

TECHNICAL COMMENT

OCEANOGRAPHY

Comment on “Glacial cycles drive variations in the production of oceanic crust”

John A. Goff

Crowley *et al.* (Reports, 13 March 2015, p. 1237) propose that abyssal hill topography can be generated by variations in volcanism at mid-ocean ridges modulated by Milankovitch cycle-driven changes in sea level. Published values for abyssal hill characteristic widths versus spreading rate do not generally support this hypothesis. I argue that abyssal hills are primarily fault-generated rather than volcanically generated features.

Crowley *et al.* (1) purport to show evidence that topographic profiles through abyssal hill morphology perpendicular to the spreading ridge axis exhibit periodicities that correspond well to Milankovitch cycles. The argument is that this correspondence could be explained by volcanic output at the mid-ocean ridge (MOR) modulated by the lithostatic pressure variations associated with rising and falling sea level. A contemporaneous paper by Tolstoy (2) reaches the same conclusion. I will refer to this argument as the “CT hypothesis.” Crowley *et al.* also formulate a sophisticated numerical model to predict seafloor variations that could result from sea-level variability over the past 1.2 million years.

The CT hypothesis makes specific predictions about the variation of abyssal hill horizontal scales in the direction perpendicular to the spreading axis (the “width” of the abyssal hill) as a function of spreading rate; these predictions can be tested with existing published results. In the simplest possible case, the CT hypothesis predicts that abyssal hill width will scale linearly with spreading rate. For example, if we assume that the 100,000-year Milankovitch cycle is the dominant driver for abyssal hill formation, as suggested by Tolstoy (2), then abyssal hill width will be 1 km for every 1 cm/year of half-spreading rate. Thus, widths would be ~1 km at ultraslow half-spreading rates of 1 cm/year and ~7 km at ultrafast rates of 7 cm/year. The numerical modeling by Crowley *et al.*, however, suggests that shorter-period Milankovitch cycles may be more dominant at faster rates. Depending on certain modeling parameters, the 41,000-year cycle might dominate at 4 cm/year half-spreading rate, and the 23,000-year cycle might dominate at 7 cm/year half-spreading rate [see figure 1 in (1)]. If so, this would suggest a much lower sensitivity of abyssal hill width on spreading rate, varying from ~1 km at 1 cm/year half-rate to just 1.6 km at 7 cm/year half-rate.

Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA.
E-mail: goff@ig.utexas.edu

Global, averaged estimates of the characteristic abyssal hill width (3, 4) are presented as a function of half-spreading rate (Fig. 1). The characteristic width is formally estimated by the width of the covariance function but can also be derived with the von Kármán statistical model (5) from the inverse of the corner frequency of a power spectrum modeled as a band-limited fractal (6). The characteristic width describes the dominant visual scale (6). The von Kármán spectral model, being fractal in nature, does not contain periodicities. However, if this model were fit to the spectral functions modeled by Crowley *et al.* in their figure 1, the corner frequency would correspond to the periodicity with the highest amplitude, because this is where the spectrum transitions from being approximately white (flat) at low frequencies to red (fractal) at high frequencies. Therefore, the characteristic width should represent a reasonable estimate of the dominant abyssal hill width if the abyssal hills were, in fact, periodic. Under this assumption, the characteristic width values shown in Fig. 1 are incompatible with the predictions of the CT hypothesis in two important ways: (i) average widths measured at the slowest

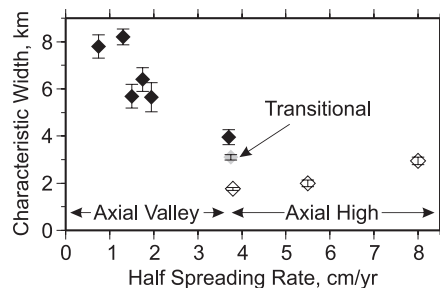


Fig. 1. Abyssal hill characteristic widths, averaged by region, plotted as a function of half-spreading rate. Error bars, mean \pm 1 SD. Figure adapted from Goff *et al.* (3), with additional data from Sloan *et al.* (4). Black symbols indicate regions formed at axial valley MORs; open symbols at axial high MORs; and gray symbol at transitional MOR.

spreading rates, ~8 km, are far too large to be correlated with Milankovitch cycles, and (ii) the trend of widths with spreading rate is negative, rather than the predicted positive or flat trend, at least to half-rates of ~3.7 cm/year (or the transition from axial valley to axial high MOR morphology). The characteristic widths also exhibit a large (>2 km) downward step, independent of spreading rate, where the MOR morphology transitions from axial valley to axial high; these values were estimated on the flanks of the Southeast Indian Ridge (3).

The negative trend in characteristic width with spreading rate can be seen as consistent with a faulted origin. Fault offset and spacing scale with elastic plate thickness (7, 8), which is dependent on thermal structure (9). Thermal structure is, in turn, dependent on spreading rate (10). As a result of these relationships, colder lithosphere at slower spreading rates should result in larger offsets on more widely spaced faults. Faulting may also be controlled by variations in magma supply (11), which could explain variations in abyssal hill morphology that are independent of spreading rate, such as along the Southeast Indian Ridge (3). Observational studies have shown that abyssal hills are primarily fault-controlled horst-and-graben features, rather than volcanic-controlled constructs, at both fast (12) and slow (13) spreading rates. Indeed, the abyssal hills displayed by Crowley *et al.* exhibit a strikingly linear, axis-parallel morphology, which is likely most consistent with a faulted origin. Although the correlation between axial volcanism and sea-level variations is certainly plausible, it appears more likely to translate only as a secondary superposition on the primarily tectonic abyssal hill morphology (12).

At half-spreading rates greater than ~3.7 cm/year, where the axial high ridge morphology dominates, the trend of characteristic width with spreading rate is no longer negative and, in fact, may be slightly positive in going from ~2 km at 3.7 cm/year to ~3 km at 8 cm/year (Fig. 1). Goff *et al.* (3) argued that lack of sensitivity of abyssal hills to spreading rate at these higher rates could be associated with a nearly uniform presence of a weak zone in the lower crust at axial high ridges (14), which would decouple surface faulting from deeper strain. We cannot, however, discount the possibility that Milankovitch cycle-driven volcanism is contributing, at least in part, to the increase in measured characteristic width with spreading rate at axial high ridges; no other plausible explanation for this observation has been offered, to my knowledge.

REFERENCES AND NOTES

1. J. W. Crowley, R. F. Katz, P. Huybers, C. H. Langmuir, S.-H. Park, *Science* **347**, 1237–1240 (2015).
2. M. Tolstoy, *Geophys. Res. Lett.* **42**, 1346–1351 (2015).
3. J. A. Goff, Y. Ma, A. Shah, J. R. Cochran, J.-C. Sempéré, *J. Geophys. Res.* **102**, 15521–15534 (1997).
4. H. Sloan, D. Sauter, J. A. Goff, M. Cannat, *Geochem. Geophys. Geosyst.* **13**, Q0AE06 (2012).
5. J. A. Goff, A. Levander, *J. Geophys. Res.* **101**, 8489–8501 (1996).
6. J. A. Goff, T. H. Jordan, *J. Geophys. Res.* **93**, 13589–13608 (1988).
7. A. Malinverno, P. A. Cowie, *J. Geophys. Res.* **98**, 17921–17935 (1993).

8. P. R. Shaw, J. Lin, *J. Geophys. Res.* **98**, 21839–21851 (1993).
9. M. K. McNutt, *J. Geophys. Res.* **89**, 11180–11194 (1984).
10. J. Phipps Morgan, Y. J. Chen, *Nature* **364**, 706–708 (1993).
11. W. R. Buck, L. L. Lavier, A. N. Poliakov, *Nature* **434**, 719–723 (2005).
12. K. C. Macdonald, P. J. Fox, R. T. Alexander, R. Pockalny, P. Gente, *Nature* **380**, 125–129 (1996).
13. C. Durant, V. Ballu, P. Gente, J. Dubois, *Tectonophysics* **265**, 275–297 (1996).
14. W. J. Shaw, J. Lin, *J. Geophys. Res.* **101**, 17977–17993 (1996).

ACKNOWLEDGMENTS

The author thanks G. Christeson for helpful comments on an earlier draft.

30 March 2015; accepted 24 July 2015
10.1126/science.aab2350

TECHNICAL RESPONSE

OCEANOGRAPHY

Response to Comment on “Glacial cycles drive variations in the production of oceanic crust”

John W. Crowley,^{1,2*} Richard F. Katz,^{1†} Peter Huybers,²
Charles H. Langmuir,² Sung-Hyun Park^{3†}

Goff comments that faulting is important for creation of abyssal hills and is the dominant process at slow-spreading ridges. We respond that faulting is indeed important but cannot alone explain the bathymetric signal predicted by our models and observed at the Australian-Antarctic Ridge. We show that for intermediate- to fast-spreading ridges, abyssal hill spacing is consistent with the periodicity of the obliquity cycle.

We appreciate Goff's Comment (1) and the opportunity to reemphasize a point that may have been lost to some readers of our paper [Crowley *et al.* (2)]: Faulting is an important and ubiquitous process in abyssal hill creation, particularly at slow-spreading ridges. However, our paper also shows, through modeling and observations, that sea level has a substantial effect on melt delivery to ocean ridges and an influence on the fabric of the sea floor. The greater importance of faulting at slow-spreading

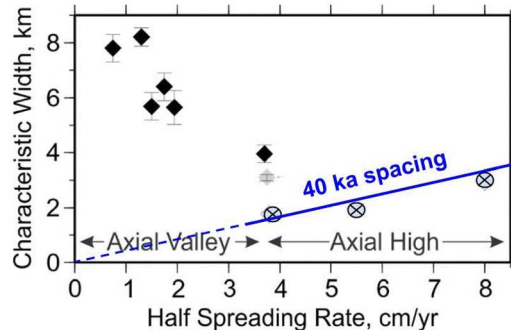
ridges led us to consider bathymetry at a faster-spreading ridge, where the subaxial lithosphere is thin and the magma supply is robust.

Because of the balance between faulting and magma supply, intermediate- and faster-spreading ridges offer the best opportunity to detect crustal thickness variations driven by glacial cycles. Goff's figure can be used to emphasize this point. In Fig. 1 here, we add a line to his figure 1 indicating the predominant spacing that would be produced by 40,000-year periodicity. At slow spreading rates, there is no correspondence between this line and the spacing data. At intermediate and fast spreading rates, however, both the absolute value and the relative increase in spacing are in accord with the Milankovitch periodicity. Goff also notes this slight increase. As he states, “no other plausible explanation for this observation

¹Department of Earth Sciences, University of Oxford, Oxford, UK. ²Department of Earth and Planetary Sciences, Harvard University, Cambridge, USA. ³Division of Polar Earth-System Sciences, Korea Polar Research Institute, Incheon, Korea. *Present address: Engineering Seismology Group Canada, Kingston, Canada. †Corresponding author. E-mail: richard.katz@earth.ox.ac.uk (R.F.K.); shpark314@kopri.re.kr (S.-H.P.)

Fig. 1. Characteristic width of abyssal hills versus half-spreading rate.

Adapted from figure 1 of Goff's Comment. The line indicates the predominant spacing that would be produced by a 40,000-year periodicity.



has been offered.” It would be premature, however, to rule out other speculative mechanisms that might relate fault-generated bathymetry to sea-level change.

Although we are thus in overall agreement with the Comment, it should be noted that the characteristic width determined by the von Kármán spectral model may not be an apt statistical measure of the variability in bathymetry. As noted by Goff and Jordan (3), the von Kármán spectral model assumes power-law scaling that rolls off to white at a corner frequency and does not provide a very good approximation in the presence of periodicities. Furthermore, our detection of excess spectral energy at Milankovitch bands involves prewhitening, which in this case systematically deemphasizes lower-frequency contributions. Those lower-frequency contributions are expected to influence characteristic width estimates and cause some disconnect between our results and Goff's results.

Finally, it should be noted that faulting may be mechanically coupled with temporal variations in magma supply. Ito and Behn (4) found that fault spacing depends on the periodicity of cycles between magmatic and tectonic extension at ~100,000 years and greater periods. If this is the case, the admittance structure from our paper would need to be modified. Ultimately, a more complete model is needed that consistently combines faulting, glacially induced variations in magma supply, and variations caused by other processes (e.g., mantle fertility or instabilities in the melting regime).

We are in broad agreement with Goff's Comment that faulting is dominant at slow-spreading ridges and that the hypothesis of sea-level-induced changes in magma production is currently the most plausible explanation for spectral energy at Milankovitch frequencies found in bathymetry at faster-spreading ridges.

REFERENCES AND NOTES

1. J. A. Goff, *Science* **349**, 1065 (2015).
2. J. W. Crowley, R. F. Katz, P. Huybers, C. H. Langmuir, S.-H. Park, *Science* **347**, 1237–1240 (2015).
3. J. A. Goff, T. H. Jordan, *J. Geophys. Res.* **93**, 13589–13608 (1988).
4. G. Ito, M. D. Behn, *Geochem. Geophys. Geosyst.* **9**, Q09012 (2008).

ACKNOWLEDGMENTS

Funding was provided by the European Research Council (ERC) under the European Union's Seventh Framework Programme (FP7/2007–2013)/ERC grant agreement 279925, the U.S. National Science Foundation under grant 1338832, and the Korea Polar Research Institute as part of projects PPI3040 and PE14050.

13 May 2015; accepted 24 July 2015
10.1126/science.aab3497