



90 kaBP 以来阿拉伯海中部海域沉积物来源及沉积过程

陶 菁, 刘升发, 艾丽娜, 曹 鹏, 黄 牧, 张 辉, 吴凯凯, 齐文菁, 方桐冰, 孟元库, 石学法

Sediment sources and sedimentary processes in the middle Arabian Sea since 90 kaBP

TAO Jing, LIU Shengfa, AI Lina, CAO Peng, HUANG Mu, ZHANG Hui, WU Kaikai, QI Wenjing, FANG Tongbing, MENG Yuanku, and SHI Xuefa

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90 kaBP 以来阿拉伯海中部海域沉积物来源及沉积过程

陶菁^{1,2}, 刘升发^{1,2,3}, 艾丽娜², 曹鹏², 黄牧², 张辉², 吴凯凯², 齐文菁⁴, 方桐冰², 孟元库¹, 石学法^{2,3}

1. 山东科技大学地球科学与工程学院, 青岛 266590

2. 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

3. 青岛海洋科技中心海洋地质过程与环境功能实验室, 青岛 266237

4. 中国海洋大学海洋地球科学学院, 青岛 266100

摘要:通过对阿拉伯海中部 AS06-13 岩芯的地球化学特征、黏土矿物组成特征分析, 结合有孔虫壳体 AMS¹⁴C 年龄和氧同位素数据建立的年代框架, 探讨了阿拉伯海中部海域沉积物的来源及沉积过程。结果显示: AS06-13 岩芯涵盖了阿拉伯海 90 kaBP 以来的沉积序列, 平均沉积速率为 2.34 cm/ka; 稀土元素含量为 64~194 μg/g, 平均值为 114 μg/g, δEu (平均值为 0.71) 负异常显著; 黏土矿物主要由伊利石 (平均含量为 56%)、坡缕石 (平均含量为 18%)、绿泥石 (平均含量为 15%)、高岭石 (平均含量为 8%) 和蒙脱石 (平均含量为 2%) 组成。球粒陨石标准化的稀土元素配分曲线表现为轻稀土元素富集, 重稀土元素亏损的右倾模式, 表明研究区沉积物以陆源碎屑为主, 通过 δEu_{UCC}-(La/Yb)_{UCC} 判别图进一步将 90 kaBP 以来阿拉伯海中部海域沉积物来源变化划分为 3 个阶段: S1 阶段 (90~73 kaBP) 研究区主要接受印度河入海物质和阿拉伯半岛风生物物质的输入; S2 阶段 (73~11 kaBP) 仍然以印度河和阿拉伯半岛风尘的物质输入为主, 但逐渐受到印度半岛的片麻岩区物质的影响; S3 阶段 (11~0 kaBP) 主要接受来自印度河的河流沉积物、阿拉伯半岛风尘、印度半岛的片麻岩区和德干高原物质的共同沉积。坡缕石含量和高岭石/伊利石比值指示 90 kaBP 以来阿拉伯海中部海域沉积物的陆源物质输入和沉积演化主要受季风和海平面的共同控制, 西南季风的减弱和海平面下降导致印度河、德干高原物质对研究区的输入量增多, 东北季风的增强和西北风相对增强使阿拉伯半岛的风尘输入增加; 全新世海平面快速上升使输入阿拉伯海的河流沉积物急剧减少。

关键词: 沉积物; 稀土元素; 黏土矿物; 物源; 沉积过程; 阿拉伯海

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Sediment sources and sedimentary processes in the middle Arabian Sea since 90 kaBP

TAO Jing^{1,2}, LIU Shengfa^{1,2,3}, AI Lina², CAO Peng², HUANG Mu², ZHANG Hui², WU Kaikai², QI Wenjing⁴, FANG Tongbing², MENG Yuanku¹, SHI Xuefa^{2,3}

1. College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

2. Key laboratory of Marine Geology and Metallogeny, First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China

3. Laboratory for Marine Geology, Qingdao Marine Science and Technology Center, Qingdao 266237, China

4. College of Marine Geosciences, Ocean University of China, Qingdao 266100, China

Abstract: Based on the geochemical characteristics and clay mineral composition of Core AS06-13 in the middle Arabian Sea, we combined the age of foraminifera shell AMS¹⁴C and the dating framework of oxygen isotope data, the provenance and sedimentary evolution of the middle Arabian Sea were studied. Results show that Core AS06-13 was deposited since 90 kaBP, with average depositional rate of 2.34 cm/ka. The Rare Earth Element (REE) content ranged from 64.38 to 194.33 μg/g, with average of 113.66 μg/g. The δEu, on average of 0.71, displayed significant negative anomaly. The clay minerals were mainly composed of illite (56% in average), palychite (18% in average), chlorite (15% in average), kaolinite (8% in average), and montmorillonite (2% in average). The chondrites normalized patterns of REEs had shown a right-leaning pattern of the enrichment in light REEs and deficit in heavy REEs, suggesting that sediments in the study area were mainly terrigenous detritals. According to the δEu_{UCC}-(La/Yb)_{UCC} discriminant diagram, the provenance changes in the middle Arabian Sea can be divide into three stages since 90 kaBP. The stage S1 (90~73 kaBP) were mainly sourced from the Indus River and the Arabian Peninsula dust. The stage S2

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作者简介: 陶菁 (1998—), 女, 硕士研究生, 主要从事海洋沉积学研究, E-mail: taojmaga@163.com

通讯作者: 刘升发 (1979—), 男, 研究员, 研究方向为海洋沉积学, E-mail: liushengfa@fio.org.cn

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(73~11 kaBP) exhibited similarities to the stage S1, albeit with a discernible tendency towards being influenced by the Peninsular Gneissic rock region. The stage S3 (11~0 kaBP) had a mixed sources including the Indus River, Arabian Peninsula dust, gneiss region, and the Deccan Plateau. The content of palygorskite and the ratio of kaolinite/illite indicated that the terrigenous input and sedimentary evolution in the central Arabian Sea were mainly controlled by monsoon and sea level changes since 90 kaBP. The weakening of the southwest monsoon and decrease in sea level led to an increase in fluvial sediment inputs from Indus River and Deccan Plateau to the study area. The enhanced winter winds and the relative strengthened northwesterly winds resulted in an elevated dust input originating from the Arabian Peninsula. The Holocene sea-level rise led to a rapid decline in fluvial sediments supply to the Arabian Sea.

Key words: sediment; rare earth elements; clay minerals; provenance; sedimentary processes; Arabian Sea

海洋沉积物可保存历史时期的环境和气候变化信息^[1-2], 全球海底沉积物中陆源物质占总量的一半以上, 主要通过冰川、河流、风尘等方式输送入海^[3-4], 在此过程中保存了丰富的气候与环境信息^[5-6], 是探究陆海相互作用和过去气候演化历史的良好载体。大量的研究表明, 海底沉积物的组成特征和时空分布规律与气候变化、海平面波动及环境变迁等有着十分密切的联系^[7-9], 因而可通过选择有效的替代性指标, 追踪历史时期海底沉积物来源、洋流演化及气候和环境变化等关键地质因素的演化过程^[6,10]。

阿拉伯海位于印度洋北部, 西侧毗邻阿拉伯半岛, 东侧与印度大陆相邻, 在青藏高原隆升的大背景下接受了大量陆源碎屑物质输入(图 1), 形成了全球重要的沉积物“源-汇”体系^[11]。表层沉积物综合研究表明阿拉伯海物源较为复杂, 且空间分布差异明显, 其北部主要接受印度河输入的西喜马拉雅和青藏高原物质^[12-13], 而东部陆架和陆坡区的沉积物主要来自德干高原的火山区和南印度半岛的片麻岩区^[14-18]。此外, 阿拉伯海的沉积物来源还包括: 阿拉伯半岛、印度北部(主要来自塔尔沙漠)、东非的风尘物质^[19] 嘉士伯岭的海底风化产物和孟加拉

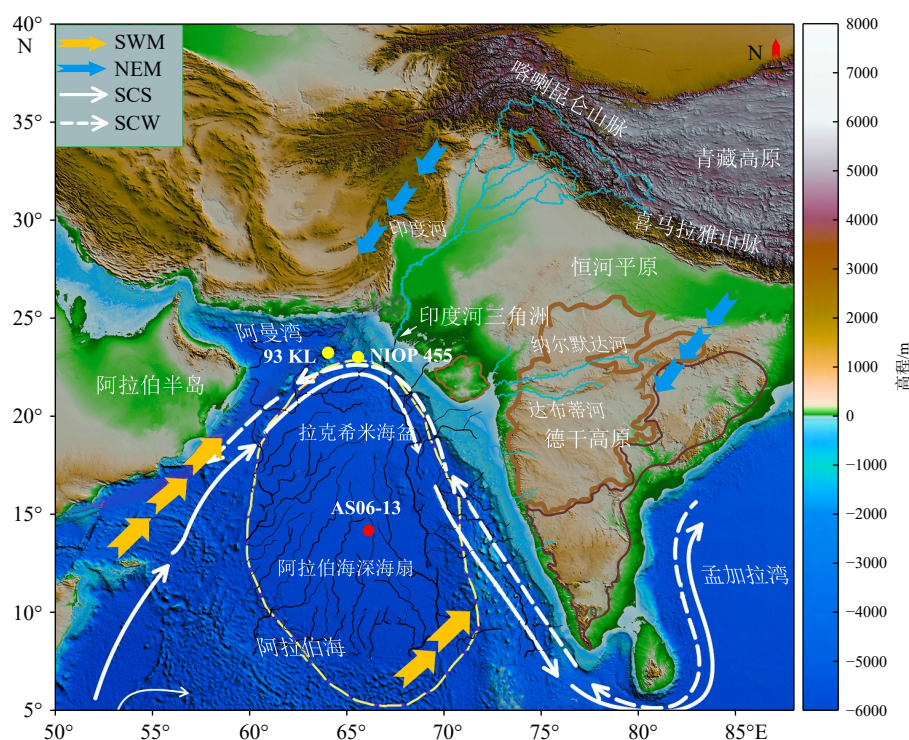


图 1 阿拉伯海 AS06-13 岩芯位置及周边季风与洋流示意图^[21]

红点为 AS06-13 岩芯, 黄点为对比分析站位, 黑线为拉克西米海盆内现代深海水道系统的位置, 黄色虚线为深海扇大致范围。SWM: 西南季风, NEW: 东北季风, SCS: 夏季表层环流, SCW: 冬季表层环流。

Fig.1 Location of core AS06-13, monsoons and oceanic circulations in the Arabian Sea^[21]

Red dot: the location of Core AS06-1; yellow dots: all the cores discussed in this study; black lines: the locations of modern deep-sea channel systems in the Laxmi Basin; yellow dotted lines: approximate extent of the deep-sea fan; SWM: southwest summer monsoon; NEW: northeast winter monsoon; SCS: surface currents in summer; SCW: surface currents in winter.

湾的沉积物^[15]。

阿拉伯海以季风气候为主,风和降水的季节性逆转导致海水性质和沉积物运输有较大的周期性变化^[20]。在阿拉伯海及周边大陆,印度夏季风带来了大部分降雨(>3000 mm),而冬季风在降雨上的影响较低^[22]。印度夏季风期间,西南风带来的强降雨控制着周边大陆表层的风化剥蚀强度,进而影响通过河流搬运入海的陆源碎屑物质运移过程^[23-24]。此外,海平面升降和洋流活动对陆源入海物质的搬运和沉积过程也发挥了重要作用^[23,25],冰期-间冰期海平面波动可改变从大陆向深海输送的沉积物的总体收支平衡^[18,26-28],而季风流的强弱变化则是陆源物质在海洋环境中搬运、沉积和改造的直接动力^[29]。

当前对阿拉伯海沉积物运输和演化方面的研究主要集中在东部大陆架和印度河峡谷^[13,30],而对阿拉伯海中部深海盆的沉积特征研究较少^[31-32],极大地限制了对阿拉伯海沉积环境特征和陆海相互作用过程的深入研究。本文以阿拉伯海中部的AS06-13岩芯为研究对象,通过AMS¹⁴C年龄和氧同位素数据建立高精度年代框架,在此基础上分析岩芯沉积物的稀土元素和黏土矿物组成特征,揭示阿拉伯海中部海域沉积物来源及其沉积演化过程,为深入研究北印度洋的陆海相互作用提供理论支撑。

1 材料与方法

1.1 样品

AS06-13岩芯(14.54°N、65.80°E)位于阿拉伯海中部的阿拉伯海深海扇,取样站位水深3909 m,岩芯长193 cm(图1),样品由2020年“全球变化与海气相互作用”专项西印度洋海洋底质调查航次采集。岩芯剖开后进行了详细的岩性描述,按照1 cm间隔分样后置于4℃冷库低温保存。

1.2 AMS¹⁴C测试

根据沉积物岩性特征选取上段(0~100 cm)5个典型层位进行AMS¹⁴C测试。沉积物样品经55℃低温烘干,过筛冲洗选取>63 μm组分,低温烘干后在光学显微镜下挑选直径大于250 μm且个体均匀的浮游有孔虫单种*Globorotalia menardii*壳体8~10 mg。AMS¹⁴C测试在美国BETA实验室完成,使用Calib 8.2程序将原始年龄数据校正至日历年龄^[33],区域碳库年龄ΔR选择45±62 a^[34-35]。

1.3 δ¹⁸O同位素测试

岩芯上段(0~100 cm)按照1 cm间隔,下段(100~193 cm)按照10 cm间隔共挑取118件样品进行δ¹⁸O同位素测试。沉积物样品经55℃低温烘干,过筛冲洗选取>63 μm组分,低温烘干后在光学显微镜下挑选浮游有孔虫单种*Globigerinoides ruber*的完整壳体(直径约300~350 μm)10~15枚,加入无水乙醇经超声处理后放入55℃烘箱中6 h以上取出,放在碳酸盐制备样品瓶中,在70℃温度下加适量磷酸溶液除去CO₂,然后用稳定同位素质谱仪(MAT 253)分析测试,测试工作在同济大学海洋地质国家重点实验室完成,测试结果参考国际标样NBS 19转换为Pee Dee Belemnite(PDB)国际标准。为保证分析精密度和准确度,确保测试标准偏差小于0.5,测试过程中使用国标NBS 19进行质量控制。

1.4 稀土元素测试

根据沉积物岩性特征选取20个典型层位进行稀土元素测试。取2 g左右沉积物样品冷冻干燥,研磨至200目,在100℃烘箱中烘干,称取50 mg样品置于聚四氟乙烯消解罐,加入3 mL 1:1的HNO₃和HF后密闭,放置于190℃烘箱中48 h后取出冷却,置于150℃电热板赶尽HF后加入3 mL 50%的HNO₃,密闭后在150℃烘箱中反应8 h以上,冷却后移液定容等待测试。用电感耦合等离子体质谱(ICP-MS)法测定稀土元素含量,测试工作在自然资源部第一海洋研究所海洋地质测试中心完成。测试分析过程严格控制流程,用GSD-9标样作为质控样,选取10%重复样监测精密度,确保测试相对误差小于5%^[36]。

1.5 黏土矿物测试

根据沉积物岩性特征选取20个典型层位进行黏土矿物测试。取2 g沉积物样品,用10%的过氧化氢和冰醋酸分别去除有机质和碳酸钙。依据斯托克斯沉降原理,提取小于2 μm的颗粒离心富集。采用涂片方法制成定向薄片,在60℃下用乙二醇饱和24 h后等待上机,测试工作在自然资源部第一海洋研究所海洋地质测试中心完成。测试仪器采用D/max 22500转靶X射线衍射仪,铜靶,管电流100 mA、管电压40 kV;连续扫描,扫描速度为2(°)/min、步长0.02°(2θ),扫描范围3°~30°(2θ)。测得数据用Jade 6.0软件处理,选取蒙脱石(17Å)、坡缕石(10.5Å)、伊利石(10Å)、高岭石+绿泥石(7Å)

为特征衍射峰。参考 Biscaye 和 Ehrmann 的计算方法选取权重系数对蒙脱石、坡缕石、伊利石、高岭石、绿泥石 5 类黏土矿物进行半定量计算^[37,38]。

2 结果

2.1 岩性特征

AS06-13 岩芯结构均一, 以含有孔虫的黏土质粉砂为主, 沉积记录连续无间断, 揭示了较为稳定的沉积环境, 其中 0~45 cm 段有孔虫含量较多, 并含深棕色砂质夹层和斑块; 45~48 cm 处见灰绿色夹层; 77~173 cm 段有孔虫含量较少, 119~132 cm 处有浅灰色夹层, 151~152 cm 处见黑色夹层; 173~193 cm 段有棕黑色薄层。

2.2 年龄框架和沉积速率

AS06-13 岩芯上段样品 AMS¹⁴C 测年结果如表 1 所示, 通过线性内插法获得岩芯上段(0~84 cm)年龄框架, 测年结果涵盖了 37.45 kaBP 以来的沉积记录, 平均沉积速率为 2.15 cm/ka。下段(84~193 cm)样品有孔虫壳体 δ¹⁸O 结果如图 2 所示, 通过与全球低纬地区广泛应用的 LR04 标准 δ¹⁸O 曲线^[39]进行

对比, 获取 AS06-13 岩芯下段沉积物年龄数据。综合两种方法建立的 AS06-13 岩芯年龄框架覆盖了 90 kaBP 以来的连续沉积序列, 时间跨度可追溯至深海氧同位素阶段 5 期。

2.3 稀土元素特征

AS06-13 岩芯沉积物稀土元素含量和相关参数的垂向分布如图 3 所示, 总稀土元素(ΣREE)含量为 64.38~194.33 μg/g, 平均值为 113.66 μg/g, 其中轻稀土元素(ΣLREE)含量(平均值为 83.66 μg/g)远高于重稀土元素(ΣHREE)含量(平均值为 11.29 μg/g), 轻重稀土元素的比值(ΣLREE/ΣHREE)为 5.73~9.31,

表 1 AS06-13 岩芯有孔虫壳体 AMS¹⁴C 测年数据
Table 1 AMS¹⁴C dating data of foraminifera shell from Core AS06-13

层位/cm	AMS ¹⁴ C 年龄/aBP	日历年龄/kaBP	沉积速率/(cm/ka)
3~4	4 040±30	3.828	0.91
23~24	11 910±40	13.195	2.14
43~44	20 180±60	23.315	1.98
63~64	27 920±120	31.138	2.56
83~84	33 610±240	37.452	3.17

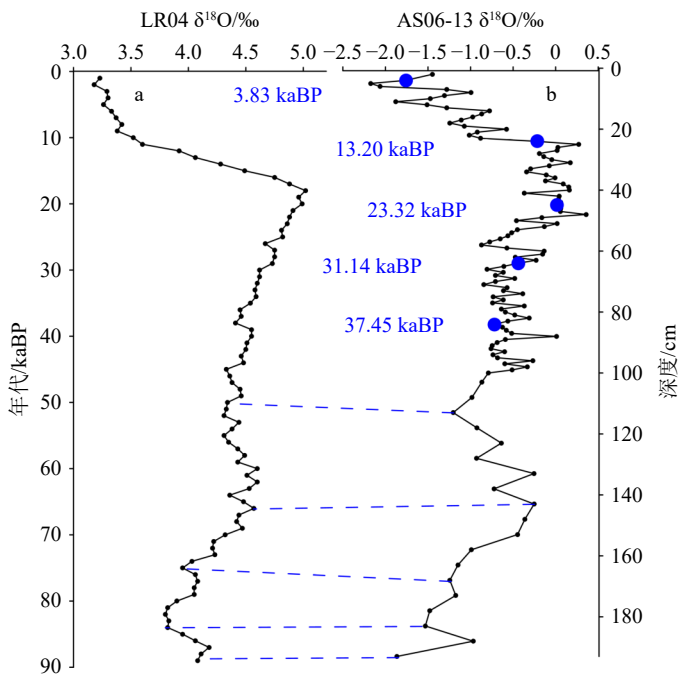


图 2 AS06-13 岩芯年龄框架
LR04 δ¹⁸O 数据据文献^[39]。蓝色圆点代表 AMS¹⁴C 测年值。

Fig.2 The age framework of Core AS06-13

The data of LR04 δ¹⁸O are from reference^[39]. The blue dots represent the AMS¹⁴C ages.

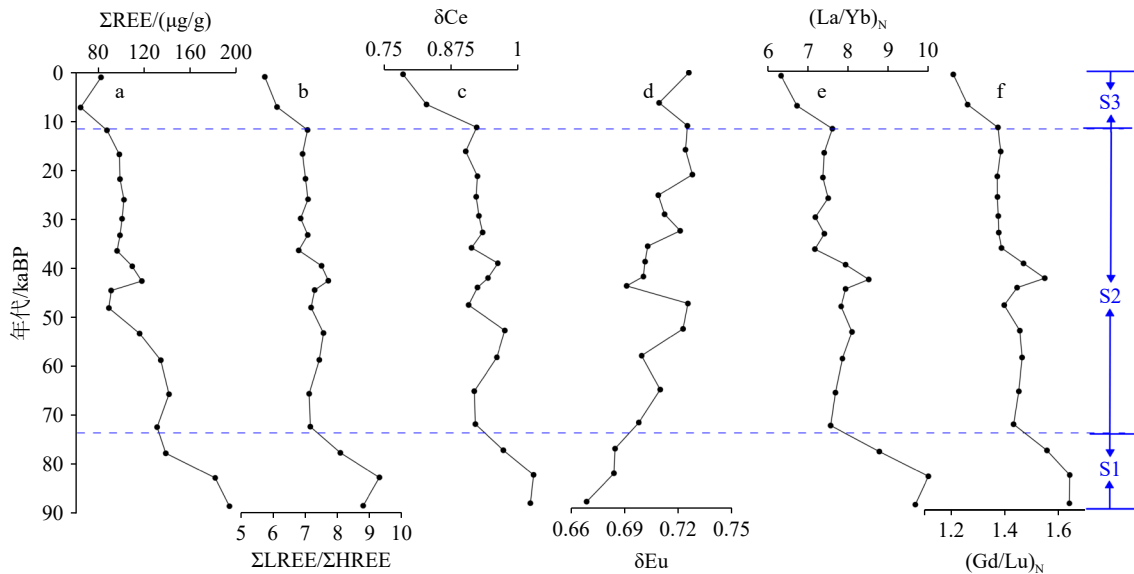


图3 AS06-13 岩芯沉积物稀土元素含量及相关参数垂向分布

球粒陨石标准化数引自文献 [40]。

Fig.3 Vertical distribution of rare earth element content and related parameters of Core AS06-13

The data of the normalized chondrite are from reference [40].

平均值为 7.28。球粒陨石标准化的 δCe 平均值为 0.93, 表现为微弱的负异常, 球粒陨石标准化的 δEu 平均值为 0.71, 呈现明显负异常。 $(\text{Gd/Lu})_{\text{N}}$ 平均为 1.43, $(\text{La/Yb})_{\text{N}}$ 平均为 7.82。AS06-13 岩芯沉积物稀土元素垂向分布上呈现明显阶段性特征, 以 11、73 kaBP 为界可将岩芯大致划分为 3 个阶段, 分别为 S1 阶段 (90~73 kaBP)、S2 阶段 (73~11 kaBP)、S3 阶段 (11~0 kaBP), 在 S1 和 S3 阶段, 稀土元素含量呈逐渐降低趋势, 而在 S2 阶段稀土元素含量较为稳定。

2.4 黏土矿物组成

AS06-13 岩芯沉积物共鉴定出 5 类黏土矿物, 含量最高的为伊利石, 含量为 46%~67%, 平均值为 56%; 其次为坡缕石和绿泥石, 平均值分别为 18% 和 15%; 高岭石和蒙脱石含量较低, 平均值分别为 8% 和 2%。垂向分布上, 伊利石、蒙脱石、绿泥石三者的含量表现为自下而上逐渐降低的趋势, 而坡缕石和高岭石变化趋势则相反, 以 73、11 kaBP 为界可划分为 S1、S2、S3 三个阶段, 5 类矿物均在 S2 阶段呈现出较大的波动 (图 4)。

3 讨论

3.1 90 kaBP 以来阿拉伯海中部海域沉积物来源

探究沉积环境演化及其驱动机制的前提是明

确沉积物来源, 前人研究表明阿拉伯海的沉积物以陆源碎屑物质为主, 河流和风尘输入是其主要来源, 而海洋自生物质和火山物质的贡献量相对较少 [17,41-42]。

稀土元素的地球化学性质稳定, 在风化、剥蚀、搬运、沉积过程中并不发生分异, 影响其地球化学性质的主要因素为其原岩组成, [43-45], 因此沉积物中的稀土元素被广泛用作物源识别的指标 [11,46-47], 其中 $(\text{La/Sm})_{\text{UCC}}$ 、 $(\text{La/Yb})_{\text{UCC}}$ 、 $(\text{Gd/Lu})_{\text{UCC}}$ 、 $\delta\text{Eu}_{\text{UCC}}$ 、 $\delta\text{Ce}_{\text{UCC}}$ 等稀土元素比值和参数被广泛应用于海洋沉积物来源判别 [11,48], 效果良好。为揭示阿拉伯海中部海域沉积物相对原始地球物质的分异程度, 将 AS06-13 岩芯沉积物以球粒陨石为标准进行标准化 [40], 结果表明 AS06-13 岩芯沉积物轻重稀土元素分异显著, 不同阶段的稀土元素配分模式均表现为轻稀土元素富集, 重稀土元素亏损的右倾模式, 轻稀土的含量远高于重稀土, Eu 负异常显著, 揭示了 AS06-13 岩芯沉积物的陆源属性 (图 5)。另外, 通过对比分析发现, AS06-13 岩芯沉积物与印度河河流沉积物、德干高原物质、片麻岩区物质和阿拉伯半岛风尘的稀土元素配分曲线非常相似, 说明其潜在物源区可能为印度半岛西侧和阿拉伯半岛。

为了进一步明确研究区物质来源, 采用上陆壳标准化的 $\delta\text{Eu}_{\text{UCC}}$ 与 $(\text{La/Yb})_{\text{UCC}}$ 来判识 AS06-13 岩芯不同阶段 (S1、S2、S3) 沉积物来源 [49], 结果显示 AS06-13 岩芯沉积物整体上与印度河沉积物、片麻岩区物质和阿拉伯半岛风尘相近, 德干高原亦有一

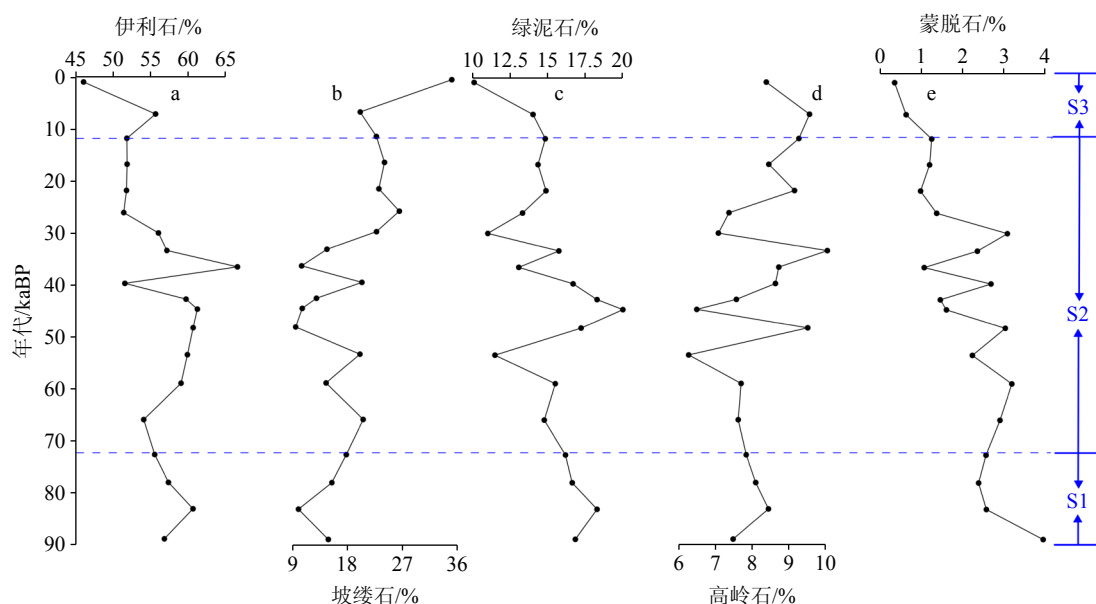


图 4 AS06-13 岩芯黏土矿物含量垂向分布

Fig.4 Vertical distribution of clay mineral content of Core AS06-13

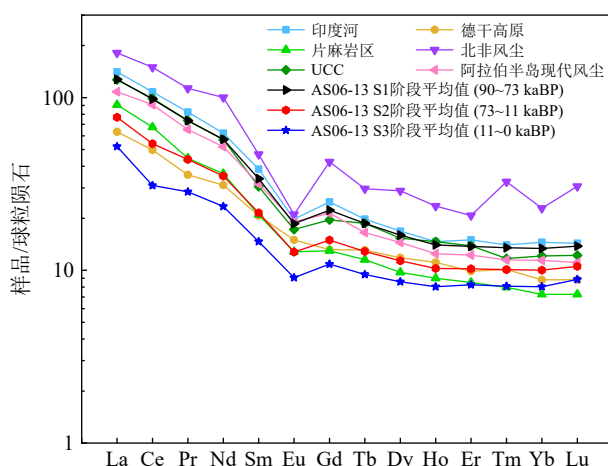


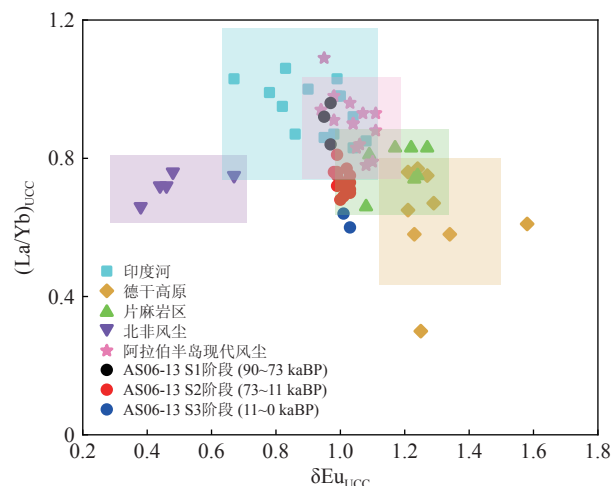
图 5 AS06-13 岩芯沉积物稀土元素球粒陨石标准化配分曲线

潜在沉积物来源选取印度河^[22]、德干高原^[50,51]、片麻岩区^[50]、北非风尘^[52]和阿拉伯半岛现代风尘^[53]；稀土元素经球粒陨石标准化^[40]。

Fig.5 Chondrite normalized rare earth element patterns in Core AS06-13

Potential sediment sources are from the Indus River^[22], the Deccan Traps^[50,51], the Peninsular Gneissic rock^[50], the North African dust^[52] and modern dust of the Arabian Peninsula^[53]; rare earth elements are normalized by chondrite^[40].

定物质贡献, 而北非风尘对研究区的物质几乎没有贡献(图 6)。黏土矿物中的坡缕石出现也证明了风尘物质的输入^[4,48], 这与稀土元素指标判别的物源结果一致。然而, 3 个阶段物源表现出明显的不同, S1 阶段研究区主要受印度河源区和阿拉伯半岛风尘控制, S2 阶段除了印度河和风尘的物质输入, 其物

图 6 AS06-13 岩芯沉积物 $\delta Eu_{UCC}-(La/Yb)_{UCC}$ 物源判别图

潜在沉积物来源选取印度河^[22]、德干高原^[50,51]、片麻岩区^[50]、北非风尘^[52]和阿拉伯半岛现代风尘^[53]; UCC: 上陆壳数据^[49]。

Fig.6 $\delta Eu_{UCC}-(La/Yb)_{UCC}$ provenance discrimination diagram of Core AS06-13

Potential sediment sources are from the Indus River^[22], the Deccan Traps^[50,51], the Peninsular Gneissic rock^[50], the North African dust^[52], and modern dust of the Arabian Peninsula^[53]; UCC: Upper Continental Crust^[49].

源还受到片麻岩区的影响; S3 阶段受到来自印度河、阿拉伯半岛风尘、片麻岩区和德干高原的综合影响。由此可见, 90 kaBP 以来阿拉伯海中部海域沉积物受控于周边陆源入海物质, 且呈现出明显的阶段性特征, 印度河、阿拉伯半岛风尘、片麻岩区和德干高原等物源区的贡献量处于动态平衡的关系, 进一步指示了北印度洋陆海相互作用的复杂性。

3.2 90 kaBP 以来阿拉伯海中部海域沉积过程

黏土矿物是—定气候条件下源区沉积物风化蚀变的产物,其含量和组合已被广泛应用于沉积环境和古气候演化研究^[54]。阿拉伯海中部海域沉积物源区黏土矿物各具特色,印度河搬运的沉积物主要为西喜马拉雅山脉和青藏高原的风化剥蚀产物,以结晶度良好的伊利石和绿泥石为特征^[21,23],德干高原主要由基性玄武岩组成,其气候条件有利于生成大量的蒙脱石^[14,17],片麻岩区处在亚热带-热带地区,黏土矿物以高岭石为主^[17,55]。Pourmand 等^[56]用阿拉伯海东北部 93 KL 岩芯的 ^{232}Th 通量作为风尘通量的替代指标,重建了 110 kaBP 以来阿拉伯半岛风尘输入演变过程,发现风尘输入与季风存在密切联系,高风尘通量归因于减弱的西南季风和加强的西北风^[4]。另有研究表明,来自阿拉伯半岛的风尘有较高的坡缕石含量(8%~37%)^[42,53],坡缕石作为特征矿物种类已被广泛用于示踪阿拉伯海沉积物中的风尘输入^[42,54]。因此,AS06-13 岩芯坡缕石含量的变化可作为阿拉伯半岛风尘物质的供应指标;伊利石结晶度是反映气候的有效指标,低值指示源区气候寒冷干燥^[21];高岭石作为温暖潮湿条件下经强烈化学风化形成的黏土矿物,与强烈物理侵蚀形成的伊利石作比值,可以反映化学风化的强弱,进而指示印度河和片麻岩区物源供应变化。

因此,在明确研究区物源的基础上,我们将 AS06-13 岩芯黏土矿物与海平面^[57]、印度夏季风强度指标^[58]等进行对比(图 7),并绘制了不同阶段的沉积演化示意图(图 8),以此来进一步探讨 90 kaBP 以来阿拉伯海中部海域沉积过程。

(1) S1 阶段(90~73 kaBP)

S1 阶段属于间冰期,该阶段全球气候温暖潮湿,全球海平面比现今低,西南季风较强,该阶段研究区物源受到印度河和阿拉伯半岛风尘控制,印度河为主要源区(图 8a)。强烈的西南季风导致的高降水量促进了喜马拉雅山脉的机械剥蚀^[53,54],大量碎屑物质经印度河及其周边河流输送至阿拉伯海深海扇,在沿岸流和深海通道的驱动下重新搬运至研究区。此外,研究区高坡缕石含量体现了阿拉伯半岛的风尘影响(图 7d),这与 ^{232}Th 通量变化一致。西南季风减弱期间,阿拉伯海中部通过相对加强的西北风接收来自阿拉伯半岛的风尘输入^[56,59]。温暖干燥的西北风携带大量灰尘,在抬升期间遇到了西南季风的潮湿低空急流,导致两个气团的季风逆转,风尘被输送到阿拉伯海中部海域^[4,60]。

(2) S2 阶段(73~11 kaBP)

S2 阶段属于末次冰期,该阶段气候寒冷干燥,海平面快速下降,西南季风减弱,这在 $\delta^{18}\text{O}$ 、 $\delta^{15}\text{N}$ 曲线上都有所体现。研究区除了受到印度河和风尘的物质输入,还受到片麻岩区物质的影响(图 8b)。

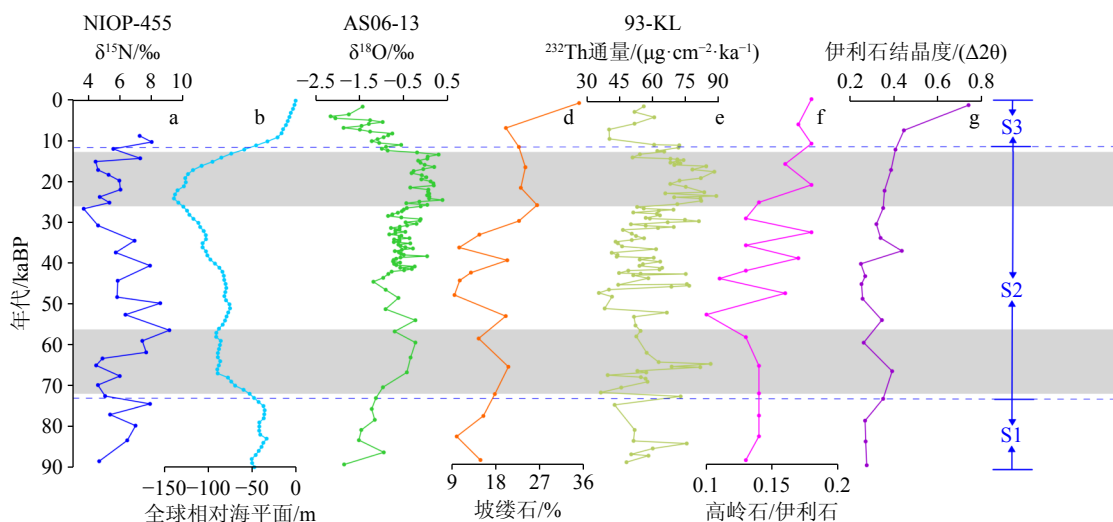


图 7 AS06-13 岩芯 90 kaBP 以来的沉积过程综合分析图

a: 阿拉伯海北部 NIOP 455 $\delta^{15}\text{N}$ 值^[58], b: 全球相对海平面^[57], c: AS06-13 岩芯 $\delta^{18}\text{O}$ 变化, d: AS06-13 岩芯坡缕石含量, e: 阿拉伯海北部 93KL ^{232}Th 通量^[56], f: AS06-13 岩芯高岭石/伊利石比值, g: AS06-13 岩芯伊利石结晶度。灰色阴影部分代表冰阶; S1—S3 表示不同阶段。

Fig.7 Comprehensive analysis of sedimentary processes of Core AS06-13 since 90 kaBP

a: The $\delta^{15}\text{N}$ record in Core NIOP 455 in the northern Arabian Sea^[58], b: the global relative sea level^[57], c: the $\delta^{18}\text{O}$ record in Core AS06-13, d: the palygorskite content of Core AS06-13, e: ^{232}Th flux of Core 93KL in the northern Arabian Sea^[56], f: the kaolinite/illite ratio of Core AS06-13, g: the illite crystallinity in Core AS06-13. Grey shadows represent glacial step. S1-S3 indicates different stages.

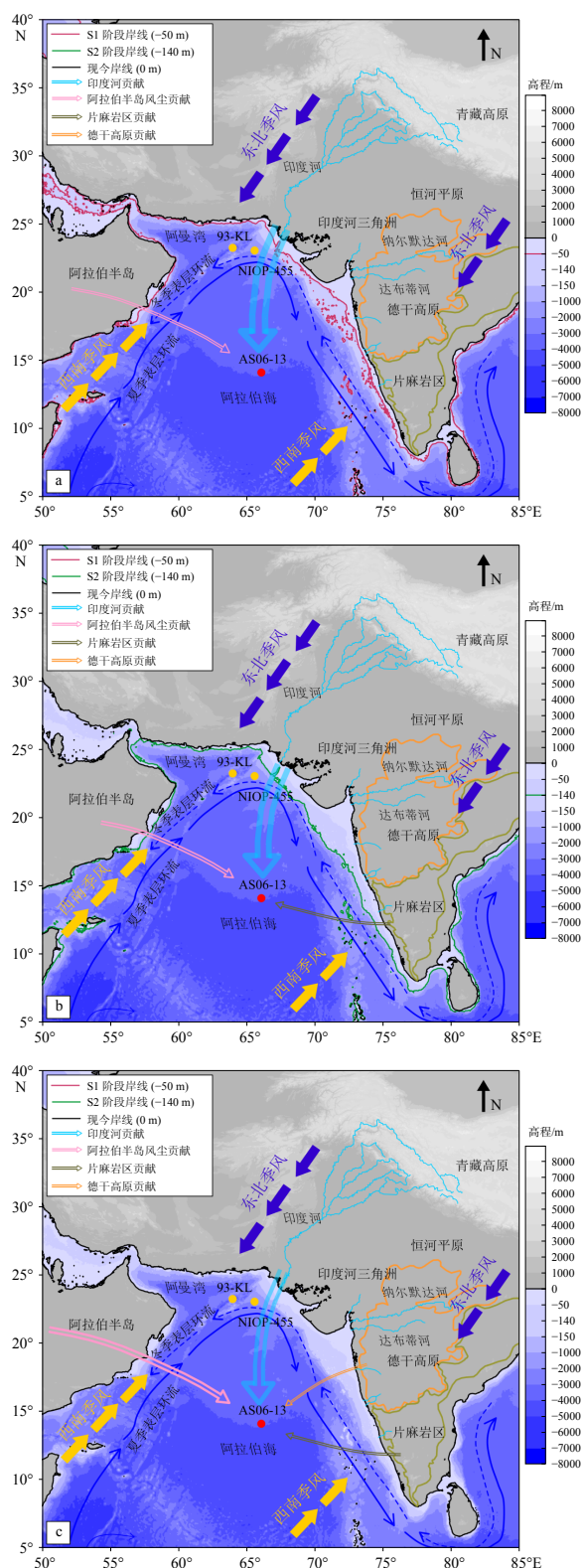


图 8 阿拉伯海中部海域 90 kaBP 以来沉积演化示意图
据文献 [21] 修改。a: S1 阶段 (90~73 kaBP), b: S2 阶段 (73~11 kaBP), c: S3 阶段 (11~0 kaBP)。

Fig.8 Schematic diagram of sedimentary evolution in the middle Arabian Sea since 90 kaBP

The datasets are referred from [21]. a: Stage S1 (90~73 kaBP), b: Stage S2 (73~11 kaBP), c: Stage S3 (11~0 kaBP).

研究区高岭石/伊利石比值降低, 伊利石结晶度较低 (图 7f, g), 表明在冰期寒冷干燥的气候下, 化学风化较低, 高岭石形成缓慢, 而喜马拉雅和青藏高原的冰川侵蚀加速, 导致大量来自印度河源区的物质输入到阿拉伯海中部海域。同时, 海平面快速下降导致大陆架大范围出露和河口向海迁移^[25,61], 提高了陆源碎屑沉积物向海洋输送的效率^[28]。图 7d 显示此阶段坡缕石含量增加, 指示末次冰期西南季风减弱, 较强的西北风将大量来自阿拉伯半岛的风尘物质输送到阿拉伯海中部^[4,60], 研究区风尘输入增多。在末次冰期的间冰阶 (56~26 kaBP), 西南季风有所增强, 伊利石结晶度显示化学风化增强 (图 7g), 气候较为温暖潮湿, 高岭石/伊利石比值升高 (图 7f), 更多来自片麻岩区的物质通过季风驱动的表层沿岸流被输送到研究区^[17], 而来自印度河的沉积物相对减少^[62]。

(3) S3 阶段 (11~0 kaBP)

S3 阶段属于全新世, 海平面迅速上升, 研究区 $\delta^{18}\text{O}$ 下降 (图 7c), 反映印度半岛及周边海域的季风降雨量增强, 伊利石结晶度的快速上升表明气候逐渐变为温暖湿润 (图 7g)。全新世研究区物质输入为混合来源, 整体表现为来自印度河、德干高原和片麻岩区的河流碎屑沉积减少, 而来自阿拉伯半岛的风尘输入增加 (图 8c)。由图 7f 可知, 全新世高岭石/伊利石的比值相对 S2 阶段 (末次冰期) 有所升高, 表明阿拉伯海来自印度河的沉积物输送减少, 而高坡缕石含量反映来自阿拉伯半岛的风尘增多^[48], 这与 ^{232}Th 通量变化一致 (图 7d, e), 推测此阶段阿拉伯海沉积物来源的转变主要受海平面的波动影响, 而季风为次级影响因素^[61]。海平面的升降和随后大陆架的淹没或出露, 使沉积物路径形态改变, 从而导致输送到海底的沉积物通量发生变化^[61-62]。全新世海平面的快速上升导致阿拉伯海深海扇系统的河流沉积物供应减少, 沿海海平面上升的速度不及河流沉积物输入的速度, 陆架沉积空间有限^[63], 陆源河流物质被限制在深海扇的浊流通道的内, 导致输入阿拉伯海中部海盆的河流沉积物急剧减少。

4 结论

(1) 阿拉伯海中部 AS06-13 岩芯的总稀土元素平均含量为 $113.66 \mu\text{g/g}$, 球粒陨石标准化的配分曲线表明轻稀土元素富集重稀土元素亏损, δEu (平均为 0.71) 存在明显负异常, 陆源特征明显。AS06-13 岩芯沉积物共鉴定出 5 类黏土矿物, 其中伊利石含

量最高(平均值为 56%),蒙脱石含量最低(平均为 2%)。此外,岩芯中还发现了一定量的坡缕石(平均含量为 18%)。

(2) $\delta\text{Eu}_{\text{UCC}}-(\text{La}/\text{Yb})_{\text{UCC}}$ 判别结果显示 90 kaBP 以来 AS06-13 岩芯的物源为混合来源,并呈现出明显的阶段性特征,可以划分为 3 个阶段(S1、S2、S3),其中 S1 阶段研究区主要受印度河源区和阿拉伯半岛风尘控制,S2 阶段除了受到印度河和风尘的物源输入,还受到来自片麻岩区的物质影响;S3 阶段受到来自印度河、阿拉伯半岛风尘、片麻岩区和德干高原的综合影响。

(3) 90 kaBP 以来阿拉伯海中部 AS06-13 岩芯的沉积物来源和沉积演化过程主要受季风和海平面的共同控制,且不同阶段影响程度不同。S1、S2 阶段研究区物源演化受季风、海平面的共同驱动,海平面的降低导致大陆架裸露,更多河流沉积物经深海通道输送到研究区,西南季风的减弱和海平面下降导致印度河、德干高原物质对研究区的输入量增多,东北季风的增强和西北风相对增强使阿拉伯半岛的风尘输入增加。S3 阶段则受到全新世海平面快速上升的强烈影响,使输入阿拉伯海的河流沉积物急剧减少。

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