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陆源与火山物质的向海输送过程及其控制机制

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摘 要: 海洋沉积物的源-汇过程是连接陆地风化、海洋动力系统和全球气候变化的关键纽带,对重建古环境演化具有重要意义.本文综述了陆源与火山物质向海洋的输送过程及其控制机制.陆源物质输运受岩性-气候-海平面-洋流系统共同调控——源岩性质和气候条件通过控制风化作用决定沉积物的产量和理化性质,海平面变化主导沉积物的输送距离,洋流格局决定最终沉积分布.火山物质的输入则受火山活动强度、气候、水文及区域构造背景的多元控制.近年来,地球化学与矿物学示踪技术的发展提升了物源识别能力,但该领域仍面临从定性描述到定量解析的方法学挑战.未来研究需进一步发展多学科交叉方法,以深化对海洋沉积源-汇系统演化规律的认识.

关键词: 源-汇系统;河流沉积;风尘沉积;冰川沉积;火山物质沉积;沉积学;气候变化.

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Transport Processes and Control Mechanisms of Terrigenous and Volcanic Materials to the Ocean

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Abstract: The source-to-sink process in marine sediments is a critical link connecting terrestrial weathering, oceanic dynamics, and global climate change, playing a vital role in reconstructing paleoenvironmental evolution. This paper reviews the transport processes of terrestrial and volcanic materials to the ocean and their control mechanisms. The transport of terrestrial materials is regulated by the lithology-climate-sea level-current system: the nature of the source rocks and climate conditions determine the output and physicochemical properties of the sediments by controlling weathering; sea level changes dominate the distance of sediment transport; and the current pattern determines the final distribution of the sediments. The input of volcanic materials is controlled by the intensity of volcanic activity, climate, hydrology and regional tectonic context. Recent advances in geochemical and mineralogical provenance techniques have significantly improved the identification capacity of sediment sources. However, this field still faces methodological challenges in transitioning from qualitative assessments to quantitative reconstructions. Future research should focus on developing integrated, multidisciplinary approaches to enhance our understanding of the evolution of marine sedimentary source-to-sink systems.

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Key words: source-to-sink system; fluvial deposits; aeolian deposits; glacial deposits; volcanic deposits; sedimentology; climate change.

0 引言

海洋沉积物源-汇过程是连接陆地风化、海洋动力系统以及全球气候变化的关键纽带,其研究对于揭示全球碳循环(Leithold *et al.*, 2016; Tao *et al.*, 2023)、古环境演化(Wan *et al.*, 2017; 石学法等, 2023; Yu *et al.*, 2024)以及矿产资源勘探(Garba and Mustapha, 2024)等具有重要的科学意义. 在全球气候变化日益加剧的背景下,如何准确预测未来气候变化趋势并制定合理有效的适应性策略成为了地球系统科学的前沿课题,而深入理解古气候、古环境的演化历史是准确预测未来气候变化的前提. 近年来,随着地球化学、矿物学等示踪方法的进步以及多学科交叉方法的突破,显著提升了物源识别精度以及物源过程解析能力,推动该领域从定性描述向定量分析发展.

海洋沉积物源-汇过程受多种因素协同控制. 气候系统主要通过控制风化速率和河流输沙量等影响陆源沉积物供给. 温暖潮湿的条件有利于原始矿物化学分解为风化产物,导致化学风化程度更高(Kump *et al.*, 2000; West *et al.*, 2005; Clift *et al.*, 2020). 降水是物理侵蚀强度和河流沉积物输送的关键控制因素,比如最近的研究表明在以高山短源河流为主的新几内亚北部,降水增加提高了物理侵蚀速率,导致流域土壤停留时间和沉积物储存时间减少,从而减少了沉积物化学风化的时间,这一过程促进了化学风化程度较低的碎屑矿物的输送(Yu *et al.*, 2024). 此外,热带辐合带、ENSO(厄尔尼诺-南方涛动, El Niño-Southern Oscillation)、印度洋偶极子等气候因子也会通过影响季风或降水等方式来影响海洋沉积物的源-汇过程(Yu *et al.*, 2016; Kang *et al.*, 2024; Tang *et al.*, 2024).

海平面波动对陆架暴露程度与沉积物输运路径具有重要的控制作用,一方面海平面升降会影响河口以及海岸线位置,进而影响沉积物输运和沉积的过程(Boulay *et al.*, 2007; Huang *et al.*, 2011). 另一方面,海平面升降会通过控制陆架暴露程度,进而影响陆架沉积物的风化和侵蚀(Wan *et al.*, 2017; Xu *et al.*, 2018). 比如,相对于海平面较高的时期,低海平面时期,河口向海迁移,有利于河流将大量沉积物输送至拉克希米盆地,沉积物粒度相对更粗(Cai *et al.*, 2022). 洋流与地形耦合则决定了沉积物的再分配模式与堆积中心位置,比如晚第四纪的海平面变化和黑潮路径主要决定了冲绳海槽陆源沉积物的扩散和沉积(Dou *et al.*, 2012); 黑潮入侵的增强可能是晚第四纪台湾岛沉积物向南海东北部输送的主要原因(Zhang *et al.*, 2022); 印度沿岸流的季节性转向控制了印度半岛南端沉积物的冷暖期变化(Goswami *et al.*, 2012; Kang *et al.*, 2024). 此外,构造活动,如青藏高原隆升(Clift *et al.*, 2004; Song *et al.*, 2024),通过改变流域侵蚀速率与物源区格局,对沉积通量产生长期影响.

源-汇过程复杂的控制机制决定了不同海域的源-汇系统显示出显著的空间异质性. 边缘海系统(如南海(Liu *et al.*, 2016; Cao *et al.*, 2023)、孟加拉湾(Li *et al.*, 2017; Liu *et al.*, 2019)、阿拉伯海(Cai *et al.*, 2022; Fang *et al.*, 2024)等)以陆源碎屑输入为主导,其物源解析需聚焦临近河流及区域环流特征; 而重建开阔大洋物源演化则需重点关注风尘输送、火山活动、生物源以及自生组分的贡献; 对于高纬海区(如北冰洋(Meinhardt *et al.*, 2016; Dong *et al.*, 2024))沉积物来源则需要重点考虑冰川作用的贡献. 这种空间分异特征要求人们在追踪物源时需针对不同海区的环境特征进行差异化分析,进而更准确地解析沉积物"从源到汇"的过程.

由于海洋沉积物源-汇过程受气候、海平面变化、构造活动和洋流演化等多因素的协同控制,使得海洋沉积物不仅是这些过程的产物,也是记录其演化历史的天然档案. 通过分析沉积物的地球化学组成、矿物学特征和沉积结构等信息,可以高精度重建古气候波动、海平面升降、构造活动以及洋流格局的长期演化序列,为理解地球系统演变提供关键证据. 本文将聚焦河流、风尘、冰川、火山等主要海洋沉积物来源类型,系统解析沉积物向海输送的过程,并阐明不同环境背景下沉积物源-汇过程的主要驱动机制,为海洋沉积物源-汇过程研究提供理论框架.

1 陆源物质输入及其控制机制

陆源沉积物,主要包括石英、长石、云母等矿物碎屑. 陆源沉积物输入是指陆地岩石经化学风化和

表1 全球陆源沉积物向海洋输送通量的估算

Table 1 Estimates of global fluxes of terrestrial sediment transport to the ocean

搬运机制	全球通量(Gt/a)
河流输入	25
风尘输入	0.7
冰川输入	2

注：表中数值据Syvitski *et al.*（2003)以及其中所引用的参考文献.

物理剥蚀等作用产生的碎屑物质，经河流、风以及冰川等外力搬运至海洋，并在洋流的作用下在海洋发生进一步搬运和沉积.陆源沉积物从源到汇的过程主要受到源区岩性、气候条件、海平面变化以及洋流强度/方向的控制.根据搬运方式，陆源沉积物输入类型可分为河流物质输入、风尘输入以及冰川物质输入，各类型陆源物质输入特征及其控制机制各有特点.

1.1 河流输入及其控制机制

全球河流每年向海洋输送的沉积物通量约占海洋接收陆源沉积物总量的95%（Syvitski *et al.*, 2003)，是陆源物质向海洋输入的最主要方式（表1)，河流向海洋输送沉积物的过程如图1所示.这些沉积物主要由碎屑颗粒（如石英、长石和黏土矿物)、有机质（如陆源植物碎屑和土壤有机碳)以及溶解态组分（如Si、Fe、Al等元素)构成.进入海洋的河流沉积物，是在海洋周围不同的气候、构造和岩性等环境中形成的（Liu *et al.*, 2016)，这些环境因素的变化控制了沉积物的物理和化学性质.

不同岩性岩石的抗风化能力不同，使得岩性成为源区沉积物产量的关键控制因素.酸性岩的抗风化能力相对基性岩更强，化学风化速率相对较慢（Bufe *et al.*, 2022)，这种特性直接影响着源区沉积物的供给强度.比如由于印度-太平洋交汇区岛屿岩性以中基性火山岩为主，地处热带，降水量大，水系以高山短源河流为主，易于风化、剥蚀和搬运（Yu *et al.*, 2023).因此，印度-太平洋交汇区岛屿面积虽小，但其河流入海沉积物量巨大，研究表明这些岛屿约占陆地总面积3%，但是其河流沉积物入海通量约占全球36%（Milliman and Farnsworth, 2011).相比之下，在气候条件一定时，花岗岩流域因岩石抗风化能力更强，其沉积物产出效率显著低于玄武岩流域（Ibarra *et al.*, 2016).

不同气候类型通过降水、温度等因素显著调控着河流向海洋的沉积物输送过程.在现有海洋沉积研究中，季风气候和热带雨林气候是探讨河流沉积物输入时受关注较多的两种气候类型，因此，笔者重点针对这两种气候类型对河流沉积物输送的影响机制展开讨论.在年际时间尺度上，季风气候区降水主要集中在夏季（Fazal *et al.*, 2023)，风向在夏季由海洋吹向陆地，冬季由陆地吹向海洋.在地质时间尺度上，主要表现为暖期夏季风较强，季风降水多；冷期夏季风较弱，季风降水少（Sarim *et al.*, 2023; Ning *et al.*, 2024).季风气候的这种明显的冷暖期变化特征，主要通过控制源区的剥蚀风化强度以及河流径流量来影响河流向海洋的沉积物输送过程.一般情况下，夏季风较强时，高温多雨，剥蚀和风化速率高，河流径流量大，可向海洋输送更多

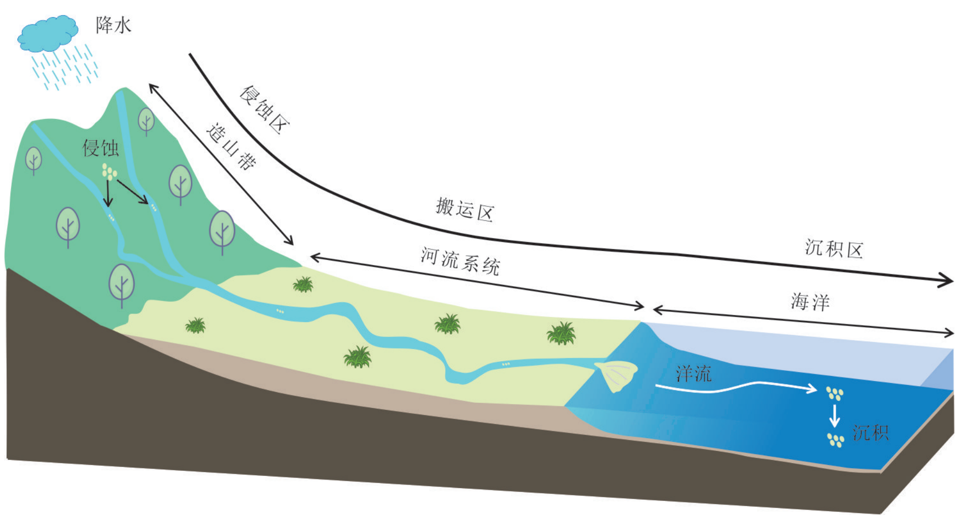

图1 河流物质输入示意（参考自Tofelde *et al.*, 2021)

Fig.1 Schematic diagram of fluvial material inputs (referenced from Tofelde *et al.*, 2021)

陆源沉积物(Clift and Jonell, 2021),比如黄河(Xu *et al.*, 2025)、印度河(Clift and Jonell, 2021)等主要河流均呈现出此特点.值得注意的是,并非所有河流沉积物输入量都呈现出夏季风盛行期增加,冬季风盛行期减少的规律.比如位于南冲绳海槽的岩心记录表明,由于在夏季风减弱时,锋面系统南撤,导致中国南部降水量增加,源区剥蚀风化增强,河流净流量增加,从而导致陆源物质输入比例增加;反之,在夏季风增强时,其陆源物质输入比例减少(陈金霞等, 2009).对于热带源区而言,当发生冷暖期的气候变化时,其温度和降水同样会发生变化,该变化控制着源区的剥蚀、风化速率以及河流径流量,进而控制了河流向海洋的沉积物输送.但与季风气候不同,即使是在冷期,热带源区的剥蚀和风化速率可能依旧处于一个较高的水平,河流径流量可能也一直较大,所以其冷暖期的剥蚀、风化变化特征可能与季风气候区不同.比如,对于热带新几内亚岛鸟头半岛北部而言,由于暖期降水量大,物理侵蚀速率快,并且沉积物被快速输送至海洋,导致沉积物化学风化的时间较短,进而导致沉积物在暖期化学风化程度更低,而在冷期化学风化程度相对更高(Yu *et al.*, 2023).

海平面变化主要通过控制大陆架的裸露来影响河流向海洋输送沉积物的情况.宽广大陆架受海平面影响较大,在高海平面或海平面上升期间,随着大陆架逐渐被海水覆盖,陆源碎屑物质被向海搬运的过程中会在陆架区沉积(Prins and Postma, 2000; Kessarkar *et al.*, 2003);在低海平面或海平面下降时,大陆架裸露,河流入海口向海延伸(Huang *et al.*, 2011),沉积中心向海迁移(Li *et al.*, 2020a).一方面,这会导致裸露陆架上的沉积物再次被剥蚀、风化并搬运,最终输送至海洋并沉积(Wan *et al.*, 2017);另一方面,岸线和河口的向海迁移会导致粒度带整体向海推移,致使同一地理位置出现沉积物粒度明显粗化的现象(Boulay *et al.*, 2007).二者共同作用,最终控制着河流输入沉积物的物理和化学性质,例如巽他陆架(Hanebuth *et al.*, 2002).但是,需要特别指出的是,这种海平面变化对沉积物输送的调控效应主要集中在具有宽广大陆架的海域,而对于日本岛周边(Zhao *et al.*, 2020)和新几内亚岛北部海域(Tang *et al.*, 2024)等陆架狭窄的区域,河流输送沉积物的特征受海平面波动的影响则相对有限.

在沉积物进入海洋之后,主要随洋流被进一步的搬运.洋流的方向和强度控制了河流沉积物入海后的最终分布和特征.尤其是受季风控制季节性转向的洋流,比如沿岸流.洋流的转向控制了位于洋流路径区域的沉积物来源和特征的季节性变化,在地质时间尺度上可能体现为冷暖期的变化(万世明等, 2008; Goswami *et al.*, 2012; Kang *et al.*, 2024).而洋流的强度对沉积物具有重要的分选效应,当洋流搬运能力较强时,沉积在某一位置的沉积物粒度相对可能会更粗;反之,沉积物粒度相对会更细(Wang *et al.*, 2015; 宋震等, 2024).

1.2　风尘输入及其控制机制

海洋风尘沉积是指陆源物质通过大气动力搬运后最终在特定海区沉降形成的一类沉积物,其源–汇过程如图2所示.其主要来源于干旱–半干旱地区的表层风化物质,在风力作用下被抬升进入大气,并随全球环流系统进行远距离传输.当风速达到临界阈值时,在土壤湿度低、植被少和可侵蚀沉积物供应充足的地区,风尘沉积物就会被释放出来(Maher *et al.*, 2010; Rowland, 2021).这类沉积物主要由小于10 μm的细小颗粒组成(Rea and Hovan, 1995; Rea *et al.*, 1998).全球每年约有2 000 Mt风尘进入大气循环系统,其中约四分之一最终沉降在海洋环境(Shao *et al.*, 2011),尽管其通量仅相当于河流输入量的5%(Duce *et al.*, 1980),但在远离大陆的远洋深水区,风尘沉积却成为深海沉积物的主要来源(万世明和李安春, 2004; Serno *et al.*, 2014).

风尘输入也主要受岩性、气候和洋流等多重因素的协同控制.源区岩性和洋流对风尘输入的控制机制与上述河流物质输入类似,这里不再重复.海平面变化导致的大陆架裸露并非风尘输入的主要影响因素.在地质时间尺度上,冷暖期的气候变化是海洋风尘输入的重要控制因素.冰期较高的干旱程度、较少的植被以及较强的风,导致风尘输入量更高(Muhs, 2013; Wan *et al.*, 2020).冰期全球的风尘通量比间冰期高2~5倍(Maher *et al.*, 2010; Wan *et al.*, 2020).降水和风等气候因子是影响风尘输入的关键因素.其中风的强度决定了风尘的粒度,源区的干旱程度决定了风尘通量(Rea *et al.*, 1985; Rea, 1994; Wan *et al.*, 2020).风力越强,风尘的粒度一般会更大(Stuut *et al.*, 2014).随着风尘源区干旱程度的增加,风尘通量一般也会相应增加,比如,菲律宾海西部风尘输入的增加与东亚冬季

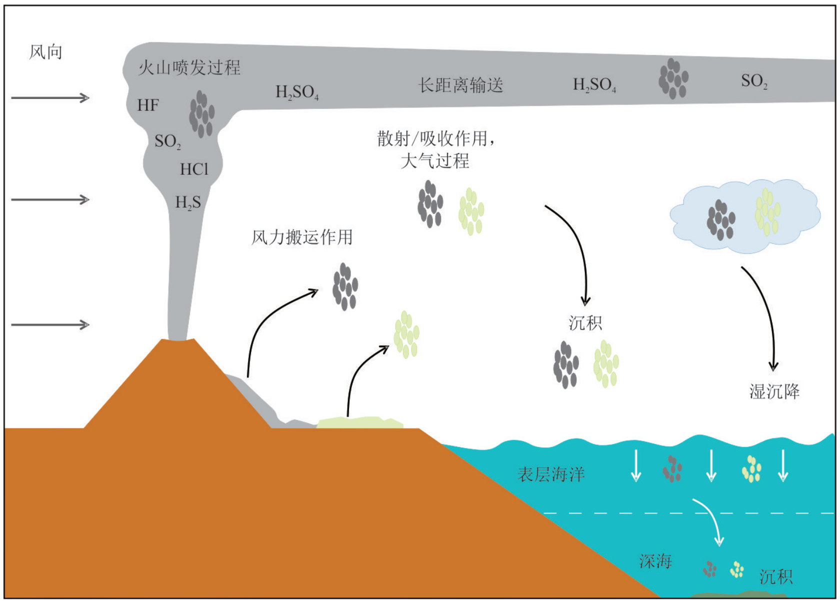

图 2　风尘及火山物质输入示意

Fig.2　Schematic diagram of dust and volcanic material input

图改自 Langmann（2013）；图中灰色颗粒物质代表火山喷发的碎屑物质，指示火山物质源-汇过程；淡黄色颗粒物质代表陆源碎屑物质，指示风尘物质源-汇过程

表 2　主要源区现代年平均风尘通量模拟结果对比

Table 2　Comparison of modern annual average eolian flux simulation results for major source regions

文献	非洲		亚洲			美洲		澳大利亚	全球
	北部	南部	阿拉伯	中部	东部	北部	南部		
Tanaka and Chiba, 2006	1 087（58%）	63（3%）	221（12%）	140（7.5%）	214（11%）	2（0.1%）	44（2%）	106（6%）	1 877
Werner *et al.*, 2002	693（65%）		101（9.5%）	96（9%）				52（5%）	1 060
Luo *et al.*, 2003	1 114（67%）		119（7%）		54（3%）			132（8%）	1 654
Zender *et al.*, 2003	980（66%）		415（28%）			8（0.5%）	35（2%）	37（2.5%）	1 490
Ginoux *et al.*, 2004	1 430（69%）		496（24%）			9（0.4%）	55（3%）	61（3%）	2 073
Miller *et al.*, 2004	517（51%）		43（4%）	163（16%）	50（5%）	53（5%）		148（15%）	1 019

注：通量数值据 Maher *et al.*(2010)，单位：Tg/a；括号内为全球占比.

风强度和亚洲大陆干旱程度的增加基本一致（Wan *et al.*, 2012；孙军等，2025），而源区降水的增加会导致输送至菲律宾海的风尘通量相对较低（Wang *et al.*, 2020）. 但需要注意的是，长时间持续极端干旱可能会因源区风尘物质供应匮乏而导致通量减少（万世明和李安春，2004）.

北非、东亚和中亚以及阿拉伯的干旱地区是三个主要的现代沙尘源区（表 2），均位于北半球（Rea, 1994；Maher *et al.*, 2010）. 从全球范围来看，太平洋、北大西洋和西北印度洋是风尘沉积的主要海区（于兆杰，2013）. 中亚东部的半干旱和干旱地区是太平洋最大的风尘来源，来自该区域在中国下风方向的风尘沉降率超过 1 000 mg/(cm^2·ka)（Rea, 1994）. 但是，除了中亚东部的半干旱和干旱地区，太平洋也会接收来自其他区域的风尘，比如东南信风可以将秘鲁和智利的半干旱至极度干旱地区的沉积物输送至太平洋东南部（Saukel *et al.*, 2011），澳大利亚东南部和新西兰的沉积物会通过

风被输送至太平洋西南部(Stancin *et al.*, 2008).

撒哈拉沙漠向大西洋输送的沙尘总量约为(970±325) Tg/a,是大西洋的主要沙尘源(Rowland, 2021).大西洋表层沉积物中Ti/Al证据表明,北非地区的风尘是加那利盆地陆源物质的主要来源(Govin *et al.*, 2012).在千年时间尺度上,非洲湿润期、海因里希事件和新仙女木事件等对北非风尘通量具有显著影响,非洲西北边缘20 ka以来的风尘通量记录显示,在海因里希事件和新仙女木事件期间风尘通量达到峰值,而在非洲湿润期风尘通量显著降低(McGee *et al.*, 2013).24万年以来,撒哈拉沙漠风尘通量的变化主要受岁差周期驱动,与北半球夏季日照变化高度一致,而受冰期-间冰期旋回的影响较弱(Skonieczny *et al.*, 2019).但是,撒哈拉沙漠并非大西洋风尘沉积的唯一来源.例如位于北大西洋的U1313站位的放射性成因同位素(Sr、Nd、Pb)证据表明,上新世期间其陆源沉积物主要为来自北美中纬度地区的风尘(Lang *et al.*, 2014).

东阿拉伯海通过西南季风的湿沉降(降水)接收了大量的风尘物质(Ramaswamy *et al.*, 2017; Suresh *et al.*, 2021).地球化学证据表明,阿拉伯半岛对季风开始(6月)和季风中期(7~8月)的风尘贡献显著,非洲东北部也在季风中期贡献了部分风尘物质,亚洲西南部和塔尔沙漠贡献了季风末期(9月)的风尘物质(Suresh *et al.*, 2021).西赤道印度洋的Sr-Nd同位素证据表明,其陆源风尘主要来源于阿拉伯半岛(Zhou *et al.*, 2024).北半球千年时间尺度气候振荡通过影响季风强度调控了阿拉伯海的风尘输送,海因里希事件期间风尘输入量减少,Dansgaard-Oeschger期间夏季风强度增强,风尘输入量增加(Sebastian *et al.*, 2023).间冰期,夏季降水量增加,源区植被覆盖扩张,阿拉伯海的风尘供应减少;冰期,高纬度冰盖扩张导致全球温度梯度增加,季风减弱,副热带西风急流更偏南、更冷和下沉,源区干旱加剧,风尘供应又急剧增加(Zhou *et al.*, 2024).

从陆地向海洋的风尘输入给海洋提供了大量浮游植物生长所必需的营养元素(Wan *et al.*, 2020),对海洋生产力以及海洋生物地球化学循环具有重要影响(Jickells *et al.*, 2005).南大洋和太平洋的沉积记录显示风尘铁通量与海洋生产力之间存在很强的相关性(Han *et al.*, 2011; Martínez-García *et al.*, 2014).海洋生产力的变化又可能会对碳循环产生影响(Han *et al.*, 2011).比如,在寒冷干旱的气候条件下,风尘通量的增加和上升流的增强,会导致大陆边缘营养物质增加,初级生产力升高,进而导致海洋缺氧,促进有机碳保存(Zhai *et al.*, 2018).

1.3 冰川物质输入及其控制机制

冰川物质输入是极地和高纬度海域沉积物的重要来源,其主要通过冰山漂移、冰筏碎屑释放以及冰川融水携带的细颗粒物质等方式进入海洋环境,其源-汇过程如图3所示.例如,Xiao *et al.*(2024)基于北极楚科奇海边缘沉积岩心的分析认为,其沉积物主要来自东西伯利亚冰盖、劳伦泰德冰盖等的冰川输入,沉积物主要包括粗粒冰筏碎屑以及与融水相关的沉积物等.在晚更新世期间,北美北极地区的冰盖和欧亚大陆北部的冰盖崩裂了大量的冰山,这些冰山通过弗拉姆海峡漂流到格陵兰海,沉积了氧化铁颗粒和粗粒岩屑等(Darby *et al.*, 2002).

冰川物质输入主要受气候、洋流以及冰川动力学等的共同影响.气候变暖会加速冰川消融,更多冰川融水进入海洋;同时,冰体流动性增加甚至解体,从而将冰川沉积物输送至海洋(黄晓璇等, 2018; 张鑫悦等, 2023).洋流系统将海冰及其中的沉积物从冰架上搬运到整个北冰洋,海冰漂移构成了从北极沿岸和陆架向整个海盆输送碎屑物质的主要途径(Meinhardt *et al.*, 2016).洋流强弱和方向的变化还会控制冰川物质在海洋的分布及特征.比如,北极群岛的碳酸盐岩碎屑被冰山和海冰以冰筏碎屑的形式在波弗特环流(Beaufort Gyre)的作用下被输送至北冰洋并沉积(Meinhardt *et al.*, 2016).间冰期较强的波弗特环流可以将携带冰筏碎屑的冰山等搬运至西北冰洋并沉积,而冰期较弱的波弗特环流无法将粗的冰筏碎屑搬运至西北冰洋(黄晓璇等, 2018).冰川动力学决定了沉积物的侵蚀效率和物质输运量.在末次冰期旋回中,湿底型的白令冰川至少三次前进至大陆架边缘,以极高平均速率(可达10 m/ka)向大陆架和大陆坡输送了至少925 km^3的冰川沉积物(Montelli *et al.*, 2017).冰盖消退或崩解可能会导致大量海冰或冰山携带沉积物进入深海(Kaparulina *et al.*, 2016).这些控制机制的相互作用使得冰川物质输入在千年至轨道时间尺度上呈现显著的变异性,并为重建古气候和冰盖演化提供了关键沉积学指标.

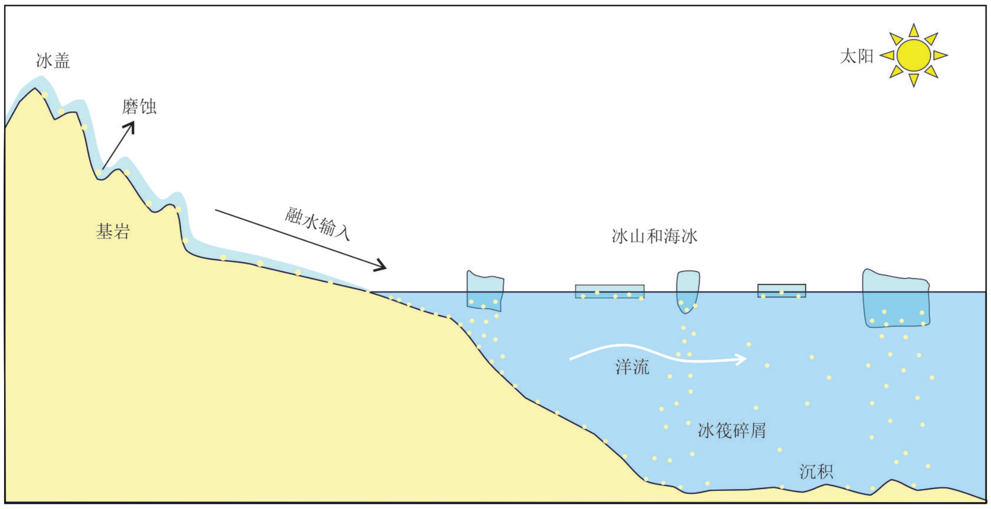

图 3　冰川物质输入示意(参考自 Kaparulina *et al*., 2016)

Fig.3　Schematic diagram of glacial material input (referenced from Kaparulina *et al*., 2016)

2　火山物质输入及其控制因素

火山沉积物可分为陆上火山喷发物质和洋中脊或海底火山喷发物质.本文重点讨论来自陆地火山活动的物质.火山物质指的是由火山活动产生的各类碎屑物质,包括火山灰、火山玻璃及火山碎屑岩等,其形成与搬运过程构成了一个复杂的地球表层物质循环系统,其源-汇过程如图 2 所示.这些物质主要通过火山喷发直接进入大气圈或水体环境,随后经历物理化学风化、搬运和沉积等一系列地质作用.火山碎屑颗粒的形态特征可提供有关破碎过程和形成环境的重要信息(Carey and Schneider, 2011).火山灰是由岩浆和火山口围岩物质的破碎作用形成的,平均粒径小于 2 mm (Zimanowski *et al*., 2003),其成分包括细小的火山玻璃颗粒、矿物碎片等.火山玻璃是火山喷发出的熔岩在迅速冷却过程中未能及时结晶而形成的玻璃质结构岩石.它通常缺乏规则的形状,可能呈现珍珠状、气孔状或不规则状.Bao *et al*.(2023)在南海东部深海盆地发现的火山玻璃以棕色为主,伴生少量白色和无色类型,表明安山岩可能是主要源岩,其中白色火山玻璃具有典型的流动结构.

在喷发过程中,火山物质被喷射至不同高度的大气层,强烈的火山喷发甚至能将火山灰输送至平流层(Robock, 2000).这些悬浮的火山碎屑随后在大气环流系统的驱动下进行扩散传输,最终通过干沉降(重力作用)或湿沉降(随降水)过程从大气中移除(Brown *et al*., 2012),并在海洋和陆地等地表环境中发生沉积.值得注意的是,沉降在陆地表面的火山碎屑会经过风化侵蚀作用,随后被河流、冰川等外营力二次搬运至海洋环境.

火山碎屑物质经历的多阶段搬运与沉积过程,使得海洋沉积物中的火山物质不仅保留了原始喷发的特征信息,同时也承载了后期地质改造的印记.这一完整的物质循环系统的运行效率受到火山活动强度、气候条件以及洋流等多重因素的综合影响与调控.火山活动越强,向海洋输送的火山物质可能会越多.以南海东部深海沉积岩心为例,由于源区在间冰期的火山喷发强度显著高于冰期,这导致了沉积物在间冰期呈现 ε_{Nd} 值偏高而 $^{87}Sr/^{86}Sr$ 比值偏低的特征,即火山物质在间冰期相对含量增加(Bao *et al*., 2023).此外,气候和洋流对火山碎屑物质搬运与沉积过程的具体控制机制可参见上一节的详细论述.值得注意的是,火山活动对气候变化也会有一定影响,比如有研究表明,北半球长期冷却趋势(始于约 3.5 Ma 前)使气候系统接近冰盖形成的临界点,而 2.65 Ma 前火山活动的突然增强(叠加北纬高纬度地区的低日照条件)为冰盖快速扩张提供了最终触发条件,促使北半球冰期迅速发展(Prueher and Rea, 2001).

火山灰的大量堆积可能会改变沉积物的粒度特征,掩盖原有的沉积物粒度变化规律.火山灰层的粒径由盛行风强度、火山喷发的火山灰粒径以及火山喷发强度等共同决定(Carey and Sigurdsson, 2000).火山活动为海底沉积环境引入了大量富铁火成岩矿物,如橄榄石、辉石、角

闪石、钙铝榴石、黑云母等(Li *et al.*, 2020b).此外,在海洋环境中,火山玻璃风化会释放出Fe、Mn、Al、Mg、Ca等元素,可能对海洋的地球化学循环具有重大意义(Chen *et al.*, 2014).

大量火山物质进入海洋会影响海洋生态环境,并可能引发全球气候变化以及生物灭绝(Li *et al.*, 2020b).为应对火山活动突发性和不确定性的挑战,建立有效的监测和预警机制至关重要.在监测和预警工作中,需要综合运用地震、气体、地表形变、遥感、无人机及次声波等多种监测技术手段,以实时捕捉火山活动信号;同时构建多源数据融合的预警平台,借助大数据和人工智能优化预警的准确性与及时性.

3　地球化学与矿物学示踪技术

Sr-Nd同位素组成和黏土矿物组成是追踪沉积物来源的可靠指标,已被广泛用于南海(Cai *et al.*, 2020; Jin *et al.*, 2022)、菲律宾海(Seo *et al.*, 2014; Xu *et al.*, 2018)、阿拉伯海(Yu *et al.*, 2019; Kang *et al.*, 2024)、孟加拉湾(Liu *et al.*, 2019)等海域的沉积物来源判别,本文将着重讨论这两种物源示踪方法.

Sr-Nd同位素主要受源岩岩性和年龄的控制(Kessarkar *et al.*, 2003),而对地表过程不敏感(Hu *et al.*, 2020; Duan *et al.*, 2023),所以基于Sr-Nd同位素组成可以追踪沉积物的物源.但是,需要注意的是,由于Sr比Nd更具流动性且在风化过程中易从土壤中流失,其同位素组成更易受化学风化程度控制(Goldstein and Jacobsen, 1987; Kessarkar *et al.*, 2003).从元素地球化学行为来看,Rb和Sr表现出显著差异:首先,二者因物理化学性质的差异会选择性地进入不同硅酸盐矿物.含Sr矿物(如斜长石和方解石)的化学稳定性通常低于含Rb矿物(如云母类和钾长石),使其在风化过程中更易分解,从而导致Sr更易从矿物中析出(Feng *et al.*, 2009).其次,Sr在岩石化学风化过程中会被释放到溶液中(Brass, 1975).因此,化学风化不仅使矿物粒度减小,还会引起残留矿物中Rb/Sr比值增大,进而促进风化产物中$^{87}Sr/^{86}Sr$比值增大(Feng *et al.*, 2009).

此外,碎屑沉积物的$^{87}Sr/^{86}Sr$比值也会受到粒度效应的控制,而ε_{Nd}则主要反映沉积物来源的变化(Duan *et al.*, 2023; Gao *et al.*, 2025).这主要与Rb和Sr的不同地球化学性质以及Sm和Nd的相似地球化学性质有关,由于细粒组分中云母含量较高,而云母中Rb/Sr比值较高,因此细粒组分往往富集放射性成因^{87}Sr(Feng *et al.*, 2009).非洲西北部沿岸深海沉积物的研究也表明粒度对Sr同位素组成的影响是显著的,细粒组分比粗粒组分$^{87}Sr/^{86}Sr$比值更高,而Nd同位素则基本不受粒度影响(Meyer *et al.*, 2011).

不同岩石类型在风化过程中会形成不同类型的黏土矿物,因此,特定地区的母岩类型和风化历史会形成独特的黏土矿物"指纹".伊利石通常被视为原生矿物,其含量较高则表明在寒冷干旱的气候条件下,大陆风化作用中的水解过程减弱,而直接的物理侵蚀作用则相对增强;蒙脱石是一种次生矿物,由原生铝硅酸盐和铁镁硅酸盐在温暖潮湿条件下经化学风化而成;高岭石很容易在单硅铝化土壤中被发现,主要受大陆水解强度的控制(Liu *et al.*, 2007).在印度西北喜马拉雅前沿地区的Pinjor组,伊利石主要来源于长石和云母的风化;绿泥石主要来自中基性结晶岩和低级变质岩;高岭石主要是酸性环境下花岗岩和基性岩的风化产物(Chaudhri and Singh, 2012).台湾地区由于广泛出露第三纪沉积岩,尤其是砂岩、页岩和板岩,具有较强的物理风化作用,导致河流沉积物中伊利石和绿泥石富集(Li *et al.*, 2012).类似地,青藏高原东部隆起的古生代-中生代沉积岩和少量侵入受挤压的火成岩,构成了红河和湄公河水系中上游的主要基岩类型,其黏土矿物组成以伊利石为主,绿泥石和高岭石次之,蒙脱石含量较少(Liu *et al.*, 2007).

Sr-Nd同位素与黏土矿物组成作为两种经典且互补的物源示踪技术,在海洋沉积动力学重建及古环境演变研究中具有不可替代的重要价值.需要特别指出的是,沉积体系中的地球化学和矿物学信号往往记录了多因素耦合作用的综合地质信息.然而由于陆源物质输入的复杂性,现阶段相关研究多局限于主要物源的定性判别,而无法精准定量示踪其所有可能的物质来源.除了地球化学和矿物学物源示踪技术外,还有很多其他的方法,比如有机地球化学标志物等.在未来的研究中,可以多指标耦合分析,并结合主成分分析、机器学习等现代技术,以提高物源判别精度.

4 总结与展望

海洋沉积物源-汇过程是涉及物质产生-搬运-沉积的系统性地质过程，根据物质来源可将海洋沉积物划分为陆源物质、火山物质、生物源沉积物、自生沉积物以及宇宙源沉积物等主要类型．在前人研究的基础上，本文着重探讨了陆源和火山物质的输入过程及其控制机制．

陆源物质输入根据搬运方式又可分为河流物质输入、风尘输入和冰川物质输入，其源-汇过程主要受源岩性质、气候条件、海平面变化以及洋流强度/方向控制．具体而言，源岩性质和气候条件共同决定了源区的风化强度和类型，进而影响陆源物质的产量及理化性质；海平面变化主要调控沉积物的搬运距离，由此对沉积物通量、粒度特征等理化性质产生显著影响；洋流的强度和方向则决定了陆源物质在海洋环境中的最终沉积分布格局．除了上述共性控制机制外，各类陆源物质输入又有其独特的控制机制：降水是河流物质输入的直接气候控制因素，显著影响着沉积物的剥蚀过程与河流的搬运能力；源区干旱程度和风力条件是风尘沉积的主要控制因素，分别主导沉积物通量和粒度特征；冰川动力学是冰川输入特有的控制机制，主要控制沉积物的侵蚀效率和沉积物通量等．火山碎屑物质向海洋的输入过程则受到火山活动强度、气候条件、洋流及区域构造背景等多重因素的综合影响与调控．其中，区域构造背景决定了火山的分布及其喷发频率，火山活动强度决定了火山物质的供给量，气候条件和洋流主要控制火山物质的搬运和沉积过程．

深入理解沉积物源-汇过程及其控制机制是开展海洋沉积与古环境研究的前提，正因受到各种控制机制的约束，海洋沉积物得以成为记录古环境演化的良好档案．通过“将今论古”与“以古示今”研究范式的有机结合，古气候环境重建为理解地球系统演变规律和预测全球气候变化提供了重要理论支撑．但需注意的是，现存研究在机制解析层面仍存在双重局限：其一，沉积响应作为多因素非线性作用的综合产物，现有方法体系难以实现各控制端元的定量解耦与贡献度分离；其二，物源示踪技术虽已建立矿物和地球化学等多种方法，但在多物源混合沉积区仍面临成因多解性判识难题，现有解译多停留于定性分析层面．突破上述瓶颈需着力构建多学科协同研究体系，将传统沉积学方法与数值模拟等新技术相结合，以推动源-汇过程定量分析．

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References

Bao, C., Kong, D. M., Wei, G. Y., et al., 2023. Provenance of Deep-Sea Sediments in the Eastern South China Sea since Marine Isotope Stage 5 (MIS 5) and Implications for Climate Change and Volcanic Activity. *Marine Geology*, 463: 107118. https://doi.org/10.1016/j.margeo.2023.107118

Boulay, S., Colin, C., Trentesaux, A., et al., 2007. Sedimentary Responses to the Pleistocene Climatic Variations Recorded in the South China Sea. *Quaternary Research*, 68(1): 162－172. https://doi. org/10.1016/j.yqres.2007.03.004

Brass, G. W., 1975. The Effect of Weathering on the Distribution of Strontium Isotopes in Weathering Profiles. *Geochimica et Cosmochimica Acta*, 39(12): 1647－1653. https://doi.org/10.1016/0016-7037(75)90086-1

Brown, R. J., Bonadonna, C., Durant, A. J., 2012. A Review of Volcanic Ash Aggregation. *Physics and Chemistry of the Earth*, *Parts A/B/C*, 45: 65－78. https://doi.org/10.1016/j.pce.2011.11.001

Bufe, A., Cook, K. L., Galy, A., et al., 2022. The Effect of Lithology on the Relationship between Denudation Rate and Chemical Weathering Pathways - Evidence from the Eastern Tibetan Plateau. *Earth Surface Dynamics*, 10(3): 513－530. https://doi. org/10.5194/esurf-10-513-2022

Cai, G. Q., Li, S., Zhao, L., et al., 2020. Clay Minerals, Sr - Nd Isotopes and Provenance of Sediments in the Northwestern South China Sea. *Journal of Asian Earth Sciences*, 202: 104531. https://doi. org/10.1016/j.jseaes.2020.104531

Cai, M. J., Colin, C., Xu, Z. K., et al., 2022. Climate and Sea Level Forcing of Terrigenous Sediments Input to the Eastern Arabian Sea since the Last Glacial Period. *Marine Geology*, 450: 106860. https://doi. org/10.1016/j.margeo.2022.106860

Cao, L. C., Shao, L., van Hinsbergen, D. J. J., et al., 2023. Provenance and Evolution of East Asian Large Rivers Recorded in the East and South China Seas: A Review. *GSA Bulletin*,: 135(11－12): 2723－2752.

https://doi.org/10.1130/b36559.1

Carey, S. N., Schneider, J. L., 2011. Volcaniclastic Processes and Deposits in the Deep-Sea. Elsevier, Amsterdam, 457—515. https://doi.org/10.1016/b978-0-444-53000-4.00007-x

Carey, S., Sigurdsson, H., 2000. Grain Size of Miocene Volcanic Ash Layers from Sites 998, 999, and 1 000: Implications for Source Areas and Dispersal. *Proceedings of the Ocean Drilling Program, Scientific Results*, 165: 101—113. https://doi. org/10.2973/odp. proc. sr.165.002.2000

Chaudhri, A. R., Singh, M., 2012. Clay Minerals as Climate Change Indicators—A Case Study. *American Journal of Climate Change*, 1(4): 231—239. https://doi. org/10.4236/ajcc.2012.14020

Chen, J. X., Li, T. G., Nan, Q. Y., 2009. Variations of Terrigenous Material Discharges in the South Okinawa Trough and Its Relation to the East Asian Summer Monsoon since the Last Millennium. *Earth Science*, 34(5): 811—818 (in Chinese with English abstract).

Chen, S., Wu, Z. J., Peng, X. T., 2014. Experimental Study on Weathering of Seafloor Volcanic Glass by Bacteria (Pseudomonas Fluorescens)-Implications for the Contribution of Bacteria to the Water-Rock Reaction at the Mid-Oceanic Ridge Setting. *Journal of Asian Earth Sciences*, 90: 15—25. https://doi. org/10.1016/j.jseaes.2014.04.012

Clift, P. D., Jonell, T. N., 2021. Monsoon Controls on Sediment Generation and Transport: Mass Budget and Provenance Constraints from the Indus River Catchment, Delta and Submarine Fan over Tectonic and Multimillennial Timescales. *Earth-Science Reviews*, 220: 103682. https://doi.org/10.1016/j.earscirev.2021.103682

Clift, P. D., Kulhanek, D. K., Zhou, P., et al., 2020. Chemical Weathering and Erosion Responses to Changing Monsoon Climate in the Late Miocene of Southwest Asia. *Geological Magazine*, 157(6): 939—955. https://doi.org/10.1017/s0016756819000608

Clift, P. D., Layne, G. D., Blusztajn, J., 2004. Marine Sedimentary Evidence for Monsoon Strengthening, Tibetan Uplift and Drainage Evolution in East Asia. *Geophysical Monograph Series*, 149: 255—282. https://doi. org/10.1029/149gm14

Darby, D. A., Bischof, J. F., Spielhagen, R. F., et al., 2002. Arctic Ice Export Events and Their Potential Impact on Global Climate during the Late Pleistocene. *Paleoceanography*, 17(2): 15-11—15-17. https://doi.org/10.1029/2001pa000639

Dong, L. S., Polyak, L., Zhang, Y., et al., 2024. Isotopic Constraints on the Late Pleistocene Glacial Water and Sediment Inputs to the Central Arctic Ocean. *Quaternary Science Reviews*, 334: 108733. https://doi. org/10.1016/j.quascirev.2024.108733

Dou, Y. G., Yang, S. Y., Liu, Z. X., et al., 2012. Sr-Nd Isotopic Constraints on Terrigenous Sediment Provenances and Kuroshio Current Variability in the Okinawa Trough during the Late Quaternary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 365: 38—47. https://doi.org/10.1016/j.palaeo.2012.09.003

Duan, Z. F., Li, C., Guo, Y. L., et al., 2023. Sr-Nd Isotopic Fingerprints of Red River Sediments and Its Implication for Provenance Discrimination in the South China Sea. *Marine Geology*, 457: 106997. https://doi. org/10.1016/j.margeo.2023.106997

Duce, R. A., Unni, C. K., Ray, B. J., et al., 1980. Long-Range Atmospheric Transport of Soil Dust from Asia to the Tropical North Pacific: Temporal Variability. *Science*, 209(4464): 1522—1524. https://doi.org/10.1126/science.209.4464.1522

Fang, T. B., Liu, S. F., Wu, K. K., et al., 2024. Sediment Provenance Variations Driven by Sea Level in the Eastern Arabian Sea since the MIS 9 Period: Evidence from Geochemical Proxies. *Journal of Asian Earth Sciences*, 266: 106121. https://doi.org/10.1016/j.jseaes.2024.106121

Fazal, A. M., Varikoden, H., Reji, M. J. K., 2023. Long Term Trends and Variabilities of Rainfall of the Global Monsoon Systems during Boreal and Austral Summer Seasons. *Global and Planetary Change*, 229: 104251. https://doi.org/10.1016/j.gloplacha.2023.104251

Feng, J. L., Zhu, L. P., Zhen, X. L., et al., 2009. Grain Size Effect on Sr and Nd Isotopic Compositions in Eolian Dust: Implications for Tracing Dust Provenance and Nd Model Age. *Geochemical Journal*, 43(2): 123—131. https://doi.org/10.2343/geochemj.1.0007

Gao, X. B., Li, C., Duan, Z. F., et al., 2025. Sr-Nd Isotopic Characteristics and Their Significance in Provenance Tracing of Detrital Sediment in Major Rivers and Marginal Seas of Eastern China. *Science China Earth Sciences*, 68(2): 523—537. https://doi. org/10.1007/s11430-024-1464-5

Garba, T. E., Mustapha, K. A., 2024. Source Rock Characterisation and Petroleum System Modelling: A Review of Marginal Marine Deposit in the Permo-Triassic Sydney Basin, Australia. *Journal of Sedimentary Environments*, 9(2): 239—251. https://doi. org/

10.1007/s43217-024-00168-8

Ginoux, P., Prospero, J. M., Torres, O., et al., 2004. Long-Term Simulation of Global Dust Distribution with the GOCART Model: Correlation with North Atlantic Oscillation. *Environmental Modelling & Software*, 19(2): 113—128. https://doi.org/10.1016/S1364-8152(03)00114-2

Goldstein, S. J., Jacobsen, S. B., 1987. The Nd and Sr Isotopic Systematics of River-Water Dissolved Material: Implications for the Sources of Nd and Sr in Seawater. *Chemical Geology: Isotope Geoscience Section*, 66(3—4): 245—272. https://doi.org/10.1016/0168-9622(87)90045-5

Goswami, V., Singh, S. K., Bhushan, R., et al., 2012. Temporal Variations in $^{87}Sr/^{86}Sr$ and ε_{Nd} in Sediments of the Southeastern Arabian Sea: Impact of Monsoon and Surface Water Circulation. *Geochemistry, Geophysics, Geosystems*, 13: 2011GC003802. https://doi.org/10.1029/2011gc003802

Govin, A., Holzwarth, U., Heslop, D., et al., 2012. Distribution of Major Elements in Atlantic Surface Sediments (36°N-49°S): Imprint of Terrigenous Input and Continental Weathering. *Geochemistry, Geophysics, Geosystems*, 13: 2011GC003785. https://doi.org/10.1029/2011gc003785

Han, Y. X., Zhao, T. L., Song, L. C., et al., 2011. A Linkage between Asian Dust, Dissolved Iron and Marine Export Production in the Deep Ocean. *Atmospheric Environment*, 45(25): 4291—4298. https://doi.org/10.1016/j.atmosenv.2011.04.078

Hanebuth, T. J., Stattegger, K., Saito, Y., 2002. The Stratigraphic Architecture of the Central Sunda Shelf (SE Asia) Recorded by Shallow-Seismic Surveying. *Geo-Marine Letters*, 22(2): 86—94. https://doi.org/10.1007/s00367-002-0102-1

Hu, S. Y., Zeng, Z. G., Fang, X., et al., 2020. Increasing Terrigenous Sediment Supply from Taiwan to the Southern Okinawa Trough over the Last 3 000 Years Evidenced by Sr-Nd Isotopes and Geochemistry. *Sedimentary Geology*, 406: 105725. https://doi.org/10.1016/j.sedgeo.2020.105725

Huang, J., Li, A. C., Wan, S. M., 2011. Sensitive Grain-Size Records of Holocene East Asian Summer Monsoon in Sediments of Northern South China Sea Slope. *Quaternary Research*, 75(3): 734—744. https://doi.org/10.1016/j.yqres.2011.03.002

Huang, X. X., Wang, R. J., Xiao, W. S., et al., 2018. Transportation Mechanism of Terrigenous Sediment and Its Paleoenvironmental Implications on the Chukchi Plateau, Western Arctic Ocean during the Late Quaternary. *Marine Geology & Quaternary Geology*, 38(2): 52—62 (in Chinese with English abstract).

Ibarra, D. E., Caves, J. K., Moon, S., et al., 2016. Differential Weathering of Basaltic and Granitic Catchments from Concentration-Discharge Relationships. *Geochimica et Cosmochimica Acta*, 190: 265—293. https://doi.org/10.1016/j.gca.2016.07.006

Jickells, T. D., An, Z. S., Andersen, K. K., et al., 2005. Global Iron Connections between Desert Dust, Ocean Biogeochemistry, and Climate. *Science*, 308(5718): 67—71. https://doi.org/10.1126/science.1105959

Jin, H. L., Wan, S. M., Clift, P. D., et al., 2022. Birth of the Pearl River at 30 Ma: Evidence from Sedimentary Records in the Northern South China Sea. *Earth and Planetary Science Letters*, 600: 117872. https://doi.org/10.1016/j.epsl.2022.117872

Kang, X. Y., Yu, Z. J., Song, L. N., et al., 2024. Wind-Driven Sediment Exchange between the Indian Marginal Seas over the Last 18 000 Years. *Environmental Research Letters*, 19(8): 084004. https://doi.org/10.1088/1748-9326/ad5bf4

Kaparulina, E., Strand, K., Lunkka, J. P., 2016. Provenance Analysis of Central Arctic Ocean Sediments: Implications for Circum-Arctic Ice Sheet Dynamics and Ocean Circulation during Late Pleistocene. *Quaternary Science Reviews*, 147: 210—220. https://doi.org/10.1016/j.quascirev.2015.09.017

Kessarkar, P. M., Rao, V. P., Ahmad, S. M., et al., 2003. Clay Minerals and Sr-Nd Isotopes of the Sediments along the Western Margin of India and Their Implication for Sediment Provenance. *Marine Geology*, 202(1—2): 55—69. https://doi.org/10.1016/S0025-3227(03)00240-8

Kump, L. R., Brantley, S. L., Arthur, M. A., 2000. Chemical Weathering, Atmospheric CO_2, and Climate. *Annual Review of Earth and Planetary Sciences*, 28: 611—667. https://doi.org/10.1146/annurev.earth.28.1.611

Lang, D. C., Bailey, I., Wilson, P. A., et al., 2014. The Transition on North America from the Warm Humid Pliocene to the Glaciated Quaternary Traced by Eolian Dust Deposition at a Benchmark North Atlantic Ocean Drill Site. *Quaternary Science Reviews*, 93: 125—141. https://doi.org/10.1016/j.quascirev.2014.04.005

Langmann, B., 2013. Volcanic Ash Versus Mineral Dust: Atmospheric Processing and Environmental and Climate Impacts. *ISRN Atmospheric Sciences*, 2013: 245076.

https://doi.org/10.1155/2013/245076

Leithold, E. L., Blair, N. E., Wegmann, K. W., 2016. Source-to-Sink Sedimentary Systems and Global Carbon Burial: A River Runs through It. *Earth-Science Reviews*, 153: 30−42. https://doi.org/10.1016/j.earscirev.2015.10.011

Li, C. S., Shi, X. F., Kao, S., et al., 2012. Clay Mineral Composition and Their Sources for the Fluvial Sediments of Taiwanese Rivers. *Chinese Science Bulletin*, 57(6): 673−681. https://doi.org/10.1007/s11434-011-4824-1

Li, J. R., Liu, S. F., Shi, X. F., et al., 2017. Distributions of Clay Minerals in Surface Sediments of the Middle Bay of Bengal: Source and Transport Pattern. *Continental Shelf Research*, 145: 59−67. https://doi.org/10.1016/j.csr.2017.06.017

Li, J. R., Liu, S. F., Shi, X. F., et al., 2020a. Provenance of Terrigenous Sediments in the Central Bay of Bengal and Its Relationship to Climate Changes since 25 ka. *Progress in Earth and Planetary Science*, 7(1): 16. https://doi.org/10.1186/s40645-020-00328-0

Li, L., Bai, S. J., Li, J. W., et al., 2020b. Volcanic Ash Inputs Enhance the Deep-Sea Seabed Metal-Biogeochemical Cycle: A Case Study in the Yap Trench, Western Pacific Ocean. *Marine Geology*, 430: 106340. https://doi.org/10.1016/j.margeo.2020.106340

Liu, J. G., He, W., Cao, L., et al., 2019. Staged Fine-Grained Sediment Supply from the Himalayas to the Bengal Fan in Response to Climate Change over the Past 50, 000 Years. *Quaternary Science Reviews*, 212: 164−177. https://doi.org/10.1016/j.quascirev.2019.04.008

Liu, Z. F., Colin, C., Huang, W., et al., 2007. Climatic and Tectonic Controls on Weathering in South China and Indochina Peninsula: Clay Mineralogical and Geochemical Investigations from the Pearl, Red, and Mekong Drainage Basins. *Geochemistry, Geophysics, Geosystems*, 8(5): Q05005. https://doi.org/10.1029/2006GC001490

Liu, Z. F., Zhao, Y. L., Colin, C., et al., 2016. Source-to-Sink Transport Processes of Fluvial Sediments in the South China Sea. *Earth-Science Reviews*, 153: 238−273. https://doi.org/10.1016/j.earscirev.2015.08.005

Luo, C., Mahowald, N. M., del Corral, J., 2003. Sensitivity Study of Meteorological Parameters on Mineral Aerosol Mobilization, Transport, and Distribution. *Journal of Geophysical Research: Atmospheres*, 108(D15): 2003JD003483. https://doi.org/10.1029/2003jd003483

Maher, B. A., Prospero, J. M., Mackie, D., et al., 2010. Global Connections between Aeolian Dust, Climate and Ocean Biogeochemistry at the Present Day and at the Last Glacial Maximum. *Earth-Science Reviews*, 99(1−2): 61−97. https://doi.org/10.1016/j.earscirev.2009.12.001

Martínez-García, A., Sigman, D. M., Ren, H. J., et al., 2014. Iron Fertilization of the Subantarctic Ocean during the Last Ice Age. *Science*, 343(6177): 1347−1350. https://doi.org/10.1126/science.1246848

McGee, D., DeMenocal, P. B., Winckler, G., et al., 2013. The Magnitude, Timing and Abruptness of Changes in North African Dust Deposition over the Last 20, 000yr. *Earth and Planetary Science Letters*, 371: 163−176. https://doi.org/10.1016/j.epsl.2013.03.054

Meinhardt, A. K., Pahnke, K., Böning, P., et al., 2016. Climate Change and Response in Bottom Water Circulation and Sediment Provenance in the Central Arctic Ocean since the Last Glacial. *Chemical Geology*, 427: 98−108. https://doi.org/10.1016/j.chemgeo.2016.02.019

Meyer, I., Davies, G. R., Stuut, J. W., 2011. Grain Size Control on Sr-Nd Isotope Provenance Studies and Impact on Paleoclimate Reconstructions: An Example from Deep-Sea Sediments Offshore NW Africa. *Geochemistry, Geophysics, Geosystems*, 12(3): Q03005. https://doi.org/10.1029/2010GC003355

Miller, R. L., Tegen, I., Perlwitz, J., 2004. Surface Radiative Forcing by Soil Dust Aerosols and the Hydrologic Cycle. *Journal of Geophysical Research: Atmospheres*, 109(D4): 2003JD004085. https://doi.org/10.1029/2003jd004085

Milliman, J. D., Farnsworth, K. L., 2011. River Discharge to the Coastal Ocean—A Global Synthesis. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511781247

Montelli, A., Gulick, S. P. S., Worthington, L. L., et al., 2017. Late Quaternary Glacial Dynamics and Sedimentation Variability in the Bering Trough, Gulf of Alaska. *Geology*, 45(3): 251−254. https://doi.org/10.1130/g38836.1

Muhs, D. R., 2013. The Geologic Records of Dust in the Quaternary. *Aeolian Research*, 9: 3−48. https://doi.org/10.1016/j.aeolia.2012.08.001

Ning, D. L., Xiao, X. Y., Tang, S. Q., et al., 2024. Millennial to Orbital Scale Indian Summer Monsoon Evolution Inferred from Grain Size End-Members in Tengchongbeihai Wetland, Southwestern China. *Quaternary Science Reviews*, 334: 108723. https://doi.org/10.1016/j.

quascirev.2024.108723

Prins, M. A., Postma, G., 2000. Effects of Climate, Sea Level, and Tectonics Unraveled for Last Deglaciation Turbidite Records of the Arabian Sea. *Geology*, 28(4): 375－378. https://doi. org/10.1130/0091 - 7613(2000)0280375: eocsla>2.3.co;2

Prueher, L. M., Rea, D. K., 2001. Volcanic Triggering of Late Pliocene Glaciation: Evidence from the Flux of Volcanic Glass and Ice-Rafted Debris to the North Pacific Ocean. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 173(3/4): 215－230. https://doi.org/10.1016/S0031-0182(01)00323-6

Ramaswamy, V., Muraleedharan, P. M., Prakash Babu, C., 2017. Mid-Troposphere Transport of Middle-East Dust over the Arabian Sea and Its Effect on Rainwater Composition and Sensitive Ecosystems over India. *Scientific Reports*, 7(1): 13676. https://doi. org/10.1038/s41598-017-13652-1

Rea, D. K., 1994. The Paleoclimatic Record Provided by Eolian Deposition in the Deep Sea: The Geologic History of Wind. *Reviews of Geophysics*, 32(2): 159－195. https://doi.org/10.1029/93rg03257

Rea, D. K., Hovan, S. A., 1995. Grain Size Distribution and Depositional Processes of the Mineral Component of Abyssal Sediments: Lessons from the North Pacific. *Paleoceanography*, 10(2): 251－258. https://doi. org/10.1029/94pa03355

Rea, D. K., Leinen, M., Janecek, T. R., 1985. Geologic Approach to the Long-Term History of Atmospheric Circulation. *Science*, 227(4688): 721－725. https://doi.org/10.1126/science.227.4688.721

Rea, D. K., Snoeckx, H., Joseph, L. H., 1998. Late Cenozoic Eolian Deposition in the North Pacific: Asian Drying, Tibetan Uplift, and Cooling of the Northern Hemisphere. *Paleoceanography*, 13(3): 215－224. https://doi.org/10.1029/98pa00123

Robock, A., 2000. Volcanic Eruptions and Climate. *Reviews of Geophysics*, 38(2): 191－219. https://doi. org/10.1029/1998rg000054

Rowland, G. H., 2021. Muddying the Waters: Tracing Terrigenous Fluxes to the North Atlantic Ocean (Dissertation). University of Bristol, Bristol.

Sarim, M., Xu, J., Zhang, P., et al., 2023. Late Quaternary Clay Mineral and Grain-Size Records from Northwest Australia and Their Implications for Paleoclimate, Ocean Currents, and Paleodrainage of the Bonaparte Basin. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 610: 111353. https://doi. org/10.1016/j. palaeo.2022.111353

Saukel, C., Lamy, F., Stuut, J. W., et al., 2011. Distribution and Provenance of Wind-Blown SE Pacific Surface Sediments. *Marine Geology*, 280(1－4): 130－142. https://doi.org/10.1016/j.margeo.2010.12.006

Sebastian, T., Nath, B. N., Mascarenhas-Pereira, M. B. L., et al., 2023. A 50 kyr Record of Eolian Sedimentation in the Eastern Arabian Sea-Dust Deposition Changes Synchronous with the Northern Hemisphere Climatic Oscillations. *Marine Geology*, 459: 107046. https://doi.org/10.1016/j.margeo.2023.107046

Seo, I., Lee, Y., Yoo, C., et al., 2014. Sr-Nd Isotope Composition and Clay Mineral Assemblages in Eolian Dust from the Central Philippine Sea over the last 600 kyr: Implications for the Transport Mechanism of Asian Dust. *Journal of Geophysical Research*: *Atmospheres*, 119: 11, 492－11, 504. https://doi. org/10.1002/2014JD022025

Serno, S., Winckler, G., Anderson, R. F., et al., 2014. Eolian Dust Input to the Subarctic North Pacific. *Earth and Planetary Science Letters*, 387: 252－263. https://doi.org/10.1016/j.epsl.2013.11.008

Shao, Y. P., Wyrwoll, K. H., Chappell, A., et al., 2011. Dust Cycle: An Emerging Core Theme in Earth System Science. *Aeolian Research*, 2(4): 181－204. https://doi.org/10.1016/j.aeolia.2011.02.001

Shi, X. F., Li, J. R., Qiao, S. Q., et al., 2023. Research Progress of the Tibetan Plateau-Bay of Bengal "Source-Sink" System since the Last Glacial Maximum. *Marine Geology & Quaternary Geology*, 43(3): 14－25 (in Chinese with English abstract).

Skonieczny, C., McGee, D., Winckler, G., et al., 2019. Monsoon-Driven Saharan Dust Variability over the Past 240, 000 Years. *Science Advances*, 5: eaav1887. https://doi.org/10.1126/sciadv.aav1887

Song, Z. H., Wan, S. M., Yu, Z. J., et al., 2024. The Major Uplift in Himalayas Was no Earlier than the Miocene: Evidence from Marine Sediment Record in the Bay of Bengal. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 648: 112275. https://doi.org/10.1016/j.palaeo.2024.112275

Song, Z., Li, Y. L., Zhao, Y., et al., 2024. Holocene Depositional Environment Evolution at Mulanxi Estuary in Fujian Province: Evidences from XRF Core Scanning. *Earth Science*, 49(6): 2213－2226 (in Chinese with English abstract).

Stancin, A. M., Gleason, J. D., Hovan, S. A., et al., 2008. Miocene to Recent Eolian Dust Record from the Southwest Pacific Ocean at 40° S Latitude. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 261(3－4): 218－233. https://doi.org/10.1016/j.palaeo.2007.12.015

Stuut, J. W., Temmesfeld, F., De Deckker, P., 2014. A 550 ka Record of Aeolian Activity near North West Cape, Australia: Inferences from Grain-Size Distributions and Bulk Chemistry of SE Indian Ocean Deep-Sea Sediments. *Quaternary Science Reviews*, 83: 83－94. https://doi.org/10.1016/j.quascirev.2013.11.003

Sun, J., Wu, H. C., Huang, W., et al., 2025. Magnetic Records of Quaternary Sediments in the Eastern West Philippine Sea Basin and Its Paleoclimatic Implications. *Earth Science,* 50(3): 918－933 (in Chinese with English abstract).

Suresh, K., Singh, U., Kumar, A., et al., 2021. Provenance Tracing of Long-Range Transported Dust over the Northeastern Arabian Sea during the Southwest Monsoon. *Atmospheric Research*, 250: 105377. https://doi.org/10.1016/j.atmosres.2020.105377

Syvitski, J. P. M., Peckham, S. D., Hilberman, R., et al., 2003. Predicting the Terrestrial Flux of Sediment to the Global Ocean: A Planetary Perspective. *Sedimentary Geology*, 162(1－2): 5－24. https://doi. org/10.1016/S0037-0738(03)00232-X

Tanaka, T. Y., Chiba, M., 2006. A Numerical Study of the Contributions of Dust Source Regions to the Global Dust Budget. *Global and Planetary Change*, 52(1－4): 88－104. https://doi.org/10.1016/j.gloplacha.2006.02.002

Tang, X. J., Yu, Z. J., Lu, Z. Y., et al., 2024. Orbital Hydroclimate Variability Revealed by Grain-Size Evidence in the Tropical Pacific Islands since 140 ka. *Global and Planetary Change*, 236: 104429. https://doi. org/10.1016/j.gloplacha.2024.104429

Tao, S. Q., Wang, A. J., Liu, J. T., et al., 2023. Characteristics of Sedimentary Organic Carbon Burial in the Shallow Conduit Portion of Source-to-Sink Sedimentary Systems in Marginal Seas. *Geochimica et Cosmochimica Acta*, 353: 92－111. https://doi.org/10.1016/j.gca.2023.05.006

Tofelde, S., Bernhardt, A., Guerit, L., et al., 2021. Times Associated with Source-to-Sink Propagation of Environmental Signals during Landscape Transience. *Frontiers in Earth Science*, 9: 628315. https://doi. org/10.3389/feart.2021.628315.

Wan, S. M., Clift, P. D., Zhao, D. B., et al., 2017. Enhanced Silicate Weathering of Tropical Shelf Sediments Exposed during Glacial Lowstands: A Sink for Atmospheric CO_2. *Geochimica et Cosmochimica Acta*, 200: 123－144. https://doi.org/10.1016/j.gca.2016.12.010

Wan, S. M., Li, A. C., 2004. Research Progress of Marine Eolian Deposition on Paleoclimatology. *Advance in Earth Sciences*, 19(6): 955－962 (in Chinese with English abstract).

Wan, S. M., Li, A. C., Xu, K. H., et al., 2008. Characteristics of Clay Minerals in the Northern South China Sea and Its Implications for Evolution of East Asian Monsoon since Miocene. *Earth Science*, 33(3): 289－300 (in Chinese with English abstract).

Wan, S. M., Sun, Y. B., Nagashima, K., 2020. Asian Dust from Land to Sea: Processes, History and Effect from Modern Observation to Geological Records. *Geological Magazine*, 157(5): 701－706. https://doi. org/10.1017/s0016756820000333

Wan, S. M., Yu, Z. J., Clift, P. D., et al., 2012. History of Asian Eolian Input to the West Philippine Sea over the Last One Million Years. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 326: 152－159. https://doi. org/10.1016/j.palaeo.2012.02.015

Wang, J. Z., Li, A. C., Xu, K. H., et al., 2015. Clay Mineral and Grain Size Studies of Sediment Provenances and Paleoenvironment Evolution in the Middle Okinawa Trough since 17 ka. *Marine Geology*, 366: 49－61. https://doi.org/10.1016/j.margeo.2015.04.007

Wang, W., Xu, Z. K., Li, T. G., et al., 2020. Sources and Origins of Eolian Dust to the Philippine Sea Determined by Major Minerals and Elemental Geochemistry. *Geological Magazine*, 157(5): 719－728. https://doi. org/10.1017/s0016756819001031

Werner, M., Tegen, I., Harrison, S. P., et al., 2002. Seasonal and Interannual Variability of the Mineral Dust Cycle under Present and Glacial Climate Conditions. *Journal of Geophysical Research*: *Atmospheres*, 107(D24): AAC 2-1－AAC 2-19. https://doi. org/10.1029/2002jd002365

West, A. J., Galy, A., Bickle, M., 2005. Tectonic and Climatic Controls on Silicate Weathering. *Earth and Planetary Science Letters*, 235(1－2): 211－228. https://doi. org/10.1016/j.epsl.2005.03.020

Xiao, W. S., Polyak, L., Zhang, T. L., et al., 2024. Depositional and Circulation Changes at the Chukchi Margin, Arctic Ocean, during the Last Two Glacial Cycles. *Global and Planetary Change*, 233: 104366. https://doi.org/10.1016/j.gloplacha.2024.104366

Xu, Q. M., Yi, S. W., Xiao, Z. B., et al., 2025. Deciphering the Grain Size Fining and Provenance Variation of Lower Yellow River Fluvial Sediments in Light of Holocene Climatic Changes and Anthropogenic Influences.

Geomorphology, 471: 109552. https://doi.org/10.1016/j.geomorph.2024.109552

Xu, Z. K., Li, T. G., Clift, P. D., et al., 2018. Bathyal Records of Enhanced Silicate Erosion and Weathering on the Exposed Luzon Shelf during Glacial Lowstands and Their Significance for Atmospheric CO_2 Sink. *Chemical Geology*, 476: 302−315. https://doi. org/10.1016/j.chemgeo.2017.11.027

Yu, Z. J., 2013. Research on Asian Eolian Input to the West Philippine Sea over the Last One Million Years (Dissertation). Institute of Oceanology Chinese Academy of Sciences, Qingdao (in Chinese with English abstract).

Yu, Z. J., Colin, C., Wan, S. M., et al., 2019. Sea Level-Controlled Sediment Transport to the Eastern Arabian Sea over the Past 600 kyr: Clay Minerals and Sr-Nd Isotopic Evidence from IODP Site U1457. *Quaternary Science Reviews*, 205: 22−34. https://doi. org/10.1016/j.quascirev.2018.12.006

Yu, Z. J., Ruan, J. Y., Song, L. N., et al., 2024. Late Pleistocene Island Weathering and Precipitation in the Western Pacific Warm Pool. *NPJ Climate and Atmospheric Science*, 7: 91. https://doi.org/10.1038/s41612-024-00642-0

Yu, Z. J., Tang, X. J., Colin, C., et al., 2023. Millennial-Scale Precipitation Variability in the Indo-Pacific Region over the Last 40 kyr. *Geophysical Research Letters*, 50(2): e2022GL101646. https://doi.org/10.1029/2022gl101646

Yu, Z. J., Wan, S. M., Colin, C., et al., 2016. Co-Evolution of Monsoonal Precipitation in East Asia and the Tropical Pacific ENSO System since 2.36 Ma: New Insights from High-Resolution Clay Mineral Records in the West Philippine Sea. *Earth and Planetary Science Letters*, 446: 45−55. https://doi.org/10.1016/j.epsl.2016.04.022

Zender, C. S., Bian, H. S., Newman, D., 2003. Mineral Dust Entrainment and Deposition (DEAD) Model: Description and 1990s Dust Climatology. *Journal of Geophysical Research* (*Atmospheres*), 108(D14): 4416. https://doi.org/10.1029/2002JD002775

Zhai, L. N., Wu, C. D., Ye, Y. T., et al., 2018. Fluctuations in Chemical Weathering on the Yangtze Block during the Ediacaran-Cambrian Transition: Implications for Paleoclimatic Conditions and the Marine Carbon Cycle. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 490: 280−292. https://doi.org/10.1016/j.palaeo.2017.11.006

Zhang, X. Y., Deng, B., Du, J. Z., 2023. A Historical Sedimentary Record of Glacial Activity in Krossfjorden, Arctic. *Journal of East China Normal University* (*Natural Science*), (3): 43−52 (in Chinese with English abstract).

Zhang, C., Yang, S. Y., Huang, X. T., et al., 2022. Sea Level Change and Kuroshio Intrusion Dominated Taiwan Sediment Source-to-Sink Processes in the Northeastern South China Sea over the Past 244 Kyrs. *Quaternary Science Reviews*, 287: 107558. https://doi. org/10.1016/j.quascirev.2022.107558

Zhao, D. B., Wan, S. M., Lu, Z. Y., et al., 2020. Response of Heterogeneous Rainfall Variability in East Asia to Hadley Circulation Reorganization during the Late Quaternary. *Quaternary Science Reviews*, 247: 106562. https://doi.org/10.1016/j.quascirev.2020.106562

Zhou, L., Jiang, Z. X., Larrasoaña, J. C., et al., 2024. Aridity Record of the Arabian Peninsula for the Last 200 kyr: Environmental Magnetic Evidence from the Western Equatorial Indian Ocean. *Quaternary Science Reviews*, 341: 108876. https://doi. org/10.1016/j. quascirev.2024.108876

Zimanowski, B., Wohletz, K., Dellino, P., et al., 2003. The Volcanic Ash Problem. *Journal of Volcanology and Geothermal Research*, 122(1−2): 1−5. https://doi.org/10.1016/S0377-0273(02)00471-7

中文参考文献

陈金霞,李铁刚,南青云,2009. 冲绳海槽千年来陆源物质输入历史与东亚季风变迁. 地球科学, 34(5): 811−818.

黄晓璇,王汝建,肖文申,等,2018. 西北冰洋楚科奇海台晚第四纪以来陆源沉积物搬运机制及其古环境意义. 海洋地质与第四纪地质, 38(2): 52−62.

石学法,李景瑞,乔淑卿,等,2023. 末次盛冰期以来青藏高原-孟加拉湾"源-汇"系统研究进展. 海洋地质与第四纪地质, 43(3): 14−25.

宋震,李亚龙,赵云,等,2024. 基于XRF岩心扫描证据的福建木兰溪河口全新世沉积环境演化重建. 地球科学, 49(6): 2213−2226.

孙军,吴怀春,黄威,等,2025. 西菲律宾海盆东部第四纪沉积物磁学记录及其古气候意义. 地球科学, 50(3): 918−933

万世明,李安春,2004. 海洋风尘沉积的古气候学研究进展. 地球科学进展, 19(6): 955−962.

万世明,李安春,胥可辉,等,2008. 南海北部中新世以来粘土矿物特征及东亚古季风记录. 地球科学, 33(3): 289−300.

于兆杰,2013. 近百万年以来西菲律宾海风尘沉积研究(硕士学位论文). 青岛:中国科学院海洋研究所.

张鑫悦,邓兵,杜金洲,2023. 北极克罗斯峡湾冰川活动的沉积记录. 华东师范大学学报(自然科学版), (3): 43−52.