Comment on "Do geochemical estimates of sediment focusing pass the sediment test in the equatorial Pacific?" by M. Lyle et al.

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1. Introduction

[1] Accurately estimating the vertical flux of material reaching the seafloor from the overlying surface waters is essential for the paleoceanographic reconstruction of a wide variety of oceanic processes. Two approaches are currently being used. One consists of estimating mass accumulation rates (MAR) between dated horizons as the product of linear sedimentation rates, sediment dry bulk densities, and concentrations. One pitfall with this approach is that sediments can be redistributed on the seafloor by bottom currents, and their accumulation may not necessarily reflect the true vertical rain rate originating from the overlying water column. To address this problem, the method of ^{230}Th normalization was developed [*Bacon*, 1984]. This method is based on the assumption that the rapid scavenging of ^{230}Th produced in the water column by decay of dissolved uranium results in its flux to the seafloor always being close to its known rate of production. To the extent that this assumption is correct, scavenged ^{230}Th can be used as a reference to estimate the settling flux of other sedimentary constituents and to correct for sediment redistribution on the seafloor [*Henderson and Anderson*, 2003; *Francois et al.*, 2004].

[2] MAR calculation and ^{230}Th normalization sometimes give widely divergent results. This is particularly true in the equatorial Pacific, where MARs often indicate higher fluxes during the last glacial period [*Lyle et al.*, 2002], while ^{230}Th normalization suggests unchanged or even lower glacial fluxes [*Marcantonio et al.*, 2001; *Loubere et al.*, 2004]. The proponents of ^{230}Th normalization argue that changes in MAR mainly reflect changes in sediment focusing and do not record actual changes in vertical flux from the overlying water. In a recent paper, *Lyle et al.* [2005] dispute this interpretation and contend that ^{230}Th normalization grossly overestimates sediment focusing in the equatorial Pacific. They argue that lateral transport of ^{230}Th in the water column is much larger than generally appreciated. We disagree with this view and in the following we point to shortcomings in their arguments.

2. Correlation Between Surface Productivity and Sediment Burial Rates of Biogenic Particles

[3] One argument presented by *Lyle et al.* [2005] to support their interpretation of MAR is that "bulk sediment burial correlates with surface productivity." Yet burial rates of biogenic particles in the eastern equatorial Pacific are clearly influenced by seafloor topography, as already discussed at length by *Loubere et al.* [2004]. For instance, calcite MAR at the foot of Carnegie Ridge (Y69–71; 0.1°N; 86.5°W; 2740 m) is ~2.5-fold higher [*Lyle et al.*, 2002] than at the top (V19–27; 0.5°S; 82.1°W; 1373 m), in spite of the fact that V19–27 lies well above and Y69–71 lies at the calcite lysocline [*Thunell et al.*, 1981] and the two cores are located under similar productivity regimes. There is thus a mismatch between calcite MAR and productivity at these two sites. This is by no means exceptional for this region. A compilation of late Pleistocene-Holocene calcite MAR in Panama Basin [*Lyle*, 1992] clearly shows a general increase with depth above the lysocline (~ 2800 m), where some of the calcite MARs reach values more than fivefold greater than the mean calcite MAR observed above 2000 m (Figure 1). It would be difficult to explain such a trend in terms of surface productivity and the most likely explanation is substantial sediment redistribution by down-slope transport.The relative merit of ^{230}Th normalization and MAR calculation is particularly well illustrated when comparing the results obtained from Y69–71 and nearby core ME0005-24JC (0.02°N; 86.5°W; 2941 m) in Panama Basin [*Kienast et al.*, 2007]. Owing to their close proximity (~10 km apart), we can expect similar surface productivity

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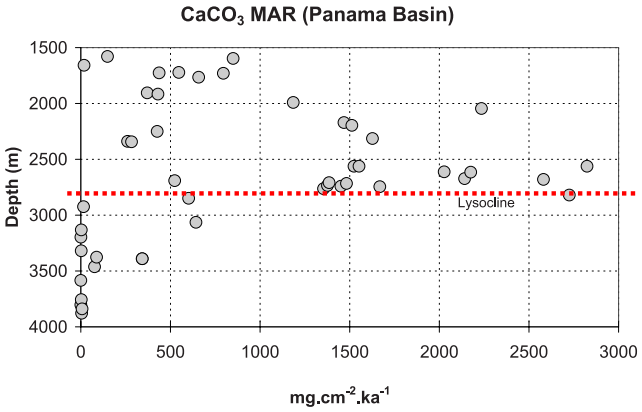

Figure 1. Changes in carbonate mass accumulation rates as a function of water depth in Panama Basin [*Lyle*, 1992] and estimated depth of the lysocline (~2800 m [*Thunell et al.*, 1981]).

and vertical particle rain rates at the two sites. While ^{230}Th-normalized fluxes are strikingly identical (Figure 2a), meeting this expectation, MARs are not (Figure 2b).

3. High-Resolution Chirp Subbottom Profile and Sediment Focusing

[4] *Lyle et al.* [2005] argue against significant sediment focusing using a 15 nautical mile chirp profile just north of Carnegie Ridge that intercepts the Y69–71 and ME0005-24JC coring sites. Continuous reflectors reveal that sediment cover is about half on top of abyssal hills compared to the troughs. Using this observation, they calculated a focusing factor of 1.1 (Y69–71) and 1.5 (ME0005-24JC) by dividing the sediment thickness at each site by the mean sediment thickness for the entire section. In contrast, using ^{230}Th normalization, *Kienast et al.* [2007] calculate higher focusing factors for the same cores (3.1 and 5.3, respectively, over the past 27 kyr). It is noteworthy that although much larger absolute focusing factors are estimated using ^{230}Th normalization, the ratio of the focusing factors estimated from ^{230}Th (3.1/5.3 = 0.6) is in good agreement with the ratio of accumulation rate obtained from acoustic data (1.1/1.5 = 0.7), considering the disparity of timescales over which the two averages were calculated (27 kyr versus 270 kyr). Clearly, ^{230}Th normalization captures the relative degree of focusing between the two sites documented by the chirp profile. The crux of the problem is thus to establish whether the accumulation of ^{230}Th observed in these cores, much larger than expected from production rate, is due to lateral redistribution of sediment on the seafloor [*Loubere et al.*, 2004; *Kienast et al.*, 2007] or lateral transport of ^{230}Th in the water column [*Lyle et al.*, 2005].

[5] Focusing factors calculated by *Lyle et al.* [2005] are only valid if the small section of the seafloor acoustically surveyed is a closed system with respect to sedimentation (i.e., that sediment redistribution only occurs within the surveyed area of the ocean floor, without lateral sediment input from outside this area), which is difficult to justify. While the advocates of ^{230}Th normalization argue that sediment (and adsorbed ^{230}Th) must be laterally transported from farther afield, *Lyle et al.* [2005] dismiss that possibility based on their reckoning that if focusing factors as large as deduced from ^{230}Th normalization in Y69–71 were extrapolated over the entire region of the EEP where a glacial MAR spike has been identified (an area greater than 6° by 6° [*Lyle et al.*, 2002]), that would produce a 17° by 17° area of sediment-barren seafloor, which is not observed. Instead, they propose that ^{230}Th is laterally transported in the water column independently of sediment mass. Considering that sediment focusing is controlled by both local and regional topography and is therefore highly variable and site-specific [e.g., *Mangini and Kuhnel*, 1987; *Turnewitsch et al.*, 2004], we question the validity of extrapolating sediment focusing measured in one core to a 6° × 6° area of the seafloor and find this simple regional sediment mass balance calculation unwarranted. We submit that it is nearly impossible to gather the comprehensive data set necessary to convincingly balance zones of sediment winnowing and focusing over the entire equatorial Pacific. On the other hand, testing the validity of ^{230}Th normalization is more readily amenable to

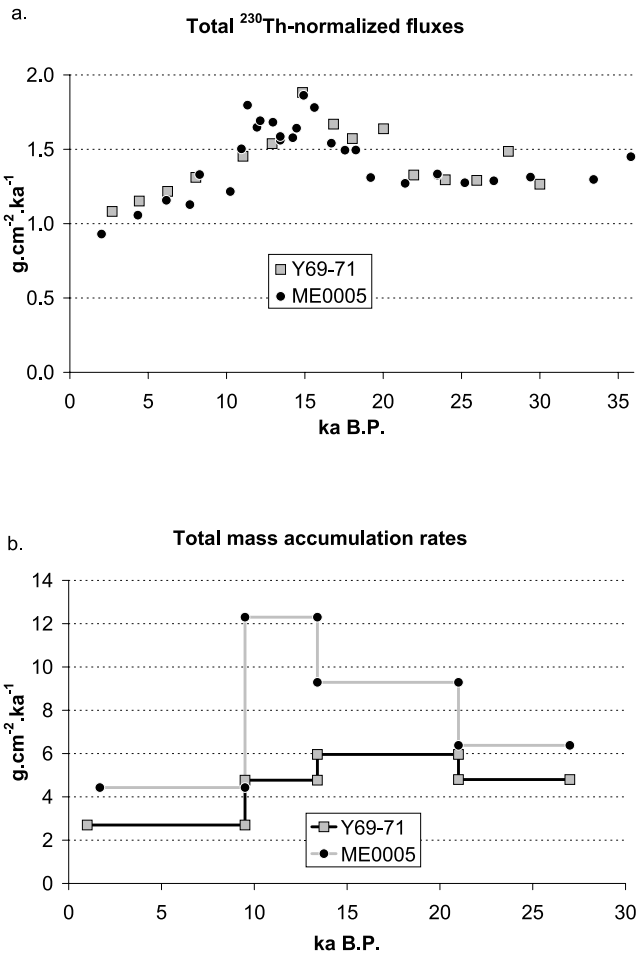

Figure 2. The (a) ^{230}Th-normalized fluxes and (b) mass accumulation rates in two adjacent cores (Y69-71 and ME0005-24JC) subjected to different degree of sediment focusing [*Kienast et al.*, 2007].

deductions from more fundamental principles, since it is based on our understanding of the geochemical behavior of ^{230}Th in the water column.

4. Are the Mechanisms Proposed by *Lyle et al.* [2005] to Explain Lateral Transport of ^{230}Th in the Water Column Consistent With Measurements of ^{230}Th in the Ocean?

[6] The most basic argument against the possibility of extensive lateral transport of ^{230}Th in the water column rests on its residence time, which can be readily calculated from the disequilibrium between ^{230}Th and ^{234}U [*Anderson et al.*, 1983]. ^{230}Th activities range from < 0.1 dpm m^{-3} in surface waters to $\sim$ 1.5 dpm m^{-3} in the deep Pacific Ocean [*Francois*, 2007], corresponding to residence times from a few months in surface waters to ~50 years in Pacific bottom waters. Using accepted estimates for lateral eddy diffusion coefficient, models of various complexity [*Bacon*, 1988; *Anderson et al.*, 1990; *Henderson et al.*, 1999; *Marchal et al.*, 2000] invariably show that lateral transport of ^{230}Th in seawater must be limited, resulting in vertical ^{230}Th flux within 30% of the production rate over most of the ocean. To argue for a more extensive lateral transport of dissolved ^{230}Th, the onus is thus on Lyle et al. to demonstrate that ^{230}Th activity in seawater can be much higher than thus far measured. Profiles of ^{230}Th have been measured in most ocean basins and it is unlikely that such high concentrations would have remained unnoticed.

[7] *Lyle et al.* [2005] suggest two mechanisms to laterally transport ^{230}Th in the water column: (1) with small suspended particles and (2) as a result of leakage of ^{230}Th from slowly accumulating sediments.

4.1. Lateral Transport With Small Suspended Particles

[8] In this scenario, most of the sediment mass reaching the seafloor would be carried by large particles originating from the surface and sinking rapidly with relatively little direct uptake of dissolved ^{230}Th from seawater or exchange with the suspended particle pool. Instead, ^{230}Th would be mainly adsorbed on small suspended particles and laterally transported toward regions of high particle flux to be incorporated into the settling flux. This would add a lateral flux of ^{230}Th with little additional mass of particles; that is, high accumulation of ^{230}Th in sediment would not necessarily indicate an equivalent lateral transport of sediment mass.

[9] There are several lines of evidence that argue strongly against this idea:

[10] 1. Vertical profiles of ^{230}Th associated with suspended particles indicate that their average sinking velocity is typically 500–1000 m yr^{-1} [e.g., *Marchal et al.*, 2000]. Therefore the mean residence time of suspended particles (and adsorbed ^{230}Th) in the water column is $\sim$5–10 years, i.e., shorter than for dissolved ^{230}Th in deep water ($\sim$40 years). Lateral transport of ^{230}Th with particles must therefore be even more limited than lateral transport in its dissolved form. Again, to convincingly argue in favor of this mechanism, Lyle and coworkers would have to provide evidence for sinking rates of particulate ^{230}Th much slower than found to date.

[11] 2. In order to have a net lateral transport of suspended particles by turbulent diffusion from low- to high-productivity regions, lateral particle concentration gradients would be needed, with lower suspended loads in the latter. The opposite is observed [*Beardsley et al.*, 1970; *Biscaye and Eittreim*, 1977]. Therefore such lateral transport, if significant at all, would occur in the opposite direction required to explain sediment focusing in the eastern equatorial Pacific.

[12] 3. The mechanism proposed for transporting ^{230}Th laterally would require that the ^{230}Th concentration per unit mass of suspended particles be many times higher than ^{230}Th concentration in sinking particles. Comparing ^{230}Th concentration in suspended and settling particles in the Panama Basin, *Anderson et al.* [1983] show that suspended particles have ^{230}Th concentrations only 1.5 to 3 times greater than sinking particles. Therefore lateral transport of particulate ^{230}Th would automatically be accompanied by significant lateral addition of particle mass.

[13] We thus conclude that the ^{230}Th concentration differences between sinking and suspended particles are too small and lateral transport of suspended particles too limited (and going in the wrong direction) to allow significant lateral transport of particulate ^{230}Th independently of particle mass from the central gyres toward the margins or other regions of high particle flux.

4.2. Leakage of ^{230}Th From Slowly Accumulating Sediments

[14] *Lyle et al.* [2005] also argue that ^{230}Th scavenged in central gyre regions could diffuse back from the sediment to the water column as settling particles are remineralized at the sediment water interface.

[15] A significant seafloor release of ^{230}Th would create a clear deviation from the linear dissolved ^{230}Th profiles predicted by the reversible scavenging model of *Nozaki et al.* [1981] and *Bacon and Anderson* [1982]. This is illustrated by adding to the model a diffusive flux originating from the sediment (Figure 3). The dissolved and particulate ^{230}Th profiles obtained for a range of vertical eddy diffusion coefficient (Kz) and ^{230}Th remobilization from the seafloor (F) display sharp increases in ^{230}Th concentration toward the bottom, which is not observed in profiles measured in central gyre regions [*Nozaki and Nakanishi*, 1985; *Roy-Barman et al.*, 1996; *Francois*, 2007].

5. The ^{230}Th Fluxes Measured With Sediment Traps

[16] Sediment traps have been used to further assess the extent to which the vertical flux of ^{230}Th can deviate from its rate of production [*Yu et al.*, 2001; *Scholten et al.*, 2005]. *Lyle et al.* [2005, paragraph 41] misrepresent the work of *Yu et al.* [2001], who did not simply assess trapping efficiency from the intercepted flux of ^{230}Th by assuming a constant vertical supply rate and neglecting lateral transport. On the contrary, the bulk of the paper is devoted to assessing the extent of this lateral transport by combining the intercepted flux of ^{230}Th and ^{231}Pa and taking advantage of the

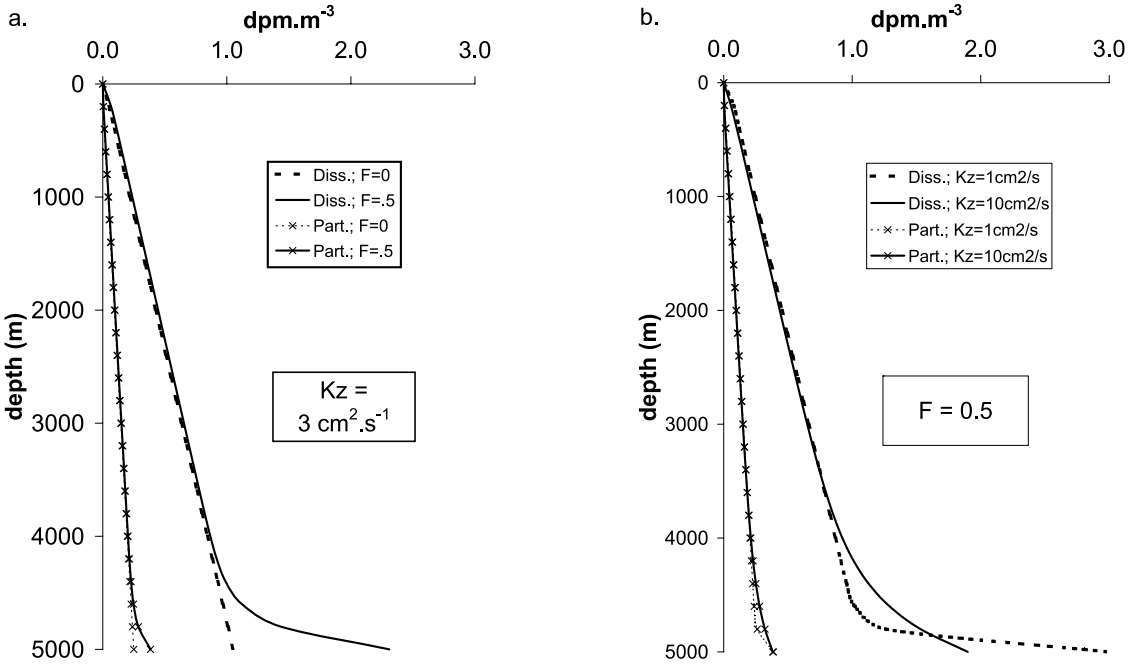

Figure 3. Expected dissolved and particulate ^{230}Th concentration profiles that would result if ^{230}Th were released from bottom sediments: (a) no release (F = 0) or 50% of production released (F = 0.5) and (b) 50% release with two different vertical eddy diffusion coefficients (Kz).

difference in residence time between these two nuclides. The conclusion that the mean annual vertical flux of ^{230}Th is within 30–50% of its production rate over most of the ocean is further corroborated by new sediment trap data. *Scholten et al.* [2005] found similar ^{230}Th fluxes, close to the rate of production, in the eastern and western Arabian Sea, even though mass fluxes were four times larger at the latter site. Annually averaged fluxes of ^{230}Th in the equatorial Pacific at 140°W are also nearly equal to production rates (data available athttp://usjgofs.whoi.edu/jg/dir/jgofs/eqpac/). *Lyle et al.* [2005] rightly note that sediment trap data often display a strong dependency between particle flux and ^{230}Th flux, but they fail to point out that these variations happen on short timescales (subannual) and reflect short-term imbalances between production and scavenging, which are largely averaged out when integrating over a full year or more [*Bacon et al.*, 1985].

6. Increased Sediment Focusing During the Last Glacial Period

[17] Compilation of existing ^{230}Th-normalized flux data indicates a general increase in sediment focusing during the last glacial period, particularly in the eastern equatorial Pacific region [*Kienast et al.*, 2007]. This is an intriguing observation, which has also been used to argue against ^{230}Th normalization. If sediment focusing is such a variable and site specific process, how could we explain such a systematic increase? Instead, this spatial coherence seems to point to the classical interpretation of MARs as reflecting changes in particle export flux. Recent findings provide an alternative explanation, however, which is compatible with increased sediment focusing. *Wunsch* [2003] argues that tidal dissipation, which occurs today mainly on the continental shelves, must have migrated to the deep sea during periods of low sea level stand. Stronger tidal currents in the deep ocean during glacial periods could thus be responsible for the higher focusing factors observed during MIS2 [*Kienast et al.*, 2007]. Coring is preferentially done in areas of sediment ponding, which would have a tendency to receive more laterally transported sediment during periods of stronger tidal currents (this sampling bias also explains why focusing is commonly found in core collections). Two bathymetric profiles of ^{230}Th-normalized flux from the equatorial Atlantic also show evidence for increased down-slope transport during MIS2 [*Francois et al.*, 1990], while *Mangini and Kuhnel* [1987] report enhanced accumulation of siliceous clays in sediment focusing pockets of the Clarion-Clipperton zone, suggesting that this may be a global phenomenon, as would be expected if controlled by tidal dissipation.

[18] Another possible explanation may be that there are actually no real (or much smaller) increases in sediment focusing (and MAR) during the last glacial period. Chronology-based MARs and focusing factors are very sensitive to chronological errors [*Francois et al.*, 2004; *Kienast et al.*, 2007; *Loubere and Richaud*, 2007]. Core chronologies used to estimate focusing and MARs are often based on δ^{18}O stratigraphy. A recent study comparing isotopic stratigraphy in radiocarbon dated cores from the North Atlantic and eastern equatorial Pacific has revealed that the decrease in benthic δ^{18}O linked to the last deglaciation occurs ~4000 years later in the Pacific, because of a late rise in deep water temperature [*Skinner and Shackleton*, 2005]. Focusing

factors and MAR calculated on the assumption that the shift in benthic $\delta^{18}O$ represents a purely glacioeustatic signal (i.e., placing the event at ~15 ka instead of 11 ka) would attribute too much material accumulating during the glacial period, thereby overestimating both glacial MARs and focusing.

[19] On the basis of these considerations, we thus stand by our position that ^{230}Th normalization largely corrects the most serious errors associated with earlier interpretations of sediment mass accumulation rates and should be systematically used to retrieve information on particle flux from the Late Quaternary sedimentary record.

References

Anderson, R. F., M. P. Bacon, and P. G. Brewer (1983), Removal of Th-230 and Pa-231 from the open ocean, *Earth Planet. Sci. Lett.*, *62*, 7–23.

Anderson, R. F., Y. Lao, W. S. Broecker, S. Trumbore, H. J. Hofmann, and W. Wolfli (1990), Boundary scavenging in the Pacific Ocean: A comparison of Be-10 and Pa-231, *Earth Planet. Sci. Lett.*, *96*, 287–304.

Bacon, M. P. (1984), Glacial to interglacial changes in carbonate and clay sedimentation in the Atlantic Ocean estimated from ^{230}Th measurements, *Isotope Geosci.*, *2*, 97–111.

Bacon, M. P. (1988), Tracers of chemical scavenging in the ocean: Boundary effects and large scale chemical fractionation, Philos, *Trans. R. Soc. London, Ser. A*, *325*, 147–160.

Bacon, M. P., and R. F. Anderson (1982), Distribution of thorium isotopes between dissolved and particulate forms in the deep sea, *J. Geophys. Res.*, *87*, 2045–2056.

Bacon, M. P., C.-A. Huh, A. P. Fleer, and W .G. Deuser (1985), Seasonality in the flux of natural radionuclides and plutonium in the deep Sargasso Sea, *Deep Sea Res., Part A*, *32*, 273–286.

Beardsley, G. F., H. Pak, K. L. Carder, and B. Lundgren (1970), Light scattering and suspended particulates in the eastern equatorial Pacific Ocean, *J. Geophys. Res.*, *75*, 2837–2845.

Biscaye, P. E., and S. Eittreim (1977), Suspended particulate loads and transport in the nepheloid layer of the abyssal Atlantic Ocean, *Mar. Geol.*, *23*, 155–172.

Francois, R., (2007) Paleoflux and paleocirculation from sediment ^{230}Th and $^{231}Pa/^{230}Th$, in *Methods in Late Cenozoic Paleoceanography*, edited by C. Hillaire-Marcel and A. de Vernal, Elsevier, New York.

Francois, R., M. P. Bacon, and D. O. Suman (1990), Th-230 profiling in deep-sea sediments: High-resolution records of flux and dissolution of carbonate in the equatorial Atlantic during the last 24000 years, *Paleoceanography*, *5*, 761–787.

Francois, R., M. Frank, M. M. Rutgers van der Loeff, and M. P. Bacon (2004), ^{230}Th normalization: An essential tool for interpreting sedimentary fluxes during the late Quaternary, *Paleoceanography*, *19*, PA1018, doi:10.1029/2003PA000939.

Henderson, G. M., C. Heinze, R. F. Anderson, and A. M. E. Winguth (1999), Global distribution of the ^{230}Th flux to ocean sediments constrained by GCM modeling, *Deep Sea Res., Part I*, *46*, 1861–1893.

Henderson, G. M., and R. F. Anderson (2003), The U-series toolbox for paleoceanography, *Rev. Mineral. Geochem.*, *52*, 493–531.

Kienast, S. S., M. Kienast, A. C. Mix, S. E. Calvert, and R. Francois (2007), Thorium-230 normalized particle flux and sediment focusing in the Panama Basin region during last 30,000, *Paleoceanography*, doi:10.1029/2006PA001357, in press.

Loubere, P., and M. Richaud (2007), Some reconciliation of glacial-interglacial calcite flux reconstructions for the eastern equatorial Pacific, *Geochem. Geophys. Geosyst.*, doi:10.1029/2006GC001367, in press.

Loubere, P., F. Mekik, R. Francois, and S. Pichat (2004), Export fluxes of calcite in the eastern equatorial Pacific from the Last Glacial Maximum to present, *Paleoceanography*, *19*, PA2018, doi:10.1029/2003PA000986.

Lyle, M. (1992), Composition maps of surface sediments of the eastern tropical Pacific Ocean, *Proc. Ocean Drill. Program Initial Rep.*, *138*, 101–115.

Lyle, M., A. Mix, and N. Pisias (2002), Patterns of $CaCO_3$ deposition in the eastern tropical Pacific Ocean for the last 150 kyr: Evidence for a southeast Pacific depositional spike during marine isotope stage (MIS) 2, *Paleoceanography*, *17*(2), 1013, doi:10.1029/2000PA000538.

Lyle, M., N. Mitchell, N. Pisias, A. Mix, J. I. Martinez, and A. Paytan (2005), Do geochemical estimates of sediment focusing pass the sediment test in the equatorial Pacific?, *Paleoceanography*, *20*, PA1005, doi:10.1029/2004PA001019.

Mangini, A., and U. Kuhnel (1987), Depositional history in the Clarion-Clipperton zone during the last 250,000 years–^{230}Th and ^{231}Pa methods, *Geol. Jahrb.*, *D87*, 105–121.

Marcantonio, F., R. F. Anderson, S. Higgins, M. Stute, P. Schlosser, and P. W. Kubik (2001), Sediment focusing in the central equatorial Pacific Ocean, *Paleoceanography*, *16*, 260–267.

Marchal, O., R. Francois, T. F. Stocker, and F. Joos (2000), Ocean thermohaline circulation and sedimentary $^{231}Pa/^{230}Th$ ratio, *Paleoceanography*, *15*, 625–641.

Nozaki, Y., and T. Nakanishi (1985), ^{231}Pa and ^{230}Th profiles in the open ocean water column, *Deep Sea Res., Part A*, *32*, 1209–1220.

Nozaki, Y., Y. Horibe, and H. Tsubota (1981), The water column distributions of thorium isotopes in the western North Pacific, *Earth Planet. Sci. Lett.*, *54*, 203–216.

Roy-Barman, M., J. H. Chen, and G. J. Wasserburg (1996), ^{230}Th-^{232}Th systematics in the central Pacific Ocean: The sources and the fates of thorium, *Earth Planet. Sci. Lett.*, *139*, 351–363.

Scholten, J. C., et al. (2005), Radionuclide fluxes in the Arabian Sea: The role of particle composition, *Earth Planet. Sci. Lett.*, *230*, 319–337.

Skinner, L. C., and N. J. Shackleton (2005), An Atlantic lead over Pacific deep-water change across termination I: Implications for the application of the marine isotope stage stratigraphy, *Quat. Sci. Rev.*, *24*, 571–580.

Thunell, R. C., R. S. Keir, and S. Honjo (1981), Calcite dissolution: An in situ study in the Panama Basin, *Science*, *212*, 659–661.

Turnewitsch, R., J.-L. Reyss, D. C. Chapman, J. Thomson, and R. S. Lampitt (2004), Evidence for a sedimentary fingerprint of an asymmetric flow field surrounding a short seamount, *Earth Planet. Sci. Lett.*, *222*, 1023–1036.

Wunsch, C. (2003), Determining paleoceanographic circulations, with emphasis on the Last Glacial Maximum, *Quat. Sci. Rev.*, *22*, 371–385.

Yu, E.-F., R. Francois, M. P. Bacon, and A. P. Fleer (2001), Fluxes of ^{230}Th and ^{231}Pa to the deep sea: Implications for the interpretation of excess ^{230}Th and $^{231}Pa/^{230}Th$ profiles in sediments, *Earth Planet. Sci. Lett.*, *91*, 29–230.

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