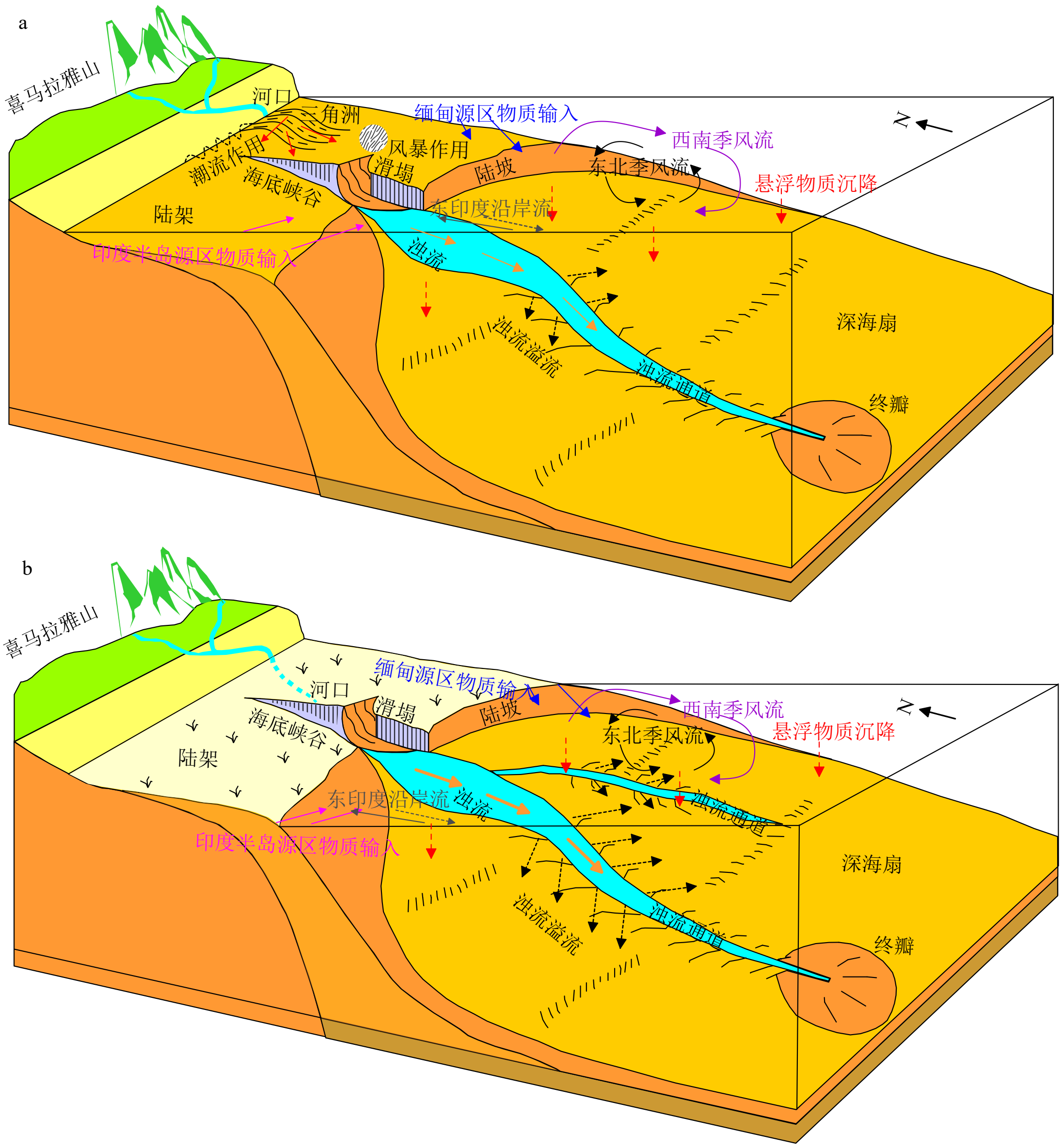

图 3　孟加拉湾沉积模式图[55]

a. 高海平面时期-现代，b. 低海平面时期-末次盛冰期。

Fig.3　Schematic diagram of sedimentary patterns in the BoB[55]

a: High stand of sea level period– present; b: lower stand of sea level period– LGM.

角洲物质[77-82]，西部和东部陆坡海底峡谷欠发育。与“无底大峡谷”相连的深海浊流通道周边的钻孔岩心中常见浊积层，物源识别结果表明其物质主要来自喜马拉雅山地层[53,59,83-84]，证实了浊流搬运模式的存在。未受浊流影响的岩心沉积物表现出多源性[35,51-52,56]，即是表层环流搬运物质混合的结果。一个典型的例子是，“Active Valley”水道的浊流沉积发生于末次冰消期以来（约 12.8 ka 至今）[78,85]，而其余水道供给的岩心中浊积层均发生于低海面-海侵期[53,59,79]，这表明海平面变化对浊流沉积模式具有明显的控制作用。从长期物源供给的角度看，陆源物质输入显著受控于季风气候控制的源区风化侵蚀过程。这表明末次冰盛期以来的孟加拉扇沉积模式以底层浊流和表层环流为主要动力，以深海浊流沉积层和半远洋沉积层为基本单元，受海平面和季风气候控制（图 3）。

当前高海面时期，海底峡谷浊流活动强度相对低海面时期大大减弱，“Active Valley”成为唯一活跃的浊流通道[72,80]。上扇区浊流通道宽而深，因此浊流活动主要发生于水道内部；浊流活动强度从上扇区向中扇区逐渐减弱，但中扇区水道的横截面积和垂向梯度相比上扇大为减小，因而浊流溢出水道两侧堤坝形成溢流，随动力减弱逐渐沉积于扇体表面[72]。另一方面，恒河-布拉马普特拉河入海物质通量在夏季风期间达到峰值，卫星遥感图片显示河口羽状流可以一直扩散到 15°N[86]，并随表层季风环流继续向南输运，印度半岛和缅甸入海物质亦通过表层流向海方向搬运，分别对西部和东部海域有所贡献。这两种输运途径构成了当前高海面时期孟加拉扇物质供应的主要机制。

在冰期-间冰期时间尺度上，海平面控制着沉积中心在陆架和深海扇之间的转移。末次冰期时海平面处于低位，陆架暴露，河口向海延伸至海底峡谷或陆架边缘，因此更多沉积物被运往深海，浊流频发，沉积中心位于孟加拉扇。全新世时海平面上升至高位，大量沉积物被水下三角洲和陆架捕获，使得沉积中心转移至陆架和水下三角洲，恒河-布拉马普特拉河仅约 30% 的沉积物被运往深海峡谷乃至深海扇[74]，因此全新世孟加拉扇沉积速率显著降低。研究发现沉积岩心顶部 AMS^{14}C 年代自北向南逐渐变老，从几百年至几千年不等（图 4），这既反映了近源到远源沉积区物质供应量的差异性，又表明深海区现代沉积速率相对末次冰期显著降低，甚至自北向南从陆源输入为主转为海源输入为主[54]。

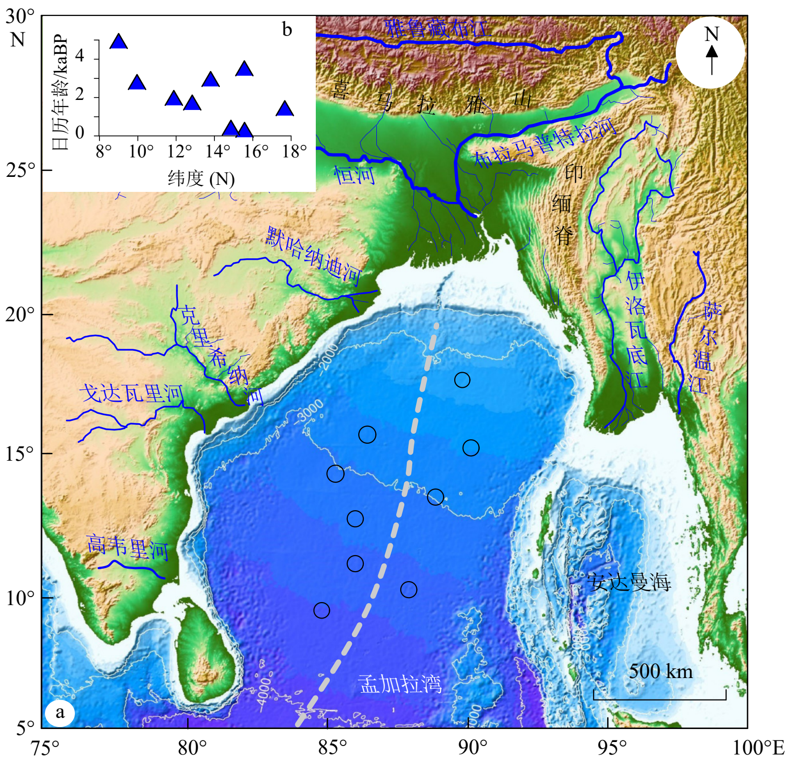

图 4　孟加拉扇沉积岩心顶部 (＜3cm) 年代自北向南逐渐变老

a. 岩心站位分布图，b. 岩心顶部年代随纬度变化图示。

Fig.4　Records of core top sediments (＜3cm) in the Bengal fan from north to south (gradually older)

a: Core sites distribution, b: diagram of the change of the age of the core top with latitude.

印度季风对沉积模式的影响主要表现在两个方面，一是季节性环流的强度，如全新世夏季风相对于末次冰期显著增强，西南季风流将更多的印度半岛物质搬运至孟加拉扇西部[34-35,48,51-52]；二是对源区侵蚀物质产量的影响，如早全新世降水量处于极大值，即使是海平面已处于较高水平，在深海扇沉积记录中仍然能捕捉到沉积速率、陆源输入指标（如Ti/Ca）或喜马拉雅源区贡献比例的高值[52-53,80]。

4 “源-汇”系统的气候控制

末次盛冰期以来，青藏高原-孟加拉湾区域构造稳定，其源-汇系统的发育演化总体上受气候控制，尤其是受印度季风控制。相比东亚大陆边缘以长江为代表的大河梯级“源-汇”系统[87]，恒河-布拉马普特拉河径流量和输沙量更大[88]、沉积物从源到汇时间更短，具有明确的源-汇联系和快速响应的特点。将流域与海洋沉积记录结合，可以发现从河流源头山间峡谷至深海扇的一系列地貌单元，记录了青藏高原-孟加拉湾源汇系统对印度季风气候变化的整体、同步响应[24,30,33,41,52-53,73,89-102]，表现最明显的是 MIS 3 期、末次盛冰期和早全新世气候最适宜期 3 个阶段沉积体系的变化（图 5）。

与气候干冷的末次盛冰期相比，MIS 3 期喜马拉雅山气候湿冷、降水较多、冰川推进加快[41]，这导致源区侵蚀产量更大。此时，流域的山间峡谷和冲积扇内发生了广泛且显著的沉积作用[30,89,95]，流域内沉积物大量滞留，导致孟加拉扇陆源输入减少，相应的海洋自生碳酸盐输入增加[103]。

末次盛冰期由于气候干旱，冰川后退[41,97]，融水的缺乏导致沉积物原地卸载堆积[94,96]，此时冲积扇逐渐停止加积，很多地方甚至出现侵蚀[30]。恒河北部喜马拉雅支流水道发生下切，冲积扇表面也不活跃；与此相反，南部支流河道持续加积[85]，这表明印度中部山脉由于更靠近副热带辐合带 (ITCZ)，因而在季风减弱的情况下仍然接受了一定程度的降水，这种情况可能与 MIS 3 期的喜马拉雅山区一样，略微减少的降水和持续较高的沉积物负载导致河道加积。河流径流量和沉积物输运量的减少导致孟加拉湾北部盐度在末次盛冰期与全球平均值相当，表明降水刚好与蒸发达到平衡，而现代河流淡水输入可将海水盐度降低约 4‰[24,84]。外陆架出现鲕粒碳酸盐砂体[104]，年代为 19～24 ka，形成于海岸线的障壁脊，揭示当时为浅水、高盐、蒸发性环境[83]，并靠近低位河口位置，表明此时陆源物质和淡水输入一定很低。

早全新世气候最适宜期季风降雨量的强化导致沉积物供应量达到峰值，山区发生广泛的滑坡，并输运至峡谷河道，这些巨量物质输入短期内超过了河流的搬运能力，导致了近 80 m 的峡谷充填[96]。持续湿润的气候条件导致的高径流量最终将这些沉积物向下游输运，几百年内即将基岩表面暴露出来。喜马拉雅源的峡谷河道和冲积扇、印度克拉通源的峡谷河道均在早全新世发生刻蚀[85,96]，表明它们均受控于同一个因素，即早全新世气候最适宜期强化的季风降雨。此时处于河流系统中下游的洪泛平原快速堆积，孟加拉盆地和陆上三角洲沉积了巨厚的地层，深海扇沉积速率相对末次盛冰期加快，深海扇“Active Valley”水道发育显著的浊流活动建造[80,93,105-106]。

5 结论与展望

5.1 结论

（1）恒河-布拉马普特拉河流域尺度的物理侵蚀过程主要受控于季风气候变化，而化学风化过程与季风气候关系复杂，温度、降水、植被和冰川等因子在特定时期均可能起着重要的控制作用。

（2）孟加拉湾沉积物主要来自周边河流输入的流域风化侵蚀产物，以恒河-布拉马普特拉河输入的青藏高原物质为主；同时也有部分来自印度半岛和缅甸的物质，它们分别影响孟加拉湾西部和东部海域的沉积作用；末次盛冰期以来青藏高原源区物质贡献占据绝对优势（平均＞70%），且整体变化不大，但各物源端元贡献比例在千年尺度上出现明显波动变化。

（3）孟加拉湾陆架发育典型的风暴控制型三角洲-陆架沉积，而底层浊流和表层环流作为孟加拉湾最重要的两个输运动力，对孟加拉深海扇沉积物组成和分布起着重要的控制作用，半远洋沉积层和深海浊积层是孟加拉扇最重要的两类沉积单元。

（4）青藏高原-孟加拉湾“源-汇”系统联系明确，物质搬运高效，能够对扰动产生快速响应。总体看来，末次盛冰期以来青藏高原-孟加拉湾“源-汇”系统演化主要受印度夏季风和海平面变化控制。

5.2 研究展望

（1）加强海陆结合的现代沉积过程长期连续观测。“将今论古”是海洋沉积学研究的指导原则，通

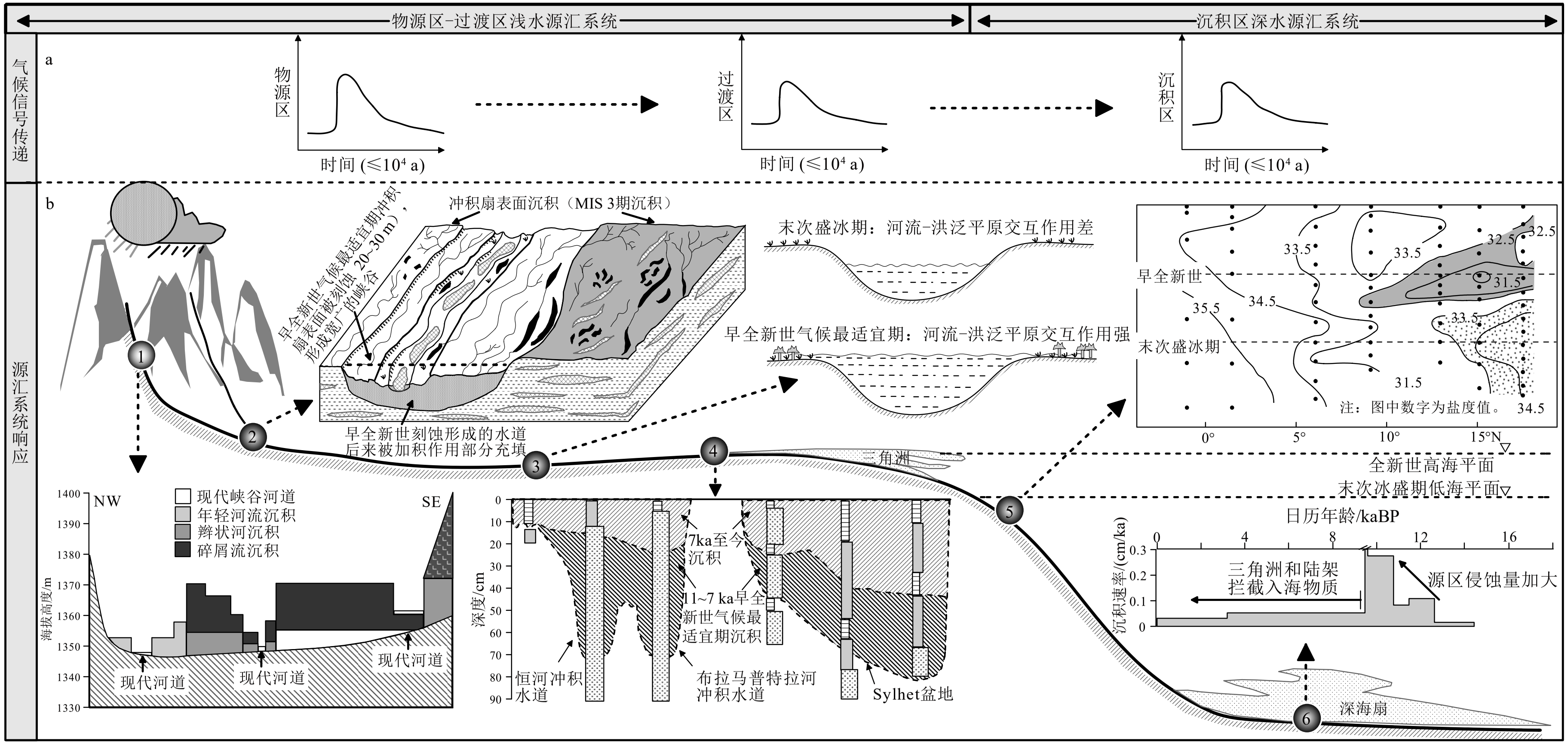

图 5　青藏高原-孟加拉湾源汇系统的气候信号传递 (a) 与系统响应 (b)

气候信号传递曲线引自文献 [107]；沉积记录实例资料引自文献 [30,41,62,80,84,93-94,96]。

Fig.5　Climate signal transmission (a) and system response (b) in the Tibetan Plateau - Bay of Bengal “source-sink” system

Climate signal curves are from [107]; sedimentary records are from [30,41,62,80,84,93-94,96].

过对现代沉积过程及规律的深入剖析,解译地层沉积记录中蕴含的沉积学动力机制,实现对未来演变趋势的预测。目前针对孟加拉湾现代沉积过程的观测工作相当匮乏,因此未来研究需要加强海陆结合的现代沉积过程的长期连续观测,特别是对孟加拉湾陆架风暴和深海浊流等区域特色沉积过程的实时观测。精细化、多层次、长时间序列的海洋环境基础数据和资料,是深化对现代沉积过程的认知和过去环境演化解释的基础。

(2)深化流域风化过程控制机制研究。在当前气候快速变化的背景下,阐明大河源-汇系统如何响应气候变化,不仅具有重要的科学价值,对流域管理决策也具有重要的参考价值。目前对青藏高原-孟加拉湾"源-汇"系统流域风化过程对季风气候变化的响应机制还存在很大争议,主要与示踪指标的精度和研究的时空尺度有关。伴随着测试技术的进步,非传统稳定同位素等新兴指标的发展,提高了风化过程的示踪精度,但也各自存在局限性。加强探索发展新指标,并将其与传统示踪指标相结合,对风化过程进行联合约束,从而准确提取不同时空尺度上的流域风化信息,揭示其差异性控制机制,可能是未来一个重要的突破方向。

(3)发展数值模拟技术,加强海洋大数据方法的挖掘和使用。要准确理解并预测不同时空尺度内的沉积物搬运和沉积过程,数值模拟技术必不可少。目前应用的海洋沉积数值模型还不完善,这既与模型本身有关,也与初始条件的设立和输入参数密切相关。因此,未来要在优化现有模型或创建新模型基础上,结合现代观测手段获取准确的边界条件参数,实现对青藏高原-孟加拉湾"源-汇"系统演化过程的重建和对未来演变趋势的预测,并加强与其他沉积源-汇系统的比较研究。大数据是地球科学研究的一种新思路和新方法。孟加拉湾海洋沉积学研究涉及领域多、数据量大且类型多样,目前以分散型的孤点研究为主,缺少海洋沉积大数据的挖掘和应用,而这正是未来深化孟加拉湾沉积学研究的重要基础。数值模拟和海洋观测大数据的有机融合有望实现孟加拉湾海洋沉积学研究的突破。

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