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Bathymetric gradients of lineated abyssal hills: Inferring seafloor spreading vectors and a new model for hills formed at ultra-fast rates

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Abstract

Abyssal hill morphology provides a preliminary measure of the direction and rate of seafloor spreading, however, additional information (e.g., magnetic anomaly data or a nearby mid-ocean ridge) is usually required to verify these estimates. Previous attempts to identify a unique spreading rate proxy from abyssal hill dimensions (e.g., height, length, width) have largely failed due to the relatively large scatter of data or the non-linear character of spreading rate trends. We present a new, stand-alone method of determining both spreading rate and spreading direction using the distribution of azimuths for slopes facing toward and away from the ridge axis. The spreading rate is determined with the Δ peak height parameter, defined as the difference in the height (maximum frequency) of the two dominant modes observed in the azimuthal histograms. This parameter exhibits a clear, nearly linear spreading rate trend and allows half spreading rates to be estimated to within 10–20 km/Myr. The spreading direction is determined with the Δ peak width parameter, which compares the average width of the two dominant modes in the azimuthal histograms. The wider distribution of slope azimuths is oriented away form the paleo-ridge axis for all spreading rates, and thus spreading direction can be determined. The trends in the peak height and width parameters are used to constrain a new model of abyssal hill formation at ultra-fast spreading rates, which require greater off-axis extensional faulting resulting in a few large-throw faults on the outward-facing hillsides, and many smaller throw faults on the inward-facing hillsides.

Keywords: Abyssal hills; seafloor morphology; plate tectonics; mid-ocean ridges; slope analysis

1. Introduction

Abyssal hills constitute ~80% of the seafloor and thus are the most common landform on Earth [1]. The morphology of abyssal hills is best observed on relatively young ocean crust flanking mid-ocean ridges where sediment accumulation has not masked their appearance. In these settings, the hills are elongate parallel to the ridge axis, have relief of 50–500 m, and characteristic width of 1–10 km [2]. The proximity of abyssal hills to the ridge axis suggests these features are the result of the interplay between tectonic and volcanic processes occurring within the plate boundary zone. Once formed, the hills are transported onto the ridge flanks by plate motion and their basement morphology is preserved.

Since the early days of seafloor mapping, it has been realized the general morphology of abyssal hills varies

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as a function of spreading rate; basically, slower spreading rates generate larger abyssal hills [3]. With the advent of swath mapping systems, this spreading rate dependence has become even more apparent and a three-dimensional description is available. In general, abyssal hills created at slower spreading rates are higher, wider and longer than those hills created at faster spreading rates [2]. These relationships led to the development and refinement of abyssal hill formation models where tectonic processes dominate at slower spreading rates and volcanic processes dominate at faster spreading rates (Fig. 1). At slow spreading rates (<25 km/Myr, half-rate), back-tilted or listric fault blocks suggest a predominantly tectonic origin of abyssal hills [4,5]. At intermediate spreading rates (25–40 km/Myr, half-rate), the split volcano model suggests tectonic and volcanic processes contribute equally as waxing phases of volcanism create an axial rise that is subsequently bisected during waning volcanic phases [6,7]. At fast spreading rates (40–60 km/Myr, half-rate), the presence of a steady-state magma chamber precludes the formation of split volcanoes at the ridge axis, so the abyssal hills are generated slightly farther off-axis by the formation of a graben along the "shoulders" of the axial high [8]. In this model, the fault scarp closest to the ridge axis is subsequently covered by volcanic flows emanating from the ridge axis.

The goal of many seafloor morphology studies has been to identify a parameter or set of parameters that can be used to determine the kinematic setting in which a parcel of seafloor was created. This would be particularly useful in sections of the seafloor where conventional methods of determining spreading rates with seafloor magnetic anomalies are compromised due to the lack of correlatable magnetic anomalies in crust created at north–south trending mid-ocean ridges near the magnetic equator and in crust created during periods of uniform magnetic polarity (e.g., Cretaceous magnetic superchron, 121–84 Ma). Abyssal hill morphology would initially seem to be an attractive alternative within these magnetically challenged regions; however, the spreading rate variability of these first-order morphologic parameters (relief, width, length) often is not linear and the scatter is too large to identify a unique spreading rate. Even when combined with lower-order parameters (e.g., vertical skewness and kurtosis), a unique spreading rate cannot be obtained [2].

In this study, we explore the use of bathymetric gradients (magnitude and direction of seafloor slope) to determine the kinematic environment of abyssal hill formation. Since the abyssal hill formation models predict asymmetric distributions for volcanism and tectonism on the sides of abyssal hills facing toward and away from the ridge axis, our analysis compares the

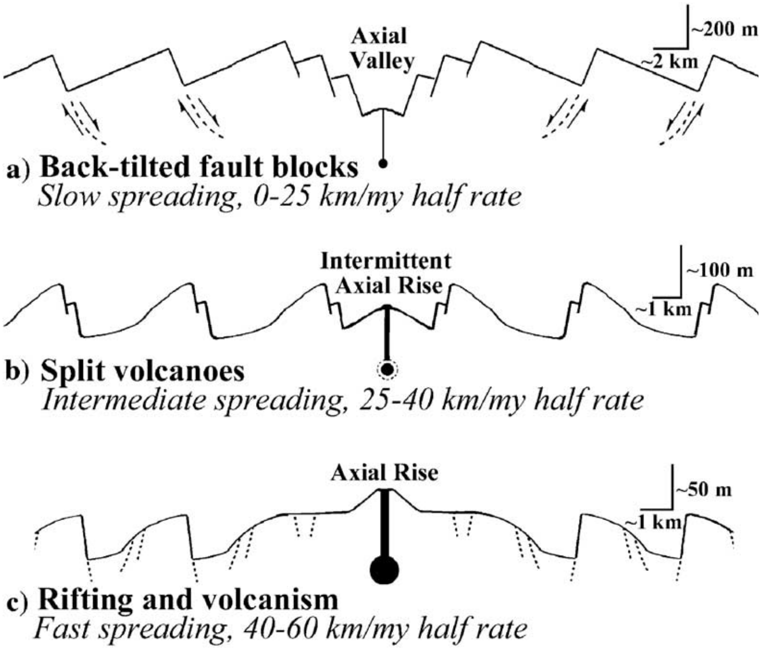

Fig. 1. Three general models of abyssal hill formation and associated ridge morphologies for a) slow, b) intermediate, and c) fast spreading rates (after Macdonald et al. [8]).