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利用钍-230（^{230}Th）修正的钍-232（^{232}Th）重建古风尘通量研究进展及其在西太平洋的应用

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摘要：风尘通过影响大气辐射平衡和海洋生态系统的营养物质供应从而调控全球气候，是国际学术界广泛关注的热点问题之一。近年来，风尘的相关研究取得一系列重要进展，并提出将^{232}Th 作为一种准确重建约 50 万年以来风尘沉积通量的途径。本文首先介绍基于^{230}Th 的标准化方法，它可用于修正由于海洋底流频繁扰动引起的沉积物沉积速率变化，然后结合^{230}Th 标准化方法修正后的^{232}Th 通量，并利用 10.5 μg/g 换算得出的风尘沉积通量，通过和实测值对比，阐明了此方法的准确性。进一步通过对比晚全新世与末次冰盛期^{230}Th 标准化后的基于^{232}Th 获取的风尘沉积通量，也验证了此方法的可靠性。通过总结该方法在西太平洋的前期应用，认为此方法在西太平洋有着广阔的应用前景。

关键词：^{230}Th 标准化方法；^{232}Th；古风尘重建；西太平洋
中图分类号：P734　　**文献标识码：**A

The ^{230}Th-normalized ^{232}Th method in reconstructing paleo-dust flux and its applications in the Western Pacific

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Abstract: Eolian dust constitutes a potent modulator in the global climate by altering the radiative balance of the atmosphere and iron supply to the global ocean. In particular, the thorium-based method has been evoked to calibrate the sedimentary mass accumulation rate (MAR) for the past ～500,000 years, which offers an important approach for reconstructing paleo-dust flux accurately. Here, ^{230}Th normalization, an appealing approach to calibrate MAR, is comprehensively deconvolved. In conjunction with ^{232}Th, novel ^{230}Th-normalized data synthesis is compiled to elucidate the precision of this method with the aid of the measured value, which ultimately in line with the Th-derived result by using convert parameter uniformly (i.e. 10.5 μg/g). Further, comparison of the dust reconstruction based on this approach between Late Holocene and the Last Glacial Maximum (LGM) also indicates the validation of this method. Within this context, ^{230}Th-normalized ^{232}Th serves as a reliable proxy in determining dust input to the global ocean and thus can unveil unambiguous interpretation with respect to the reconstruction of paleo-dust flux to the western Pacific during the Late Quaternary. In contrast, the paucity of applications based on this method in the western Pacific is found, by summarizing previously published dissertations, with implication of foreshadowing a broad future in utilizing this tool at the western Pacific.

Key words: thorium-230 normalization; thorium-232; paleo-dust reconstruction; western Pacific

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矿物气溶胶(风尘)是一种连接陆源区域、大气环流、海洋生产力和全球气候的纽带，其可以通过改变大气辐射量、大气化学组成、陆地和海洋生态系统的营养物质供应，与全球气候系统耦合[1]。因此，海洋沉积物[2]、冰心[3]、湖泊[4]和黄土[5]样品中记录的古风尘信息受到了越来越多的关注。有关冰期—间冰期尺度的研究揭示了大气二氧化碳浓度的显著变化(如末次冰盛期比晚全新世时期显著降低了 80～100 μg/gv[6])，被认为与风尘变化导致的海洋输出生产力的变化密切相关[7-8]，凸显了研究海洋沉积物中风尘记录的重要性。

在全球海洋中，由于生物碳泵的作用，大气中的二氧化碳会被表层海水中的浮游植物所吸收。但是，在高营养盐低叶绿素海域，浮游植物对磷酸盐、硝酸盐、硅酸盐等营养物质的利用很可能受制于由风尘“有限铁”的供应。传统的观点认为，风尘通量的增加能够带来更多的铁，从而提高赤道太平洋海域的海洋生产力[9]。根据位于东赤道太平洋的钻孔，由风尘变化引起铁供应的改变被认为是控制东赤道太平洋海域10万年以来的生产力变化的主要因素[10]。但也有研究表明赤道潜流引起的上升流所携带的溶解态铁远高于风尘带来的铁，即：在赤道太平洋的大部分海域，上升流被认为是表层海水中溶解态铁的主要来源[11-12]。事实上，位于西赤道太平洋、中赤道太平洋和东赤道太平洋的高分辨率的钻孔数据已经证实风尘不是铁的主要来源，并进一步揭示了在中赤道太平洋海域，由上升流供应的铁是由风尘供应的铁的20～100倍，而在西赤道太平洋海域，由上升流带来的铁是由风尘输入的铁的7～10倍。因此，海洋动力过程的变化被认为是控制50万年以来赤道太平洋海域生产力变化的根本原因[13]。

在西太平洋，由于存在复杂的海洋环流，底流扰动对海底沉积物(包括风尘)的影响更加剧烈。作为西太平洋主要的西边界流，黑潮能够从赤道向中纬度海域运输大量热量从而强烈地影响西北太平洋的气候[14]。但是相比于现在，其强度[15]和方向[16]被认为在末次冰盛期发生了改变，使得准确的重建其古沉积通量更加困难。除此之外，由东亚夏季风强度变化[17]驱动的沿岸上升流的改变，以及北太平洋中层水在北半球的寒冷时期会变深[18]，都潜在地影响着西太平洋海域的海洋环流，进而对该海域海洋沉积物中风尘的沉积通量重建造成了很大的干扰。

^{230}Th标准化[19-20]是一种可以修正在地层层序不发生改变的情况下，由频繁的底流扰动引起的海洋沉积物的沉积通量发生改变的一种方法。事实上，钍一共有3种同位素，分别是^{230}Th、^{232}Th、^{234}Th，它们的化学性质有共同点也有不同点。在海洋中，^{230}Th和^{234}Th分别是由溶解于海水中的铀-234(^{234}U)和铀-238(^{238}U)通过α衰变产生的，而^{232}Th主要是通过风尘或者河流输入进入海洋。由于铀具有很长的半衰期并且在海水中是几乎均匀分布的[21]，因此，海水中^{230}Th的生产速率可以被认为是恒定的。由^{238}U衰变之后，^{230}Th以快速吸附于沉降颗粒物的方式从水体中被快速地移除，而^{232}Th被认为从搬运进海洋开始就一直被锁在碎屑矿物中。这些特性构成了利用^{230}Th和^{232}Th进行海洋学中有关沉积颗粒的动力学研究的重要基石。

本文首先介绍利用^{230}Th标准化修正的^{232}Th作为示踪保存到海洋沉积物中的古风尘通量的方法，包括其原理和涉及此方法参数的计算。随后，汇总了553个利用此方法在全球海洋中重建风尘通量方法的数据，并通过和实测值进行对比，以及晚全新世和末次冰盛期的古风尘通量记录的对比，探讨了该方法的准确性。最后，本文总结了在西太平洋，包括西北太平洋、西赤道太平洋、西南太平洋中利用^{230}Th修正的^{232}Th重建风尘沉积通量的成功应用。

1　^{230}Th修正的^{232}Th作为风尘通量的示踪剂

1.1　^{230}Th修正方法

^{230}Th标准化的前提假设是基于从水体中移除并到达海底的^{230}Th的量是已知的，并且等于上覆水体中溶解态^{234}U产生的^{230}Th的量[19-20]。考虑到^{230}Th在水中的滞留时间很短且其具有很强的颗粒吸附性，上述假设在大多数情况下是合理的。在海洋沉积物中，^{230}Th起源于3种方式，分别是由碎屑起源的^{230}Th($C_{\mathrm{Th-230}}^{\mathrm{det}}$)、由水体产生后吸附在沉降颗粒上的^{230}Th($C_{\mathrm{Th-230}}^{\mathrm{scav}}$)，和由自生^{234}U经过α衰变产生的^{230}Th($C_{\mathrm{Th-230}}^{\mathrm{auth}}$)。碎屑起源的^{230}Th是指永久的被锁在矿物晶格中并且不会和水体进行相互作用的那部分^{230}Th；吸附到沉降颗粒上的^{230}Th是指不受到自生^{234}U影响并通过衰变而减少的那部分^{230}Th，其半衰期为7.569万年[22]；自生起源的^{230}Th是指在缺氧或次氧化条件下沉积物自生^{234}U衰变生成的^{230}Th。在通常条件下，大多数深海沉积物处于氧化条件，并不会富集^{234}U，使得获取由水体产生后吸附在沉降颗粒上的^{230}Th变得更加简便。因此，由水体

中转移到海洋沉积物中的^{230}Th 可以由下式决定[20]：

$$C^{scav}_{Th-230}=C^{total}_{Th-230}-C^{det}_{Th-230}-C^{auth}_{Th-230}=C^{total}_{Th-230}-0.7\times C^{total}_{Th-232}-1.14\times(C^{total}_{U-238}-0.7\times C^{total}_{Th-232})\times[1-e^{-(0.693t/75.69)}] \tag{1}$$

式中，C^{total}_{Th-230}是海洋沉积物中^{230}Th 的总浓度，C^{total}_{Th-232}是海洋沉积物中^{232}Th 的总浓度，C^{total}_{U-238}是海洋沉积物中^{238}U 的总浓度，t 近似等于从沉积物沉积到海底开始直到其被测量的时间（单位为 ka）。垂向沉积通量的修正参数（FF）可由下式得出[23]：

$$FF=\frac{\rho\times\int_{z_1}^{z_2}C^{scav}_{Th-230}\times e^{(0.693t/75.69)}dz}{\lambda_{Th-230}\times A^{SW}_{U-234}\times(t_2-t_1)\times z} \tag{2}$$

式中，ρ是沉积物的干密度（单位为 g/cm^3），z 为水深（单位为 m），z_1 和 z_2 以及 t_1 和 t_2 分别是沉积物所在深度及其对应的时间，λ_{Th-230}是^{230}Th 的衰变常数，A^{SW}_{U-234}是海水中 U-234 的浓度，且对于盐度为 35 permil 的海水，其值为 2 910 dpm/m^3[24]。校正后的沉积速率（RF）为：

$$RF=\frac{F}{FF} \tag{3}$$

式中，F 是运用传统方法算出的沉积通量。近年来此方法在全球海洋沉积通量研究中被广泛应用[19]。

1.2 ^{232}Th 作为风尘的示踪剂

利用^{232}Th 作为风尘的示踪剂是基于其在上地壳中的浓度范围变化很小[25]。对全球范围内不同风尘起源的研究结果表明，中国黄土起源[26-32]、澳大利亚起源[33-34]、北美起源[34-35]；非洲北部起源[36]、赤道非洲起源[37]和阿根廷起源[38]的风尘^{232}Th 浓度大致为 9.7～11.7 μg/g，由^{232}Th 代表的海洋沉积物中风尘沉积通量可由下式所获取：

$$F_{dust}=\frac{RF}{TF} \tag{4}$$

式中，RF 是利用^{230}Th 标准化方法修正后的^{232}Th 通量，TF 是^{232}Th 在风尘中的浓度，可近似使用^{232}Th 在上地壳中的平均浓度 10.5 μg/g[39]。^{232}Th 作为风尘的示踪剂被广泛应用于南大洋[40-42]、北大西洋[43]、赤道大西洋[44]、南大西洋[45]、北印度洋[46]、南印度洋[47]、北太平洋[48]、赤道太平洋[49]和南太平洋[50]。

1.3 ^{230}Th 修正的^{232}Th 方法的准确性——与实测值的比较

为了验证^{230}Th 标准化方法修正后的基于^{232}Th 获取的风尘沉积通量是否可靠，本文汇总了前人利用此方法获取的 553 个风尘通量数据（图 1），并和 11 个实测的风尘通量数据进行了对比。数据来源包括：利用^{230}Th 修正的^{232}Th 重建古风尘通量的数据[2, 40-103]，以及利用^{230}Th 标准化后的^{232}Th 风尘沉积通量与其附近位置的实测值[104-109]。

总体来看，无论是处于高风尘通量沉积的海域（如印度洋西北部的亚丁湾），还是处于低风尘通量沉积的海域（如中赤道太平洋），利用^{230}Th 标准化后的基于^{232}Th 获取的风尘沉积通量结果都与实测值十分接近。具体而言，在印度洋西北部的亚丁湾，由于受到撒哈拉沙漠来源的风尘影响，钻孔 KL15 中利用此方法得出的结果为 7.70 g·m^{-2}·a^{-1}[46]，相比之下，其实测值为 7.10 g·m^{-2}·a^{-1}[107]。在北大西洋海域，基于钍同位素计算得出的风尘通量结果分别为 7.47[52]和 12.90 g·m^{-2}·a^{-1}[71]，对应的实测值分别为 8.80[108]和 13.50 g·m^{-2}·a^{-1}[109]。在更远离风尘源区的南大西洋和南印度洋海域，基于钍同位素得出的风尘沉积通量分别是 0.91[68]和 0.88 g·m^{-2}·a^{-1}[65]，对应的实测值分别为 0.82[107]和 0.47 g·m^{-2}·a^{-1}[107]。基于我们汇总的数据结果，在风尘沉积通量最少的赤道太平洋海域，利用^{230}Th 修正后的^{232}Th 得出的风尘沉积通量[49, 57, 78]与附近位置得出的实测值[104-107]也十分接近，两者差值大多小于 0.04 g·m^{-2}·a^{-1}。以上结果表明，利用^{230}Th 标准化后的^{232}Th 沉积通量来重建风尘沉积通量是一种可靠的方法。

进一步利用实测的风尘通量数据和^{230}Th 标准化后的^{232}Th 沉积通量建立了回归方程，除两个异常数据外，两者呈显著正相关（图 2a）。钻孔 GGC-37[77]获取的风尘通量数据偏离实测数据的程度最大，我们注意到原始文献中采用的^{232}Th 浓度为 5.6 μg/g，远低于上地壳均值 10.5 μg/g，经重新计算后的沉积通量符合回归方程。原文作者主要考虑此钻孔受到火山物质的影响，且同位素数据表明其火山组分达 80%。然而，火山物质的^{232}Th 浓度是上地壳的 1%～10%[110]，因此，火山来源的^{232}Th 难以对基于^{232}Th 的重建结果产生重大影响[111]。计算结果表明即使此钻孔中的火山组分达到 80%，也不会对该孔基于^{232}Th 的风尘通量重建结果造成显著影响，因此，使用上地壳的^{232}Th 浓度 10.5 μg/g 作为转换参数更为合理。另一个钻孔 RC16-66[44]同样严重偏离了回归方法，且利用 10.5 μg/g 重新计算后，此异常数据也回到了期望值附近。注意到其使用的转换参数 15 μg/g 是受到^{232}Th 浓度高于上地壳的河流物质（15 μg/g）的影响，然而风尘模拟结果表明 RC16-66 孔是以风尘沉积为主[112]，因此，使用上地壳背景值获取风尘沉积通量更为可靠。上述结果进一步

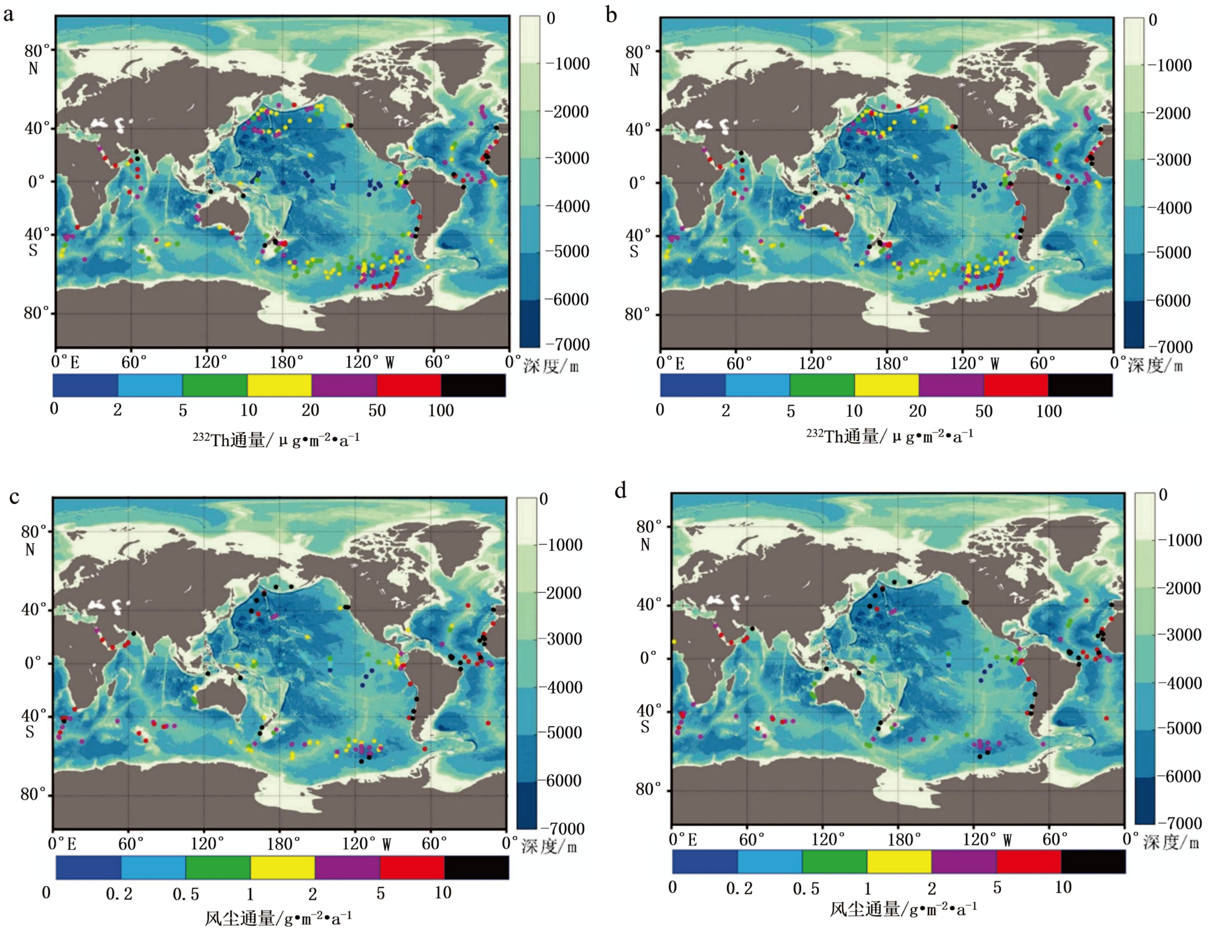

图 1　^{232}Th 通量和风尘通量的分布图

利用海洋沉积物中的^{230}Th 标准化方法修正后的^{232}Th 在晚全新世(a)和末次冰盛期(b)的通量及其分布，及其基于此通量获取的在晚全新世(c)和末次冰盛期(d)的风尘沉积通量及其分布。

Fig.1　Distribution of the newly compiled ^{232}Th flux and dust flux

The ^{230}Th-normalized ^{232}Th flux and distribution during (a) the Late Holocene and (b) the last glacial maximum, and the dust flux and distribution during (c) the Late Holocene and (d) the last glacial maximum.

确认了利用^{230}Th 标准化后的^{232}Th 风尘沉积通量的可靠性。但对于靠近陆地的一些海域，利用^{230}Th 标准化后的^{232}Th 风尘沉积通量需排除其他陆源输入物质的影响(如河流输入，冰筏沉积物等)，因此，远离陆地的开阔大洋是应用基于该方法获取风尘沉积通量的理想海域。

1.4　基于钍同位素的风尘沉积通量在末次冰盛期和晚全新世的对比

为了更准确的重建末次冰盛期的风尘沉积通量，在晚全新世时期基于钍同位素获取的沉积物附近，加入了由于模型模拟获得的风尘沉积通量[112]，并把基于模型模拟的风尘通量回归直线与实测值获取的风尘沉积通量的回归直线进行对比(图 2b)。总体来看，无论是在风尘沉积通量高的海域，还是风尘沉积通量低的海域，模型结果与实测值的线性拟合均表现为显著正相关。进一步加入基于钍同位素获取的晚全新世的风尘沉积通量数据，并利用由实测值和模拟值获取的回归方程得出了每一个基于钍同位素的风尘沉积通量的近似值，结果表明：三者保持了很好的一致性(图 2c)。

结合实测值和模型模拟得出的风尘通量结果，发现几乎所有钻孔在末次冰盛期的风尘沉积通量均高于晚全新世(图 2d)，与传统的观点一致，进一步证明了利用^{230}Th 标准化后的^{232}Th 进行风尘沉积通量重建是一种可靠的方法。进一步地，少数钻孔的风尘沉积通量表现为与晚全新世相比，末次冰盛期的数值几乎相同甚至降低，其可能是由于生物扰动因素(如 PC32 孔[54])或冰期/间冰期尺度上局地气候变化(如 57GC15 孔[87])所导致的。

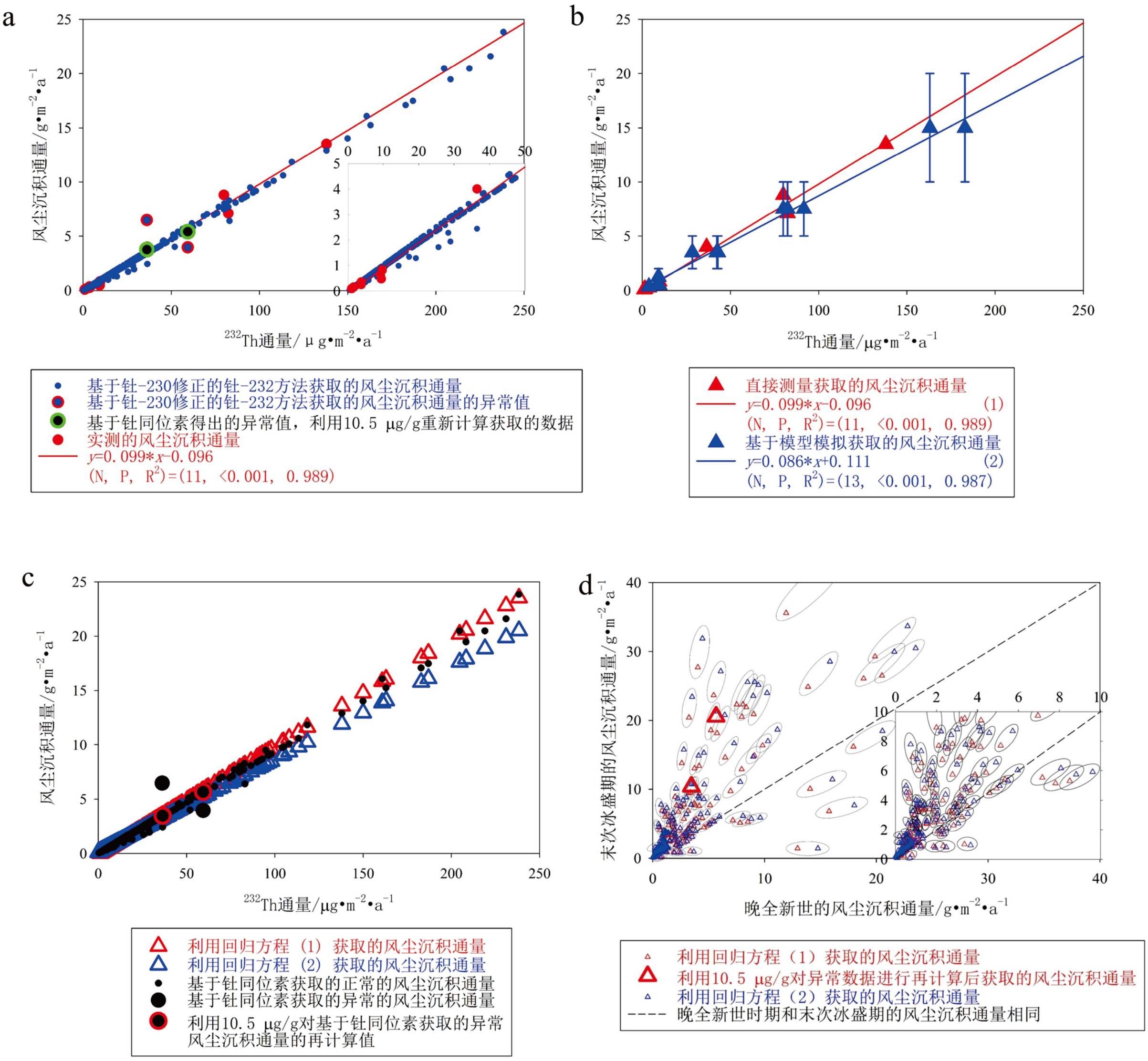

图 2 基于^{232}Th 获取的风尘通量数据的分析图

a. 晚全新世海洋沉积物中的^{230}Th 标准化方法修正后的^{232}Th 获取的风尘沉积通量与实测值的对比, b. 基于汇总的由钍同位素方法获取的风尘通量所在的表层沉积物附近位置的风尘实测值和模型模拟值及其回归直线, c. 利用实测值和模型模拟值获取的对每个晚全新世基于钍同位素得出的风尘沉积通量的对比, d. 末次冰盛期和晚全新世的风尘沉积通量的对比。

Fig.2 Analysis of the ^{232}Th-derived dust flux

a. the dust flux obtained by ^{230}Th-normalized ^{232}Th in the marine sediments and the measured values during the Late Holocene, b. The measured and simulated values obtained by ^{230}Th-normalized ^{232}Th and the regression lines of the dust flux near the surface sediments, c. The measured and simulated values obtained by ^{230}Th-normalized ^{232}Th of the dust flux during the Late Holocene, d. The dust flux during the last glacial maximum and the Late Holocene.

2 ^{230}Th 修正的^{232}Th 方法重建风尘通量的不确定性

利用^{230}Th 标准化后的^{232}Th 风尘沉积通量的不确定性主要来自边界去除效应、海洋环流、雾状层、热液喷口和沉积颗粒的粒度大小。

早期，边界去除效应被认为是由于沉积通量增大而导致易于吸附于颗粒的化学元素在大陆边缘出现增强的的吸附作用[113]。20 世纪 80 年代，在大洋内部[114] 和大陆边缘海[115] 的研究结果表明：易于吸附于颗粒的化学元素（如钍、镤）更倾向于在大陆边缘海域的海水中被吸附于沉积颗粒表面。但是，近年来的研究结果揭示了边界去除效应并不仅仅局限于边缘海域[116]，也可以在远离陆地的大洋内部出现，如由上升流驱动的中赤道太平洋海域[117]，表明边界去除效应对海水^{230}Th 的移除作用不可忽略。为了降低由此带来的误差，定义了^{230}Th 的埋藏

速率（F）与在上覆水体中的产生速率（P）的比值（F/P）。近年来利用此比值在东赤道太平洋的研究揭示了 F/P 从低边界去除效应海域的 0.76，上升到高边界去除效应海域的 1.23，定量化了边界去除效应，为降低由边界去除效应引起误差提供了一种途径[118]。

海洋环流会对海水中^{230}Th 浓度的垂向分布造成影响。早期模拟结果表明海水中^{230}Th 浓度随水深而线性增加[119]，而真实情况却显示：只有在很少的海域[59]能发现这样理想的线性关系。虽然^{230}Th 在海水中的停留时间只有 20～40 年，而海盆尺度的海水混合通常为百年时间尺度[120]，但海水中^{230}Th 垂向分布模式依然会随着海洋环流变化而发生改变。为了重建海洋环流对^{230}Th 浓度的垂向分布的影响，采用了优化后的 2D 模型对海洋环流影响下的海水中^{230}Th 浓度的垂向分布进行拟合[121]。进一步地，结合镤-231（^{231}Pa），利用此模型获取的大西洋^{231}Pa/^{230}Th 的垂向分布特征能够重建末次冰盛期大西洋径向翻转环流的强度变化[122]。在受深层环流影响强烈的海域，侧向传送也会改变海水中^{230}Th 的浓度，导致^{230}Th 标准化方法存在不确定性在今后的应用中需要重点考虑。

雾状层和海底热液也会对海水中^{230}Th 的浓度造成影响。雾状层是由近海底较高速海流引起的[123]，雾状层内的^{230}Th 从水体中被移除，导致沉积物中^{230}Th 浓度迅速偏离正常的线性垂向分布特征[19]。类似的情况也发生在海底热液喷口附近，表明海洋中热液活动对^{230}Th 浓度的影响不能忽视[124]。目前关于雾状层对^{230}Th 标准化方法影响的研究仍处于起步阶段，今后工作可以通过结合全球海洋中雾状层的信息进行更深入的探索[125]；数值模型能够大致模拟由海底热液引起的^{230}Th 埋藏速率的变化[19]，从而定量化与海底热液相关的^{230}Th 埋藏速率，为未来进一步降低^{230}Th 标准化方法的误差奠定了基础。

沉积颗粒的粒度大小对^{230}Th 浓度的影响，是源于早期利用涉及^{230}Th 示踪海洋生产力的研究[126]，随后的研究表明：颗粒的沉积通量[127]、化学组成[128]、粒度大小[129]都可能对^{230}Th 产生影响。在南大洋和东南大西洋的海洋沉积物中，粒度小于 2 μm 组分的^{230}Th 浓度[130]与东赤道太平洋粒度小于 4 μm 组分的^{230}Th 浓度[80]存在明显差异。但近年来的结果表明，仅粒度大小对^{230}Th 浓度的影响可以忽略[131]，推测南大洋与东南大西洋中不同粒度沉积物之间^{230}Th 浓度的不同是由其他因素主导的（如雾状层）。

3　^{230}Th 修正的^{232}Th 方法重建风尘通量在西太平洋的应用

西赤道太平洋被认为是全球海洋中风尘输入的低值区，也是全球海洋中主要的高营养盐低叶绿素海域之一。利用^{230}Th 标准化后的^{232}Th 进行的风尘沉积通量重建结果表明，虽然西赤道太平洋海域的风尘输入通量在末次冰期比全新世增加了 0.15～0.19 $g\cdot m^{-2}\cdot a^{-1}$，但同时浮游植物对硝酸盐的消耗却没有明显增加，这可能是由于从南大洋供应到此海域的硝酸盐含量的降低所导致的[61]。除此之外，西赤道太平洋海域获取的风尘通量也很低[13, 57, 78, 95]，并且赤道太平洋和南极的风尘通量在冰期-间冰期旋回尺度上是同步变化的[13]。

相比之下，西北太平洋海域由于受到中国黄土高原风尘的影响，其风尘输入通量在末次冰期有一定程度的增加。在亚北极的西北太平洋海域，尤其是靠近陆地的边缘海海域，火山物质、冰筏物质和河流物质对风尘输入估算结果影响较大，风尘输入通量大致为 2～4 $g\cdot m^{-2}\cdot a^{-1}$，而在远离陆地的海域，风尘输入通量只有 1～2 $g\cdot m^{-2}\cdot a^{-1}$[132]。利用此方法可较为精确地重建风尘沉积通量变化的时间序列，为揭示北太平洋末次冰消期的风尘沉积通量、海水层化作用与海洋生产力之间的内在关系提供了关键性证据[77]。进一步和其他研究对比，在西北太平洋海域利用此方法重建的风尘沉积通量结果都表现出了很好的一致性[48, 76, 78]。

西南太平洋由于受到澳大利亚风尘来源的影响，风尘输入通量也相对较高。在新西兰附近海域，受此区域末次冰盛期冰川作用引起风化作用和侵蚀作用增强的影响，末次冰盛期的风尘输入通量显著高于末次冰消期和全新世[133]。在更加靠近南大洋的西南太平洋海域，通过重建末次冰期以来的风尘输入通量变化（铁供应的变化），浮游植物对全球大气中二氧化碳浓度变化的贡献得以更加精确的估算[86]。在巴布亚新几内亚南部的海域，基于该方法重建的 5 万年以来风尘通量结果与反映陆源物质输入变化的 BIT 指数的重建结果具有较好的一致性[101]，也为此方法在西太平洋海域更加广泛的应用于重建陆源物质影响奠定了基础。

4　结论

本文介绍了一种可以修正由频繁的底流扰动

引起的海洋沉积物沉积速率变化的方法（^{230}Th 标准化）和一种重建风尘输入通量的代用指标（^{232}Th）。汇总了海洋沉积物中 553 个由^{230}Th 标准化方法修正的^{232}Th 获取的风尘沉积通量数据，并通过与 11 个风尘实测值的比较，以及通过基于钍同位素获取的风尘通量在末次冰盛期和晚全新世的对比，进一步验证了这种方法的准确性。基于汇总的此方法在全球海洋中的应用，认为此方法在西太平洋有广阔的应用前景，尤其是在亚赤道西太平洋海域。

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