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Long Eccentricity Pervasively Modulates Abyssal Hill Formation at Mid-Ocean Ridges

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Abyssal hills along mid-ocean ridges (MORs) show magmatic modulation by certain Milankovitch cycles, yet these patterns are not ubiquitous, observed within the last million years only, and no study reported records of the long eccentricity cycle (~400 kyr; LEC). Here, we analyze 122 topographic profiles across 22 regions worldwide with available magnetic survey data, spanning fast- to ultraslow-spreading ridges, and primarily identify narrow magnetic stripes during the Matuyama Chron to recover their topographic spectral signatures. Results reveal that abyssal hills along MORs globally preserve the LEC recovered from longer-term topographic records. We reevaluate the direct Milankovitch-sea level link and propose that periodic solar gravitational perturbations, arising from eccentricity-driven changes in perihelion/aphelion distance, directly modulate ridge magmatism and imprint LEC-paced abyssal hills. Specifically, larger orbital eccentricity generates stronger tidal-force 'trigger pulses' that initiate magma chamber eruptions more frequently. This regulation dominates at slow and ultraslow ridges under extensional tectonic forcing, and points to the LEC as a global pacemaker for deep Earth responses to astronomical forcing.

The ~400 kyr long eccentricity cycle (LEC), a Milankovitch cycle, is a stable orbital pacemaker recorded in paleoclimate and sediments¹⁻³. Such orbital forcing extends to the abyssal hills along mid ocean ridges (MORs), where sea level changes driven by glacial interglacial cycles have been invoked to explain variations in mantle depressurization, melt production, and eruption rates^{4, 5}. In theory, Milankovitch cycles⁶⁻⁸, mainly including the 23 kyr precession, 41 kyr obliquity, and 100- and 400-kyr eccentricity, could be recorded in the spectral signatures of abyssal hills along MORs. The obliquity signal has been typically observed at fast-spreading ridges, whereas the short eccentricity signal has been more typical at intermediate spreading ridges⁹. Yet the observed record is incomplete: the precession signal is often absent, the LEC remains unobserved at any spreading center, and no single Milankovitch periodicity has been robustly detected across all ridge systems. Existing studies are largely confined to the last million years old seafloor due to dating uncertainties¹⁰. They have focused primarily on Earth's internal processes and climate driven sea level change as the key modulators, largely overlooking the gravitational influence of other Solar System planets.

Here, we collected and analyzed bathymetric and magnetic data from 22 areas across global MORs spanning the full rate range (Fig. 1 and Figs. S1 to S4). To extend the topographic record of abyssal hills over longer time scales and achieve higher temporal resolution, we used magnetic data to identify narrow magnetic stripes within the Matuyama Chron. On fast and intermediate ridges, we identified the short Jaramillo normal interval (Chron 1r.1n, 0.99~1.07 Ma, average 1.03 Ma)¹¹, whereas on slower ridges we identified older chrons such as the Olduvai normal interval (Chron 2n, 1.77~1.95 Ma, average 1.86 Ma). Analyzing the frequency spectrum of bathymetry for crust formed at different spreading rates, we found a robust LEC, previously unrecognized in abyssal hill topography, present on all spreading ridges and dominant on slow and ultra-slow ones. In contrast, Quaternary sea-level changes exhibit no such LEC characteristics^{12, 13}. These observations raise the question of what drives this pervasive LEC modulation. We propose that gravitational variations induced by Earth's orbital LEC, rather than sea-level change, directly modulate oceanic crust formation.

LECs Revealed in Ultraslow Spreading Ridge Topography

We initially studied oceanic crust accretion along the ultra-slow Southwest Indian Ridge (SWIR), on Segments 28 (U1)¹⁴ and 27 (U2)¹⁵. The southern flank of U1 area presents intermittent detachment faulting with approximately 400 kyr (or multiple) interval time¹⁴. Furthermore, the U2 area exhibits alternating waxing and waning magmatic phases over cycles of at least 300 kyr in duration¹⁵, a periodicity derived from the 780 kyr record spanning the nearby Brunhes-Matuyama reversal boundary. These observations suggest a quasi-periodicity of ~400 kyr possibly related to the LEC. Abyssal hills formed at intermediate-spreading rate could be modulated by the short eccentricity cycle of 100 kyr (Ref.⁹), so it is not unlikely that those formed at ultraslow-spreading rate exhibit the LEC. If so, the cycle may also be present on other spreading ridges.

We therefore analyzed the spectral characteristics of abyssal hills in the U1 and U2 areas and in the U3 region where bathymetric and shipborne magnetic data were also collected (Fig. 1; Fig. S1). The profiles of abyssal hills spectra of all three regions exhibit peaks at ~400 kyr (Fig. 2A; see Methods for specifications of the applied processing). Specifically, on the northern flank of U1 area, the structural trend is generally parallel to the spreading ridge, and the highest spectral peak falls at ~ 400 kyr. In the U2 area, our study extends over seafloor formed between magnetic Chrons C2An.1n and C1n (2.581 Ma to present), and the bathymetry of both ridge flanks show six groups of abyssal hills (Fig.3C) that present an average periodicity of ~400 kyr, coincident

with the highest peak of the filtered bathymetric spectrum. Based on the magnetic anomaly identification¹⁶, the abyssal hills in the U3 region also exhibit the ~400 kyr period, and the 100 kyr period as well in strongly magmatic areas (red dashed box in Fig. 2A).

LECs pervasive in global mid-ocean ridges

We re-analyzed bathymetric and magnetic data from fast- (e.g. F3) and intermediate- (e.g. IS1) spreading ridges⁹ and extended the analysis to include slow-spreading ones (e.g. S4) obtained from NCEI (National Centers for Environmental Information) of NOAA¹⁷. After detrending using the 400 kyr moving-window average (See methods), the spectral power in the eccentricity band was enhanced, and spectral analysis of the abyssal hills consistently revealed significant peaks in the long-period 400 ± 50 kyr frequency band. Specifically for the fast-spreading ridge F3, the abyssal hills display small amplitudes but high frequencies, with multiple peaks in the spectrum including a notable one at 100 ± 10 kyr and even 41 ± 2 kyr. This is primarily due to a strong magma supply which responds efficiently to Milankovitch cycles during crustal accretion⁴. In contrast, for intermediate- and slow-spreading ridges, the abyssal hill amplitudes increase while the frequencies decrease, with most peaks occurring above the 200 kyr frequency band. This is because abyssal hills are essentially fault-bounded, orderly arranged topographic highs, under conditions of decreasing magma supply¹⁸, so that the scale of oceanic crust formed within the 100 kyr timescale is insufficient to generate faults¹⁹. In other words, the LEC ~400 kyr covers longer periods of magmatic and amagmatic accretion and may therefore be recorded by abyssal hills at all spreading rates.

Additionally, we analyzed bathymetric spectra from 122 profiles across 22 regions of the World's oceans, including fast-, intermediate-, slow-, and ultraslow-spreading ridges (See Fig.1, Fig. S1 to S4 and Table S1). The crust accretion age along these profiles was constrained by identifying magnetic anomalies. Indeed, without detrending, the Milankovitch cycles observed are in general agreement with previous studies, with fast-spreading ridges showing a dominant 41-kyr cycle and a weak 23-kyr cycle at sufficiently high rates, intermediate ridges presenting a 100-kyr cycle, and slow ridges lacking a clear Milankovitch signal⁹ (Fig. S5). After detrending, however, a peak in the 400 ± 50 kyr band appears across all spreading rates, whereas the 100 ± 10 kyr peak becomes apparent only at faster rates or where magma supply is locally enhanced (Fig. 2C). This is because seafloor-shaping processes act as a low-pass filter on variations in magma supply, strongly damping fluctuations shorter than about 100 kyr (Ref.²⁰). Besides, the short eccentricity cycle is essentially a ~100 kyr envelope modulated by the ~95 kyr and ~124 kyr cycles²¹. This explains why the peaks in the spectra of Fig. 2 are commonly observed slightly offset from 100 kyr.

How does the long eccentricity modulate topography?

Sea-level fluctuations influence seabed pressure, modulate magmatism at MORs and the morphology of abyssal hills, as documented for the 100 kyr short eccentricity or shorter Milankovitch cycles^{22, 23}. Notably, the current eccentricity is low but nearing a local peak, a phase coinciding with high solar insolation and a sea-level highstand (Fig. 3). Consequently, MORs, particularly intermediate-spreading ridges, are often strongly modulated by the 100 kyr cycle, which adjusts the relief of their axial valleys (Fig. S3). Likewise, the current low in the LEC should be associated with a sea-level lowstand with the 400 kyr cycle, yet no such signal is documented. This is because the current Quaternary (since 2.58 Ma) is in an icehouse climate, where this signal is subdued and sea-level changes are instead characterized by the 100 kyr or higher-frequency Milankovitch cycles^{12, 13} (Fig. 3D). Importantly, recent evidence confirms

LEC-regulated magmatism even on the subaerially exposed islands of Mauritius and Réunion, although its causal mechanism remains unclear²⁴. These indicate that the 400 kyr cycle in topographic modulation may not be primarily mediated by sea-level change. Our analysis points to a direct cause instead: magmatic changes modulated by gravitational perturbations during Earth's orbital motion, for the reasons detailed below.

The eccentricity cycles of Earth's orbit are primarily modulated by the gravitational forces of Venus and Jupiter²⁵. Jupiter, orbiting outside Earth, primarily affects long-term eccentricity by flattening Earth's orbit through its gravity. Venus, orbiting inside Earth's orbit, mainly influences short-term eccentricity, by contributing to orbital circularization. These interactions collectively cause periodic variations in the Earth's aphelion and perihelion distances, modulating the solar gravitational force and radiation intensity on Earth.

During one LEC, eccentricity varies within a range of approximately 0.0005 to 0.0607 (Ref.²⁶). Given that the semi-major axis can be considered invariant²⁷, it can be inferred that an increase in eccentricity leads to a decrease in both the semi-minor axis and the perihelion distance (See methods). This geometric change increases the Sun's gravitational force on Earth from 593.4 mGal to 671.9 mGal. This variation is two orders of magnitude larger than Moon's gravitational force on Earth, which currently ranges between 2.901 and 3.615 mGal (See Table S2) and currently accounts for ~32% of the measurable solid Earth tide²⁸. Increases in orbital eccentricity should exert a stronger pull on MORs magmatic material²⁹. Meanwhile, because tidal forces act as a 'trigger' for magmatic activity³⁰, larger orbital eccentricity produces stronger and more effective 'trigger pulses' of tidal forces, which trigger magma chambers more frequently for eruption. Notably, Jupiter's moon Io, the closest of the Galilean satellites (Fig. 4A), serves as another prominent example. The tremendous gravitational pulls on Io, generated by its proximity to Jupiter, exceeds 70,000 mGal, with a tidal force of more than 1,000 mGal. This pull force is two orders of magnitude greater than the Sun's gravitational influence on Earth and is sufficiently large to directly drive volcanic activity³¹. Consequently, this subtle, long-term solar gravitational perturbation, tied to eccentricity cycles, should regulate mid-ocean ridge magmatism.

Eccentricity positively modulates both the solar gravitational forcing that modulates ridge magmatism and, on short cycles, sea-level change. The negative feedback of sea-level change on magmatism, though less direct than gravitational forcing, would overall dampen the influence of short eccentricity cycles on abyssal hill relief along mid-ocean ridges²⁰ (Fig. S6). We developed a model based on the U2 region to explain how LEC modulates the topography of abyssal hills (Fig. 4). Specifically, the current low eccentricity places the perihelion at a large distance from the Sun (Fig. 4A), producing weak gravitational force that reduces both the direct pull on and the probability of triggering magmatic supply (Fig. 4B). This phase also coincides with a peak in the short eccentricity cycle and associated high sea-levels, which together further suppress magmatic supply on the seafloor (Fig. 4B). Conversely, high eccentricity reduces the perihelion distance (Fig. 4C), resulting in a strong solar gravitational pull and high trigger probability for the magma supply (Fig. 4D). If this coincides with a minimum in the short eccentricity cycle, the associated lower sea level reduces seafloor pressure, further amplifying magma production at MORs. Certainly, even during a short eccentricity peak with pronounced high sea-levels, the troughs of abyssal hills may not appear distinct due to the strong simultaneous solar gravitational force.

Relative to the Sun, the Earth is a point mass, experiencing uniform gravitational pull from the Sun. This uniformity supports why the LEC signature is observed globally on MORs as well as on islands. Besides, unlike other Milankovitch cycles, the LEC longer periodicity corresponds to

extensive oceanic crust formation at slow or ultraslow spreading ridges, reaching or exceeding the spacing between faults (~3 km) delineated in Fig. 4B, D. This coincidence significantly enhances the likelihood of fault development³² and in turn the abyssal hill relief. In contrast, crustal accretion at fast and intermediate-spreading ridges can achieve fault-forming displacements within a 100 kyr or shorter (i.e., 41 kyr) Milankovitch periodicity, thereby imprinting these orbital signals into the geologic record of abyssal hills⁸.

Our research reveals that the LEC regulates abyssal hill formation at all MORs through direct astronomical forcing of ridge magmatism. This regulation persists in the Quaternary despite the absence of a clear LEC signature in sea-level changes. Because this forcing is gravitational, its influence should be global, extending to island arcs, back-arc basins, hotspots, and on-land volcanism, all of which await future testing. The LEC thereby emerges as a true geological pendulum. Beyond ridge magmatism, these findings have important implications for magma regulation, ocean crust architecture, and associated hydrothermal activity³³⁻³⁵, offering a new perspective on the interplay among orbital forcing, tectonics, and climate. Future investigations should target a denser global distribution of spreading rates to further test the generality of this coupling, and additional theoretical and numerical work is required to clarify the mechanistic link between astronomical forcing and deep Earth responses.

Methods

Age Constraints Using Magnetic Data

The age of the abyssal hills is determined from marine magnetic anomaly profile data. We first ensure that all magnetic data have undergone removal of the International Geomagnetic Reference Field (IGRF) and reduction to pole (RTP). Azimuth correction is not required for survey lines with consistent heading. If conditions permit, applying a diurnal variation correction improves the magnetic measurement accuracy. Typically, combining existing bathymetric and magnetic surveys reveals that the Neovolcanic Zone (NVZ) corresponds to the central magnetic anomaly peak, and the latter helps to adjust the former based on terrain features. As shown in Fig. S7 (taking profile F3-8 as an example), conjugate magnetic anomaly peaks identified on both sides of the central anomaly peak are used as age constraints for the abyssal hills^{11, 14}. We do so because peaks are easier to identify compared to the transition points between positive and negative magnetic anomalies³⁶. We assume that the age derived from these peaks represents the median age of the corresponding magnetic chron. Additionally, we try to select older magnetic anomalies that are covered by all profiles within the same survey area to better assess the age reliability. Meanwhile, we also strive to select narrower magnetic stripes whenever possible, as this minimizes errors in the median age estimates derived from these selections. Specifically, in areas with smaller survey coverage, we select the C1r.1n stripe (Jaramillo event), such as in areas F3, S2, and IS3. In some of these areas, the survey coverage is too limited to allow for anything other than picking the transition point from C1n to C1r (Brunhes-Matuyama boundary). For areas with a larger coverage, such as S3 and IS1, we use the C2n anomaly (Olduvai event).

Furthermore, due to the scarcity of surveys on ultraslow-spreading MORs, we conduct separate processing and analysis for each region. Specifically, for Area U1, we analyze the magnetic anomalies of the northern flank and select the older C2An.1n chron (Gauss event)¹⁴. For Area U2, we primarily rely on previous magnetic stripe identification results¹⁶, supplemented by a small amount of near-bottom magnetic data and detailed topography for constraint³⁷. For Area U3, we entirely rely on previous magnetic anomaly identifications¹⁶ and choose regions

with more pronounced topographic undulations for age determination and subsequent spectral analysis. We identify anomalies and calculate half-spreading rates for all MOR profiles. The locations of the profiles and the identified anomalies are shown in Fig. 1 and Fig. S1-S4, while the half-spreading rates for each flank and the average half-spreading rate for the whole area are showed in Table S1.

Spectral Analysis Method for Topographic Relief

When analyzing the frequency spectrum of the abyssal hills, we first match the bathymetric data to the corresponding magnetic anomaly profiles where the age of the oceanic crust has been identified. We then calculate the (half-)spreading rates of both flanks based on the distances from the identified magnetic stripes. Following this, we determine the age of oceanic crust at each point along the profile. To highlight the eccentricity cycles of interest in the spectral analysis, we design a band-pass filter. Specifically, we perform an equidistant fitting with a step length of 1 kyr on the curve representing the temporal changes in bathymetry, and then subtract the sliding average value calculated using a 400 kyr time window, along with that from a 40 kyr window for comparison. To preserve the overall profile characteristics, we then compensate by adding the grand mean value calculated across the complete time series. These processes yield a detrended curve of abyssal hill undulations. Subsequently, we apply Fourier transform spectral analysis and normalization to obtain the spectral characteristics of the abyssal hills. It should be emphasized that the spectral peaks in the 100s kyr range are present before applying the band-pass filter, with lower energy levels. The filtering procedure only aims to enhance this component of the spectrum. Fig. S7 shows profile F3-8 as an example and compares the original abyssal hill undulations over time with the same after applying the band-pass filter, along with their respective spectral characteristics.

Calculation of Gravitational Forces from Various Planets on Earth

Based on the universal gravitational acceleration formula (Equation 1), we calculate: (1) the variation in gravitational acceleration at the Earth's own radius differences between its poles and equator; (2) the variation in lunar gravitational force on Earth resulting from the Moon's orbital progression between perigee and apogee; and (3) the gravitational forces exerted on Earth by Jupiter and Venus, the two planets in the solar system with the strongest gravitational influence on Earth, at their respective perihelion and apogee. We further estimate the consequent periodic changes in Earth's orbital eccentricity from planetary perturbations over a long cycle, which allowed for an estimation of the range of variation in the Sun's gravitational pull on Earth.

During calculations, parameters such as the masses of celestial bodies and their perihelion/aphelion distances are sourced from publicly available online data. While these values may vary, their precision is deemed sufficient for the scope of this study. Additionally, owing to the complexity in directly calculating the exact perihelion and aphelion distances of Earth's orbit as its eccentricity varies, we invoke Kepler's third law (Equation 2). This application is justified because Earth's orbital period is dynamically determined by the solar system and remains exceptionally stable. Given this stability, the orbital semi-major axis can be treated as a constant, independent of the eccentricity. Consequently, it can be derived from Equation 3 that the perihelion distance decreases with increasing eccentricity (e), while the aphelion distance increases.

$$g = F/m_1 = Gm_2/r^2 \dots\dots\dots(1)$$

$$a^3/T^2 = constant \dots\dots\dots(2)$$

$$r_{min} = a(1 - e), r_{max} = a(1 + e) \dots\dots\dots(3)$$

In Equation (1), g represents the gravitational acceleration exerted on Earth (mass m_1) by a celestial body (mass m_2), and r is the distance between that celestial body and Earth. In Equation (2), a is the semi-major axis of Earth's orbit, T is its orbital period, and the constant is solely dependent on the mass of the central star, being independent of the orbital eccentricity e . In Equation (3), r_{min} and r_{max} denote the distances at perihelion and aphelion, respectively.

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Author contributions:

Conceptualization: TW, JD, HW, CT, JL

Methodology: TW, JD, ZZ

Investigation: TW, CT, ZZ

Visualization: TW, CT, JD, JL

Funding acquisition: CT, TW,

Project administration: TW, CT

Writing – original draft: TW, JD, CT, XS, HW

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Figure Caption

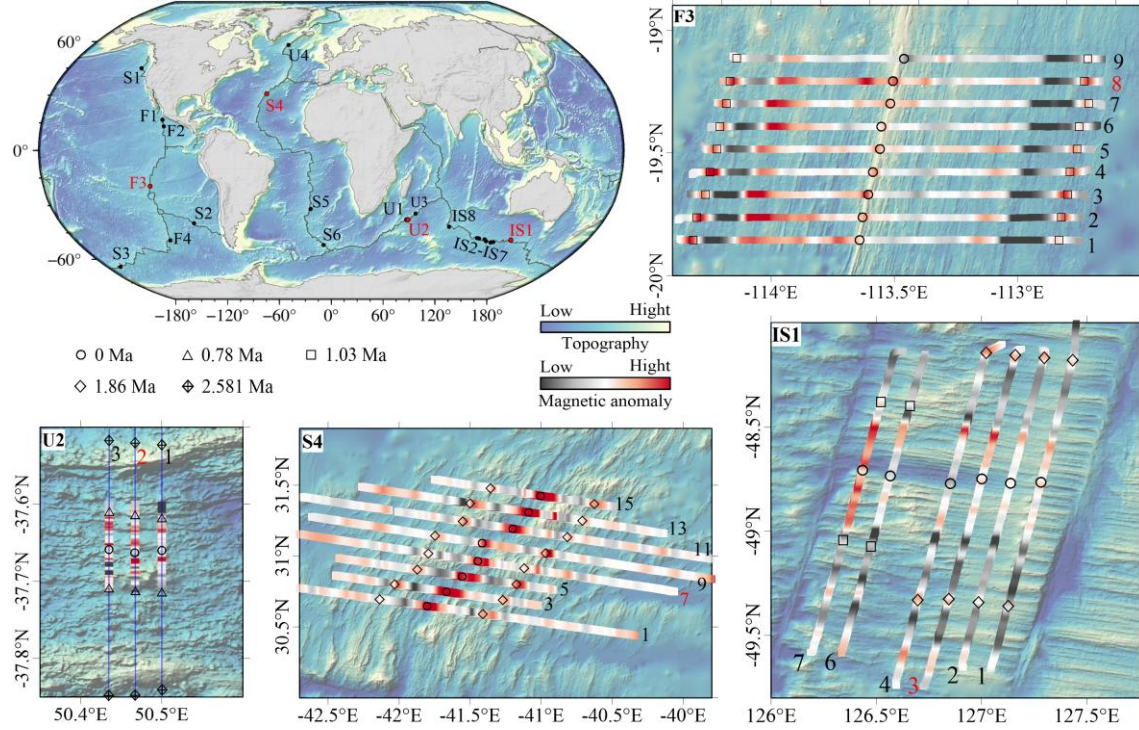


Fig. 1. Bathymetry and magnetic surveys used in this study. Top left panel: global bathymetry and the 22 abyssal-hill areas where bathymetric and magnetic data were gathered, with red circles denoting the four other panels and black circles referring to Fig.S1-S4. Each ridge type is represented by a letter code, where F stands for fast-spreading ridge, IS for intermediate-spreading, S for slow, and U for ultra-slow. Other panels: four regional topography maps show magnetic profile distributions, where the amplitude of magnetic anomalies is indicated in Gray-Red color scale. Based on these magnetic anomaly profiles, the neovolcanic zone (NVZ) and the magnetic stripe boundaries are marked (using different symbols to indicate boundaries of different ages, see legend). The profile numbers shown in red numerals correspond to the magnetic and bathymetric profiles shown in Fig. 2.

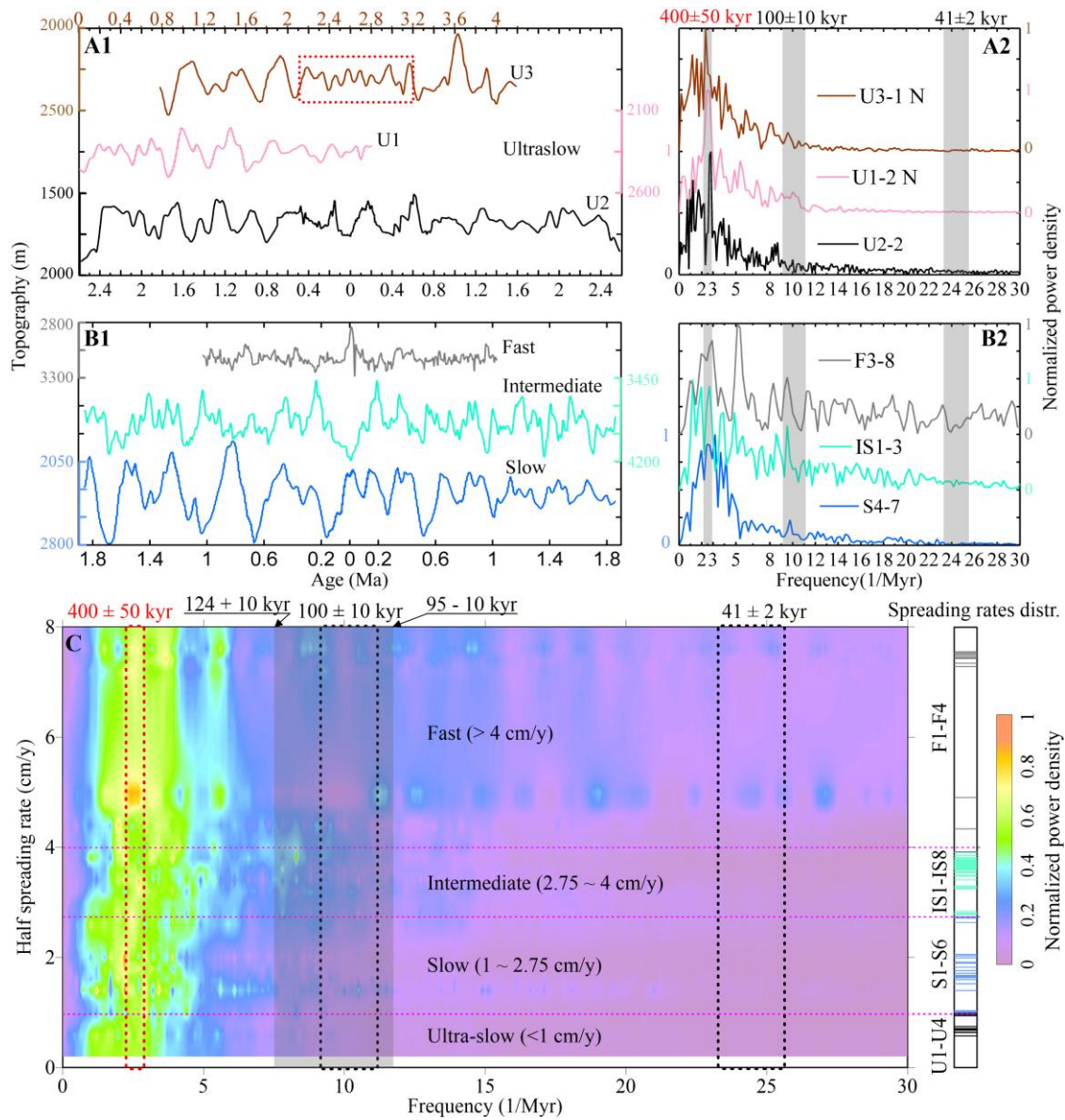


Fig. 2. Trends and rhythms of abyssal hills. (A) Abyssal hills variations (A1) and spectrum (A2) of 3 areas of the ultraslow spreading SWIR. To isolate magmatic signals from tectonic deformation, the two top profiles in A1, labeled as U3-1N and U1-2N (time axis: brown), are derived from the northern ridge flank only. The time axis of the bottom profile is in black. The interval outlined by the red dashed box in profile U3-1N in A1 corresponds to a phase of intensified magmatic activity. (B) Similar to A for 3 areas representative of fast-, intermediate-, and slow- spreading ridges. Locations are shown in Fig. 1. (C) Spectral characteristics of bathymetry for 122 profiles across the 22 areas shown in the top-left panel of Fig. 1 (see Table S1 for profile details). The spectral analysis was performed after detrending the data using a 400 kyr moving-window average. Ticks on the right side correspond to each spectrum for the spreading rate averaged between the two conjugate flanks. The 100-kyr short eccentricity cycle envelope is composed of the combined 124-kyr and 95-kyr periods.

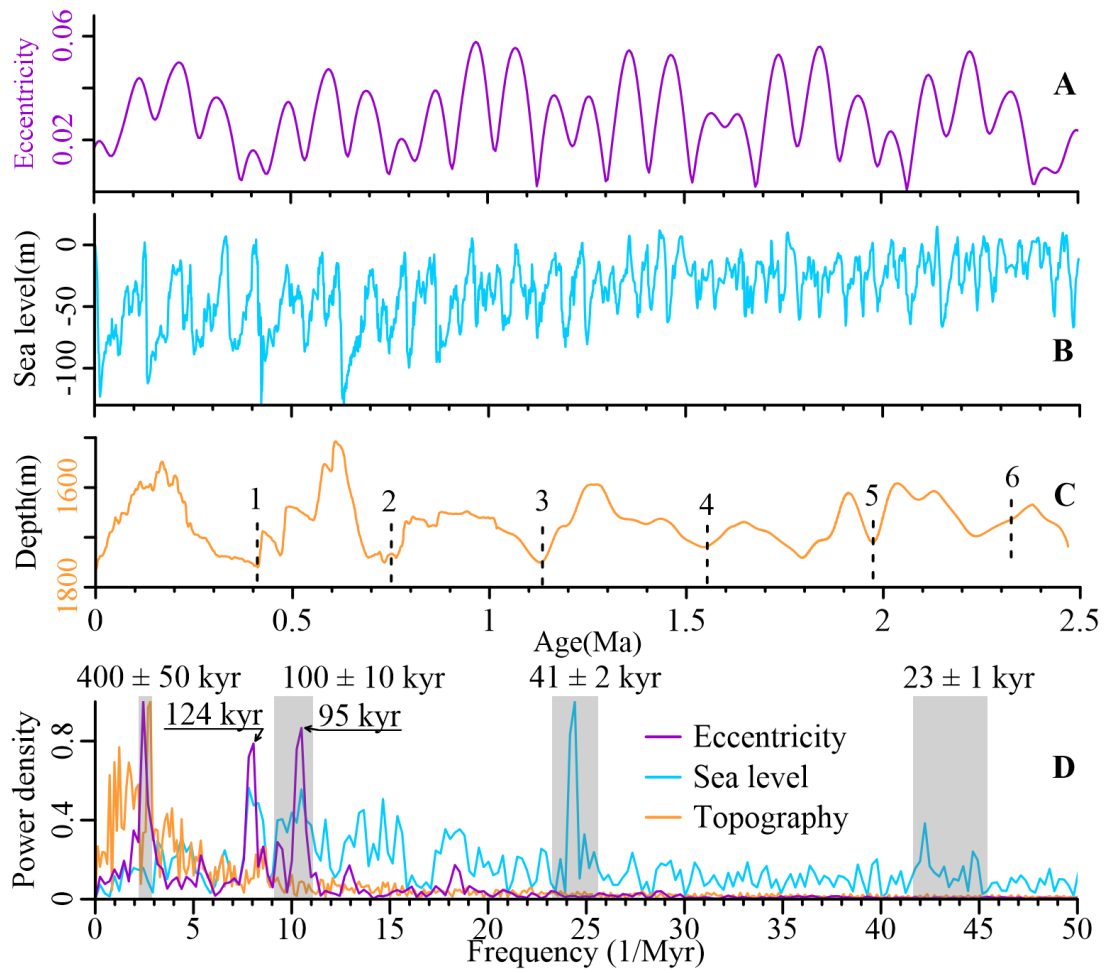


Fig 3. Trends and rhythms of sea level changes and abyssal hills. (A)~(C) show the evolution of long eccentricity, sea level, and abyssal hills, respectively, over the last 2.5 Myr. Sea level change data in (B) are based on Ref. (22). (C) The topography of abyssal hills, shown here as an example from north profile 2 in the U2 region, reveals approximately six cycles, separated by dashed lines, over a timespan of about 2.4 million years. (D) the corresponding spectral characteristics of sea-level changes and abyssal hills are analyzed.

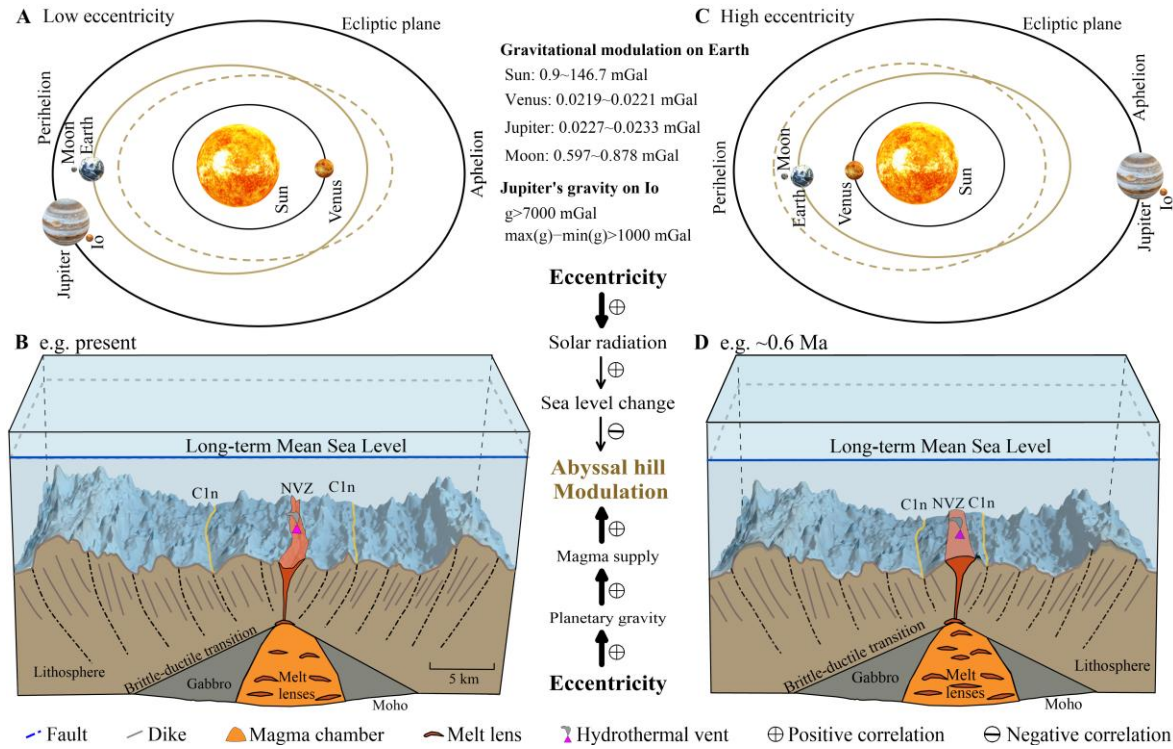


Fig 4. Conceptual Models How does the Long Eccentricity Modulate Abyssal Hills at Mid-Ocean Ridges. (A) and (C) are schematic diagrams of the orbital configurations of Earth, Jupiter, and Venus in the ecliptic plane when Earth's orbit has low and high eccentricity, respectively. Only the planets and satellites relevant to the discussion are illustrated. For Jupiter, only Io is shown among its four Galilean moons, as it is the closest to the planet. The models in (B) and (D), prototyped on U2 region, correspondingly show how the eccentricity cycle modulates volcanism. Model (B) represents the current state near a peak in the short eccentricity cycle, while model (D) takes the conditions at 0.6 Ma as an example, a time corresponding to high eccentricity. Concurrently, sea level, which shows strong coherence with the short eccentricity cycle, works in concert with variations in solar gravitational force to modulate the topography of mid-ocean ridges. The thickness of the arrows represents the strength of the association. In (B) and (D), more melt lenses imply a higher probability of magmatic activity or stronger magmatism, the yellow curve marks the Brunhes–Matuyama boundary (C1n, 0.78 Ma), while the olive zones between the curves correspond to the neovolcanic zone (NVZ).

Supplementary Files

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