The influence of rock uplift rate on the formation and preservation of individual marine terraces during multiple sea level stands

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This preprint is a non-peer reviewed version of an article submitted to Geology on May 11th 2021.

Abstract
Marine terraces are a cornerstone for the study of paleo sea level and crustal deformation. Commonly, individual erosive marine terraces are attributed to unique sea level high-stands. This stems from early reasoning that erosive marine platforms could only be significantly widened at the beginning of an interglacial. However, this implies that wave erosion is insignificant during the vast majority of sea level history. Here, we postulate that the total duration of sea level occupation at a bedrock elevation is a proxy for the erosion potential. The total duration of sea level occupation (hence wave erosion) depends strongly on rock uplift rate. Certain rock uplift rates may promote the generation and preservation of particular terraces while others prevent it. The elevations and widths of terraces eroded during specific sea level stands may vary widely from site to site and depend on local rock uplift rate. This leads to potential misidentification of terraces if each terrace in a sequence is assumed to form uniquely at successive interglacial high stands and to reflect their elevations. Representing a proxy for the entire erosion potential of sea level history allows us to address creation/preservation biases at different rock uplift rates.

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Abstract
Marine terraces are a cornerstone for the study of paleo sea level and crustal deformation. Commonly, individual erosive marine terraces are attributed to unique sea level high-stands. This stems from early reasoning that erosive marine platforms could only be significantly widened at the beginning of an interglacial. However, this implies that wave erosion is insignificant during the vast majority of sea level history. Here, we postulate that the total duration of sea level occupation at a bedrock elevation is a proxy for the erosion potential. The total duration of sea level occupation (hence wave erosion) depends strongly on rock uplift rate. Certain rock uplift rates may promote the generation and preservation of particular terraces while others prevent it. The elevations and widths of terraces eroded during specific sea level stands may vary widely from site to site and depend on local rock uplift rate. This leads to potential misidentification of terraces if each terrace in a sequence is assumed to form uniquely at successive interglacial high stands and to reflect their elevations. Representing a proxy for the entire erosion potential of sea level history allows us to address creation/preservation biases at different rock uplift rates.

Introduction
Marine terraces are key landforms for the study of paleo sea level (e.g., Broecker et al. 1968, Chappell, 1974, Machida, 1975) and crustal deformation (e.g., Otuka, 1934, Ota et al., 1978, Lajoie 1986, Armijo et al., 1996). Commonly, individual marine terraces created by bedrock erosion are interpreted to form during unique sea level high stands. This one-to-one correspondence is typically assumed for two reasons. First, low gradient, shallow water marine platforms — which become marine terraces after a fall in relative sea level (difference between the rates of eustatic change and rock uplift) — would grow by wave erosion of the coast at a faster rate when the rate of relative sea level rise is small; a condition that occurs at the beginning of interglacial periods as eustatic sea level rise slows down (see Bradley, 1958, with a review of early 20th c. literature). Second, the large eustatic sea level drops that typically follow high stands can rapidly abandon, and preserve, marine terraces.

Using this conceptual model, Yoshikawa et al. (1964) identified the rock uplift rate that best projected relative sea level high stands to the elevations of marine terraces observed around Tosa Bay, Japan (English translation in the supplementary files) — perhaps the first documented attempt to quantify rock uplift rates by combining coastal morphology and a relative sea level curve. Later, Lajoie (1986) merged this work with seminal studies on constructional coral reef terraces (e.g., Broecker et al. 1968, Chappell, 1974) and declared that “a general consensus has developed” linking strandlines and high stands on rising coastlines. This morphostratigraphic approach relies on a bijective assumption that requires each individual terrace to have a unique age linked to a unique high stand (Pastier et al., 2019). It is commonly employed at sites where independent dating of multiple terraces is unavailable or limited to a small subset.

Greater scrutiny however reveals that individual terraces can form during multiple sea level stands. Dufaure and Zamanis (1980) noted diachronous erosive terraces in the Gulf of Corinth, Greece, where three distinct terraces, separated by cliffs >10 m, merge into one as rock uplift rate decreases alongshore. At the same site, Armijo et al. (1996) suggested that reoccupation of the single terrace by successive sea level high stands where rock uplift rates are slower can lead to complex terrace structures and to the absence of specific high stands from the morphostratigraphy.

The observation of composite ages on individual coral reef terraces (e.g., Bard et al., 1996) and the occasional absence of specific MIS high stands in extensive coral terrace series (e.g., Pedoja et al., 2018) also calls into question the bijective rationale. Pastier et al. (2019) highlight that a sea level curve cannot be straightforwardly related to a coral reef terrace record since some terrace sequences may lack certain high stands and/or preserve steps formed at lower sea level stands.

Here, we question the default assumption that marine terraces can be uniquely linked to a sea level high stand and highlight how marine terraces can be created by the integrated effects of successive episodes of wave erosion during multiple occupations of the same uplifting platform by the ocean. To do this, we examine altitudinal transects of sea level occupation under varying uplift conditions and identify the uplift rates that should enhance or reduce the potential for the generation and preservation of erosional terraces. Using a compilation of uplift rates inferred from marine terraces on convergent margins, we then consider the biases that polygenetic terraces can introduce into relative sea level reconstructions and crustal deformation models when they are erroneously interpreted to have formed during a single high stand.

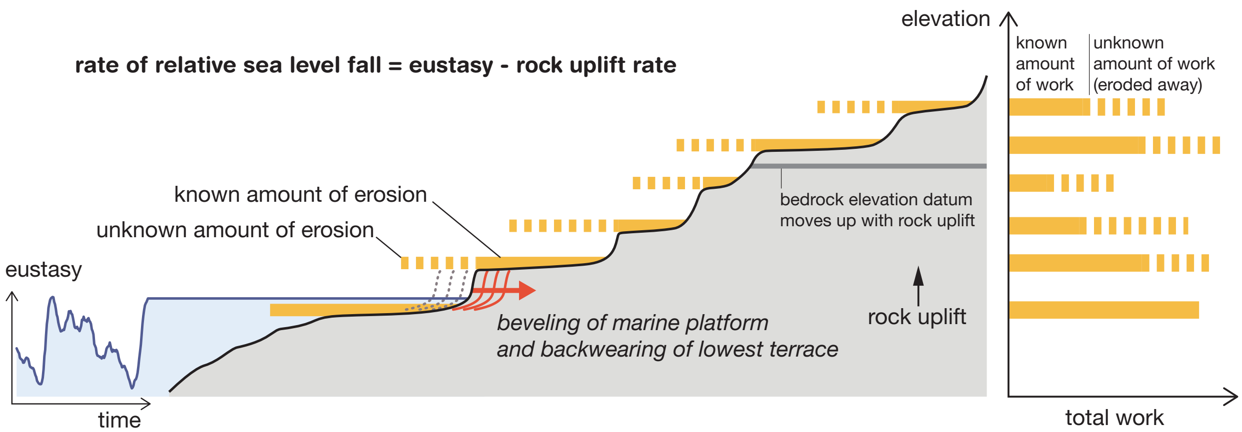

Figure 1: the steps of a terraced coastal landscape (left) record various amount of work expended by the waves at different bedrock elevations (right) to bevel marine platforms that have become terraces (brown bars) and have back-worn the terrace lying above.

Creation and preservation of marine terraces

Bedrock sea cliffs erode by weathering, mass wasting, and various processes driven by wave attack. Because waves can impact and strain sea cliffs, and mobilize sediment (Trenhaile 2019, Adams et al., 2005), sea cliff erosion rates increase with wave energy flux in a range of environments over annual to million-year timescales (e.g., Young et al. 2021, Alessio & Keller 2020, Huppert et al. 2020). Sea cliffs are thus expected to retreat further inland and etch a wider shallow water platform in their wake when they are exposed to wave action for a longer period of time. The resulting shallow water platform can be further abraded by sediment moved by shallow water waves (Bradley and Griggs, 1976) and/or by weathering processes in the intertidal zone (e.g., Kennedy et al., 2011).

Sustained and/or recurrent wave erosion at the same bedrock elevation datum (i.e., horizontal strip of bedrock that is moving with rock uplift) promotes the creation of wide, low gradient platforms that remain easily identifiable as marine terraces on uplifting coastlines. Yet a marine terrace associated with a given sea level stand can also be effectively erased from the chronostratigraphic record if a subsequent sea level stand occupies, and actively erodes, the same bedrock datum (resetting its age) or bevels a new terrace that undercuts the older one. The potential for a wide terrace to be created grows with the amount of time spent by sea level at a given bedrock datum, but the potential for that terrace to be preserved decreases with the time that sea level subsequently lingers at elevations closely below, where the coastline may easily retreat landward and undercut the abandoned terrace.

If marine terraces are only created during periods of slow relative sea level rise preceding high stands, as was initially surmised (Bradley, 1958), bedrock coasts would seemingly sit unchanged over the vast majority of their evolution, eroding only for a few millenia every hundred thousand years or so. Waves still break in the surf zone throughout the glacio-eustatic sea level cycle, so erosive potential persists even if it is modulated by varying wave energy, sediment cover, or expended only on non-cliff forming erosion of existing platforms (Mackey et al. 2014). We therefore postulate that, if marine platforms are formed by wave erosion and preserved intact, their widths should increase with the total amount of time sea level spends at that bedrock elevation datum, but this does not have to be during a continuous time-span (Fig. 1).

Sea-level occupation as a function of uplift

To represent the work of wave erosion on the coastline, it is practical to use the reference frame of the uplifting bedrock (Fig. 2A). In Fig. 2 we show the elevations of past eustatic sea levels relative to present sea level (Spratt and Lisecki, 2016) if they are uplifted at rates of 0, 0.3, 0.8, and 1.2 mm/yr. Relative sea level can be summed as a total time spent at different bedrock elevation datums (relative to present sea level; Fig. 2B). This approach was successfully used to characterize platforms and constrain rock uplift (Walker et al., 2016, Jara-Muñoz et al., 2017). Here, we display sea level change since 300 ka to focus on the periods preceding and following the last interglacial. From Fig. 2, we note that elevations of longer sea level occupation do not necessarily coincide with elevations of interglacial high stands. Coastlines uplifting at 0.3 and 1.2 mm/yr experience long durations of sea level occupation over the past 300 kyr at the elevation of MIS 5e; whereas sea level occupation at that elevation is much shorter on coastlines experiencing 0.8 mm/yr rock uplift.

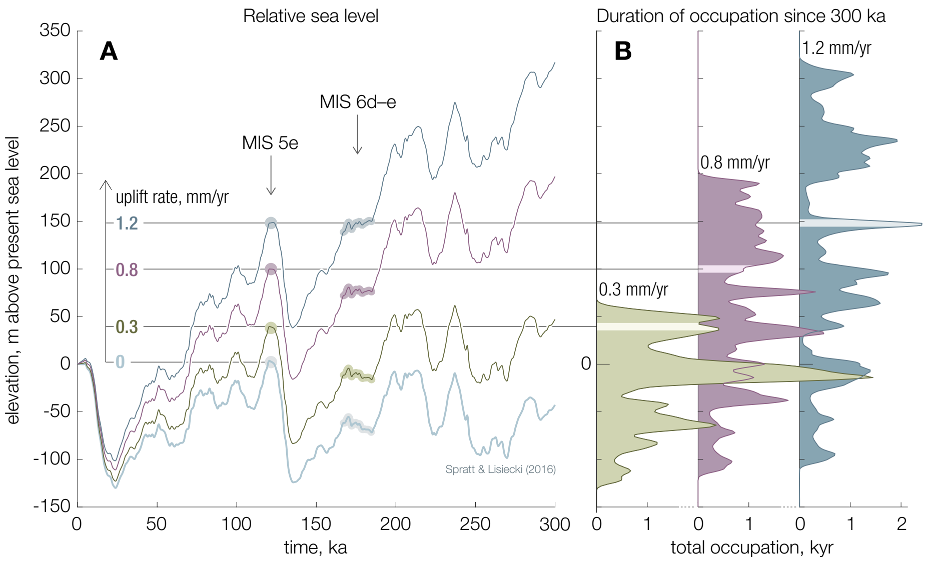

Figure 2: A. time series of relative sea level, and B., cumulative sea-level occupation of bedrock elevations for coastlines uplifting at 0.3, 0.8, and 1.2 mm/yr since 300 ka. Horizontal lines mark the present-day elevation of the MIS 5e shoreline. The density functions are made with a kernel function using a 3 m bandwidth. Supplementary video is useful to grasp the correspondence between A and B.

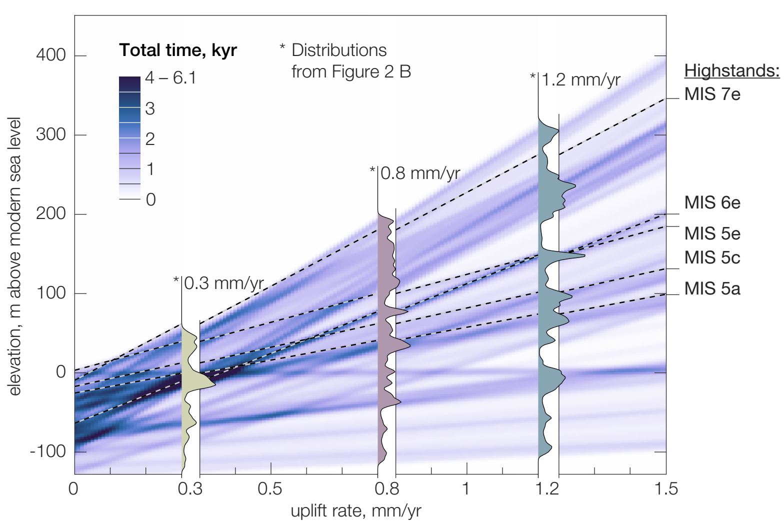

Figure 3: Duration of sea level occupation since 300 ka of bedrock datums as a function of rock uplift rate displayed by color brightness, with distributions of RSL occupation from Fig. 2B shown for select uplift rates. Dashed lines show the present-day elevation of specific MIS stages across all uplift rates. Sea level from Spratt and Lisiecki (2016).

The distributions of total sea level occupation (Fig. 2B) are shown by color brightness along a continuous spectrum of uplift rates in Fig. 3 (plot since 600 ka, alternative sea level curves, and the Python script needed for Fig. 2 and 3 are in the supplementary files). For instance, examining the color brightness along a vertical transect at an uplift rate of 0.8 mm/yr, we see that relative sea level elevations fall between -125 and ~200 m above present sea level (masl), with the longest occupation (darkest color) at ~40 masl (Fig. 2). The uplifted elevations of individual high stands are represented with dashed lines. Instances of repeated occupation are apparent at numerous other uplift rates, making it clear that a bijective interpretation of marine terrace morphostratigraphy is invalid in a wide range of tectonic settings.

An additional source of error may arise when a terrace is resubmerged by a higher high stand and draped with coral or sediment of that younger age. For example, at 0.8 mm/yr, MIS 5e and 6e high stands would be uplifted to 100 and 81 masl respectively (Fig. 2A, 3) and the attribution of a younger age to the older, and lower, platform yields an apparent rock uplift of 0.67 mm/yr. For instance, corals were deposited at ~100 ka on a resubmerged ~120 ka terrace on San Nicolas Island, California, USA, resulting in a mismatch between carbonate age and age of platform erosion at a rock uplift of ~0.25–0.27 mm/yr (Muhs et al. 2012). This potential for age-platform mismatch can be tracked across a spectrum of uplift rates in Fig. 3 by comparing high stands (dashed line) and long sea level occupation (dark streaks).

Evidence at global and local scales

A global compilation of presumed MIS 5e marine terrace ages and elevations (Pedoja et al., 2014) suggests that time-averaged rock uplift rates at convergent margins since MIS 5e cluster around a primary peak at 0.2–0.3 mm/yr and a secondary peak around 0.9 mm/yr (Fig. 4A). We calculated these uplift rates assuming a globally consistent MIS 5e sea level equivalent to the present. Individual regions included in the compilation show similar bimodality (Fig. 4B). We fail to identify a geological process that would explain an abundance of uplift rates between 0.8 and 1.1 mm/yr or a lower representation around 0.6 mm/yr.

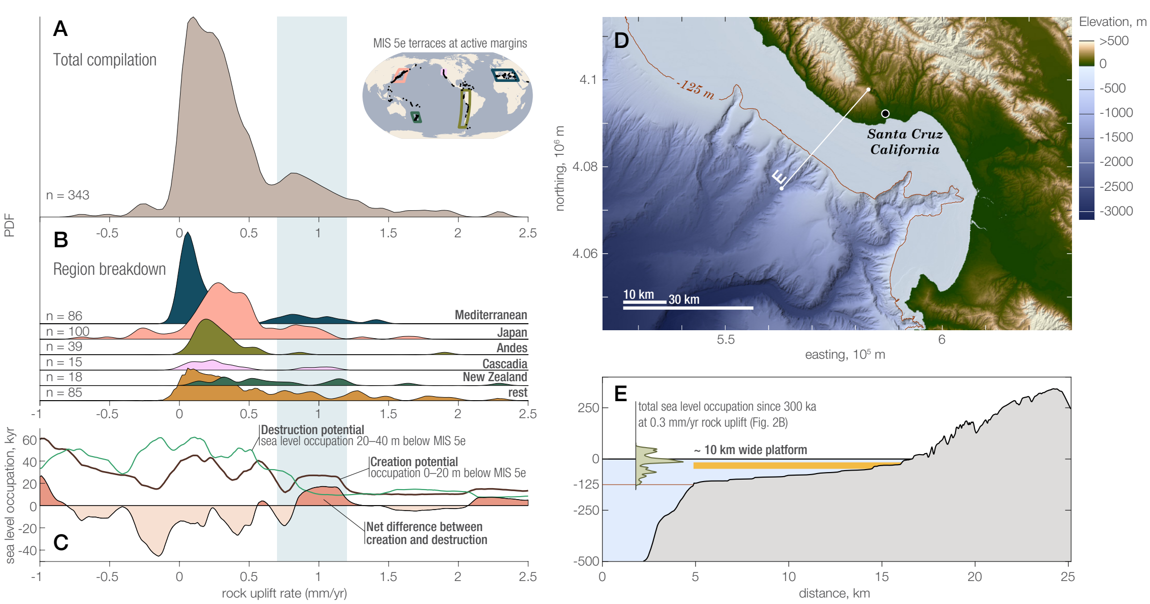

Figure 4 A. Total distribution of uplift rates at convergent margins around the globe (Pedoja et al., 2014). B. distribution of uplift rates at the six sub-sites composing A. C. total sea level occupation at the elevation of the 5e terrace and immediately below (using 20 m windows) and their difference (sea level from Spratt & Lisiecki, 2016). D. and E., Topography and profile of the Santa Cruz and Monterey Bay area (Ryan et al., 2009).

We suggest that this bimodality in apparent rock uplift rates may arise from a propensity for rock uplift rates around 0.9–1.2 mm/yr to favor the creation and preservation of MIS 5e terraces. MIS 5e sea levels reoccupy the same bedrock elevation as MIS 6d–e for uplift rates around 0.9–1.2 mm/yr (Fig. 2 & 3). This leads to a significantly longer total duration of occupation at MIS 5e elevation at these rock uplift rates (creation potential), as well as a brief occupation below (destruction potential, Fig. 4C). A MIS 5e terrace on a coastline uplifting at 0.9–1.2 mm/yr may be wider and more easily identifiable, leading to a potential sampling bias. This may explain the overrepresentation of these rock uplift rates in the global marine terrace record. The range and distribution of rock uplift rates that can be inferred from the marine terrace record is biased by the considerable influence that rock uplift rates exert on the duration of sea level occupation at a given bedrock datum.

The coast around Santa Cruz, CA, USA, is characterized by an extensive terrace staircase uplifting at ~0.4 m/yr (Bradley and Griggs, 1976, Anderson, 1990, Valensise and Ward, 1991, Gudmonsdottir et al., 2013) and a ca. 10 km-wide, <125 m deep, erosive marine platform below present sea level (Fig. 4 D, E). At this rock uplift rate, several episodes of sea level occupation would align near or below modern sea level (Fig. 2 and 3). Accordingly, we would expect a large platform carved by repeated long-term sea-level occupation and wave erosion, as is observed in the bathymetry (Fig. 4D, E).

Discussion

Some complications and pitfalls in inferring rock uplift rates from marine terraces brought about by sea-level reoccupations have already been identified (e.g., Armijo et al., 1996). Here, we seek to move past a cautionary tale and propose a strategy to quantify this source of bias and better exploit the topographic record. At this stage, we cannot falsify the hypothesis that marine terraces depend more on total sea level occupation than individual high stands. Two tests, however, could be employed: (1) differentiating ages of platform formation and coral or sediment cover; and (2) surveying the age and geometry of a continuous terrace across a gradient in rock uplift rate.

The first would identify episodes of reoccupation of wider terraces by subsequent high stands, based on observations of a difference between platform age and (multiple) sediment and/or coral cover age(s). Independently constrained rock uplift rates, e.g. from fluvial terraces or denudation rates, can guide the choice of ideal survey sites to target potential reoccupation episodes, such as those expected to occur on coasts uplifting at 0.8 mm/yr (Fig. 3).

For the second, it may be informative to investigate the geometry and surface age of terraces that increase in elevation along a coastline due to a gradient in rock uplift rates. Such terraces may provide evidence of reoccupation dependent on rock uplift rate. For example, at rock uplift rates <1.2 mm/yr, a terrace carved during MIS 6d–e would retain evidence of reoccupation during MIS 5e while the same terrace would display only MIS 6d–e ages at rock uplift rates >1.2 mm/yr (Fig. 3).

Here, we used a global benthic oxygen isotope-based eustatic sea level curve, but our graphical solution can easily be applied to alternative and local eustatic sea level curves, e.g. at high latitudes where the gravitational component of glacial isostatic adjustment differs significantly from global averages (Mitrovica et al., 2001).

Conclusions

Marine terraces provide a direct means of constraining the magnitude and timing of past sea level and solid earth deformation. Sequences of drowned or uplifted marine terraces are often interpreted to have formed at successive interstadials, with each terrace relating uniquely to a past high stand sea level. Yet, this record can be affected by the repeated occupation of specific bedrock datums by sea level. The non-linear recombination of the total duration of sea level occupation and associated wave erosion may promote or hinder the creation and preservation of marine terraces at various elevations. The dependency of SL occupation duration on uplift rate may explain both an apparent overrepresentation of rock uplift rates between 0.8 and 1.2 mm/yr inferred from the global marine terrace record and the > 10km width of the marine platform uplifting at ca. 0.4 mm/yr off the coast of Santa Cruz, CA, USA. Representing the distribution of sea level occupation time over a range of rock uplift rates illustrates the likelihood of marine terrace creation and the potential for bias in the record, improving the quality and reliability of morphostratigraphic analyses.

Acknowledgments:

Thanks to Shigeru Sueoka and Sumiko Tsukamoto for support translating Yoshikawa et al. (1964); to Anne-Morwenn Pastier and Alessio Rovere for fruitful discussions. Malatesta was supported by a Swiss National Science Foundation Post.Doc Mobility at UCSC (P2SKP2 168328).

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Supplementary files for the article “The influence of rock uplift rate on the formation and preservation of individual marine terraces during multiple sea level stands”

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1 Code to generate the occupation plot

The Python code used to plot Fig. 2 and 3 and is available in the Zenodo repository doi:xyz [*Pending revision, the code will not be assigned a doi. Instead it can be accessed at* https://github.com/geo-luca/RSL-plotting *and it can be run directly in a browser using the Binder links in the read-me file*

Summary of the code

The code can be summarized as following.

```
Import eustatic curves
Compute eustatic curve at different rock uplift rates
Calculate kernel distribution of sea level occupation time along elevation
Store kernel distribution in a matrix for each uplift rate
Represent the distribution as a heat map in elevation vs.  rock uplift space
```

2 Sea level occupation since 600 ka

Figure 1 takes the last 600 kyr into account instead of the 300 kyr presented in the main manuscript. The longer record yields additional loci of repeated occupation and spans a greater vertical

3 Plots with alternative sea level curves

Figure 2 shows alternative versions of the illustration of total sea level occupation time as a function of rock uplift rate (Figure 3 in the main manuscript) with the sea level curves of Lea et al. (2002) and Lisiecki and Raymo (2005). Additional plots can be generated using the Python code available in Section 1.

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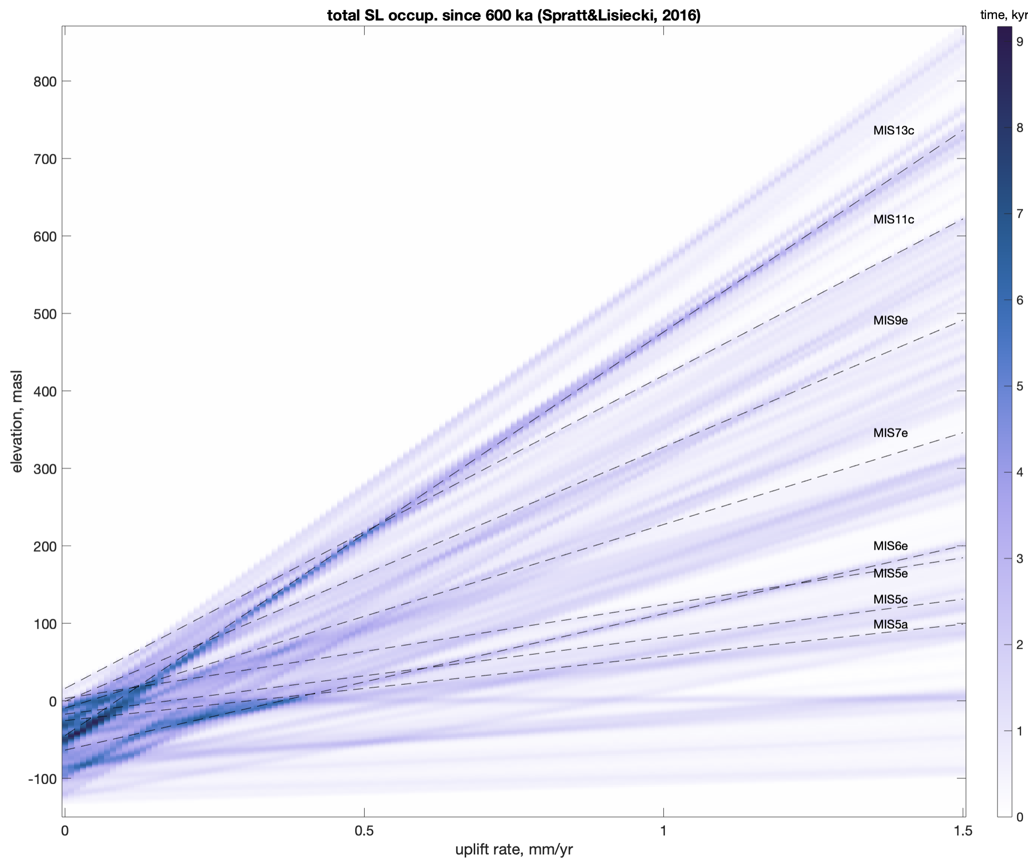

Figure 1: Total occupation time of sea level from 600 ka over a range of rock uplift rate of 0 to 1.5 mm/yr using the sea level curves of Spratt and Lisiecki (2016).

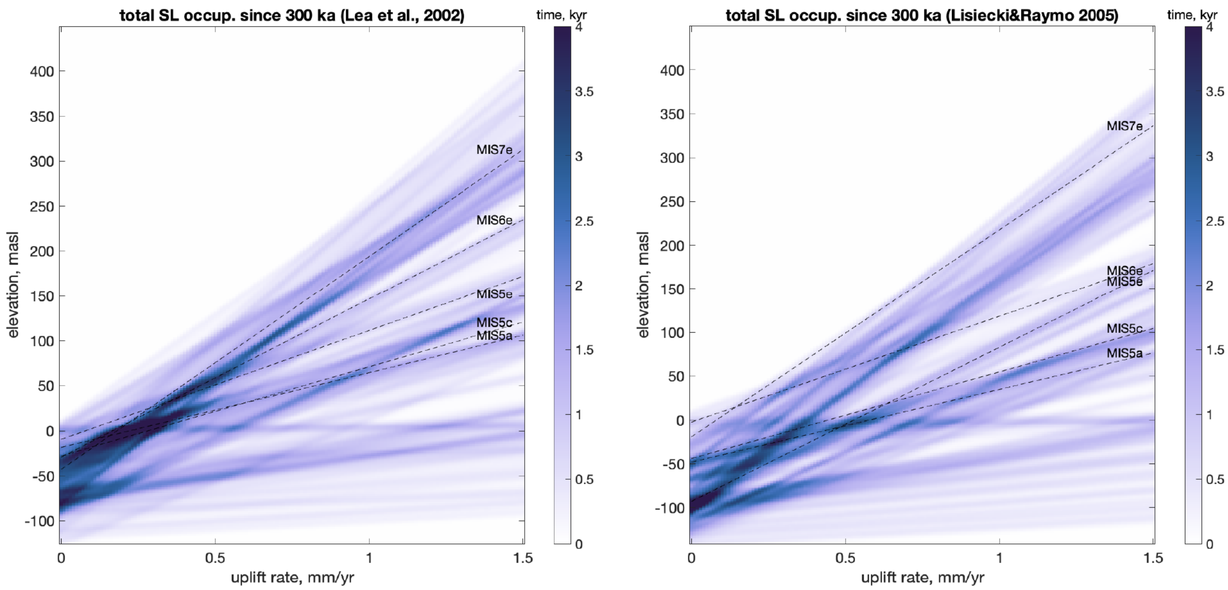

Figure 2: Alternative display of total occupation time over a range of uplift (Figure 3 in manuscript) using the sea level curves of Lea et al. (2002) and Lisiecki and Raymo (2005).

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