TECHNICAL COMMENT

OCEANOGRAPHY

Comment on “Sensitivity of seafloor bathymetry to climate-driven fluctuations in mid-ocean ridge magma supply”

Maya Tolstoy

Olive *et al*. (Reports, 16 October 2015, p. 310) and Goff (Technical Comment, 4 September 2015, p. 1065) raise important concerns with respect to recent findings of Milankovitch cycles in seafloor bathymetry. However, their results inherently support that the Southern East Pacific Rise is the optimum place to look for such signals and, in fact, models match those observations quite closely.

Olive *et al.* (*1*) and Goff (*2*) raise questions about whether recent papers (*3*, *4*) really demonstrate that “the bathymetric fabric of the seafloor…records rapid…fluctuations in ridge magma supply caused by sea level changes” (*1*) because of the importance of unrelated faulting processes. However, their criticisms are applicable primarily to Crowley *et al.* (*4*), who specifically hypothesize that “abyssal hills…record the magmatic response to changes in sea level” with a model describing static topographic compensation to changes in melt input. Tolstoy (*3*), on the other hand, hypothesizes that “Seafloor eruption rates and mantle melting fueling eruptions may be influenced by sea level and crustal loading cycles at scales from fortnightly to 100 kyr,” with the primary hypothesis of the paper being that this may feed into long-term climate cycles, regardless of the bathymetric consequences. To test this, Tolstoy looked for supporting evidence in bathymetry from the ultrafast-spreading Southern East Pacific Rise (SEPR) specifically because it “provides a site where faulting is least dominant and magmatism is most prevalent” (*3*), in consideration of the complex factors contributing to seafloor bathymetry. Models of Olive *et al.* in fact demonstrate that any sea level–related signal is more likely to be observable at faster spreading rates, and Goff (*2*) leaves open the possibility that such a signal might be observed at “axial high ridges” because a subtle increase in observed widths of abyssal hill spacing with spreading rate cannot be ruled out for faster spreading rates. It is important to note that observed fault spacing represents a lower limit—i.e., the observed ~1- to 3-km spacing at fast spreading rates [figure 3A in (*1*)] (*2*, *5*) could easily mask a ~7- to 8-km spacing [~100 thousand years (ky)] superimposed on the closer spacing.

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Olive *et al.* present three possible mechanisms for topographic expression of fluctuations in melt supply at the mid-ocean ridge: (i) static topographic compensation [favored by (*4*)], (ii) volcanic extrusion on the seafloor, and (iii) tectonomagmatic interactions during normal fault growth [the latter two favored by (*3*)]. Both topographic compensation and normal fault growth are shown not to be viable at Milankovitch frequencies for the intermediate spreading rates of the Australian-Antarctic Ridge (*4*), and any increased volcanic extrusion would not be at a scale that could explain the observations. However, what is not emphasized in Olive *et al.* is that all three mechanisms considered show that the most likely place to observe them is at the SEPR because of the thinner axial lithosphere, smaller faults, and faster spreading rate, with all three mechanisms capable of producing observable signals at ultrafast spreading rates (8 cm/year) depending on various assumptions: Static topography signals are modeled to potentially be as high as 30 to 50 m, although this assumed the thinnest possible end member for lithospheric strength; excess volcanism may yield an additional 40 to 55 m of topography at ~100-ky periodicity, although again this may be decreased given off-axis flow; and fault spacings for a fluctuating dike injection rate are not estimated at SEPR spreading rates, but the model shows a ~100-ky cutoff in sensitivity for intermediate spreading rates, which means that at SEPR spreading rates this cutoff would fall below 100 ky. Therefore, ~100-ky fault spacing could develop at SEPR spreading rates in the context of very strong ~100-ky modulations in melt supply.

Overall, the scales of the signals predicted at the SEPR (10s of meters and faulting) are strikingly similar to those observed (*3*) (Fig. 1). The SEPR therefore meets the conditions set by Olive *et al.*’s models for observing 100-ky periodicity through climatically driven fluctuations. They do not consider the possibility of a direct influence of eccentricity on melt production and eruption frequency (*3*), but any addition from this process would only further strengthen the case. They also do not consider the possibility of caldera collapse effects (*6*) after periods of high magmatism, which could result in the troughlike features observed during periods of correspondingly low CO_2 emissions (Fig. 1.).

Olive *et al.* provide an excellent starting point for discussing the likely presence and magnitude of any Milankovitch forced seafloor periodicities; however, seafloor volcanism and faulting are full of complexities that have the potential to mask such signals. For instance, at the faster spreading rates, eruptions can lead to lava flowing at least 2 km off-axis; off-axis volcanism may contribute to surface topography; and the robustness of magmatism can be highly variable along axis, the foci of which may or may not be steady through time [e.g., (*6*, *7*)]. Present-day fast-spreading ridges display areas of inflated ridge axis that may erupt more frequently and other segments that have not shown signs of an eruption for decades (*8*). As such, the approach used in Tolstoy (*3*) was to stack bathymetric

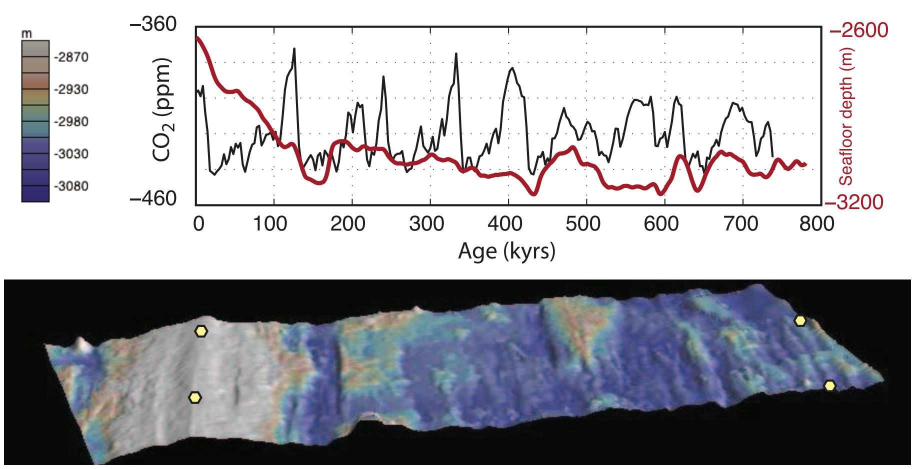

Fig. 1. Topographic data at the SEPR compared with CO_2 (*3*). (**Top**) Unfiltered stacked bathymetric profile show in red, with CO_2 (*9*) record in black. (**Bottom**) Map of area of nine axis-perpendicular bathymetric profiles (within the box shown by yellow dots) used to make the stacked profile (*10*).

profiles, a classic seismic technique for enhancing a noisy signal. In the context of all the possible causes of variability, the temporal match of an unfiltered stack of seafloor bathymetry with periods of high and low CO_2 output (*9*) (which roughly tracks sea level) is notable (Fig. 1).

It is worth considering that the lower-than-predicted present-day eruption rates (*3*), consistent with a period of present-day decreased magmatism, have implications for modeled mid-ocean ridge properties that are generally assumed to be steady state. For instance, data on accretion widths and axial lithospheric strength incorporated into models may not reflect the properties during a time of more robust magmatism. Systematic increases in global mid-ocean ridge volcanism may thus lead slower spreading rates to be more susceptible to the imprint of volcanic fluctuations. More data will help confirm or refute this.

The hypothesis that seafloor bathymetry is controlled by Milankovitch cycles (*4*) should not be conflated (*1*, *2*) with the hypothesis that sea level and orbital variations influence magmatism at ridges (*3*). Independent of bathymetric signatures, the consequences of non–steady state mid-ocean ridge eruptions should be considered in geochemical exchanges between the ocean and the lithosphere, including the global carbon cycle (*3*).

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