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Surface Uplift Due To Time-Varying Elastic Thickness in Continental Interiors

Gregory A. Ruetenik[1], **John D. Jansen**[1], **and Mike Sandiford**[2]

[1]GFÚ Institute of Geophysics, Czech Academy of Sciences, Prague, Czechia, [2]School of Earth Science, University of Melbourne, Melbourne, VIC, Australia

Key Points:

- Loads embedded within the central Australian lithosphere produce large flexural responses that may evolve cyclically over time
- Surface deflections induced by transient lithospheric rigidity can explain endorheic basins formed at wavelengths of order 100 km
- Cyclical behavior in lithospheric rigidity is consistent with the observed geomorphic record of erosion and deposition

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

G. A. Ruetenik,
ruetenik@ig.cas.cz

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Author Contributions:

Conceptualization: Gregory A. Ruetenik, John D. Jansen, Mike Sandiford
Data curation: Gregory A. Ruetenik
Formal analysis: Gregory A. Ruetenik
Investigation: Gregory A. Ruetenik
Methodology: Gregory A. Ruetenik, John D. Jansen, Mike Sandiford
Resources: Gregory A. Ruetenik
Software: Gregory A. Ruetenik
Supervision: John D. Jansen, Mike Sandiford
Validation: Gregory A. Ruetenik
Visualization: John D. Jansen
Writing – original draft: Gregory A. Ruetenik, John D. Jansen, Mike Sandiford

Abstract If, as previously hypothesized, the effective elastic response of the lithosphere is sensitive to the imposed stress regime, then it may vary in time and produce distinctive geomorphic responses. Such effects will be at their most crucial in landscapes of low relief. Motivated by the existence of numerous small endorheic (internally-drained) basins in central Australia, we examine the influence of changing elastic response in the presence of large embedded loads in the lithosphere underlying stable continental interiors. Focusing on the western Lake Eyre Basin and adjoining Lake Lewis basin—an area with a close correlation between drainage pattern and extreme Bouguer gravity anomalies—we devise a set of numerical simulations that incorporate the flexural response to time-transient horizontal stresses. The simulations demonstrate that transient changes in the effective elastic thickness can drive topographic changes in low-relief landscapes, including drainage capture and the development of endorheic basins, consistent with field observations.

Plain Language Summary Extreme density anomalies in central Australia suggest the presence of significant stress within the lithosphere, even though the region lies far from any tectonic plate boundaries. This in situ stress probably dates back to a mountain-building period in the Paleozoic. The density anomalies correlate closely with drainage patterns and a set of internally-drained catchments, suggesting an important relationship exists between the deep-earth and landscape-forming processes. We propose the driving mechanism is the result of changes in the rigidity of the lithosphere, which in the presence of in situ stress lead to surface uplift or subsidence. We use a landscape evolution model to show that topography similar to field observations can be simulated by imposing cycles of uplift and subsidence brought about by these changes in lithospheric rigidity over tens of millions of years. In consequence, the lithosphere must have fairly low rigidity counter to previously held ideas about continental interiors.

1. Motivations

Surface deflections in continental interiors—far from active plate margins—pose such an unruly problem that anomalous uplift in just one locality (the Colorado Plateau) can simultaneously sustain four hypotheses: crustal thickening (Chase et al., 2002), far-field deformation (Liu & Gurnis, 2010), denudational isostasy (Pederson et al., 2002), and dynamic topography (Moucha et al., 2009). Setting the Colorado Plateau aside, here, we propose another possibility: continental surface deflections arise from transient variations in elastic thickness of the lithosphere. We are motivated by two intersecting considerations: one observational, the other theoretical.

A distinctive feature of the continental interior of Australia is the existence of numerous endorheic drainage basins: topographic depressions containing a terminal lake or playa underlain by basin fill (Mabbutt, 1977). The Lake Eyre Basin (1.1×10^6 km^2) is the largest example and a set of smaller endorheic basins (e.g., Bullo-Bancannia, Lake Amadeus, and Lake Lewis) are observed skirting its eastern and western margins (Figure 1a). Endorheic basins are commonly attributed to extrinsic forcing that depresses the surface or dams the drainage network, such as active tectonism (Garcia-Castellanos et al., 2003; Sobel et al., 2003) or glaciation. However, neither of these are significant players in Australia's continental interior. With regard to the origin of these endorheic basins, some with sediment-fills hundreds of meters thick, it has been noted previously that the Lake Lewis and upper Finke catchments coincide with extreme negative gravity anomalies (Jansen et al., 2022). This raises the possibility of a flexural origin which, if so, begs the question why in such a tectonically quiescent setting are these basins not filled with sediment? We suggest this observation hints at some unidentified process whereby the surface deflection that generates accommodation space continues to outpace the rate of basin-filling.

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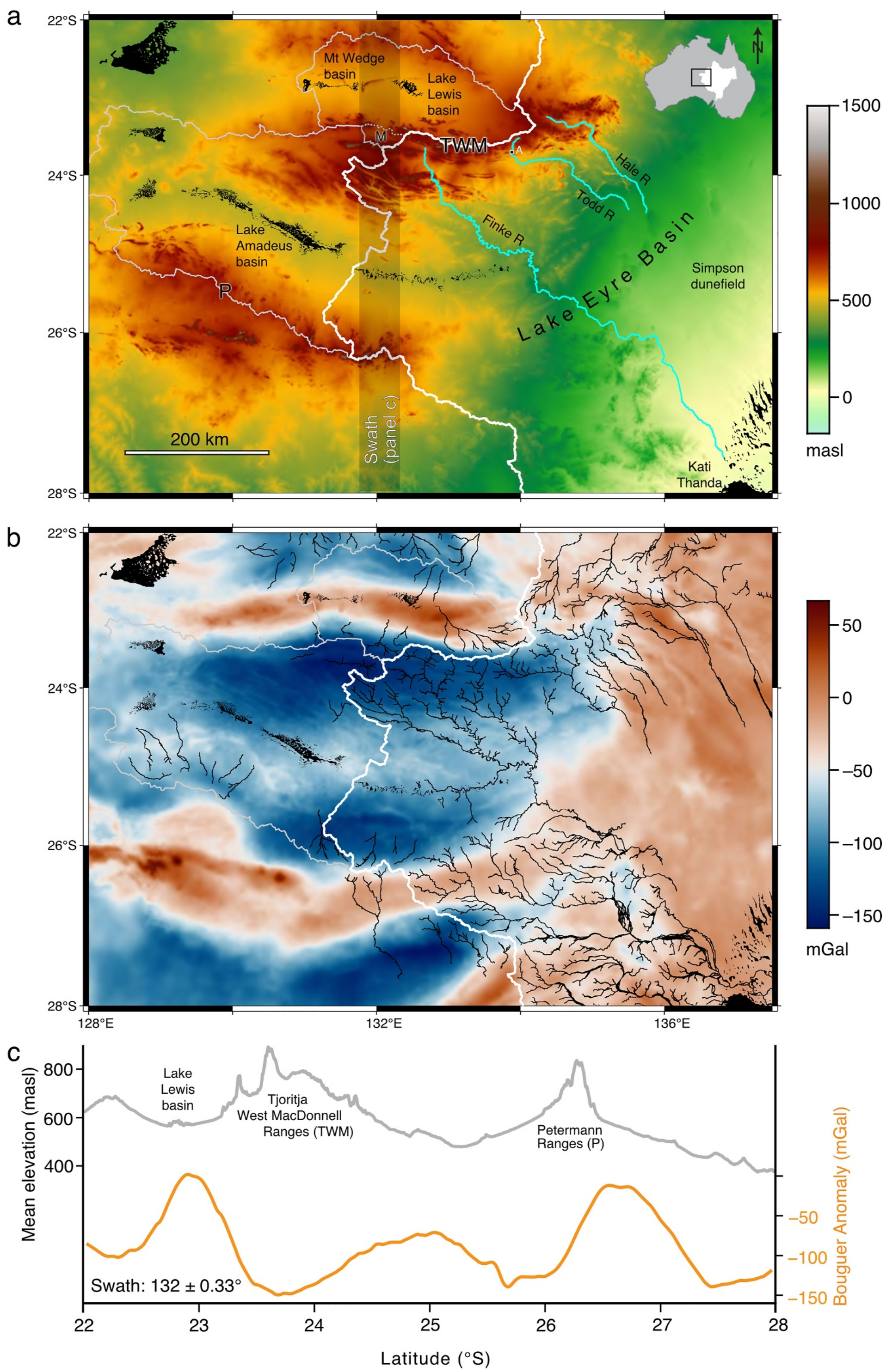

Figure 1. (a) Topographic map of central Australia (HydroSHEDS-3 elevation data, Lehner et al., 2008), showing the Lake Eyre Basin divide (thick white line); the Redbank Thrust Zone bounding the northern flanks of the Tjoritja West MacDonnell Ranges "TWM"; the Finke, Todd, and Hale rivers; major playa lakes (black); the Lake Lewis, Mt Wedge and Lake Amadeus basins (pale gray lines); and the town of Alice Springs "A." Inset shows Australia, the Lake Eyre Basin (white) and study area (black box). A potential drainage capture of the upper Finke into the Lewis basin (P. M. English, 2001) is denoted "M." (b) Complete Bouguer anomaly gravity map (Lane et al., 2020), also showing the drainage network (black lines). Note the overall correspondence between topographic highs and gravity lows (spanning −159 to 67 mGal). Streamlines (drainage area >50 km) (Stein et al., 2011), and lakes (Newey, 2022). (c) Swath of mean elevation and Bouguer anomaly (132 ± 0.33°).

The flexural response of the lithosphere to internal density loads is a fundamental geodynamic parameter (e.g., Watts, 2001) often expressed in terms of the effective elastic thickness (T_e). T_e is crucial to how we understand the topographic response to loading, including the pattern of bending of oceanic lithosphere associated with deep sea trenches at subduction zones. While T_e is often modeled as a time-invariant property of the lithosphere, it is known to be influenced by properties that vary with time, such as the contributions to the stress field arising from far field sources (e.g., Burov & Diament, 1995; McNutt & Menard, 1982), where compressive boundary forces alone can reduce T_e by as much as 30% (Burov & Diament, 1995). Since the stress state within the lithosphere is expected to vary over geologic timescales as a consequence of plate motion, we anticipate that the flexural support of loads may vary accordingly, with resultant ongoing topographic response and drainage instability even within cratonic continental interiors. Indeed, following this logic, Jansen et al. (2022) suggest that stress-dependant variations in T_e are responsible for an enigmatic set of intertwined bedrock gorges in the Finke River (central Australia), a result of multiple phases of aggradation and incision.

Here, we use numerical simulations to explore the development of endorheic drainage basins and associated aggradation-incision phases in response to cyclic changes in T_e. We focus specifically on the evolution of topography, neglecting the climate dynamics associated with lake-filling or overspills pursued by others (e.g., Garcia-Castellanos et al., 2003; Sobel et al., 2003); only deformation can produce these initial topographic depressions. We compare the experimental outcomes with topographic indices that identify notable landscape disequilibrium behavior in central Australia. Together these experiments and topographic analyses explain the hitherto unrecognized degree of transience that includes unstable drainage divides and endorheic sedimentary basins with fills hundreds of meters thick. We conclude by reflecting on how low-amplitude changes in relief drive transience in tectonically inactive landscapes, and we speculate how such responses may elucidate the time evolution of intraplate stress fields.

2. What Drives Endorheism in Australia's Interior?

Australia is the flattest, most tectonically quiescent of all the continents. Much of the continental interior yields cosmogenic nuclide-derived erosion rates of 5 ± 2 m My^{-1} integrated over the past few hundred thousand years (e.g., Fülöp et al., 2020; Heimsath et al., 2010; Jansen et al., 2022; Quigley et al., 2010; Struck et al., 2018). A result of such low rates of erosion and sediment production is that landscapes retain a characteristically long geomorphic memory and erosional-depositional responses to external perturbations tend to be slow and subtle (Mabbutt, 1977). Paradoxically, Australia is also the fastest moving continent. Significant sources of tectonic stress are associated with its rapid plate motion to the north-northeast (e.g., Coblentz et al., 1995) together with notable ongoing changes in the dynamic topographic field (e.g., Czarnota et al., 2013; Rudge et al., 2015; Sandiford, 2007). Sandiford and Quigley (2009) suggest that the geomorphic record of intraplate tectonism points to an evolving in situ stress regime that is becoming more compressional with time. While this may be a general trend, recent observations summarized by Jansen et al. (2022) suggest a more complicated cyclical stress history that is still yet to be clarified but likely rooted in the gravity field.

A set of outstanding negative gravity anomalies in central Australia (up to −160 mGal, Figure 1b) are among the most extreme known from continental interiors globally (e.g., Stephenson & Lambeck, 1985). The anomalies are attributed in part to periods of tectonism during the Petermann Range (~550–500 Ma) and Alice Springs (~450–300 Ma) orogenies (Beekman et al., 1997; Haines et al., 2001; Teyssier, 1985). The Redbank Thrust Zone (Beekman et al., 1997; Haines et al., 2001), a major structure in the Alice Springs Orogen, bounds the northern flanks of the Tjoritja West MacDonnell Ranges (Figure 1). The gravity high in the hanging wall block is composed of mafic granulites (~2.87 g cm^{-3}) that are denser than the amphibolites (~2.72 g cm^{-3}) of the footwall block to the south (Goleby et al., 1988). No significant tectonism has occurred in central Australia since the Paleozoic. Instead, we propose that any changes in the lithospheric rigidity and/or boundary conditions will change how loads are compensated, producing uplift or subsidence.

Close correlation between the gravity anomalies and drainage pattern (Jansen et al., 2022) is observed in a set of five catchments draining the western margin of Lake Eyre Basin: Finke River, Todd River, Hale River, Lake Amadeus, and Lake Lewis (Figures 1a and 1b). The Finke is the major regional river system rising in the Tjoritja West MacDonnell Ranges (1,380 m above sea level, masl), flowing southeastward ~800 km to the terminal basin and continental depocenter, Kati Thanda (15 m below sea level). The Finke's headwaters contain fluvial remnants up to 80 m thick reflecting a complex history of tilting that drove incision and aggradation over the past few million years (Jansen et al., 2022). The lower reaches of the Todd and Hale rivers are now isolated in the Simpson Desert dunefield but they once reached Kati Thanda or its precursors (Craddock et al., 2010). The Lake Amadeus drainage (Figure 1a) formerly entered the Finke prior to its excision via low-amplitude surface deformation; Karinga Ck and a line of playas trace the former flow path (Chen & Barton, 1991; Lloyd & Jacobson, 1987). The Lake Amadeus playa overlies ∼65 m of basin fill including mainly lacustrine sediment (Uluru Clay) that possibly dates to >5 Ma (Chen & Barton, 1991; Chen et al., 1993).

3. The Lake Lewis Basin

The Lake Lewis basin (∼30,000 km^2) coincides with a prominent gravity ridge that forms part of the drainage divide with the catchments of the Finke, Todd and Hale (Figures 1a and 1b). The highest peak in central Australia, Mt Zeil (1,531 masl), occurs just inside the Lewis basin, close to the Finke-Lewis divide. The Lewis basin-fill comprises two main units: (a) the basal ∼75 m Mt Wedge Clay is a pyrite-bearing lacustrine clay dating back to the Middle Late Eocene (English et al., 2001; Macphail, 1996); and (b) the upper ∼80 m Anmatyerre Clay accumulated since approximately the Late Miocene (English et al., 2001). This clay unit is veneered by sediments deposited by the Tilmouth paleolake, which at maximum highstand covered ∼1,375 km^2 and is tentatively dated to the last interglacial (English et al., 2001). Erosion of the northern flank of the Tjoritja West MacDonnell Ranges during the Miocene to Pleistocene constructed alluvial fans ∼100 m thick in the south of the Lewis basin. The western drainage divide of the Lewis basin is an ill-defined sill (∼570 masl) within an east-west axial depression connecting with the Mt Wedge basin (Figure 1a), which contains fluvio-lacustrine sediments drilled to a depth of ∼474 m (Woodgate et al., 2012). We focus on the evolution of the Lake Lewis basin because of its combination of thick basin fill, extreme negative gravity anomaly along its southern drainage divide, and the postulated capture of part of the Finke catchment by the Lewis during some unknown past interval (P. M. English, 2001) (Figure 1a).

4. Methods

4.1. Topographic Analyses

We apply two topographic indices to understand drainage network responses to low-amplitude surface deflections. The χ index yields an approximation of the steady-state shape of the river profile (Perron & Royden, 2013), a property that enables an evaluation of the stability of river catchments and their drainage divides (e.g., Hu et al., 2021; Scherler & Schwanghart, 2020; Willett et al., 2014) (Equation 3 in Supporting Information S1). As generally applied, differences in χ measured across a drainage divide indicate instability: lower χ in the headwaters of one river relative to its neighbor suggests those headwaters are expanding and gaining drainage area—and vice versa for a higher χ value. Inherent to most applications of χ is the assumption that drainage networks share the same base level, although a correction can be applied to account for base-level differences (Giachetta & Willett, 2018; Supporting Information S1). Focusing on the Lewis basin drainage divide and the adjoining headwaters of three rivers (the Finke, Todd and Hale), we calculate two sets of χ maps, each imposing different base level conditions: first, the present-day endorheic condition of the Lewis basin where base level lies at 550 masl; and second, a past condition in which the Lewis basin is part of the Lake Eyre Basin, with its base level at sea level.

The normalized channel steepness index (k_{sn}) (Equation 5 in Supporting Information S1) is a measure of the local steepness of a river channel normalized by its drainage area. In the presence of uniform substrate erodibility, k_{sn} has been shown to be sensitive to changes in uplift (e.g., Snyder et al., 2000; Val et al., 2014; Wobus et al., 2006). Areas of profile steepening (i.e., elevated k_{sn}) may indicate knickzones propagating new base level information through the drainage network. The three rivers we examine (the Finke, Todd, and Hale) have their headwaters at the potentially unstable Lewis basin drainage divide (Figure 1).

The cause of drainage instability and, in turn, cross divide variations in χ and along-channel variations in k_{sn} are a matter of debate. For example, it has been argued that large-scale drainage reorganization may occur without any external forcing from tectonics or climate (e.g., Pelletier, 2004; Willett et al., 2014). Similarly, variations in k_{sn} can be driven by not only uplift, but also by lithologic variations and spatial variations in precipitation (e.g., Gabet, 2022). Here, we take account of those concerns and limitations while applying the two topographic indices to catchments in central Australia.

4.2. Landscape Evolution Modeling

Topographic indices are effective for identifying patterns of disequilibrium in the sediment source zone, but they offer little insight to the mechanisms and timescales of uplift and they ignore evolution of the basin sink. For a more complete source-to-sink investigation of landscape transience, we devise a set of experiments using models that simulate landscape response to changes in T_e in the presence of large gravity anomalies. Specifically, we set out to address: (a) How can observations of drainage capture be reconciled in terms of χ? And (b) can changes in river steepness and basin-filling be explained by transient uplift induced by time-varying T_e?

Our landscape evolution model (LEM) solves for erosion and deposition in response to uplift. The LEM incorporates transport-limited erosion and sedimentation based on the implicit finite-difference scheme of Yuan et al. (2019) as well as a mass-conservative algorithm that allows for infilling of closed basins with available water and sediment transport (Ruetenik et al., 2018). The LEM is coupled to a spectral flexure model that assumes an infinitely thin lithosphere and inviscid asthenosphere, solving for surface deflection in response to stresses from both vertical (e.g., erosion, deposition) and in-plane loading.

To establish the initial topography for the simulations, we run our LEM forward to attain a steady-state condition using parameters observed in central Australia today (e.g., precipitation and evaporation). Uplift is imposed by cyclic changes (of wavelength 80 Myr) in T_e (initially 10 km, cf. McKenzie & Fairhead, 1997) 10% in the presence of large embedded loads (following Jansen et al., 2022; Figure S3 in Supporting Information S1). We modify T_e linearly with time, which changes the flexural response, resulting in surface deflection. For a full description of the landscape evolution parameters, see Supporting Information S1.

5. Results

5.1. River Profile Analysis

Recall that all three rivers, the Finke, Todd and Hale, have their headwaters located at the Lewis basin drainage divide, a zone of strongly negative gravity anomaly (Figure 1b). At the catchment scale, each of the river long profiles show an inverse correlation with gravity (Figure S1 in Supporting Information S1). Furthermore, in their headwater zones (Figures 2a–2c) each river displays a steepened reach broadly corresponding to peaks in the gravity anomaly at the sub-catchment scale.

5.2. χ Maps

The two sets of χ maps each impose a different base level condition: 550 masl (Figure 2d), and sea level (Figure 2e). Figure 2e shows conspicuous disequilibrium in the drainage network centred on the negative gravity anomaly and the Finke headwaters. More specifically, the high χ values marking the northern (Lewis) side of the drainage divide appear to shadow the negative gravity anomaly. Remarkably, both χ maps reveal strongly discordant χ values across the Lewis drainage divide, suggesting that the Lewis basin is losing drainage area to the Lake Eyre Basin (the Finke, Todd and Hale). In other words, the current configuration of the Lewis drainage divide is unstable, irrespective of assumed base level dynamics.

5.3. Numerical Simulations

During the initial 40 Myr of the model run, there is uplift around the negative loads (Figure 3b), while subsidence and deposition occurs around positive loads (Figure 3f). As the cumulative uplift and subsidence is maximized (by 40 Myr), the drainage network within the center of the landscape becomes isolated (endorheic), and a large lake is formed. By this time, a basin fill >100 m thick has accumulated, and transient lakes come and go sporadically around the center of the landscape.

Within each 40 Myr half-cycle, catchment boundaries migrate outward from the center of subsidence, taking a large proportion of drainage area away from the uplifting side of the model space. Now the direction of drainage capture is reversed from that shown in the χ maps (Figures 2d and 2e): the endorheic drainage network is capturing the adjoining drainage areas due to the steepening associated with subsidence. Changes in the flexural wavelength associated with a 10% change in T_e are ~3%, corresponding to a 5 km change in basin width, and thus would not play a significant role in modifying drainage areas.

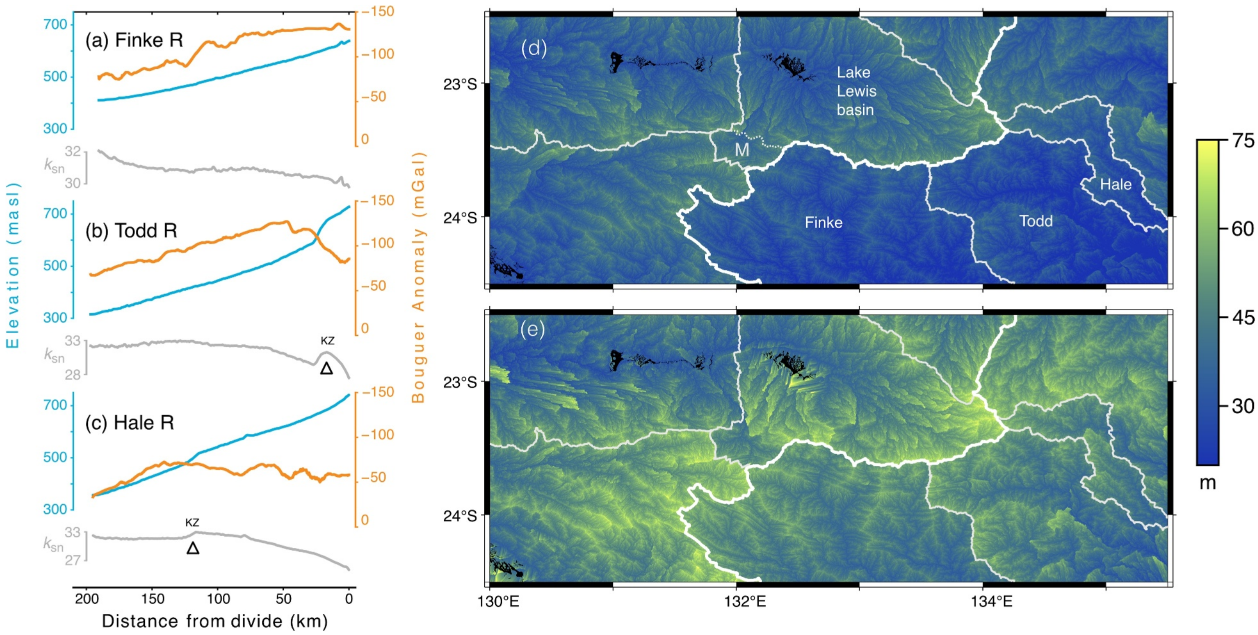

Figure 2. (a, b, c) Headwater reaches (upper 200 km) of three major rivers within the Lake Eyre Basin. Plots show longitudinal patterns in channel-bed elevation (blue), gravity anomaly (orange), normalized channel steepness, ksn (gray), and knickzones (KZ, triangle). River profiles are smoothed via a 1 km moving-window. The drainage divide at the head of the Finke and Todd follows the trace of the Redbank Thrust Zone, and the KZ in the upper Todd corresponds to advected topography associated with the suite of thrust sheets. Similar steepening does not occur on the Finke because its headwaters run along strike. The KZ on the Hale River corresponds to the highly resistant silicified sandstones of the Heavitree Formation. (d) χ map calculated according to the present-day endorheic condition of the Lake Lewis basin in which base level lies at 550 masl, following the method of Giachetta and Willett (2018). (e) χ map calculated according to a past condition in which the Lake Lewis basin is part of the Lake Eyre Basin, with base level at sea level. Both maps show strong cross-divide disequilibrium along the drainage divide. A potential drainage capture of the upper Finke into the Lewis basin (P. M. English, 2001) is denoted "M."

Although catchment drainage areas wax and wane with each 80 Myr uplift cycle, persistent changes (i.e., >80 Myr) in the drainage network can be identified. Most notably, rivers change their course in their headwaters such that they are orthogonal to their original direction (Figure 3c).

The evolution of topography and the "model river" are shown in planform (Figures 3h and 3i). When T_e is reduced, the headwaters are predominantly incisional (Figure 3h). Some of the basin-fill that accumulated during periods of subsidence is exhumed during the uplift phases. However, a remnant of the older basin-fill is locally preserved (Figure 3g). Increased T_e leads to accumulation of sedimentary fills within rivers, up to 30 m thick (Figure 3i).

6. Discussion

The idea that drainage networks in central Australia are influenced by the gravity field was first raised by Beekman et al. (1997) who argue that the associated in-plane far field compression produces "a stress-amplified downward flexure of the depocenter of the initially formed surface depression" (p. 223). Subsidence is observed in the Lake Lewis and Mt Wedge sedimentary basins (Figure 1a), the latter of which hosts a basin sequence ~500 m thick (Woodgate et al., 2012). We corroborate the observations of Beekman et al. (1997), while also introducing a transient component in the behavior of the lithosphere linked to variations in T_e.

6.1. Instability of Drainage Divides

The transient behavior we observe is manifest in the presence of numerous small endorheic basins flanking the Lake Eyre Basin. Such endorheic basins are unexpected given that cratonic continental interiors are sometimes noted for their more-or-less topographic steady-state due to slow denudation and tectonic quiescence (Bierman & Caffee, 2002). This is clearly not the case in central Australia. Endorheic basins may be relatively short-lived in the absence of tectonic forcing (Braun & Willett, 2013; Garcia-Castellanos et al., 2003), but they are nevertheless

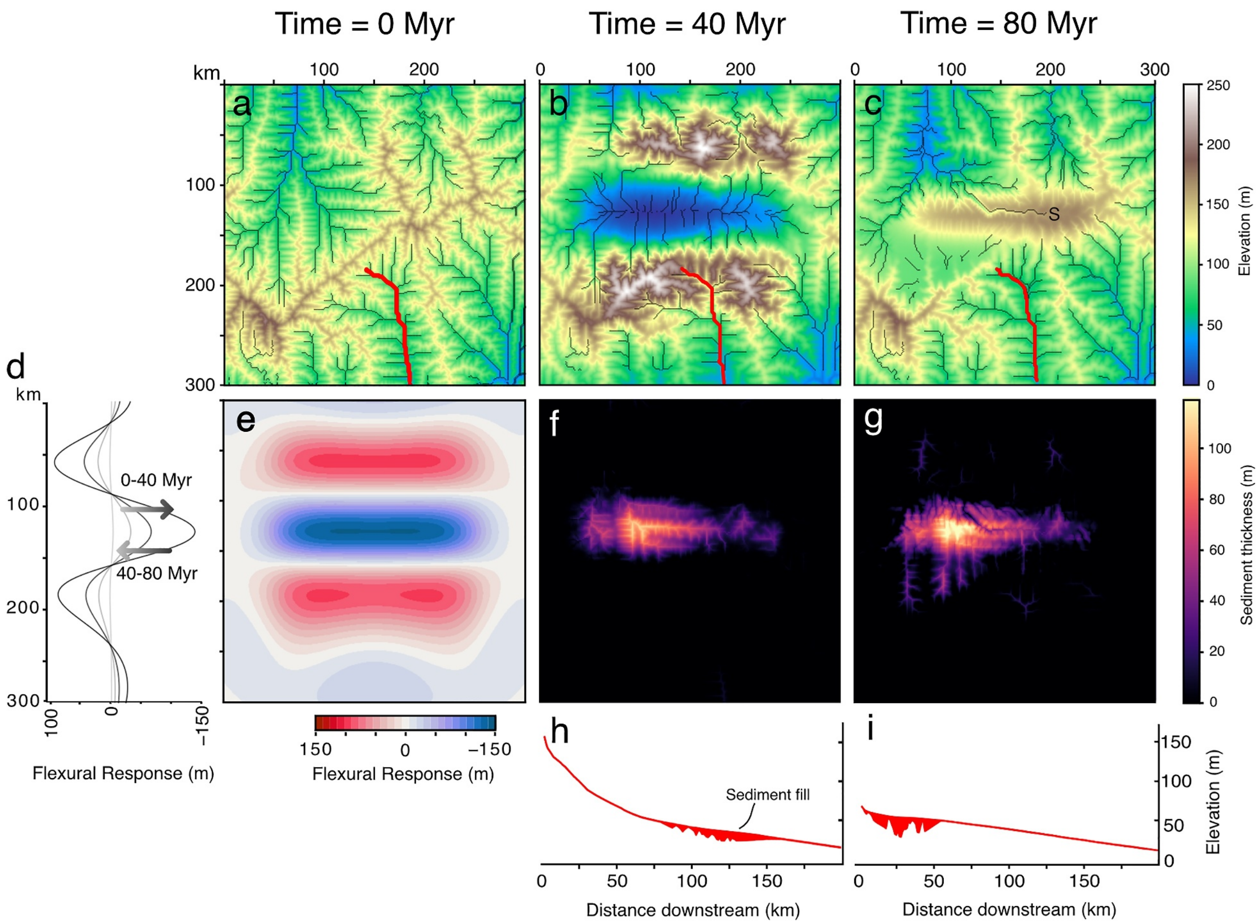

Figure 3. Model results: 0–80 Myr. (a) Initial steady-state topography. (b) After 40 Myr. (c) After 80 Myr; note the strike valley "S." (d) The time-varying load response through a swath at $x = 150$ km (using same y-scale as panels to the right). (e) Total uplift response to changes in T_e at 40 Myr, where the center of the model domain has subsided and the upper/lower edges have uplifted. (f) and (g) Modeled sediment thickness. (h) and (i) River long profiles, including sediment fill. Note the formation of the endorheic basin (panels b, c) at 40 Myr, which corresponds to the present-day Lake Lewis basin.

a compelling sign of low-amplitude surface deflections developed over wavelengths (~10^2 km) likely too short to be attributed to dynamic topography (e.g., Braun, 2010, Figure 2).

A key component of landscape transience is drainage capture, which is often attributed to shifts in fluvial base level (Ruetenik et al., 2018; Scherler & Schwanghart, 2020; Struth et al., 2021). However, in the headwaters adjoining the Lewis basin drainage divide, drainage capture is driven by the sharp gradient in surface uplift. We postulate that the steepness of the gradient in the gravity field governs the magnitude and wavelength of the resultant surface uplift in response to changes in T_e. And yet there is little evidence of this perturbation in the three rivers we study, which show remarkably uniform k_{sn} in their headwaters (Figures 2a, 2b and 2c). Only in the Todd River (Figure 2b) do we identify a response to headwater steepening associated with the underlying gravity anomaly and the Redbank Thrust Zone (Figure 1). Similar steepening does not occur on the Finke because its headwaters run along strike. Substrate erodibility also influences k_{sn}, as seen in the knickzone developed along the Hale River where it cuts the highly resistant silicified sandstones of the Heavitree Formation (Figure 2c).

The consistency in the cross-divide χ trend shown in both our maps (Figures 2d and 2e) strongly indicates that the instability at the Lewis basin divide is caused by a mechanism that is independent of base level. However, pressing questions then arise: Is the Lewis basin growing or shrinking? And if the Lewis basin is set to lose drainage area irrespective of whether it remains internally-drained (and perched >500 masl), or is connected to sea level, how does the basin persist under its current configuration? Our numerical simulations provide insights into the waxing-waning cycle of the Lewis basin.

P. M. English (2001) postulates that the Lewis basin has captured a portion (~1,085 km^2) of the Finke headwaters (Figures 2d and 2e) and therefore has expanded at some stage. In the context of our simulations, this would suggest that the stress field in central Australia is increasing while T_e is reduced (Sandiford & Quigley, 2009). However, such reasoning is at odds with the cross-divide χ trend noted above which, in turn, highlights a well-known limitation of χ analysis. Because χ values are calculated based on present-day topography, χ maps are strictly a reflection of basin behavior in the absence of spatial variations in uplift (Willett et al., 2014). Only by combining χ analysis with landscape evolution modeling can we ensure a reliable picture of drainage divide evolution (Scherler & Schwanghart, 2020). In our numerical experiments, when T_e is reduced (or in situ stress increases) and basin subsidence occurs, the basin grows as its inner edges are steepened relative to the exterior (Figure 3b). As noted above, this is counter to what our χ maps suggest. Only when subsidence stops and in-plane stresses are reduced, do we observe a net loss of drainage area as indicated by the "present-day" χ values. Hence, we agree with P. M. English (2001), the Lewis basin is gaining drainage area, and we attribute its growth to an increase in the regional stress field consistent with a cyclical stress history of the type introduced previously (Jansen et al., 2022).

6.2. Elastic Thickness and the Stress Field

The numerical simulations reproduce the widespread unconformity observed in the Lake Lewis and Mt Wedge basins (Figure S4 in Supporting Information S1). And moreover, they demonstrate that the overprinting cycles of incision, aggradation and re-incision observed in the Finke Gorge (Jansen et al., 2022) can be explained by small changes in regional surface slope linked to variations in an initially low T_e under sediment transport-limited conditions. However, these observations cannot be reproduced with high T_e values (~100 km) that are classically thought to dominate in continental interiors such as central Australia (e.g., Swain & Kirby, 2006), where surface deflection associated with 10%–20% variations in T_e would be minimal. Our results therefore support recent studies which suggest that T_e may more likely be in the range of 10–30 km in central Australia (Jackson & McKenzie, 2022; McKenzie & Fairhead, 1997).

The present-day condition within the Finke is predominantly incisional, which further supports the idea that topography is steepening and stresses within the lithosphere are increasing. As well as causing drainage diversion (Figure S2 in Supporting Information S1), subtle shifts in regional slope driven by the flexural response to changing T_e may also give rise to the modest k_{sn} variations that are correlated with gravity in our analysis (Figure 1b). The negative gravity anomaly in the headwaters of the Finke, Todd, and Hale rivers drives channel steepening. Conversely, if stresses were decreasing and T_e was increasing, we would expect positive gravity to be associated with lower k_{sn}.

When it comes to identifying the mechanisms driving long-term fluctuations of in-situ stress and lithospheric rigidity we are hesitant to over-speculate. But we can surmise that plate velocity is likely pivotal, as plate motion governs tractive forces acting on the base of the lithosphere together with far-field stress sourced at the plate boundaries (Jansen et al., 2022). The initiation of subduction to the north triggered abrupt acceleration of the Indo-Australian plate during the middle Eocene, ~44 Ma, with velocity fluctuations (from <10 to 80 mm yr^{-1}) continuing into the early Miocene, ~20 Ma, when the plate settled into a constant ~60 mm yr^{-1} (Schellart & Spakman, 2015).

Given this understanding and this timeframe, the geomorphic record in central Australia may be instructive for the tectonic history of the continent. The advent of low-amplitude surface deflections most likely led to drainage system fragmentation, potentially causing the termination of the widely distributed fluvial Eyre Formation (Wopfner, 1974) in the late Eocene (Callen, 2020). Gentle folding of the silcrete duricrust developed in the Eyre Formation (and elsewhere) now directs much of the present-day drainage in the Lake Eyre Basin (Jansen et al., 2013; Taylor & Eggleton, 2017; Wopfner, 1978). This folding is widely attributed to the Oligocene to early Miocene (Krieg et al., 1990; Wopfner, 1974), matching the interval of widely fluctuating plate velocity noted above.

The broader geomorphic implications of an uplift mechanism linked to time-varying T_e are yet to be fully explored. But it is clear that the gravity field in central Australia—a legacy of the Alice Springs orogeny in the Paleozoic—fundamentally defines the Lake Eyre Basin's western margin (Figure 1). While the Lake Amadeus basin is currently excised, cyclical tilting motions bringing the basin in and out of connection with the Finke catchment are easy to envisage. Further to the west (in Western Australia), the fragmentation of drainage networks is attributed to increasing aridity and base level lowering (e.g., Brocard et al., 2018; De Brockaert & Sandiford, 2005; Van de Graaff et al., 1977). The notion of drainage perturbation driven by time-varying T_e may be worth investigating wherever flat continental interiors coincide with extreme gravity clusters; for instance, the São Francisco river basin in Brazil, and India's Deccan Plateau.

7. Conclusions

We have used numerical simulations to test the feasibility of surface uplift driven by changes in T_e coupled with large, embedded lithospheric loads. Our modeling results reconcile observations of anomalous drainage patterns in central Australia, including instabilities in the drainage network and drainage divide as predicted by mapping χ and k_{sn} (less so). These results give credence to the idea that the lithosphere beneath central Australia is responding transiently to embedded stresses. Despite its slow rate of denudation (5 ± 2 m My^{-1}), central Australia is far from topographic steady-state and continues to adjust dynamically, albeit with a slow tempo.

Small changes in T_e are sufficient to transform the landscapes of continental interiors where long-wavelength topographic relief is in the order of a few hundred meters. We propose that, in addition to other well-known candidates (e.g., crustal thickening, far-field deformation, denudational isostasy, and dynamic topography), anomalies in the gravity field should be considered as a potential driver of endorheism, drainage capture, and reversal in continental interiors.

Data Availability Statement

The landscape evolution model is from Ruetenik et al. (2018); χ and k_{sn} were calculated using flow routing data from Hydrosheds (Lehner et al., 2008).

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