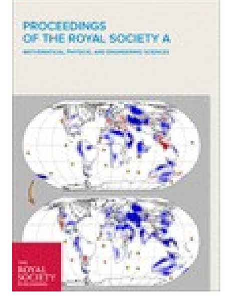
Tracking dynamic topography through hiatus surfaces

Berta Vilacís, Hamish Brown, Sara Carena, Jorge N. Hayek, Ingo L. Stotz, Hans-Peter Bunge, and Anke M. Friedrich

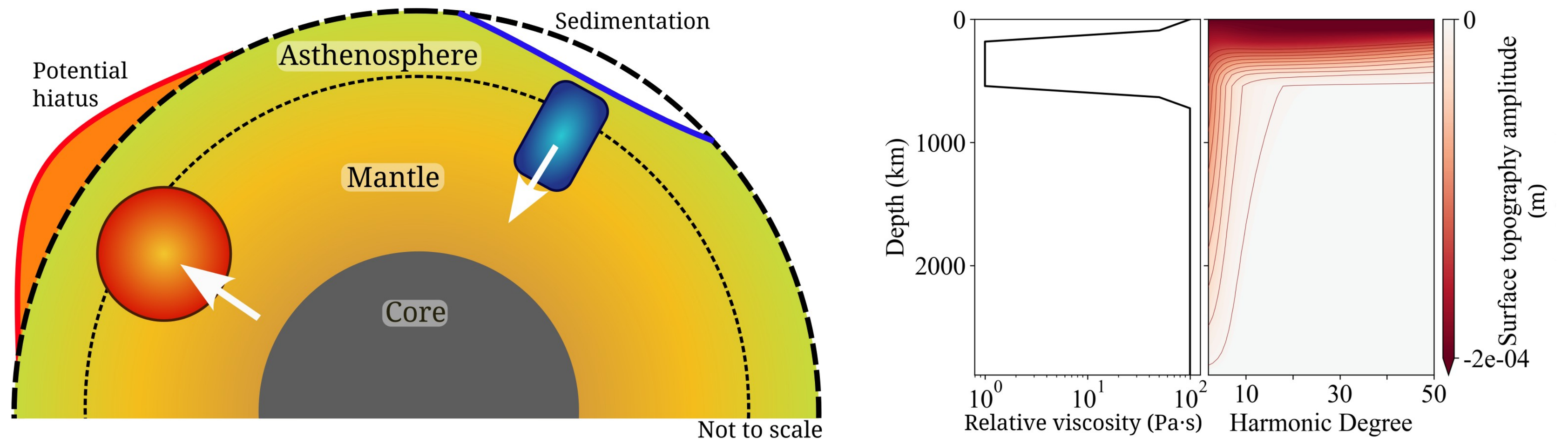
Ludwig-Maximilians-Universität München, Dept. of Earth and Environmental Sciences, Munich, 80333, Germany

EGU25-11583



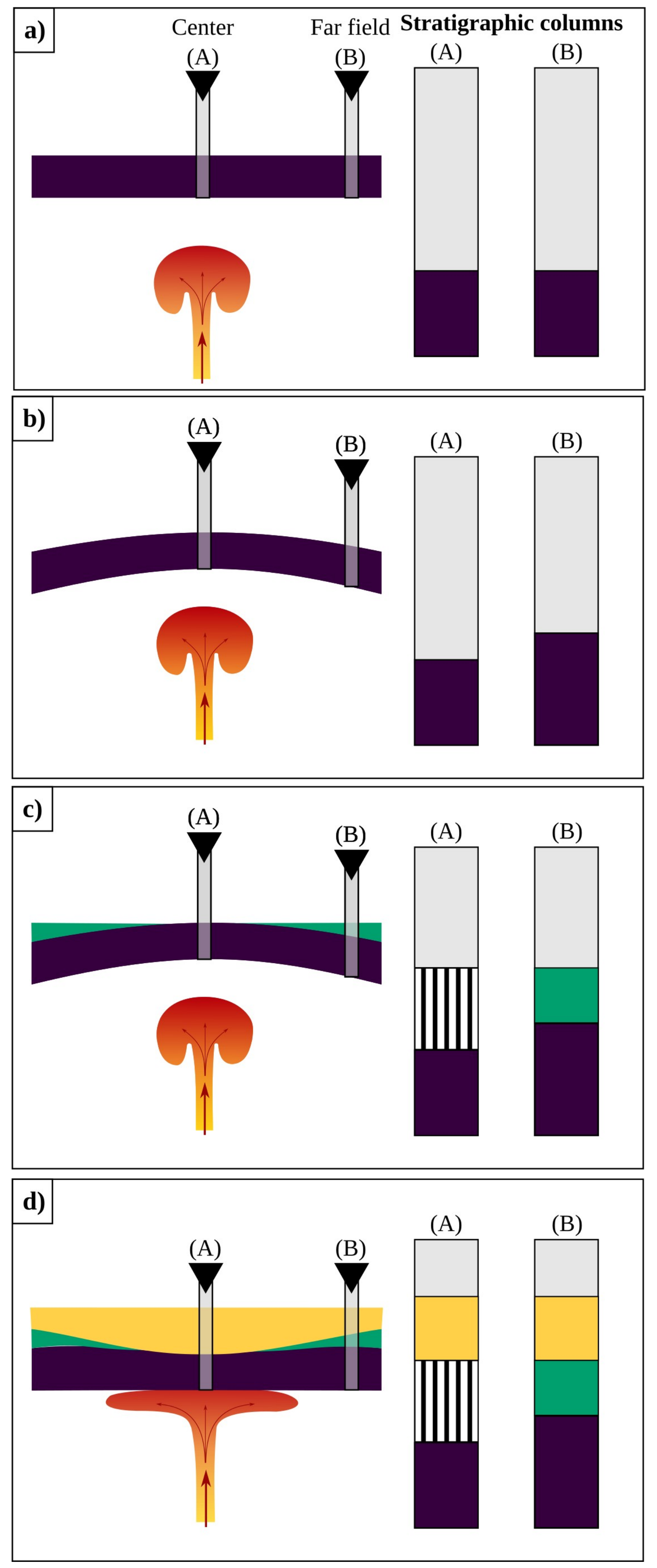
1. Motivation

- **Mantle convection** affects the **horizontal and vertical motion of the Earth's surface**. Its **vertical motion** leaves an **imprint in the geological record**.
- Hot **mantle upwellings induce positive surface deflections**, expressed stratigraphically as non-depositional/erosional environments **that leave time gaps in the sedimentary record**. In contrast, cold **mantle downwellings induce negative surface deflections, and create space for sedimentation** to occur.
- Understanding **the temporal and spatial changes in dynamic topography provides constraints on the viscosity profile** of the Earth's mantle.



(Left) Sketch showing upwards/downwards deflection of the Earth's surface induced by hot/cold anomalies transiting through the mantle. (Right) Simple layered viscosity profile and its surface topography kernel as a function of depth and spherical harmonic degree (SHD)[1]. A stratified mantle decouples the contributions of lower mantle anomalies from the surface topography, meaning that anomalies with SHD ≥ 5 contribute only when they are in the upper mantle.

2. Plume stratigraphy



Simplified version of Fig 3. in Friedrich *et al.*[2].

Surface expression of a rising plume:

a) The plume does not yet deflect the surface and the Columns A and B sediment similarly.

b) The plume interacts with the surface creating a continental uplift. This uplift may create a non-depositional or erosional environment in Column A. In the far field, in Column B, sedimentation continues.

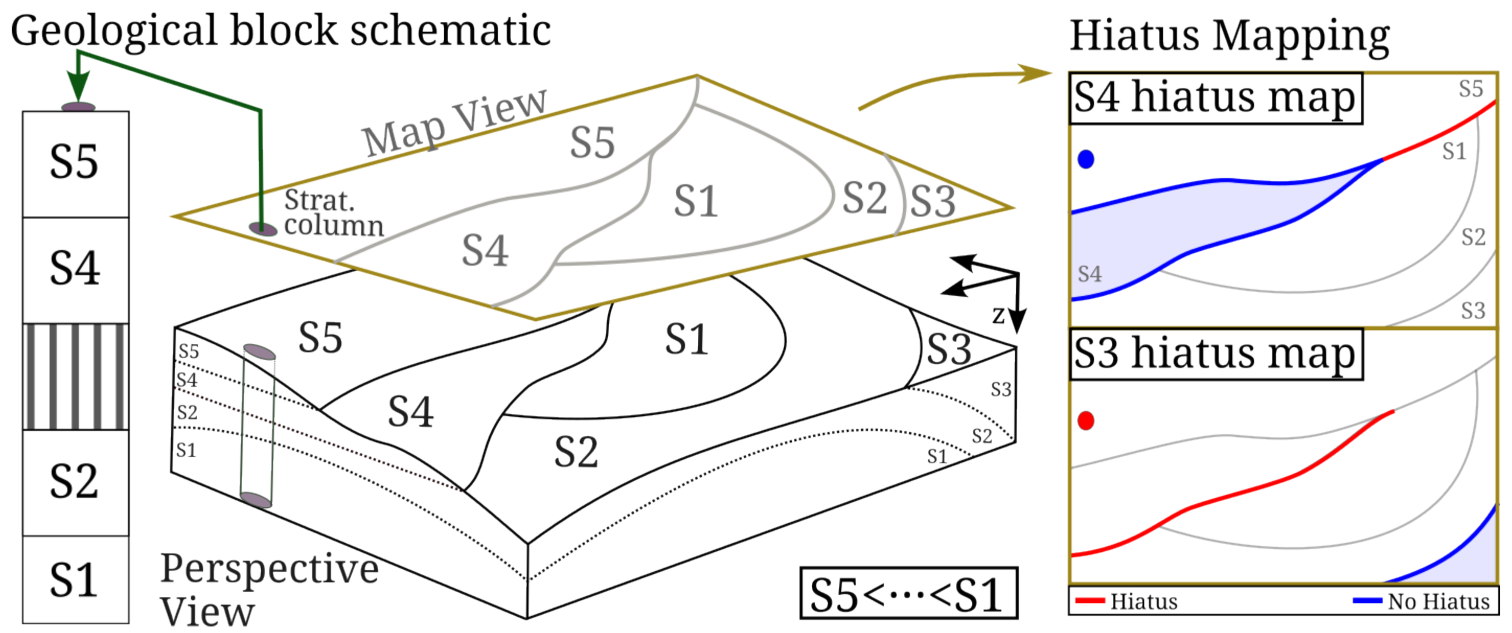
c) The next geological unit is sedimented in the far field only. This results in a time gap in sedimentation in Column A, well known as a **hiatus**.

d) The plume flattens, the surface subsides, and sedimentation resumes everywhere.

At the end, Column A has a hiatus, while Column B has the "expected" sedimentation.

Extracting hiatuses at continental scale allows us to track mantle convection because the lack of information in a region can be part of a larger signal.

3. Hiatus method



Idealised representation of a geological setting, with five sedimentary units (S1 to S5, from oldest to youngest) and a stratigraphic column (amplified on the left). It theoretically illustrates how different stages of a domal uplift and a subsequent erosive episode might be reflected in geological maps and stratigraphic columns.

The method delimits the spatial extent of hiatus by identifying where a given stratigraphic series is absent or present.

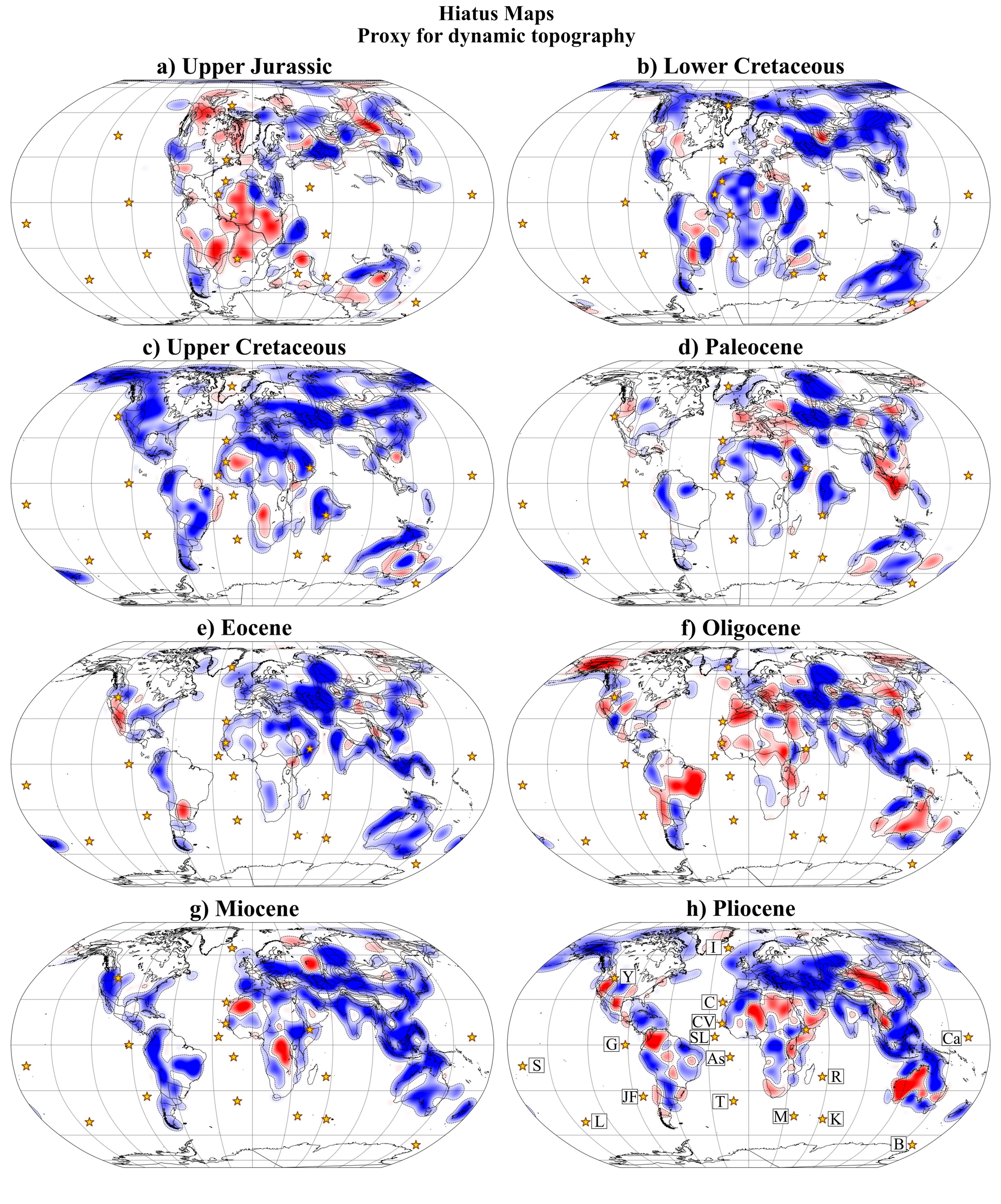
- **Hiatus**: absence of a given geological series. Mapped by locating where the younger geological series is not underlain by the given unit, but instead overlies an older unit, and thus there is a gap in the stratigraphic record.
- **No hiatus**: presence of a given geological unit. Mapped by finding its occurrence in the input data.

The S4 hiatus map shows where S4 is present (in blue) and where it is absent – but expected – (in red).

4. Results

Continental Hiatus Surfaces

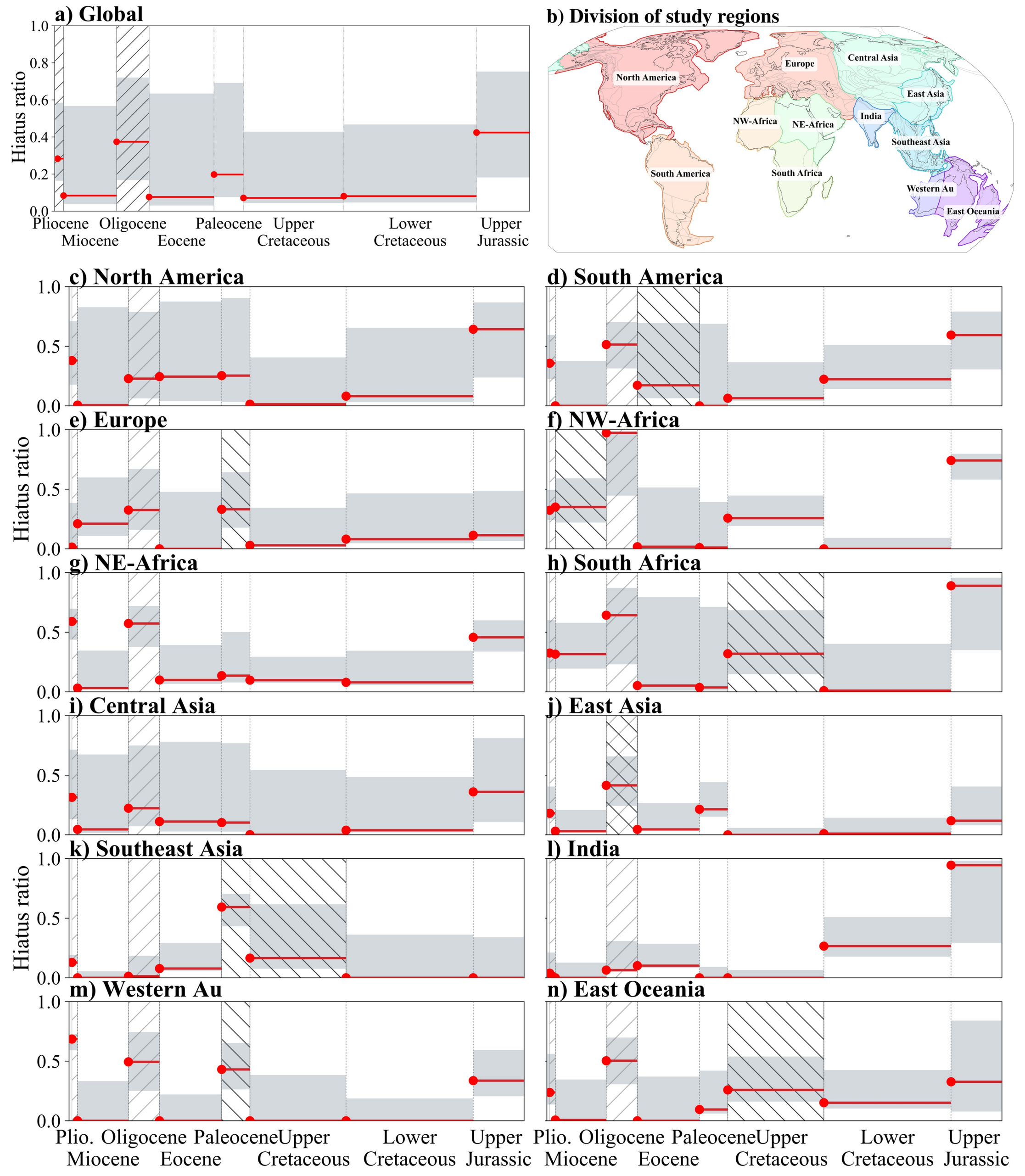
Hiatus maps serve as proxies of past dynamic topography (red = high, blue = low) **for a given series**, since the Upper Jurassic (~163 Ma). **They change** systematically **on the timescales of geological series** (ten to tens of millions of years), and have **wavelengths on the order of 10^3 km.**



Hiatus surfaces[3] for eight geological series, reconstructed with a global Phanerozoic plate motion model[4] and placed into the plate tectonic configuration of the youngest boundary of each series. Red/blue represent the hiatus/no hiatus surfaces. Stars mark the present-day locations of major hotspots[5]: Ascension (As), Juan Fernandez (JF), Caroline (Ca), Samoa (S), Yellowstone (Y), Canaries (C), Afar (A), Balleny (B), Iceland (I), Réunion (R), Sierra Leone (SL), Marion (M), Galápagos (G), Louisville (L), Tristan (T), Kerguelen (K), and Cape Verde (CV).

Hiatus ratio

- The Oligocene and Pliocene have globally high hiatus distributions, which coincides with sea-level drops due to the glaciation of the southern[6] and northern[7] hemispheres.
- The Upper and Lower Cretaceous show very low hiatus ratios, corresponding to peak values in various sea-level curves[8].
- Each regional curve reflects a unique dynamic evolution.



Hiatus ratio (red line), calculated as the area of hiatus relative to the total coloured area (hiatus + no hiatus) within each target region. Uncertainty (grey shading) reflects the ambiguity in interpreting blank surfaces – treated as hiatus (no deposition during the geological series) or as no hiatus (deposited and potentially later eroded). To separate the sea-level effects from dynamic topography, each region is plotted separately. Hatched // indicates sea-level signals, \\ indicates dynamic topography signals.

Key events

(1) **Hiatus surface in western Gondwana** during Upper Jurassic, linked to the arrival of the Tristan plume[9].

(2) **Development of the Western Interior Seaway** in North America during the Cretaceous, tied to the subduction of the Farallon slab[10].

(3) **Hiatus surface in South Africa** during the Upper Cretaceous, previously linked to the Marion plume[11].

(4) **Absence of Upper Cretaceous and Paleocene sediments** in Southeast Asia[12].

(5) **Hiatus surface in Europe during the Paleocene**, related to the arrival of Iceland at the Paleocene – Eocene boundary[13].

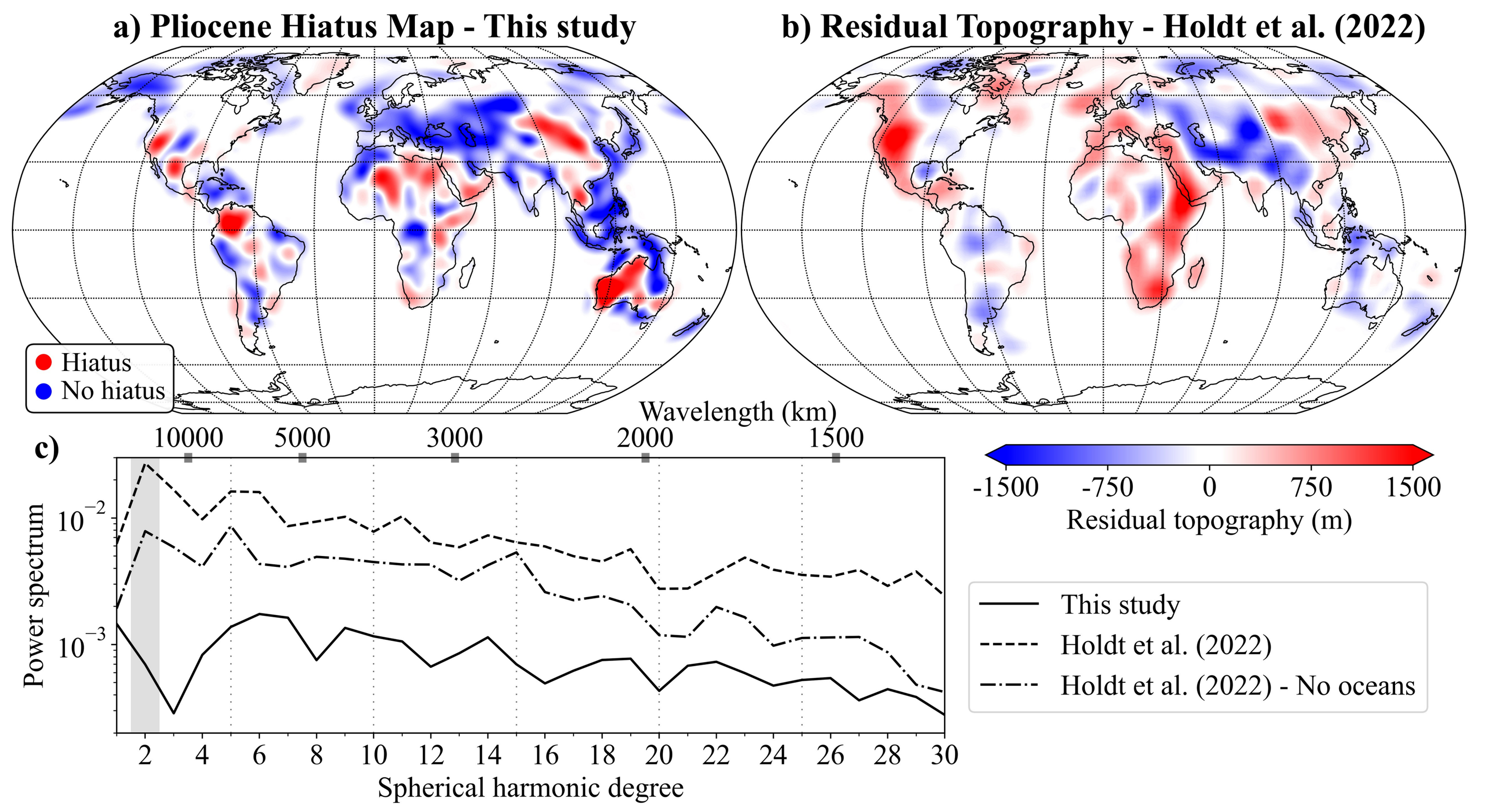
(6) **Widespread absence of Paleocene to Oligocene sediments** in South America, coinciding with anomalous volcanism in the Rio Grande Rise (RGR) and the subaerial exposure of drill site 512 at the RGR[14].

(7) **Lack of Oligocene sediments in Africa**, which cannot be explained by sea-level drop alone[15].

(8) **Extensive hiatus in East Asia** in the late Eocene-Oligocene, linked to hot asthenospheric flow between the Pacific and Asian domains[16].

5. Comparison with present-day residual topography

- The polarity of the signals coincides: regions of hiatus/no hiatus correspond to high/low residual topography, respectively.
- The power spectra of both dataset show similar shapes, with flatter spectra and significant power up to spherical harmonic degree 30, equivalent to wavelengths of ~1500 m.
- The power spectrum of the hiatus maps is flatter than expected from geoid studies.



Comparison of the Pliocene hiatus map (a), our most recent map, with the present-day residual topography map compiled by Holdt *et al.*[17] (b). Both maps are shown with the data in oceans removed for a direct comparison. (c) Power spectrum of the Pliocene hiatus map, along with global and filtered residual topography from Holdt *et al.*[17]. The grey band indicates the spherical harmonic degree corresponding to peak geoid power.

6. Conclusions

- **Hiatus Surfaces** serve as a proxy for dynamic topography. They **vary at least at the time scale of geological series** and have **wavelengths of 2000-3000 km.**
- **Hiatus surfaces** (i.e. an uplift) **occur prior to flood basalt eruptions**, linked **to the final stage of a plume ascent.**
- Our results indicate that **radial viscosity stratification** strongly influences planform of mantle convection, and are **consistent with the existence of a weak asthenosphere.**
- Our maps show that a **100 m vertical change,** induced either by dynamic topography or eustasy, **can produce a** continental- to global-scale **sedimentation signal**.
- Some inter-regional sedimentary hiatuses, not associated with any known plume or flood basalt, may be linked to lateral material transport in the asthenosphere.
- **Hiatus Maps offer a tool to observe past dynamic topography** and provide **constraints for geodynamic models of past mantle convection** through geological time.

References

[1] Colli L, Ghelichkhan S, Bunge H -P. 2016 On the ratio of dynamic topography and gravity anomalies in a dynamic Earth. *Geophys. Res. Lett.* 43, 2510–2516.

[2] Friedrich AM, Bunge HP, Rieger SM, Colli L, Ghelichkhan S, Nerlich R. 2018 Stratigraphic framework for the plume mode of mantle convection and the analysis of interregional unconformities on geological maps. *Gondwana Res*. 53, 159–188.

[3] Vilacís B, Brown H, Bunge H-P, Carena S, Hayek JN, Stotz IL, Wang ZR, Friedrich AM. 2024 Dynamic topography and the planform of mantle convection since the Jurassic inferred from global continental hiatus maps. *Proc. R. Soc. A* 480: 20240311.

[4] Müller RD, Flament N, Cannon J, Tetley MG, Williams SE, Cao X, Bodur ÖF, Zahirovic S, Merdith A. 2022 A tectonic-rules-based mantle reference frame since 1 billion years ago – implications for supercontinent cycles and plate–mantle system evolution. *Solid Earth* 13, 1127–1159.

[5] Courtillot V, Davaille A, Besse J, Stock J. 2003 Three distinct types of hotspots in the Earth's mantle. *Earth Planet. Sci. Lett*. 205, 295–308.

[6] De Lira Mota MA et al. 2023 Multi-proxy evidence for sea level fall at the onset of the Eocene-Oligocene transition. *Nat. Commun*. 14, 4748.

[7] Haug GH, Tiedemann R. 1998 Effect of the formation of the isthmus of panama on Atlantic ocean thermohaline circulation. *Nature* 393, 673–676.

[8] Müller RD, Sdrolias M, Gaina C, Steinberger B, Heine C. 2008 Long-term sea-levelfluctuations driven by ocean basin dynamics. *Science* 319, 1357–1362.

[9] Krob FC, Glasmacher UA, Bunge HP, Friedrich AM, Hackspacher PC. 2020 Application of stratigraphic frameworks and thermochronological data on the Mesozoic SW Gondwana intraplate environment to retrieve the Paraná-Etendeka plume movement. *Gondwana Res.* 84, 81–110.

[10] Mitrovica JX, Beaumont C, Jarvis GT. 1989 Tilting of continental interiors by the dynamical effects of subduction. *Tect*. 8, 1079–1094.

[11] Vilacís B, Hayek JN, Stotz IL, Bunge HP, Friedrich AM, Carena S, Clark S. 2022 Evidence for active upper mantle flow in the Atlantic and Indo-Australian realms since the Upper Jurassic from hiatus maps and spreading rate changes. *Proc. R. Soc. A*. 478, 20210764.

[12] Hayek JN, Vilacís B, Bunge HP, Friedrich AM, Carena S, Vibe Y. 2020 Continent-scale hiatus maps for the Atlantic realm and Australia since the Upper Jurassic and links to mantle flow induced dynamic topography. *Proc. R. Soc. A*. 476, 20200390.

[13] Saunders AD, Jones SM, Morgan LA, Pierce KL, Widdowson M, Xu YG. 2007 Regional uplift associated with continental Large Igneous Provinces: the roles of mantle plumes and the lithosphere. *Chem. Geol.* 241, 282–318.

[14] Barker PF. Tectonic evolution and subsidence history of the Rio Grande Rise. 1983 *Initial Reports of the Deep Sea Drilling Project*, (eds PF Barker, RL Carlson, DA Johnson), pp. 953–976. US Government Printing Office.

[15] Carena S, Bunge HP, Friedrich AM. 2019 Analysis of geological hiatus surfaces across Africa in the Cenozoic and implications for the timescales of convectively-maintained topography. *Can. J. Earth Sci.* 56, 1333–1346.

[16] Brown H, Colli L, Bunge HP. 2022 Asthenospheric flow through the Izanagi-Pacific slab window and its influence on dynamic topography and intraplate volcanism in East Asia. *Front. Earth Sci.* 10, 10:889907.

[17] Holdt MC, White NJ, Stephenson SN, Conway-Jones BW. 2022 Densely sampled global dynamic topographic observations and their significance. *J. Geophys. Res.* 127, e2022JB024391.