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# Cenozoic surface uplift from south Western Australian rivers

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## SUMMARY

Embedded within Earth's topography is a constantly evolving fluvial network sensitive to variations in horizontal and vertical motions, driving sediment transport from elevated sources to sedimentary basins. The notion that a river acts as a 'tape recorder' for positive vertical displacements suggests that changes in spatial and temporal characteristics of surface uplift can be deduced through the analysis of longitudinal river profiles. The relative tectonic quiescence of the Australian continent during the Cenozoic makes it an excellent natural laboratory to study recent large-scale variations in surface uplift, often linked with mantle convective processes. Here, we analyse X longitudinal river profiles from south Western Australia. Major knickzones in the longitudinal profiles of rivers in southwest Australia suggest recent surface uplift. Given the lack of recent large-scale tectonic activity in that region, this uplift requires an explanation. Applying an inverse algorithm to river profiles of south Western Australia reveals that this surface uplift started in the Eocene and culminated in the mid-late Neogene. The surface uplift rates deduced from this river profile analysis generally agree with independent geological observations including preserved shallow-marine sediment outcrops across the Eucla Basin and south Western Australia. The timing of this event is also to be compared with offshore stratigraphic sections to link onshore surface uplift to offshore sedimentation. We show that the interplay between global sea level and long-wavelength dynamic topography associated with south Western Australia's plate motion path over the remnants of an ancient Pacific slab is a plausible mechanism driving this surface uplift.

**Key words:** geomorphology, surface uplift, Australia, Cenozoic, dynamic topography, base level

## 1. INTRODUCTION

Observations of Cenozoic surface uplift preserved in the present-day topography of south Western Australia have long been documented (e.g. Jutson, 1914), however discrepancies still remain regarding the spatial and temporal evolution of this event (Cope, 1975, Beard 2000, 2003, Quigley et al., 2010). In a broad context, the Australian continent has displayed remarkable intermediate ($10^2$ km) to long-wavelength ($10^3$ km) tectonic stability throughout the Cenozoic. In the lack of recent large-scale tectonic activity across south Western Australia, this surface uplift requires an explanation. Previously, continent-wide inundation patterns throughout the Cenozoic, deduced from preserved ancient shallow-water sediments (Langford et al., 1995), have been shown to differ from global sea level trends and have commonly been attributed to the effects of mantle convection-induced dynamic topography (Czarnota et al., 2013; DiCaprio et al., 2009; Gurnis et al., 1998; Heine et al., 2010; Liu, 1979; Matthews et al., 2011; Sandiford, 2007; Veevers, 1984). This mantle process has been linked with the regional-scale surface uplift preserved in south Western Australia (Jakica et al., 2011, Quigley et al., 2010, Sandiford, 2007), however the relationship remains to be quantified.

Considering that uplifting areas are subject to erosion and tend to have a poor preservation potential (Flament et al., 2013; Olen et al., 2012), we employed a geomorphological method to infer rates and patterns of surface uplift over geological timescales from information contained in the present-day fluvial network (Whipple and Tucker, 1999). Specifically, longitudinal river profiles may indicate whether surface uplift with respect to sea level (England and Molnar, 1990) has affected a catchment area (Snyder et al., 2000). Recently, Pritchard et al. (2009) and Roberts and White (2010) showed that the present-day geometry of longitudinal river profiles contains time-dependent information pertaining to the evolution of landscape vertical motions over large spatial and temporal scales (i.e., ~1–100+ Myr, 10–1000 km; Roberts et al., 2012) in tectonically quiescent regions. In this method, time-dependent surface uplift rates are estimated by parameterizing the elevation of a river profile as a function of its length (Pritchard et al., 2009). Indeed, surface uplift can result in rapid changes in gradient near the river mouth that, over time, migrate upstream as knickpoints (Whipple and Tucker, 1999). Depending on retreat rate, knickpoints may be preserved in present-day longitudinal river profiles, providing information on past uplift events.

Here, we analyse 9 longitudinal river profiles across south Western Australia (Fig. 1). The shape of these profiles suggests recent surface uplift on regional scale. We use the method of Pritchard et al. (2009) to constrain the spatial and temporal evolution of this uplift event.

## 2. METHODS

### 2.1 Extraction of longitudinal river profiles

We analyse 9 individual longitudinal river profiles from south Western Australia. We followed standard protocols when delineating profiles using the Hydrology Tool in ESRI ArcGIS 10.0, extracting each final river profile from an SRTM 3 arc second DEM (Rabus et al., 2003). All profiles exceed Strahler stream order >4 (Strahler, 1954) which defines stream sizes based on a hierarchy of tributaries.

2.2 Selection of longitudinal river profiles

Rivers draining internally were excluded as they may experience changes in reference levels at their mouth, which is not located at sea level. We have also avoided, where possible, rivers affected by dams (Kollmorgen et al., 2007) or known surface uplift resulting in river captures and drainage reorganisations. For instance, the Swan/Avon and Moore rivers (profiles 7–8, Fig. 1) both experienced significant drainage reorganisation as the result of Eocene surface upwarping that produced a marginal north–south swell in south Western Australia (Beard, 1999; Beard, 2003). Furthermore, the reactivation of faults may perturb or control longitudinal river profiles, resulting in localised rather than broad knickzones (<100 km; Whittaker, 2012; Whittaker and Boulton, 2012). The Murchison River longitudinal profile (profile 9, Fig. 1) displays such a localised knickzone in close proximity to numerous Neogene reactivated faults (Fig. 1 — inset, yellow faults; Clark et al., 2012), suggesting that local tectonics, rather than a regional event, may have influenced the evolution of this river that we therefore excluded from our analysis.

2.3 Geometry of longitudinal river profiles

The profiles were analysed to determine important morphological features that point to the influence of landscape vertical motions. Using the geomorphology software Geomorph Tools (Whipple et al., 2007), we quantitatively identified all minor and major knickzones through a combination of longitudinal plots (Fig. 2) and linear regression of logarithmic slope versus drainage area plots (Snyder et al., 2003) for all selected longitudinal river profiles.

2.4 Parameterization of uplift history from longitudinal river profiles

We implemented a simple 1D inverse algorithm to determine uplift rates from the shape of longitudinal river profiles (Pritchard et al., 2009), governed by the following equations:

$$\mathrm{U}\ (\tau) = \mathrm{v_o x^m}\left(-\frac{\mathrm{dz}}{\mathrm{dx}}\right)^{\mathrm{n}} \qquad (1)$$

where τ is the characteristic time period of uplift that can be expressed as

$$\tau = \frac{\mathrm{L^{1-m}}}{\mathrm{(n-m)v_0}}\left[\frac{1-\left(\frac{\mathrm{x}}{\mathrm{L}}\right)^{1-\frac{\mathrm{m}}{\mathrm{n}}}}{\left(\frac{\mathrm{x}}{\mathrm{L}}\right)^{\frac{\mathrm{m(n-1)}}{\mathrm{n}}}}\right]\left(-\frac{\mathrm{dz}}{\mathrm{dx}}\right)^{1-\mathrm{n}} \qquad (2)$$

where $v_o$ is the reference knickpoint retreat velocity for $m = 0$ and $n = 1$, $m$ and $n$ are dimensionless parameters representing the distance and slope exponent, $k$ is the diffusivity, $x^m$ the discharge, which increases downstream, and $L$ is the total length of the river profile (Pritchard et al., 2009).

2.5 Parameter Selection

Given the known difficulties to constrain the slope exponent $n$ in Eqs. (1) and (2) (Whipple and Tucker, 1999), we followed Roberts and White (2010) in assuming $n = 1$. We calibrated $m$ and $v_o$ using the deposition age (~33.5–36.5 Ma) and present-day elevation range (100–250 m) of the Upper Eocene shallow-marine deposits of the Pallinup and Princess Royal Spongolite Formation (Fig. 3B; Gammon et al., 2000). These geological constraints imply that the cumulative uplift for the Young, Phillips, and Gardiner rivers should be between 100 and 250 m since ~36.5–33.5 Ma (white box in Fig. 3A). Systematically varying $m$ and $v_o$ within the range of published estimates, we selected $m = 0.5$ and $v_o = 5$ m$^{(1-m)}$ Myr$^{-1}$ (Fig. 3A).

# 3. RESULTS

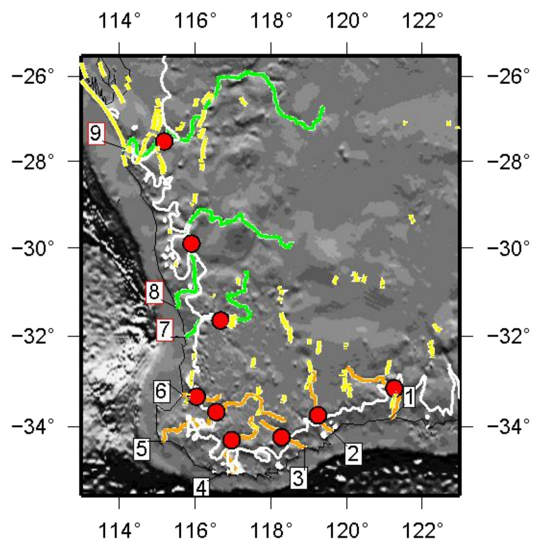


**Figure 1. Major river profiles of south Western Australia, underlain by topography and bathymetry with a directional gradient computed. Orange profiles passed the selection criteria, whereas green profiles did not (see text for criteria). Major knickzones are shown as red dots, the 200 m contour elevation is shown in white, and reactivated Late Neogene–Quaternary faults (Clark et al., 2012) are shown in yellow. Topography (Rabus et al., 2003) is shown in the background.**

3.1. Geomorphologic characteristics of Australian longitudinal river profiles

Longitudinal river profiles from south Western Australia (Fig. 2, left) all show convex shapes and knickzones at varying distances upstream from the river mouth. Interestingly, prominent south Western Australian knickzones all occur at a similar altitude (~ 200 ± 20 m), suggesting that a uniform surface uplift event may have affected those longitudinal river profiles contemporaneously (Berlin and Anderson, 2007). Niemann et al. (2001) showed that in the absence of transport-limited erosion, and of spatial heterogeneities in uplift rate or erodibility, the knickzone retreat velocity should be regionally consistent such that knickzones resulting from a particular vertical perturbation should be found at the same elevation within a basin. Therefore, knickzones occurring at the same elevation across an area suggest spatially uniform uplift (Berlin and Anderson, 2007) and a lack of transport-limited erosion (Niemann et al., 2001).

3.2. Uplift histories predicted from longitudinal river profiles

3.2.1. Predicted uplift rate history

Solving Eqs. 1 and 2 suggests that south Western Australia Rivers recorded an uplift event commencing in the mid-late Eocene with maximum uplift rates recorded in the Mid Neogene (Fig. 2, right).

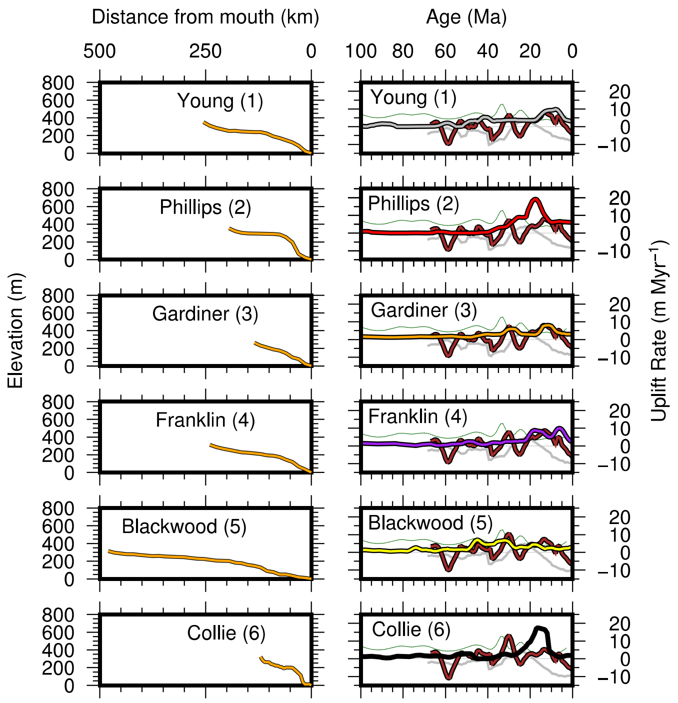


**Figure 2. (Left) Longitudinal river profiles extracted from high-resolution topography (Rabus et al., 2003). (Right) Uplift rate histories calculated using the method of Pritchard et al. (2009). Exhumation deduced from apatite fission track analysis is shown in green (green; Kohn et al., 2002), rates of dynamic topography change are shown in grey (Heine et al., 2010), and rates of base level change (see text for definition) are shown in brown.**

3.2.2 Predicted cumulative uplift history

We computed the evolution of total uplift normalised to present-day for all rivers (Fig. 3A). This revealed that south Western Australian rivers have recorded ~400 m of uplift over their history, with half of this uplift occurring since the mid-late Eocene (~200 m; 45–40 Ma).

## 4. DISCUSSION

4.1 Mechanisms driving the uplift of south Western Australia

4.1.1. Long-wavelength dynamic topography

Continental-scale dynamic topography occurs at wavelengths (>500 km) compatible with the constrained surface uplift of south Western Australia (>500 km) and has been previously recognised as a mechanism of surface uplift for this region (Czarnota et al., 2013; Quigley et al., 2010). We analysed the dynamic topography predicted by a mantle flow model (Heine et al., 2010). The rate of change of dynamic topography predicted by this model (Fig. 2 — thin grey line) shows a phase of dynamic surface uplift between ~30 and 15 Ma that is broadly compatible with a period of fast uplift rates recorded by the Phillips, Franklin and Collie (Fig. 2) rivers. However, uplift rates from all longitudinal river profiles initiate between ~5 and 10 Myr earlier than this dynamic surface uplift (Fig. 2), and the change to dynamic subsidence from ~15 Ma is at odds

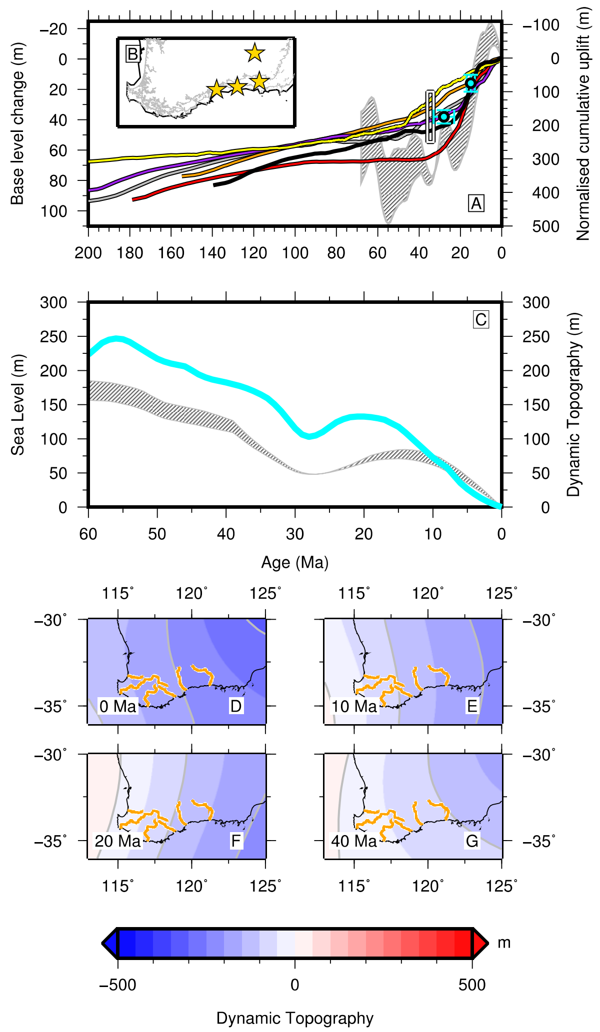


**Figure 3. A) Cumulative uplift normalised to present-day, for south Western Australian rivers, coloured as in Fig. 2. White box: present-day outcrop elevation of shallow-marine Eocene deposits (Gammon et al., 2000). Cyan: present-day outcrop elevation (and estimated associated error) of shallow-marine Oligocene (Cope, 1975) and mid-Miocene (Lowry, 1970) strata. Grey: base level change. The hatched envelope represents the range across rivers. (B) Gold stars: locations of shallow-marine Eocene deposits (Gammon et al., 2000). Grey: 100 m and 200 m elevation contours. (C) Grey: evolution of long-wavelength dynamic topography for south Western Australia. The envelope represents range of values sampled at river mouths. Cyan: evolution of long wavelength eustatic sea level (Haq and Al-Qahtani, 2005). (D – G) Dynamic topography predicted by a backward advection model at 0, 10, 20, and 40 Ma across south Western Australia (Heine et al., 2010).**

with the maximum uplift rates recorded by the Young (~ 10 Ma), Phillips (~ 18 Ma), Gardiner (~ 12 Ma), Franklin

(~ 7 Ma and ~ 20 Ma), and Collie (~ 15 Ma) rivers. This suggests that long-wavelength dynamic topography cannot explain the evolution of south Western Australian rivers if global sea level is assumed to be constant.

4.1.2. Interplays between eustasy and dynamic topography

We defined base level change as the difference between dynamic topography and sea level. Rates of base level change (brown curves in Fig. 2) and cumulative base level change (grey hatchet in Fig. 3A) are consistent with uplift rates (grey curves in Fig. 2) and cumulative uplift (Fig. 3A) constrained by river profiles. Regressions (positive rates of base level change) at ~55 Ma, ~45 Ma, ~30 Ma, and between ~20 and 5 Ma are in good agreement with peaks in uplift rate at ~30 Ma and ~12 Ma (Gardiner River, Fig. 2), ~45 Ma and ~30 Ma (Blackwood River, Fig. 2) and consistent with maximum uplift rates occurring between ~20 and 5 Ma for all rivers except the Blackwood River. This result suggests that interplays between long- wavelength dynamic topography and eustasy were the primary mechanism controlling the evolution of south Western Australian rivers.

## CONCLUSIONS

South Western Australian rivers consistently display a knickzone at ~200 ± 20 m, suggesting that they recorded a common uplift event (Niemann et al., 2001). Applying an inverse algorithm (Pritchard et al., 2009), we have shown that these rivers have recorded ~ 200 m of surface uplift since the mid-Eocene. Predicted uplift rates increased from ~45–40 Ma onwards, and peaked at 22 m $Myr^{-1}$ during the Neogene. We have shown that long - wavelength dynamic topography cannot solely account for this uplift history. However, the timing of changes in base level, defined as the difference between dynamic topography and eustasy, are consistent with the uplift history derived from longitudinal river profiles.

## FUTURE WORK

Analysis of offshore stratigraphic sections will be carried out to link between onshore surface uplift rates to offshore sedimentation rates.

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