

TECHNICAL COMMENT

OCEANOGRAPHY

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

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Olive *et al.* (Reports, 16 October 2015, p. 310) argue that ~10% fluctuations in melt supply do not produce appreciable changes in ocean ridge bathymetry on time scales less than 100,000 years and thus cannot reflect sea level forcing. Spectral analysis of bathymetry in a region they highlight as being fault controlled, however, shows strong evidence for a signal from sea level variation.

Olive *et al.* (1) argue that abyssal hills do not contain appreciable contributions from the influence of sea level change on magma production at ocean ridges. This hypothesis was originally suggested by Huybers and Langmuir (2) and further elaborated and supported by mantle melt modeling and observations on the Australian-Antarctic ridge by Crowley *et al.* (3).

Olive *et al.* consider separately intrusive and extrusive magma additions but claim that bathymetric variations from both of these can only result in topographic variations of less than 85-m amplitude for magma volumes that fluctuate at Milankovitch periods [see figure 2 in (1)]. Constructional topography of far greater extent, however, is common at slow and intermediate-spreading ridges. A split seamount and the pairs of symmetric ridges at the intermediate-spreading Endeavor segment in the northeast Pacific are both demonstrably constructional features created on-axis and preserved off-axis (4). The common axial volcanic ridges at slowly spreading ridges (5), where elastic thickness is greatest, are also constructional features, tens of km long with vertical relief of several hundred meters and a cross-sectional scale that can be less than 2 km. Lucky Strike seamount rises 1 km above the axis of the slow-spreading Mid-Atlantic ridge (6). The Southeast Indian Ridge (7, 8) and Galapagos Spreading Center (9, 10), which have near constant spreading rates but variable magma supply along axis, show marked differences in axial topography in response to melt flux variations of similar magnitudes to those proposed by Crowley *et al.* Despite the inferences Olive *et al.* draw from their models,

seafloor topography of many hundreds of meters that reflects changes in magmatic budget is a common feature of ocean ridges.

A closer examination of the Chile Ridge segment used by Olive *et al.* offers evidence for the conclusions of Crowley *et al.* Large offset faults are apparent in the bathymetry, but there are also smaller linear ridges and numerous volcanic cones with relief of about 100 m, particularly at the edges of the segment [see figure 1 in (1)]. Accordingly, we analyze a transect near 39° South from cruise PANR04MV near the northern edge of the Chile Ridge segment. Crustal age is estimated using a Brunhes-Matuyama magnetic reversal of 700 thousand years (ky). Spectral analysis is carried out following the multitaper methodology used by Crowley *et al.*, wherein statistical significance is judged at the 95% confidence level relative to a chi-square null distribution (11). Significant spectral peaks occur at the Milankovitch periods of 100 ky, 41 ky, and near the 23-ky period, matching those found in sea level variability (Fig. 1), and in agreement with the independent analysis of the Australian-Antarctica Ridge by Crowley *et al.* Other transects from the Chile Ridge show similar behavior, especially near the edges of the segment, but not as clearly. Topography associated with short-term fluctuations in magma supply may be better preserved near the ends of ridge segments on the Chile Ridge, where crustal magma reservoirs may be present only during periods of magma excess.

Olive *et al.* argue that the appearance of 100-ky variability could be an emergent time scale associated with extensional faulting and that spectral peaks at higher frequencies could result from overtones of 100-ky fault spacing. Two further observations, however, indicate that the Chile Ridge bathymetry is not faulting masquerading as Milankovitch. First, bathymetry variations before 700 thousand years ago are characterized

by smaller amplitude oscillations and a 41-ky time scale, consistent with the dominant 41-ky obliquity period variability found in Early Pleistocene sea level. Second, examination of the temporal variability shows high-frequency variations in bathymetry similar in structure to sea level estimates and distinct from the abrupt changes that give rise to strong overtones in Olive *et al.*'s simulations (see Fig. 1).

Numerous processes missing from Olive *et al.*'s models might explain their inability to produce the significant sea level-induced bathymetry emerging from observations. For example, dike-induced faulting (12) and eruption dynamics, including effusion rates that govern how lavas accumulate on the seafloor (13), are not considered. Rather than new pulses of magma effectively mixed across a 1-km-wide magma storage zone as modeled by Olive *et al.*, local crustal magma sills could wax and wane as magma supply varies (14), and large magma pulses could migrate vertically without mixing in a broader crustal reservoir. Although we agree that Crowley *et al.*'s approach of predicting bathymetric variations assuming local isostasy is probably too simple, it appears that Olive *et al.*'s models also omit important processes.

Olive *et al.* dismiss the importance of volcanic construction on the basis that it is “unlikely to strongly overprint the tectonic fabric of the seafloor, which typically consists of fault scarps greater than 200 m at slow and intermediate-spreading ridges.” Normal faults do, of course, contribute importantly to the fabric of the sea floor but do not preclude the presence of additional structure. We suggest the need for a more resolved approach than the historical characterization of abyssal hills using a single wavelength (15, 16). The approach in Crowley *et al.* of prewhitening the spectral estimate has the effect of emphasizing higher-frequency variability and leads to the identification of multiple relevant time scales, namely those associated with 100-ky glacial, 41-ky obliquity, and 23-ky precession variations. This more-detailed seafloor relief is an opportunity to better understand the relative contributions of volcanic and tectonic processes at mid-ocean ridges.

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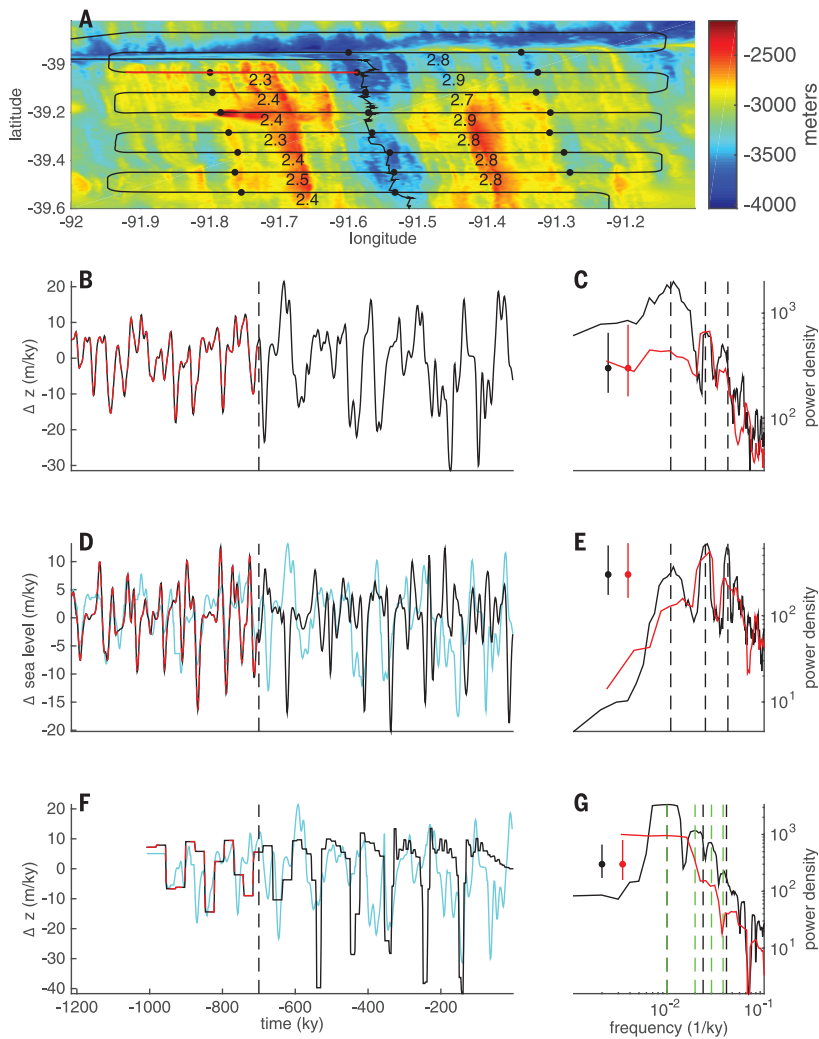


Fig. 1. Bathymetry from the Chile Ridge. (A) Map of bathymetry (coloring), the track from cruise PANR04MV (black line), Brunhes-Matuyama reversals from magnetics and visually identified ridge center (dots), inferred spreading rates (numbers in cm/year), and the transect that we focus on (thicker red line). (B) Rate of change of the bolded bathymetry section and (C) the associated spectral estimate (black), indicating peaks near the $1/100$, $1/41$, and $1/23$ ky^{-1} Milankovitch bands (marked with vertical dashed lines). Spectral peaks are statistically significant when they rise above the background continuum by more than the 95th percentile (i.e., after aligning the dot on the black confidence bar with the spectral peak, the lower vertical bar does not reach the level of the background continuum). Note the use of logarithmic axes. Also shown is a spectral estimate for the time period between 1.2 and 0.7 million years ago during the “41 ky” world (red), where there is significant spectral energy at the 41-ky obliquity band (judged using the red vertical bar) but the other Milankovitch bands are diminished. (D and E) Analysis of sea level changes (17) (note reversal of the y axis) shows spectral peaks matching (C). A version of the bathymetry rates of change are also shown (cyan) after alignment with the sea level variations using a dynamic time warping algorithm and scaling to match variance. (F and G) The analysis is repeated using the faulting simulations from Olive *et al.* with a 100-ky time scale, but which obviously cannot reproduce the transition to 41-ky variability. Overtones of the 100-ky time scale are indicated at $2/100$, $3/100$, and $4/100$ ky^{-1} (green vertical dashed lines). An aligned version of the bathymetry data is also presented (cyan) that illustrates the difference between the continuous high-frequency variability recorded in bathymetry and abrupt transitions in the fault simulation.

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