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Reply to comment by R. Francois et al. on "Do geochemical estimates of sediment focusing pass the sediment test in the equatorial Pacific?": Further explorations of ^{230}Th normalization

Mitchell Lyle,[1] Nicklas Pisias,[2] Adina Paytan,[3] Jose Ignacio Martinez,[4] and Alan Mix[3]

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1. Introduction

[1] The ^{230}Th method of *Francois et al.* [2004] to determine sediment focusing and to normalize sediment fluxes depends on the following two primary assumptions: (1) the abundance of ^{230}Th remains a constant within the sediment rain, i.e., the mass ratio of ^{230}Th to bulk sediment is the same in a horizontally transported mixture as in the particulate material falling from the surface, and (2) a sufficient source of sediments exists to supply both the sediment and the excess ^{230}Th. We show, via a mass balance of the Panama Basin, that ^{230}Th:sediment ratios of particulate rain vary by well over an order of magnitude, and that the shallow regions around the Panama Basin are too small to supply the ^{230}Th model fluxes. We reiterate the conclusion of *Lyle et al.* [2005] that there must be significant advection of ^{230}Th in the oceans without movement of large amounts of bulk sediment. *Francois et al.* [2007] have been unable to identify any independent means to test whether the ^{230}Th-based sediment focusing estimates are correct, and cannot explain why their model results do not agree with geophysical observations or other sediment measurements in cores. We stress that neither sediment focusing nor sediment fluxes can be modeled by ^{230}Th measurements alone.

[2] *Lyle et al.* [2005] present several lines of evidence to search for sediment focusing, which included subbottom profiling, seismic reflection, data from sediment cores, geographic distribution of sedimentary events, current patterns, and sediment dynamics. All of these lines of evidence imply that large-scale horizontal transport of sediment (on the order of 50% of the vertical flux) can indeed occur over length scales of tens of kilometers. However, massive sediment focusing of 100% to 700% of particle rain, over length scales of hundreds of kilometers, as suggested by *Francois et al.* [2004], are only achievable under very special (and not common) circumstances. Such extreme levels of sediment focusing should leave evidence easily detectable by marine geological methods and are independently testable.

[3] *Lyle et al.* [2005] is not the first study to suggest that ^{230}Th systematics is more complex than presented by *Francois et al.* [2004]. *Walter et al.* [2000], note that ^{230}Th inventories in the slowly accumulating sediments of the Weddell Sea basin (<0.5 cm/kyr) are only 40% of water column production. However, sediment trap measurements also indicate a vertical flux of ^{230}Th that is 40% of production. Using the ^{230}Th normalization method which assumes 100% accumulation of ^{230}Th produced in the water column would overrepresent the sediment loss by a factor of 2.5, and overcorrect the fluxes by the same factor. Similar complications were noted in the Arctic basin by *Moran et al.* [2005] who showed that 10% of the total water column ^{230}Th inventory was exported, presumably in the dissolved form, from the Arctic Ocean basin, and that 2/3 of the ^{230}Th inventory was buried on the margins, not in the deep basins where sediments should be horizontally transported.

[4] Furthermore, *Francois et al.* [2004] made it clear that the flux normalization works only if the scavenged ^{230}Th activity (ratio of Th disintegrations to mass of bulk sediment) is similar between horizontally advected and vertically falling sediment. Others also have pointed out that the fractionation of the fine from the coarse fractions in transported sediment is of major concern to ^{230}Th normalization [e.g., *Roy-Barman et al.*, 2005], specifically since ^{230}Th may be scavenged >200 times more efficiently by the lithogenic fine fraction than by biogenic fractions of sediments in the equatorial Pacific [*Luo and Ku*, 2004a, 2004b] and such scavenging may be prevalent in the water column. *Chase et al.* [2002] and *Chase and Anderson* [2004] challenged this conclusion about the lithogenic distribution coefficient, but still suggest that the apparently high distribution coefficient for lithogenic particles results from the association of ^{230}Th and the fine sediment fraction, not just the lithogenic particles.

[1]Department of Oceanography, Texas A & M University, College Station, Texas, USA.
[2]College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[3]Department of Geological and Environmental Sciences, Stanford University, Stanford, California, USA.
[4]Departmento de Geologia, Universidad Escuela de Administración, Finanzas y Tecnología, Medellin, Colombia.

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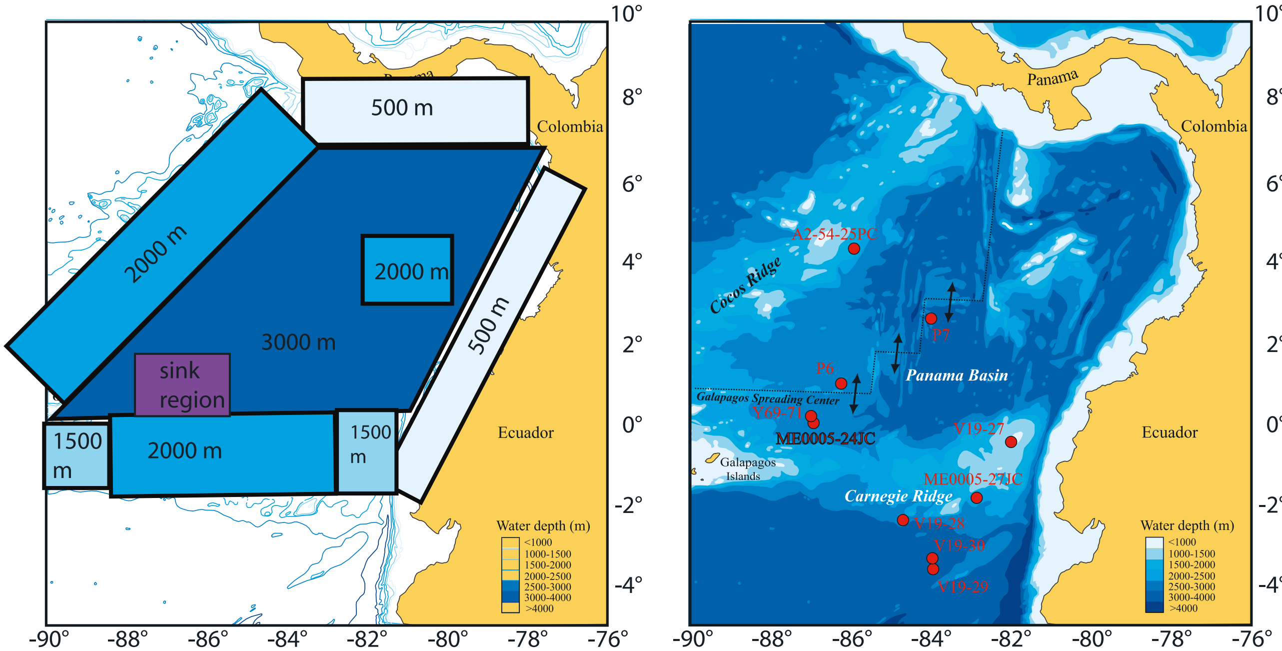

Figure 1. (left) Block model of the Panama Basin to estimate the ^{230}Th inventory for the deep basin and for the ridges and margins surrounding it. The inventory is reported in Table 1. (right) Map of Panama Basin from *Lyle et al.* [2005] showing bathymetry and location of cores that have a depositional event at the last glacial maximum.

[5] Finally, a wide spectrum of studies continues to find that slowly accumulating sediments in deep basins throughout the world's oceans consistently have smaller inventories of ^{230}Th than expected from seawater production, a fraction of which apparently is exported up and out of these basins [*Dymond and Veeh*, 1975; *Huh et al.*, 1997; *Moran et al.*, 2005]. The deep basins of the ocean should behave as sinks, not sources for ^{230}Th if ^{230}Th leaves the cycle as soon as it joins the sediment column. More studies of ^{230}Th from the deep gyre basins need to be made to understand the dynamics of ^{230}Th in slowly accumulating sediments (<0.5 cm/kyr).

2. A Mass Balance of the Panama Basin

[6] Here we explore whether the assertion made by *Francois et al.* [2004] that the ^{230}Th normalization method can indeed correct burial fluxes (sediment mass accumulation rates or MAR) in the Panama Basin in the absence of other information about the sedimentary environment. We reiterate that selective transport of the sediment fine fraction by horizontal advection contradicts their fundamental assumption: that the ^{230}Th ratio to bulk sediment rain at any given site is constant and depends only on seawater U concentration and water depth. We also show that, near continental margins, the large differences in water depth and bulk sediment fluxes to different parts of the margin naturally set variable ^{230}Th:bulk sediment ratios and make the correction based upon data from a single core impracticable. We also reiterate that ^{230}Th should be treated as an important tool in studies to understand sediment redistribution, but that it is not the whole toolbox and should be used in the context of specific geological and sedimentological conditions.

[7] Figure 1 shows a map and a first-order model of the Panama Basin, divided up into sedimentary regimes, to help clarify our arguments. In the model we have divided up the basin and its surrounding boundaries into four types of basic sedimentary regimes: (1) continental shelf and upper slope with an average depth of 500 m; (2) shallow pelagic tops of aseismic ridges at an average depth of 1500 m; (3) deep aseismic ridges with an average depth of 2000 m; and (4) the deep pelagic basin with an average depth of 3000 m. We use this model to explore quantitatively the production and movement of ^{230}Th and sediment within the Panama Basin. Note that the ^{230}Th flux can be discussed independently of total sediment flux.

[8] The model maximizes the potential size of the source regions and the potential ^{230}Th available for horizontal transport into the basin. Specifically, we deliberately skewed the depth of the ridges and margins to the deep end of their bathymetric range in order to maximize the ^{230}Th flux that might be horizontally transported (e.g., we allow for the maximum possible excess ^{230}Th to be available for redistribution). Using the assumption that U is uniformly distributed in the water column, the vertical flux of ^{230}Th to the seafloor is dependent only on the U concentration and water depth [*Francois et al.*, 2004]. The ^{230}Th inventory is a product of the vertical flux by the area for each regime (Table 1).

[9] Because the ^{230}Th inventory is dependent upon water depth, shallow areas like the Middle America shelf and the South American shelf make relatively small contributions to the total ^{230}Th inventory of the Panama Basin, although

Table 1. The ^{230}Th Inventory for Panama Basin Based on Figure 1

	Area, $m^2 \times 10^9$	Water Depth, m	Volume of Water for ^{230}Th Production, $m^3 \times 10^{12}$	Total ^{230}Th Inventory, dpm $\times 10^{12}$
Shallow blocks				
Middle America shelf	136	500	68	1.8
South America Shelf	145	500	73	1.9
Cocos Ridge	222	2000	444	11.8
Malpelo Ridge	48	2000	96	2.6
E. Carnegie Ridge	38	1500	57	1.5
Carnegie Ridge	151	2000	302	8.1
Galapagos Platform	30	1500	45	1.2
Shallow total	770			28.9
Deep Panama Basin	610	3000	1830	48.9

they have a large impact on the sediment budget. These two shelves have a combined area equal to 46% of the deep Panama Basin yet the combined ^{230}Th inventory of the two shelves is less than 8% of the deep basin inventory. The total ^{230}Th inventory of the shallow rim of the Panama Basin (plus the Malpelo Ridge in the center) is less than 60% of that of the Panama Basin floor (Table 1) even though the total shallow area is more than 25% greater than the basin floor.

[10] For ^{230}Th flux corrections to work, the ^{230}Th activity must be constant, as *Francois et al.* [2004] pointed out. Imagine, for example, that pure ^{230}Th particles are advected to a point where all the vertical sediment flux is preserved and buried in the sediment column. The focusing factor will then be greater than 1, because the ^{230}Th burial will be greater than the water column production. The normalization will overcorrect for the horizontally advected sediment because ^{230}Th is being added without any additional sediment. The same situation will occur at any time the ^{230}Th activity of the horizontally advected sediment is substantially higher than that of the vertical particulate rain. The converse is also true: Horizontally advected sediments with lower ^{230}Th activity than that of the vertical particulate rain will produce an undercorrection of the focused flux.

[11] Ocean margins are areas of high-particulate rain but low ^{230}Th inventory. Erosion from the shelves should contribute large amounts of sediment but low amounts of ^{230}Th, i.e., a low ^{230}Th:bulk sediment ratio. In contrast, erosion and redistribution within the deep basin will have a much higher ^{230}Th:bulk sediment ratio. For example, if particulate rain to the shelf zones is 5 times higher than the vertical component of particulate rain to the pelagic basins, then the ^{230}Th:bulk sediment of the shelf environment is 30 times smaller than that of the pelagic basin. The difference in water depth between the basin and the shelf causes the water column production of ^{230}Th to be 6 times higher in the basin than over the shelf. Thus horizontal movement of ^{230}Th derived from basin sediments will mark a movement of 30 times less sediment than the same amount of ^{230}Th derived from the shelf. One needs to know the various sources of sediment that accumulate at any given site, their relative contribution to the total sediment and their original ^{230}Th:bulk sediment ratio in order to convolute the original sediment rain rate from the ^{230}Th signature.

[12] The use of ^{230}Th is further complicated when sediments fractionate by size: During horizontal transport the fine sediment fraction always travels farther than the coarser fractions. ^{230}Th continuously adsorbs onto particles as they move through the water column and surface sediment. It preferentially adsorbs on the fine fraction because adsorption is correlated to surface area and the fine fraction has significantly higher surface area than coarser fractions. Any separation of fine fraction from coarse fraction along the transport route moves high amounts of ^{230}Th, but low bulk mass of total sediment. Removal of fines is often seen on ridge tops, and is a feature of the ridges around the Panama Basin [*Moore et al.*, 1973]. Size fractionation and transport of the fines can raise the ^{230}Th:bulk sediment ratio by large amounts and causes a huge overestimate of horizontal sediment flux at the site of deposition. The ^{230}Th normalization can thus either overestimate or underestimate the mass of sediment transported horizontally: It should not be used as a quantitative tool without other data to determine the source and transport process of the sediment.

[13] *Lyle et al.* [2005] explored two separate cases where the focusing factor was at least double the vertical particulate rain. The excess sediment is assumed to come through horizontal redistribution of the sediments from elsewhere. In the first case Holocene and late Pleistocene sediments under the Pacific equator from 86° W to 161°E [*Higgins et al.*, 1999; *Marcantonio et al.*, 2001; *Loubere et al.*, 2004] all typically have a focusing factor near 2, meaning that the model predicts that half the sediment was derived from elsewhere. However, in no case has a source region been identified for the excess sediment, nor is there even a plausible delivery method. In the Panama Basin, where the high surrounding ridges provide a possible source region, the few published data also reveal a focusing factor of 2.

[14] There is also a mass accumulation rate (MAR) event at the last glacial maximum in the eastern Pacific including most of the Panama Basin. The 18 ka MAR event has been attributed to high productivity [*Pedersen*, 1983; *Lyle et al.*, 1988; *Pedersen et al.*, 1991; *Lyle et al.*, 2002]. and is found throughout much of the Panama Basin, on top of the Carnegie Ridge, and in the northern Peru Basin [*Lyle et al.*, 2005]. *Loubere et al.* [2004] and *Francois et al.* [2004] contend through ^{230}Th normalization that the vertical rain of sediment did not change during the 18 ka MAR event. Instead they propose that sediment focusing increased from 2 to a factor of 8. In other words *Loubere et al.* [2004] and *Francois et al.* [2004] contend that there was no productivity event at 18 ka but instead a major sediment transport event.

[15] *Lyle et al.* [2005] determined that local redistribution on a scale of tens of kilometers has caused depositional variation in the range of 30 to 50% of the total sediment flux within the abyssal hill topography of the western Panama Basin. This is the case equivalent to what *Francois et al.* [2004] referred to as bottom nepheloid transport. We also noted that adjacent depositional areas maintained that level of difference in burial for over 2 million years, even during the 18 ka MAR event. Time series of MAR at different

spots in the basin, when normalized for different average MAR, have coherent changes in deposition.

[16] These observations imply that there is a small-scale (~10 km scale) syndepositional focusing that affects the average rate of burial but not the time series (the changes in MAR through time). Proposed high focusing events, like the 18 ka MAR event, must be derived from outside the local near-bottom region to leave the coherent MAR time series. The additional sediment must appear either through a change in vertical particle flux (e.g., export production) or by high transport from a distal sediment source. The only likely source for horizontally advected sediment to the deep Panama Basin is the high topography surrounding it.

[17] *Moore et al.* [1973] have shown that the ridges surrounding Panama Basin provide additional sediment to the basin and that much of the horizontally advected sediment may derive from water inflow into the Panama Basin across a low saddle in the Carnegie Ridge (see Figure 1). *Tsuchiya and Talley* [1998] have shown that the density, salinity, and temperature of western Panama Basin deep waters are consistent with flow into the region from the south over the Carnegie Ridge. *Lonsdale and Malfait* [1974] observed sand waves in the saddle of the Carnegie Ridge at a depth of 2650 m, about the same depth as core Y69-71 featured by *Lyle et al.* [2005], *Francois et al.* [2004], and *Loubere et al.* [2004]. Y69-71 is located over 100 km to the northwest of the Carnegie Ridge saddle, however (Figure 1). The Carnegie Ridge is clearly a viable source for horizontally advected sediment. However, can it supply enough sediment or ^{230}Th to match the model-based sediment focusing? It is important to explore this question because the 18 ka MAR event is also found on the shallowest part of the Carnegie Ridge (V19-27 [*Lyle et al.*, 2002]), even though average MAR on the top of the ridge is about half that in nearby basin cores.

[18] *Moore et al.* [1973] estimated via a simple model of carbonate accumulation and dissolution that about 14% of Panama Basin sediments were derived from the surrounding ridges. This number is probably an overestimate because they used a very high abundance of carbonate in the model particulate rain (95%) versus an observed value of 65% in the only nearby sediment trap [*Cobler and Dymond*, 1980]. Nevertheless, there is evidence for a source of fine sediment (the ridge top sediments are significantly coarser than the basin sediments) that could be horizontally advected into the western Panama Basin.

[19] Let us now explore the inventory of ^{230}Th in the Holocene and the implications for the last glacial maximum. Y69-71 (Figure 1) is located in the western Panama Basin, between the Carnegie Ridge and the active Galapagos spreading center. If the sediment source area is the Carnegie Ridge, and the additional sediment is derived via strong currents through the saddle, the minimum size of the depositional area is from the beginning of the Panama Basin just to the north of the saddle in the Carnegie Ridge to the Galapagos Spreading center, and westward to just past the position of Y69-71. We use this as a minimum because bottom current velocities should drop quickly after passing through the confined passage. We use a minimum depositional area to make the possible influence of horizontal sediment movements as large as possible. This depositional region, shown as "sink region" on Figure 1, has an area of 46×10^9 m^2, and has a vertical ^{230}Th inventory of 3.2×10^{12} dpm, using an average water depth of 2500 m.

[20] As Table 1 shows, there is sufficient area on the Carnegie Ridge to provide the excess ^{230}Th inventory to the sink region in the Holocene. The ^{230}Th inventory of the Carnegie Ridge is 2.5 times as large as the sink zone so the Carnegie ridge can produce a focusing factor of ~3.5, if the entire ^{230}Th inventory is stripped from the Carnegie Ridge and delivered to the sink zone. However, one result of this scenario is that the Carnegie Ridge could not supply large amounts of ^{230}Th or sediment to the rest of the Panama Basin.

[21] Because deep water moves into the Panama Basin from the south and must be exported over the ridge tops, any water and any horizontally advected sediment on Cocos Ridge, the northern boundary of the Panama Basin, moves out and away from the Panama Basin. The Cocos Ridge should thus supply minimal amounts of horizontally advected sediment to the deep Panama Basin.

[22] If the Carnegie Ridge is supplying sediment to the sink area to achieve a focusing factor of 2, the rest of the basin receives sediment and ^{230}Th from the Carnegie Ridge to achieve a maximum focusing factor of about 1.1, assuming all sediment is removed from the Carnegie Ridge (which it is not). Therefore we suggest that the best place to look for sediment focusing around Y69-71 is to examine sediments elsewhere in the Panama Basin and do the mass balance.

[23] At the LGM there is a major mass balance problem, because a focusing factor of 8 was measured in the sink region, for an added ^{230}Th inventory of 22.4×10^{12} dpm from sources other than the vertical particulate rain. This is equivalent to 276% of the ^{230}Th inventory to the Carnegie Ridge, or 78% of the entire ^{230}Th inventory of all the ridges and shallow sediment regimes surrounding the Panama Basin. According to the model presented by *Francois et al.* [2004], the production of ^{230}Th is a constant and independent of the sediment flux, so roughly 80% of the total ^{230}Th inventory from the ridges must somehow concentrate itself on 8% of the Panama Basin floor.

[24] Alternately the minimum depositional area could have gotten significantly smaller, so that the horizontal sediment focusing could have become significantly more focused at the last glacial maximum. If all the ^{230}Th inventory of the Carnegie Ridge were moved to the sink zone, the sink zone at the last glacial maximum must still have shrunk to one third of its Holocene size. So, at a putative time of maximum horizontal advection, the ^{230}Th model requires that the depositional area must shrink. The large focusing factor at 18 ka also requires that the rest of the Panama basin should experience drops in focusing factor at the LGM, another easy test that has yet to be conducted.

3. Conclusions

[25] We finish by coming back to our points: There can be significant horizontal movements of sediment in the pelagic

regime as has been recognized long ago by marine geologists. However, horizontal sediment focusing cannot be assessed by ^{230}Th-based models alone. Independent information is needed about source characteristics, including size of the source region, its sediment composition, and its degree of winnowing. *Francois et al.* [2007] objected to the alternate mechanisms we presented to reconcile the higher than expected levels of ^{230}Th found in some sediments with the lack of independent evidence for high levels of sediment movement. They have yet to provide alternative hypotheses of their own. We have shown here that the ^{230}Th inventories around the Panama Basin do not balance with the focusing factors calculated by ^{230}Th. As we said [*Lyle et al.*, 2005], the discrepancy could be resolved if significant ^{230}Th travels laterally without high fluxes of sediment, or if other yet undetermined mechanisms exist to decouple bulk sediments and ^{230}Th. We need to better understand these processes that lead to ^{230}Th advection and accumulation if we are to make better use of ^{230}Th as a tracer of horizontal sediment flux.

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M. Lyle, Department of Oceanography, Texas A & M University, College Station, TX 77843-3146, USA. (mlyle@ocean.tamu.edu)

J. I. Martinez, Departamento de Geologia, Universidad EAFIT, A.A. 3300 Medellin, Colombia.

A. Mix and N. Pisias, College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA.

A. Paytan, Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305-2115, USA.