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

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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, based on reasoning that marine platforms could only be significantly widened at the beginning of an interglacial. However, this logic implies that wave erosion is insignificant at other times. Here, we postulate that the erosion potential at a given bedrock elevation datum is proportional to the total duration of sea level occupation at that datum. The total duration of sea level occupation depends strongly on rock uplift rate. Certain rock uplift rates may promote the generation and preservation of particular terraces while others prevent them. For example, at ~1.2 mm/yr rock uplift, the MIS 5e high stand reoccupies the elevation of the MIS 6d–e mid-stand, favoring creation of a wider terrace than at higher or lower rock uplift rates. Thus, misidentification of terraces can occur if each terrace in a sequence is assumed to form uniquely at successive interglacial high stands and to reflect their relative elevations. Graphically representing a proxy for the entire erosion potential of sea level history allows us to address creation and 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, based on reasoning that marine platforms could only be significantly widened at the beginning of an interglacial. However, this logic implies that wave erosion is insignificant at other times. Here, we postulate that the erosion potential at a given bedrock elevation datum is proportional to the total duration of sea level occupation at that datum. The total duration of sea level occupation depends strongly on rock uplift rate. Certain rock uplift rates may promote the generation and preservation of particular terraces while others prevent them. For example, at ~1.2 mm/yr rock uplift, the MIS 5e high stand reoccupies the elevation of the MIS 6d–e mid-stand, favoring creation of a wider terrace than at higher or lower rock uplift rates. Thus, misidentification of terraces can occur if each terrace in a sequence is assumed to form uniquely at successive interglacial high stands and to reflect their relative elevations. Graphically representing a proxy for the entire erosion potential of sea level history allows us to address creation and 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 (sea level relative to a land-based datum, typically the difference between eustatic and rock uplift rates) — should grow faster by wave erosion when relative sea level rise is very slow, as at the beginning of an interglacial (see Bradley, 1958, with a review of early 20th c. literature). Second, the large eustatic sea level drops that typically follow high stands can 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 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 each individual terrace has a unique age linked to a unique high stand (Pastier et al., 2019), and it is commonly employed at sites where independent dating of terraces is scarce or infeasible.

Greater scrutiny, however, reveals that individual terraces can form and be reoccupied 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. In Northern California, Merritts and Bull (1989) explored how the relative heights of high stands contribute to preservation, reoccupation, or destruction of terraces as a function rock uplift rate. Armijo et al. (1996), also in Corinth, suggested that repeated occupation of a platform by successive high stands can lead to complex terrace structures and the absence of specific high stands from the record.

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 they can be created by the integrated effects of successive episodes of wave erosion during multiple marine occupations of the same uplifting platform. 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.

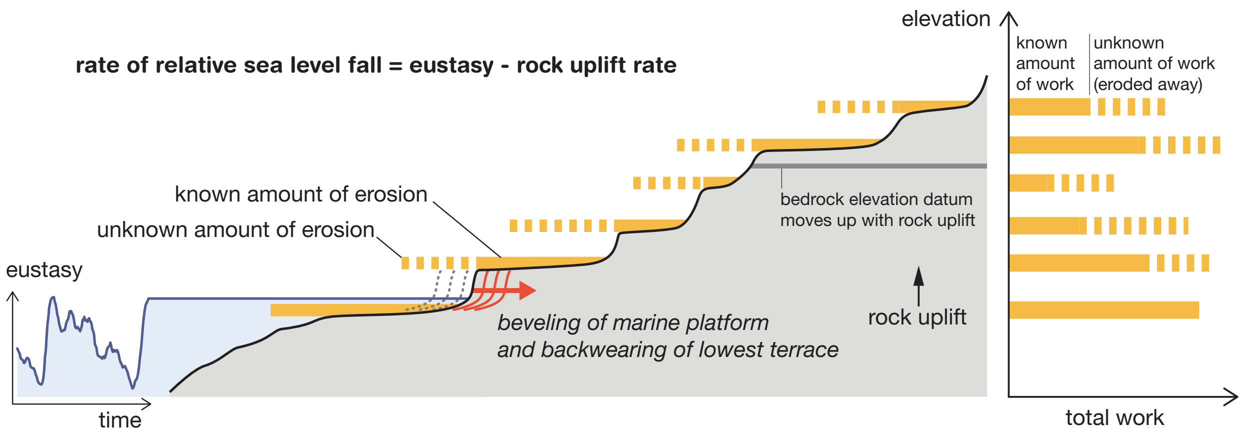

Figure 1: the steps of a terraced coastal landscape (left) record various amount of work expended by the waves at different bedrock elevations (right) to bevel marine platforms that have become terraces (brown bars) and have back-worn the terrace lying above.

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 when they are exposed to wave action for a longer period of time. This progressive widening should occur even if wave energy dissipation across an increasingly wide shelf reduces rates of sea cliff retreat and further platform widening (Anderson et al. 1999). 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 a given bedrock elevation datum (i.e., horizontal strip of bedrock in the frame of reference of uplifting rock) should promote the creation of a wide, low gradient platform that would likely remain identifiable as a marine terrace on an uplifting coastline. The potential to generate an identifiable terrace therefore grows with the amount of time sea level spends at a given bedrock elevation datum. On the other hand, marine terrace can also be effectively erased from the chronostratigraphic record if a subsequent sea level stand occupies and erodes the same bedrock datum (resetting its age). The preservation potential of a terrace can also decrease with the amount of time sea level spends at elevations closely below it, where subsequent erosion can undercut and destroy the abandoned platform.

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 for only a few millennia every hundred thousand years or so. Waves still impact coasts throughout the glacio-eustatic sea level cycle, however, so erosive potential persists even if it is modulated by changing wave energy, lithology, or sediment cover. 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).

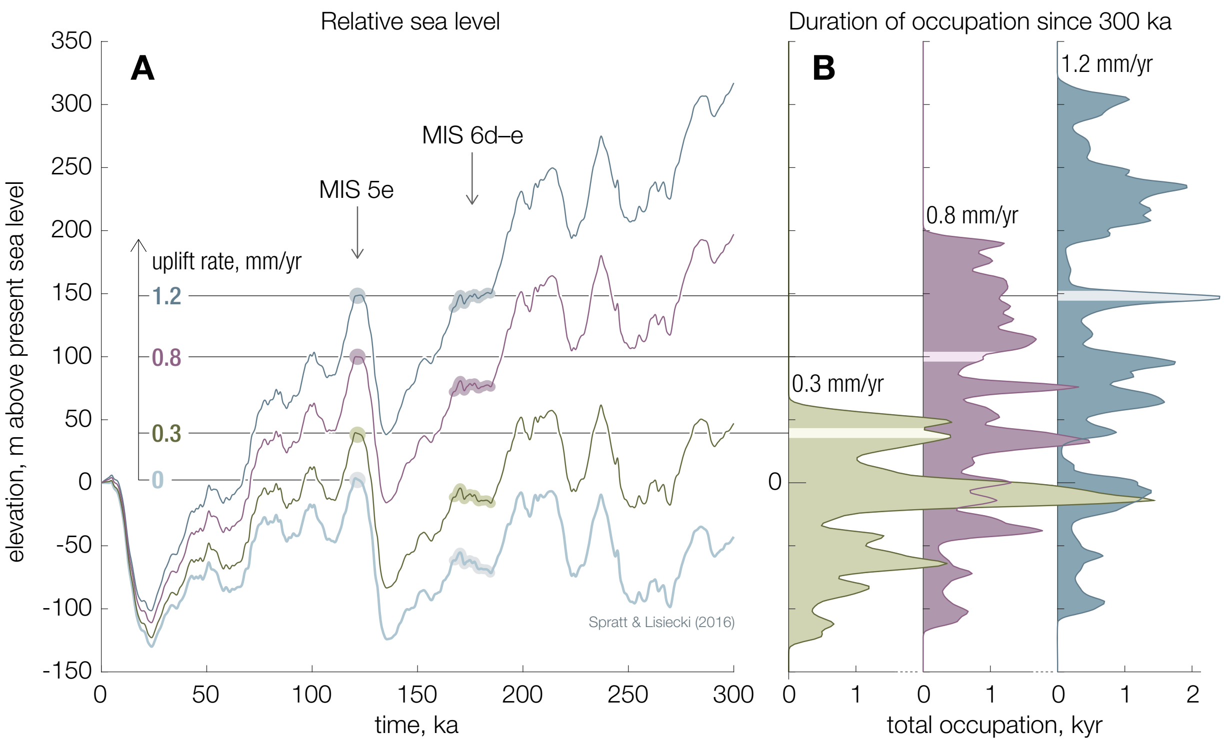

Figure 2: A. time series of relative sea level, and B., cumulative sea-level occupation of bedrock elevations for coastlines uplifting at 0.3, 0.8, and 1.2 mm/yr since 300 ka. Horizontal lines mark the present-day elevation of the MIS 5e shoreline. The density functions are made with a kernel function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

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 Lisiecki, 2016) if they are uplifted at rates of 0, 0.3, 0.8, and 1.2 mm/yr. Relative sea level can be summed to determine the total amount of time spent at different bedrock elevation datums relative to present sea level (Fig. 2B, 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 at the elevation of MIS 5e over the past 300 kyr; whereas sea level occupation at that elevation is much shorter on coastlines experiencing 0.8 mm/yr rock uplift.

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 the longest occupation (darkest color) at ~40 m above present sea level (masl). The uplifted elevations of individual high stands are represented with dashed lines, and these do not necessarily match peaks in occupation (e.g., either side of MIS 7e line). The slope of a high stand dashed line is proportional to its age. 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 subsequent high stand and draped with coral or sediment of that younger age. For example, at 0.8 mm/yr, a terrace generated at MIS 6e (0 and ~-60 masl) would be uplifted to ~80 masl (Fig. 2A, 3), <20 m below the elevation of MIS 5e occupation. If MIS 5e deposited coral or sediment on this terrace, the attribution of an MIS 5e age to this older, lower platform would yield an apparent rock uplift of only 0.67 mm/yr. Similarly, corals were deposited at ~100 ka on a resubmerged ~120 ka terrace on San Nicolas Island, California, USA, resulting in a mismatch between the ages of carbonate deposition and platform erosion at a true 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 the elevations of high stands and of long sea level occupation.

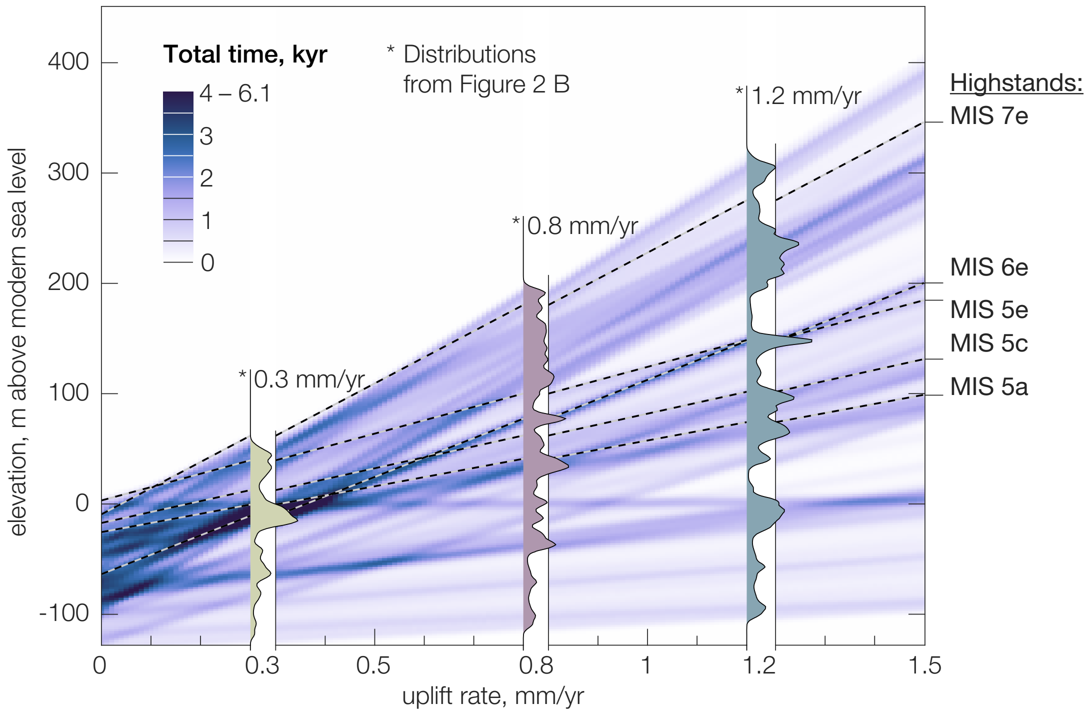

Figure 3: Duration of sea level occupation since 300 ka of bedrock datums as a function of rock uplift rate displayed by color brightness, with distributions of RSL occupation from Fig. 2B shown for select uplift rates. Dashed lines show the present-day elevation of specific MIS stages across all uplift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

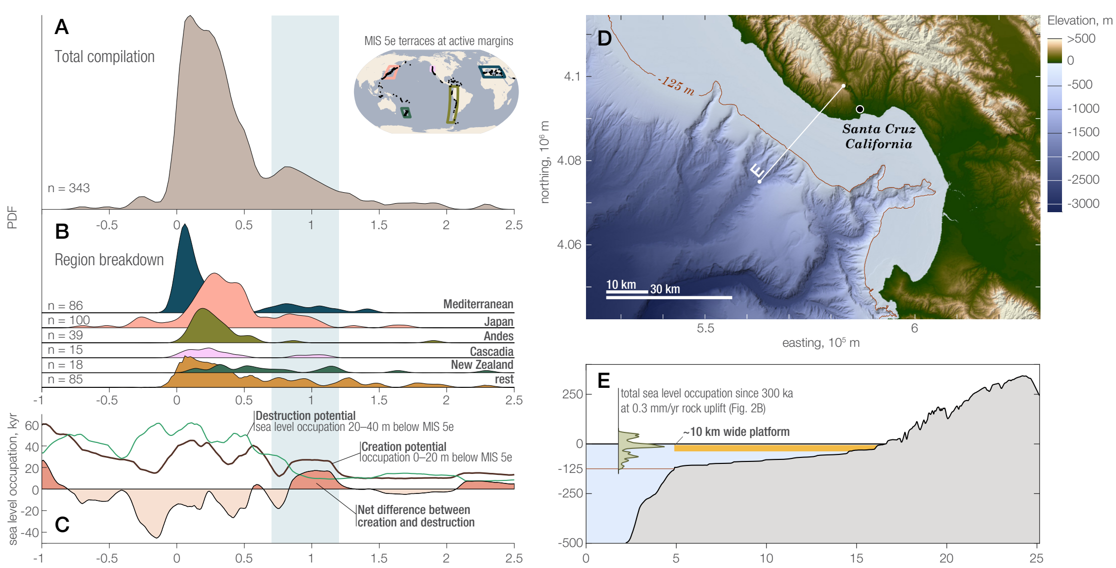

Figure 4 A. Total distribution of uplift rates at convergent margins around the globe (Pedoja et al., 2014). B. distribution of uplift rates at the six sub-sites composing A. C. total sea level occupation at the elevation of the 5e terrace and immediately below (using 20 m windows) and their difference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

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.

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 only a brief occupation below it (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, potentially leading to a further 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 a ca. 10 km-wide, <125 m deep, erosive marine platform (Fig. 4 D, E). Rock uplift rates vary along the coast, and may be as high as ~1 mm/yr (Perg et al. 2001), but generally cluster around ~0.4 mm/yr (Bradley and Griggs, 1976, Anderson, 1990, Valensise and Ward, 1991, Gudmonsdottir et al., 2013). At 0.4 mm/yr, several episodes of sea level occupation align near or below modern sea level (Fig. 2 and 3). Accordingly, we expect a large platform carved by repeated long-term sea level occupation and wave erosion at and below sea level, as is observed in the bathymetry (Fig. 4D, E).

Discussion

Some complications and pitfalls in inferring rock uplift rates from marine terraces 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 test 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 test, 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 the mid-stand MIS 6d–e would host evidence of reoccupation during MIS 5e while at rock uplift rates >1.2 mm/yr, the youngest sediment ages on the same terrace would be MIS 6d–e (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 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, Simms et al., 2016).

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 scaling between rock uplift rates and the durations of sea level occupations (arising from the recombination of complex sea level curves) may promote or hinder the creation and preservation of marine terraces at various elevations in different tectonic settings. This 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 for marine terrace creation and the potential for bias in the record, improving the quality and reliability of morphostratigraphic analyses.

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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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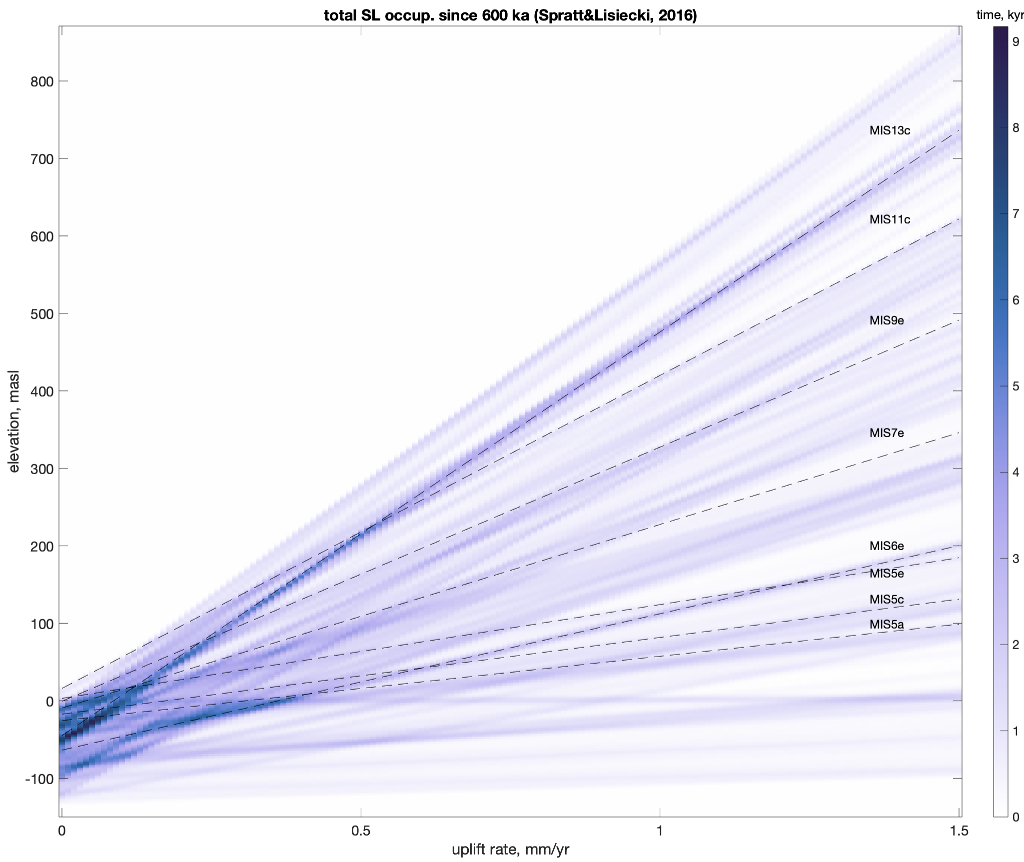

Figure 1: Total occupation time of sea level from 600 ka over a range of rock uplift rate of 0 to 1.5 mm/yr using the sea level curves of Spratt and Lisiecki (2016).

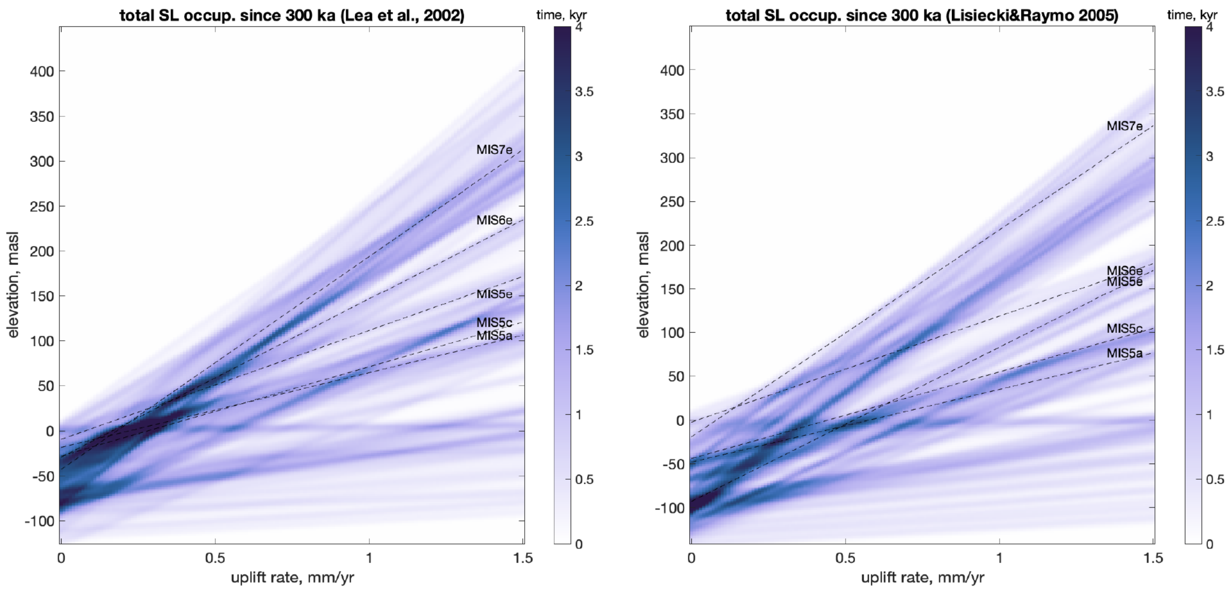

Figure 2: Alternative display of total occupation time over a range of uplift (Figure 3 in manuscript) using the sea level curves of Lea et al. (2002) and Lisiecki and Raymo (2005).

References

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