

Decoding the drivers of 150 million years of dynamic sediment transfer from mountains to margins: insights from North America

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Supplementary Materials

PART 1

The supplementary materials contains all the U-Pb data for all the samples presented in this paper. Sample numbers, stratigraphic units and/or terrains and coordinates are also included in the repository.

The scientific software used in this study, Badlands, is available from <https://github.com/badlands-model/badlands> and the software documentation can be found at <https://badlands.readthedocs.io/en/latest/>. The PALEOMAP paleoelevation reconstruction and related GPlates rotation and geometry files are downloaded from <https://zenodo.org/records/5460860>

PART 2

This part of the supplementary materials contains the following sections and additional figures mentioned in the text:

- Drainage evolution of North America
- Detrital zircon data: sample locations, kernel density estimates (KDEs), and maximum depositional ages
- Badlands constitutive equations
- Additional figures illustrating numerical modelling results

Drainage evolution of North America

Research over the last three decades has identified a number of ancient trans-continental river systems that dominated landscape evolution and sediment routing in North America at different times in the past. Early work^{1,2} used small numbers of detrital zircon (DZ) U-Pb geochronological analyses to document that trans-continental west-to-east transfer of zircon grains from the Grenville orogeny had taken place in the Mesoproterozoic, and following the development of the Appalachian-Ouachita-Marathon orogeny in the Early Mesozoic (Late Triassic). These studies were supported by isotopic data³, which showed detritus from the Appalachians overwhelmed sediment derived from older sources over large areas of western North America by ca. 450 Ma. More detailed DZ U-Pb data from the Grand Canyon in Arizona⁴ and the Big Horn Basin in Wyoming⁵, reinforced early studies and showed that development of the Appalachian Cordillera resulted in widespread mass transfer of sediment from the eastern United States and southeastern Canada to the Western Laurentian passive margin during the Late Paleozoic and earliest Mesozoic^{6, 7, 8}.

The Mesozoic development of the Western Cordillera retroarc foreland-basin system included a magmatic arc, an orogenic plateau, and the Sevier fold-and-thrust belt, which extended >2000 km in the north-south direction. Elevation of the Western Cordillera resulted in erosion of the newly uplifted Laurentian margin, and reversal of sediment transport directions during the Jurassic to and through the Sevier foreland basin: pre-Jurassic strata of the Laurentian margin now represented the source for newly developed and generally eastward-flowing river systems. This large-scale reversal in sediment transport played an important role in filling multiple basins in Late Mesozoic and Cenozoic North America, including the Sevier foreland basin of the US and Canada, the Boreal Sea and Arctic Ocean in northern Canada, the North Sagilek Basin of offshore eastern Canada, and the US Gulf of Mexico (GOM).

The Aptian McMurray Arctic Boreal Sea System

The first large-scale drainage organization of fluvial systems after the Jurassic reversal of transport directions is best represented in the Sevier foreland basin of the US and Canada by the Lower Cretaceous (Aptian) McMurray Formation in Alberta, and coeval fluvial sandstones in the US midcontinent and Rocky Mountains. A large DZ U-Pb dataset shows the McMurray axial river in western Saskatchewan and east-central Alberta had headwaters in the SW to SE United States, with a west- and east-derived tributary network that converged in the US

midcontinent and then flowed north as an axial river system to the Arctic Boreal Sea^{9, 10, 11}. The McMurray drainage basin also extended to the east in Canada, where a major tributary system transported sediment to the axial system in Alberta.

Analyses of DZ U-Pb age groups from the McMurray Formation indicate that erosion of the Sevier fold-and-thrust belt in the SW US contributed ~60% of the DZ U-Pb signature for the axial McMurray river system. This contribution is dominated by recycled Appalachian-Grenville grains (ca. 275-1200 Ma) that were previously stored in, then eroded from, the Western Laurentian margin. This recycled Appalachian-Grenville signal was diluted by a variety of provincial sources from the western US, including zircon grains derived from the Paleoproterozoic Yavapai-Mazatzal province (ca. 1600-1800 Ma), outcrops of Mesoproterozoic anorogenic granites (ca. 1300-1500 Ma), and the Late Mesozoic Western Cordillera magmatic arc (ca. 250-100 Ma). The remaining 40% of the DZ U-Pb signature for the McMurray axial system came from the Appalachian cordillera and/or foreland basin in the SE US, and is dominated by the classic Appalachian signature (Allred ¹²et al., 2023), which can be more than 85% Appalachian-Grenville grains. This axial McMurray River then merges farther to the north with a large east-derived tributary, which is dominated by DZ U-Pb ages from the Paleoproterozoic Trans-Hudson orogen (ca. 1800-2000 Ma): the axial and east-derived McMurray each provide ~50% of the final DZ U-Pb age distribution that characterizes the McMurray system.

At its zenith, the Early Cretaceous McMurray Boreal Sea system drained a large majority of the US and Canada, ($>6 \times 10^6$ km², Fig. 2). Contemporaneous Early Cretaceous drainage to the GoM was limited to relatively small south-flowing rivers that originated in the Appalachians and generally flowed to the south^{9, 10}, and there were no contributions to the GoM from the western US or Canada. Moreover, the Late Cretaceous (Albian-Cenomanian) Western Interior Seaway extended from the GoM to the Boreal Sea, and segmented North America into two landmasses, which have been referred to as Laramidia to the west and Appalachia to the east.

Paleogene GoM River Systems

Withdrawal of the Western Interior Seaway in the Late Cretaceous and Paleocene resulted in the routing of river systems from southwest Canada and across much of the US to the GoM. This rerouting is manifested in deposition of the Wilcox Group of the GoM coastal plain, shelf, and deepwater basin. The Wilcox Group represents the first major Cenozoic clastic wedge in

the GoM, and is known from outcrop and subsurface studies in Texas, Louisiana, Mississippi, and Alabama to include fluvial, deltaic, shallow-marine, and deepwater facies^{13, 14, 15}. Biostratigraphic data indicate the onshore Wilcox Group of Texas is Paleocene to Early Eocene in age, deposited ca. 61-50 Ma^{16, 17}. Moreover, multiple Wilcox basin-floor fans are now recognized in the deepwater GoM^{18, 19}, and Wilcox deepwater deposits are known to extend >400 km into the GoM deepwater basin, and are typically >1000 m thick^{10, 20}.

Paleocene Wilcox fluvial sandstones were sampled from outcrops across the GoM coastal plain, from Alabama to south Texas, for DZ U-Pb analyses, and revealed a systematic change across the outcrop belt from Appalachian-dominated U-Pb signals in the east, to dominantly western sources in southcentral Texas, as follows:

- Wilcox samples from Alabama and Mississippi have an unambiguous primary “Appalachian signal” (sensu^{21, 12}), where Appalachian-Grenville ages (275-1200 Ma.) comprise up to 85% of the total population. This primary Appalachian signal has been interpreted to represent a Paleo-Tennessee River system that drained the southern Appalachians, discharged to the east-central GoM, and constructed a basin-floor fan in the eastern GoM.
- Clear differences in Wilcox DZ U-Pb signatures begin to emerge from east to west across the outcrop belt beginning in the northern Mississippi embayment of northcentral Mississippi and central Arkansas, which have been interpreted to represent the Paleo-Mississippi River. Up to 12% of the DZ U-Pb ages in the Mississippi embayment are <275 Ma, which can only be derived from the Mesozoic Cordilleran arc and the latest Cretaceous through Paleocene volcanic terrains of the western US, and there are increased Yavapai-Mazatzal contributions that are likely derived from the SW US. This Paleo-Mississippi River delivered sediment to what has been referred to as the Holly Springs depocenter, which underlies the Late Cenozoic Mississippi Delta system, and to a genetically linked deep-sea fan in the GoM.
- Continuing farther west and south along the outcrop belt, DZ U-Pb signatures have been interpreted to represent the Paleo-Colorado and Brazos Rivers. Contributions from the <275 Ma age group increase to ~35% and 45% in western Arkansas and eastern Texas, respectively, with 10-15% of grains yielding DZ U-Pb ages of Paleocene age. Although originally interpreted to be derived from the Colorado Mineral Belt or farther west in the western US, subsequent ϵ Hf analyses²² shows that a significant

proportion of Paleocene grains from east-central Texas were derived from the magmatic arc in southcentral British Columbia, some 4000 km to the NNW, and yielded Maximum Depositional Ages (MDAs) of ca. 61-59 Ma, consistent with independent age estimates for the Lower Wilcox Group. The Paleo-Colorado and Brazos Rivers delivered sediment to what has been referred to as the Rockdale depocenter in southcentral Texas and to associated deep-sea fans in the GoM.

- Finally, DZ signatures from lower Wilcox outcrops proximal to the present-day Rio Grande corridor in SW Texas²³ are statistically distinct from Wilcox samples farther north and east because they lack significant populations of latest Cretaceous and Paleocene DZ U-Pb ages and have early Cretaceous U-Pb ages that are uncommon for the US part of the Mesozoic arc. These U-Pb age groups signify a fluvial system in southernmost Texas and northern Mexico that drained the Mexican Cordillera, and are linked to fluvial systems whose headwaters contributed to Paleocene strata of the La Popa pull-apart basin in northern Mexico²³, to the Rio Grande embayment to what has been described as the Rosita depocenter of the western GoM^{15, 24} and to associated deep sea fans of the western GoM.

Paleogene to Oligocene Reductions in GoM Drainage Areas

At their zenith, Paleocene Wilcox river systems had headwaters in the Western Cordillera magmatic arc and the Sevier fold-and-thrust belt, which stretched from British Columbia to northern Mexico in western North America, and to the Appalachians of the eastern US. The estimated total contributing drainage area for the GoM basin is $\sim 5 \times 10^6$ km². However, by the Oligocene, the contributing drainage area for the GoM had been reduced in size by $\sim 50\%$ to a total area of $\sim 3 \times 10^6$ km² (Blum et al., 2017). The Oligocene clastic wedge of the GoM has been referred to as the Vicksburg-Frio system, which also contains fluvial, deltaic, shallow-marine, and deepwater facies. Early work by Winker²⁵ noted the importance of the Rio Grande embayment in terms of sediment flux, a view supported by Galloway²⁴ and Blum et al.,¹⁰ but the Houston and Mississippi embayment's and their associated depocenters remained important as well. Blum et al.¹⁰ further proposed that:

- By the Oligocene, the Paleo-Mississippi River had incorporated the Paleo-Tennessee River into its drainage network but had lost much of the northwestern drainage area that had contributed to the system during Paleocene Wilcox deposition. There appears to have been no connection between the Oligocene Paleo-Mississippi system, the central

Rockies, and the ash-rich Eocene to Oligocene fluvial deposits in eastern Wyoming and western Nebraska^{26, 27, 28}. Instead, Oligocene River systems in that area are interpreted to have flowed to the east and north from headwaters in the Sevier fold-and-thrust belt of western Wyoming²⁸ and not to the GoM.

- Eastern GoM drainage areas were reduced accordingly by the Paleo-Mississippi's capture of the Paleo-Tennessee system, and likely consisted of fluvial systems with headwaters in the southern Appalachians, much like the Apalachicola and Alabama Rivers of the present-day eastern GoM.
- Headwaters and drainage areas for the Paleo-Colorado and Brazos systems were greatly reduced in size as well, by perhaps 75% relative to the Paleocene Wilcox system, in response to tectonic beheading of the western part of the Wilcox system, and disruption of drainage areas due to development of eolian sand seas in western New Mexico and eastern Arizona.
- Even though headwaters and contributing areas had been greatly reduced since the Paleocene, Oligocene rivers routed sediment to the same sinks of the GoM coastal plain that were referred to as the Holly Springs, Rockdale (the Houston Delta²⁴), and Rosita (the Norias depocenter²⁴) active during Wilcox deposition. Fluvial deposits that fed the Houston and Norias deltas of the GoM have abundant DZ U-Pb ages that produced maximum depositional ages of ca. 25.6 to 36.8 Ma that indicate source terrain in the volcanic centers of during a period of high eruptive flux¹⁰.

Paleogene NE Atlantic Saglek Basin System

The contributing drainage area for the McMurray system was segmented by formation of the Western Interior Seaway in the Late Cretaceous, which stretched from the GoM to the Arctic Boreal Sea. However, previous workers have inferred a successor drainage basin that developed after withdrawal of the Western Interior Seaway in the Late Cretaceous. This system has been referred to in the literature as the Bell River^{29, 30, 31, 9} and its definition was originally based on limited data compared with the McMurray and Wilcox systems discussed above. In fact, the Bell River was little more than a set of observations over ~11 decades until the 2020s when (a) interpretation of modern industry seismic data acquired on the Newfoundland-Labrador shelf identified, described, and named the Churchill Deltaic depocenter, a shelf and shelf-margin delta system of Eocene to Miocene age that is ~8 km in thickness, and has been interpreted to be the Bell River sink³² and (b) cores from the Saglek Basin were sampled for

DZ U-Pb analyses, and show the signature of the Western Cordillera magmatic arc and other typical US-derived age groups (Appalachian-Grenville, Midcontinent anorogenic, and Yavapai-Mazatzal) are missing from samples of Cretaceous age, but are present in small proportions in overlying Eocene to Miocene deltaic sandstones^{33, 34, 35}.

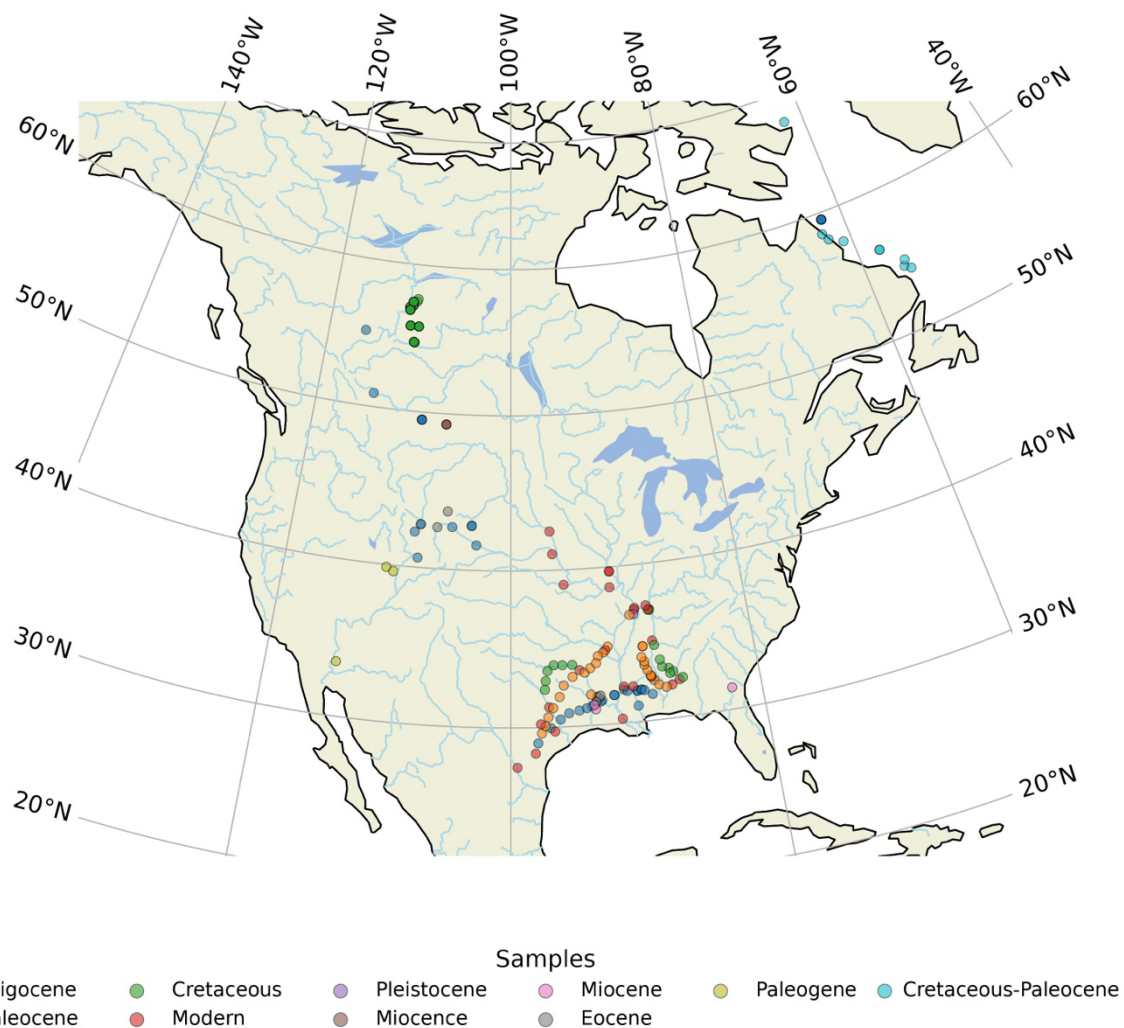


Figure S1. Locations of detrital zircon (DZ) samples used to constrain the timing of drainage reorganization and to provide benchmarks for evaluating model results. Sample IDs and locations are available in the supplementary data. Data is from ^{10,11,28,33,35-37}

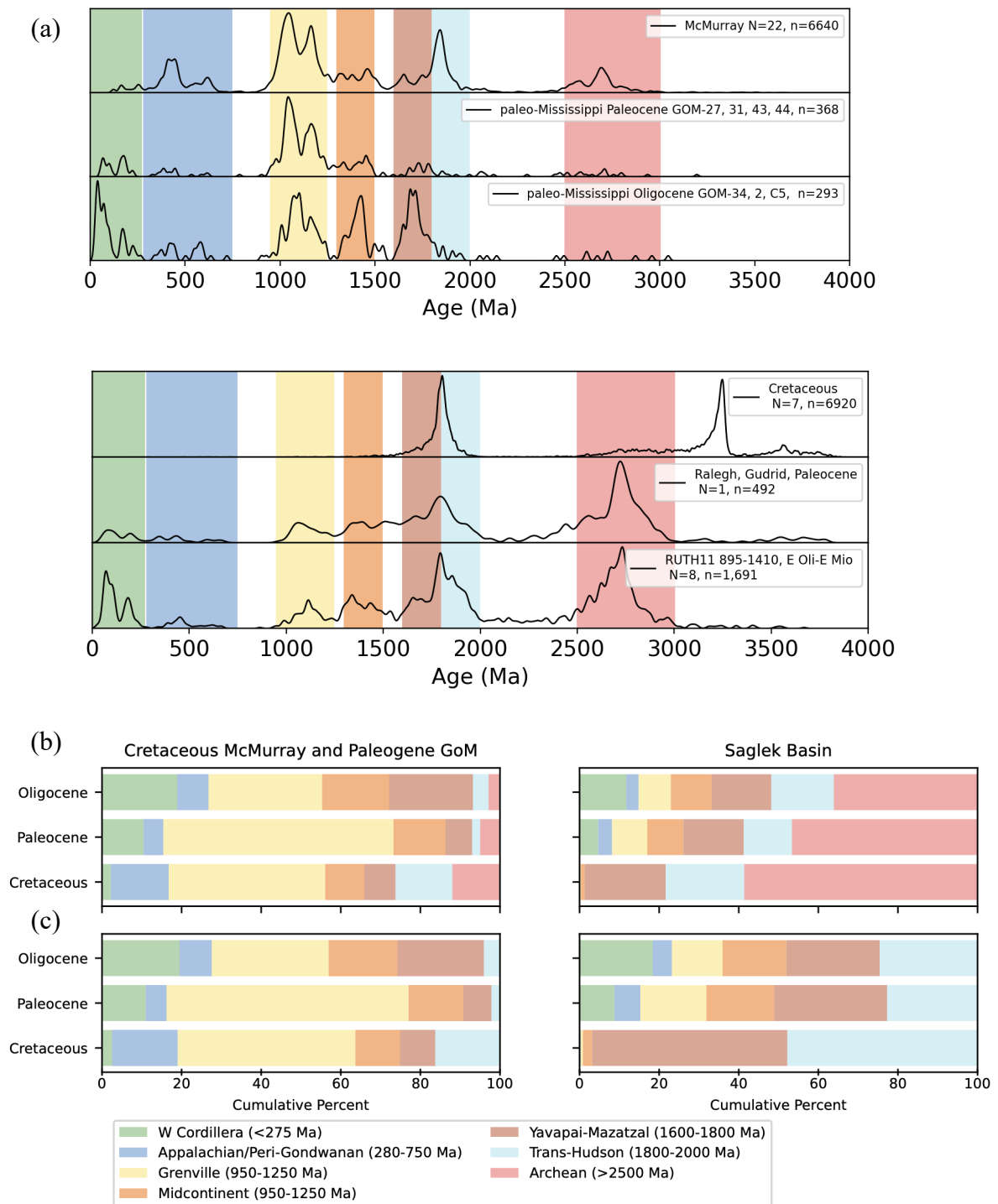


Figure S2 (a) Normalized kernel density estimate plots of detrital zircon age populations from fluvial deposits of the McMurray, paleo-Mississippi (top), and Saglek Basin (bottom); (b) comparison of the relative proportions of age groups shown in (a); and (c) the same comparison with the Archean population removed. Data is from ^{10,11,35}

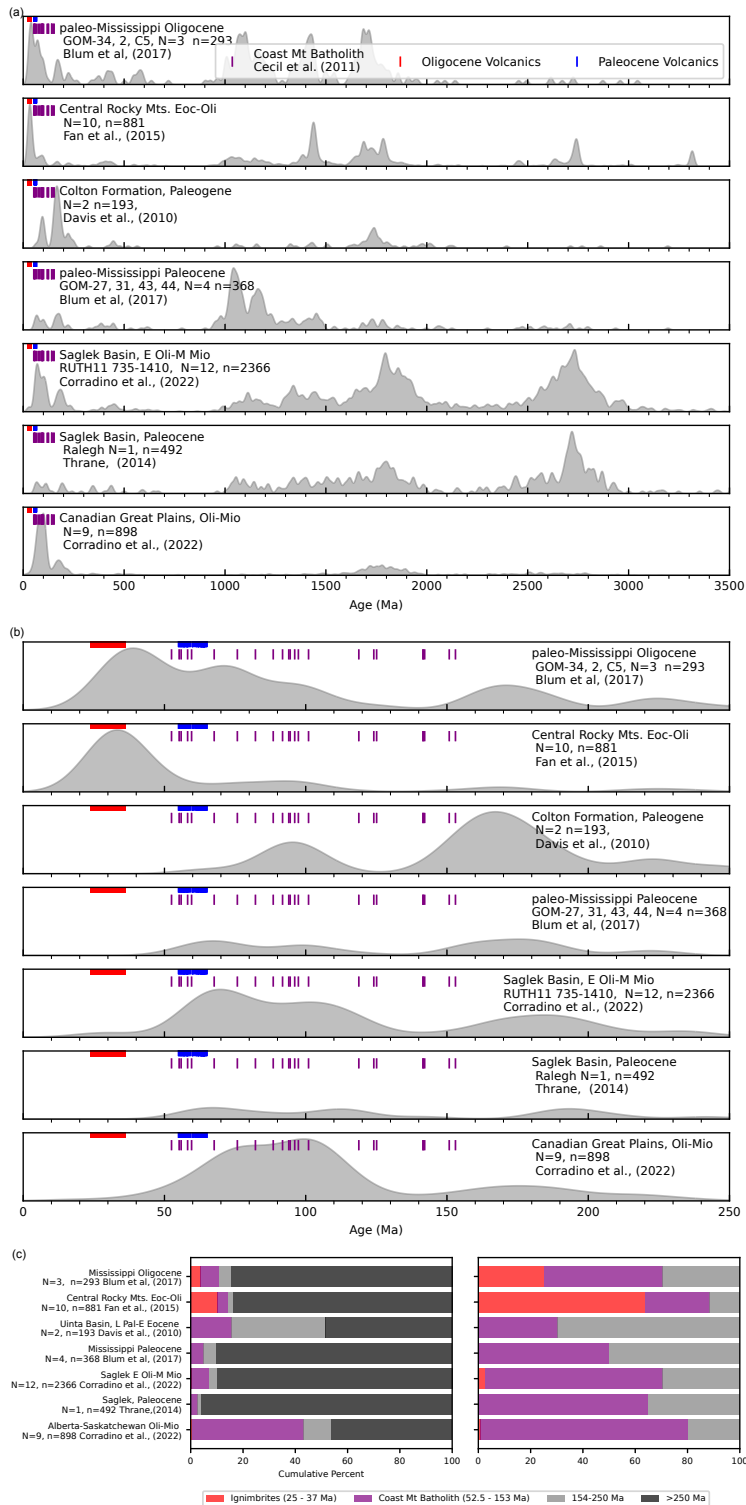


Figure S3. (a) Normalized kernel-density estimate plots of detrital-zircon age populations for fluvial deposits of the Paleo-Mississippi River system and the Central Rocky Mountains (Fan et al., 2015), the Colton Formation³⁷, the Saglek Basin, and Oligocene-Miocene deposits from the Alberta-Saskatchewan region³⁵. (b) Normalized kernel-density estimate plots of the detrital-zircon populations shown in (a), restricted to ages younger than 250 Ma. (c) Comparison of the relative proportions of three diagnostic age groups present in the fluvial deposits shown in (a) (left) and in the populations younger than 250 Ma (right).

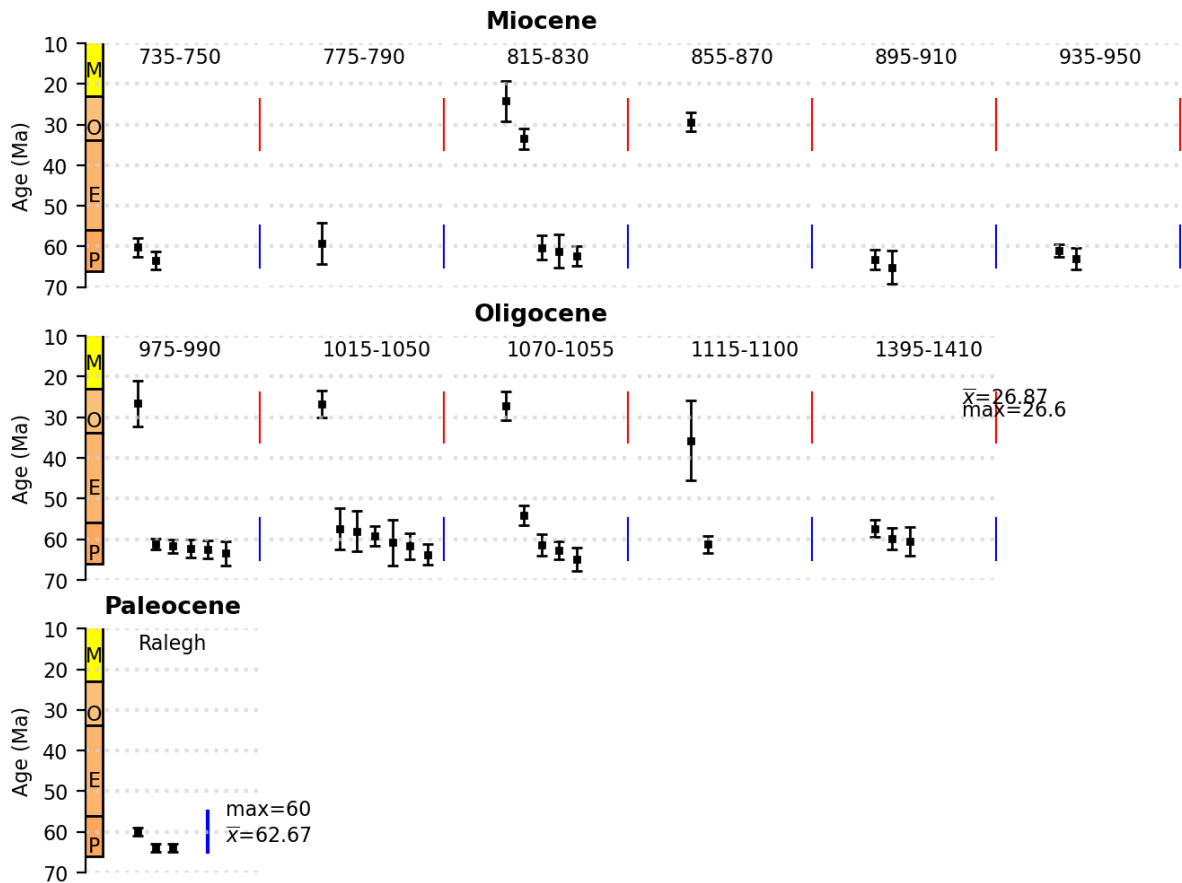


Figure S4. Maximum depositional ages for Oligocene to Miocene deposits of the Saglek Basin. Data is from Corradino et al.,³⁵. Vertical lines represent the age distribution of radiometrically dated felsic and intermediate volcanic rocks of early–middle Paleocene age to late Paleocene–earliest Eocene age (blue) and latest Eocene and Oligocene age (red) from the NAVDAT community database (<http://navdat.org>).

Forward modeling – Constitutive equations

Time-varying dynamic and tectonic vertical displacements are imposed on the evolving surface and subsequently passed to the landscape evolution model BADLANDS³⁸ to evaluate their influence on long-term paleogeographic development. BADLANDS simulates erosion, sediment transport, and deposition over continental spatial scales and multimillion-year timescales. To ensure computational efficiency, surface processes are calculated using simplified representations of fluvial incision and hillslope transport within sub-basins.

Surface elevation evolves according to mass conservation,

$$\frac{\partial z}{\partial t} = -\nabla \cdot q_s + u,$$

where z is bedrock elevation, u represents imposed tectonic and/or dynamic vertical motion (m yr^{-1}), and q_s is the depth-integrated sediment flux per unit width ($\text{m}^2 \text{yr}^{-1}$), incorporating contributions from both channelized flow (q_r) and hillslope diffusion (q_d).

Fluvial incision is described using a stream-power formulation,

$$-\nabla \cdot q_r = -\epsilon(PA)^m(\nabla z)^n,$$

where ϵ is a spatially and temporally uniform erodibility coefficient, reflecting the assumption of homogeneous substrate properties and no distinction between regolith and bedrock (Table 1). Net precipitation is denoted by P , A is drainage area, and the exponents $m = 0.5$ and $n = 1$ follow commonly adopted values in landscape evolution modeling.

Hillslope transport is represented by linear diffusion,

$$-\nabla \cdot q_d = -k\nabla^2 z,$$

where k is the diffusion coefficient. In the models presented here, k is set to $10^{-2} \text{m}^2 \text{yr}^{-1}$ in subaerial environments and increased to $5 \times 10^{-2} \text{m}^2 \text{yr}^{-1}$ in marine settings to approximate enhanced sediment reworking by waves and currents.

The model domain encompasses the North American continent over an area of approximately $8540 \times 5020 \text{ km}$ and is discretized using an unstructured triangular mesh with a mean resolution of $\sim 5 \text{ km}$. Initial large-scale paleotopography at 150 Ma is derived by modifying present-day relief following the approach of Salles et al. (2017). Predicted present-day dynamic topography is first removed from the ETOPO1 global elevation model (Amante and Eakins, 2009), after which dynamic topography predicted for 150 Ma is added,

$$z = z_{\text{ETOPO1}} - \text{Dyn}_{0\text{Ma}} + \text{Dyn}_{150\text{Ma}}$$

Temporal variations in dynamic topography are introduced incrementally at 1 Myr intervals by adding the difference between successive time steps to the evolving surface. In the absence of surface processes, this approach would recover present-day topography at 0 Ma.

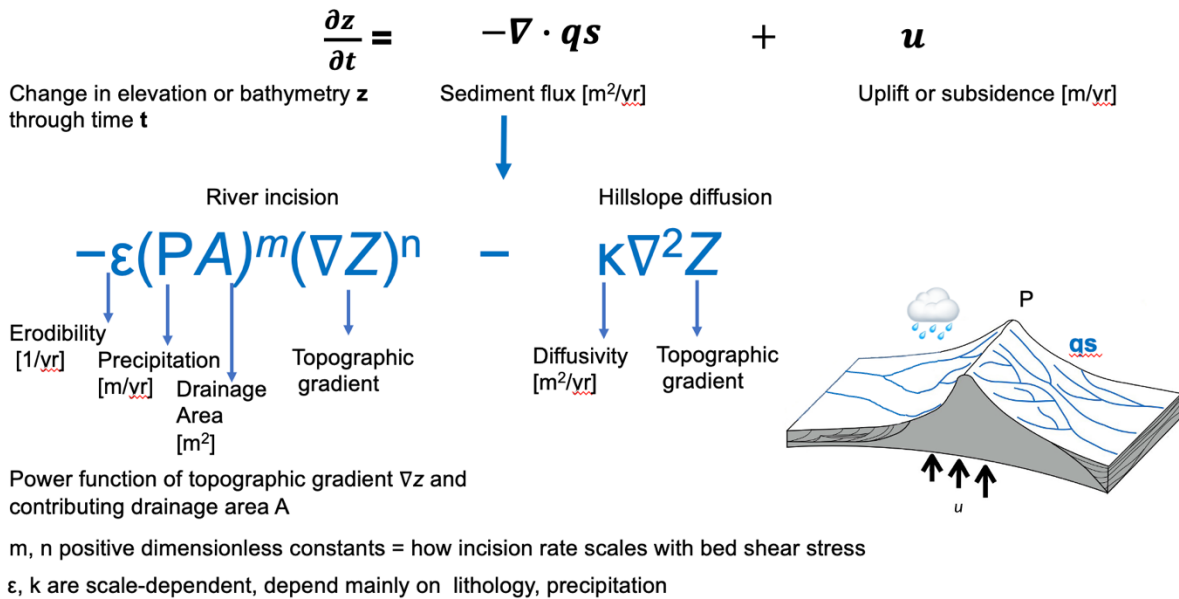
Sediment accumulated since 150 Ma is removed using published sediment thickness reconstructions for both ocean basins³⁹ and the North American continent⁴⁰. The mass of removed sediment is redistributed uniformly over non-depositional continental regions. Basement elevations are further adjusted through an isostatic correction⁴¹.

Because the magnitude and spatial pattern of Laramide uplift remain poorly constrained⁴², initial elevations within the Laramide province are limited to a maximum of 2 km. The removed relief is subsequently reintroduced progressively between 80 and 55 Ma^{42, 43}, producing a transition from dominantly depositional to erosional conditions between approximately 80 and 70 Ma.

Climate forcing is prescribed using a simplified precipitation framework that varies in space and time. Present-day precipitation fields from the NOAA/GFDL CM2.1 model⁴⁴ are used to define latitudinal precipitation gradients. Paleolatitudes derived from plate reconstructions⁴⁵ are then used to interpolate precipitation maps at 1 Myr intervals back to 150 Ma.

Elastic lithospheric flexure is modeled using the two-dimensional finite-difference code gFlex⁴⁶, coupled to BADLANDS. A bimodal elastic thickness structure is prescribed, with effective elastic thicknesses of ~20 km beneath the thermally weakened western Cordillera and increasing smoothly to ~80 km beneath the stable craton⁴⁷. Pore-pressure evolution and sediment compaction within the sedimentary column are calculated following⁴⁸ and compaction-driven adjustments are applied to both sediment thickness and surface elevation through time.

Constitutive equations



Flexural deformation

aFlex (Wickert, 2016)

Elastic bending of the lithosphere in response to loading and unloading

Flexural deflection of the Earth's surface

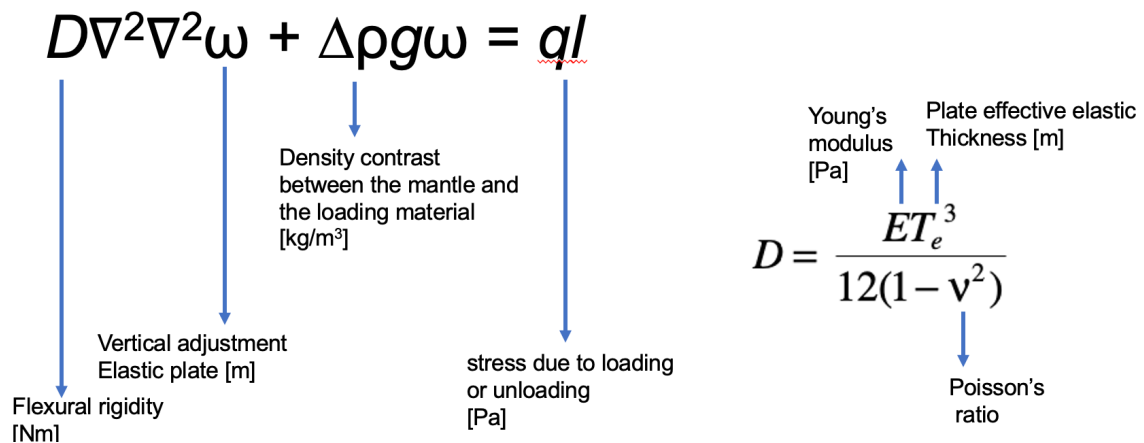


Figure S5 Top: Constitutive equations used in BADLANDS³⁸. BADLANDS complete documentation and code are available online at <https://badlands.readthedocs.io/en/latest/> and <https://github.com/badlands-model>

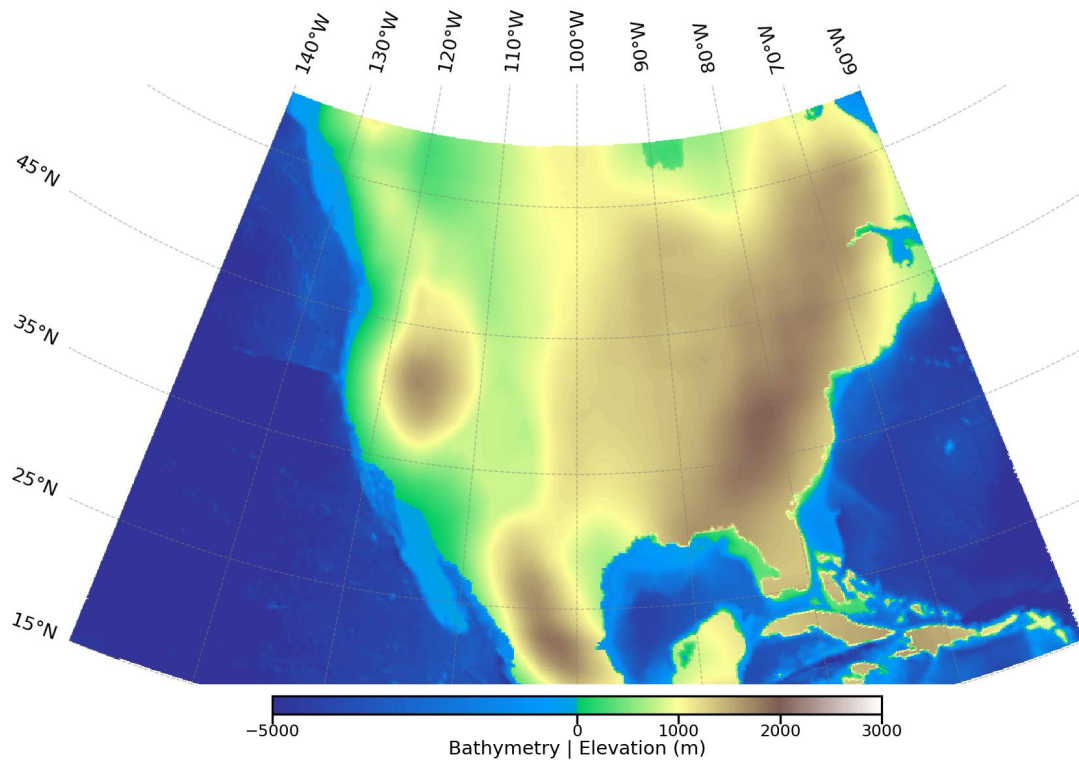


Figure S6. The model is initialized from present-day topography, modified to approximate large-scale paleotopography at 150 Ma following Wang et al. (2020). Present-day dynamic topography is removed and replaced with predicted dynamic topography at 150 Ma derived from mantle convection models. This reconstruction establishes a physically consistent starting surface that provides a first-order representation of continental-scale topographic elevation.

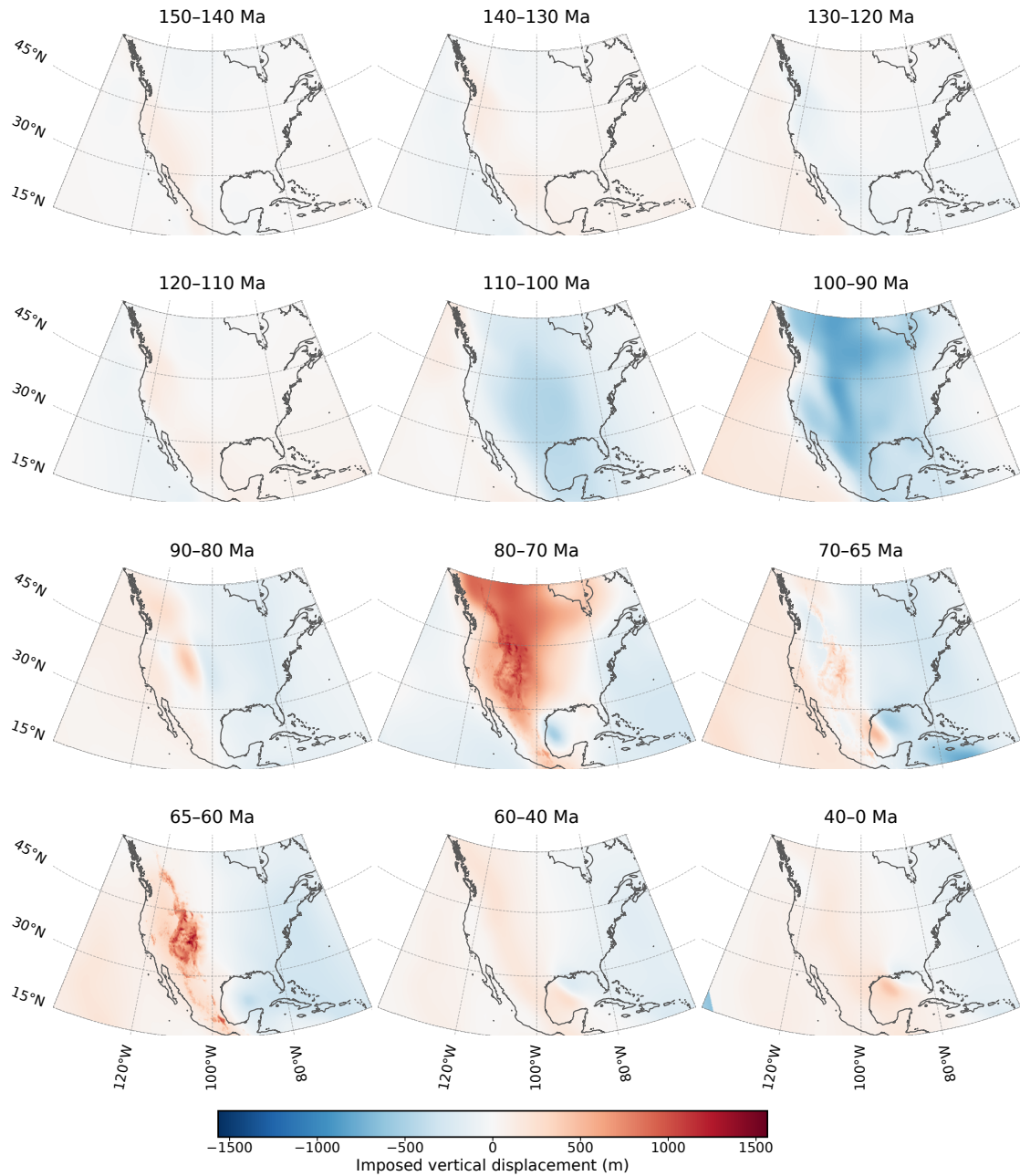


Figure S7. Vertical displacements imposed in the model to represent tectonic and geodynamic forcing. The prescribed displacements account for (i) surface deformation associated with the sinking of the Farallon plate, (ii) uplift of the Laramide orogenic province, and (iii) subsidence in the GoM resulting from the transformation of an oceanic plateau within the Farallon slab.

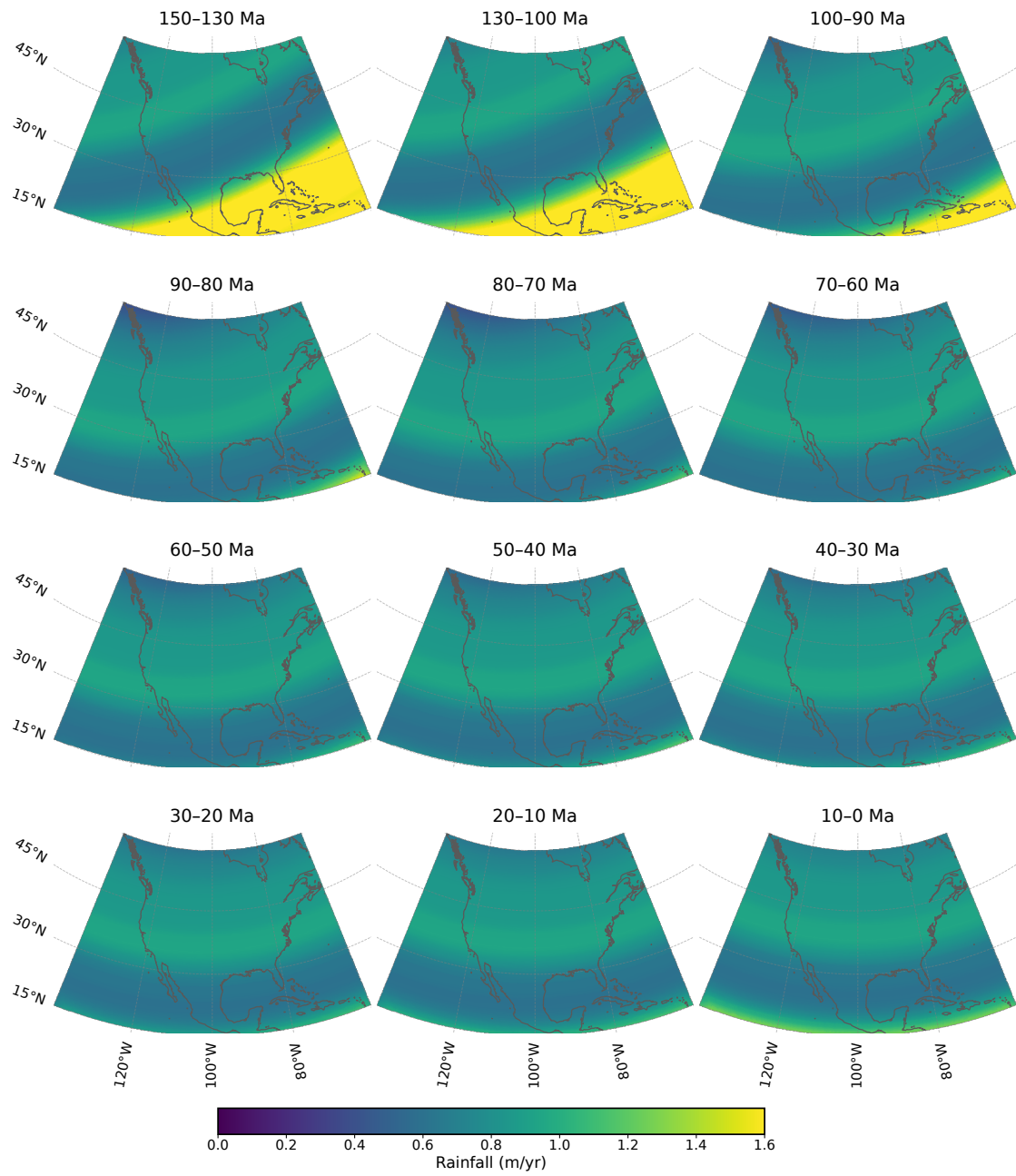


Figure S8. Rainfall magnitude imposed in the model to represent climatic forcing.

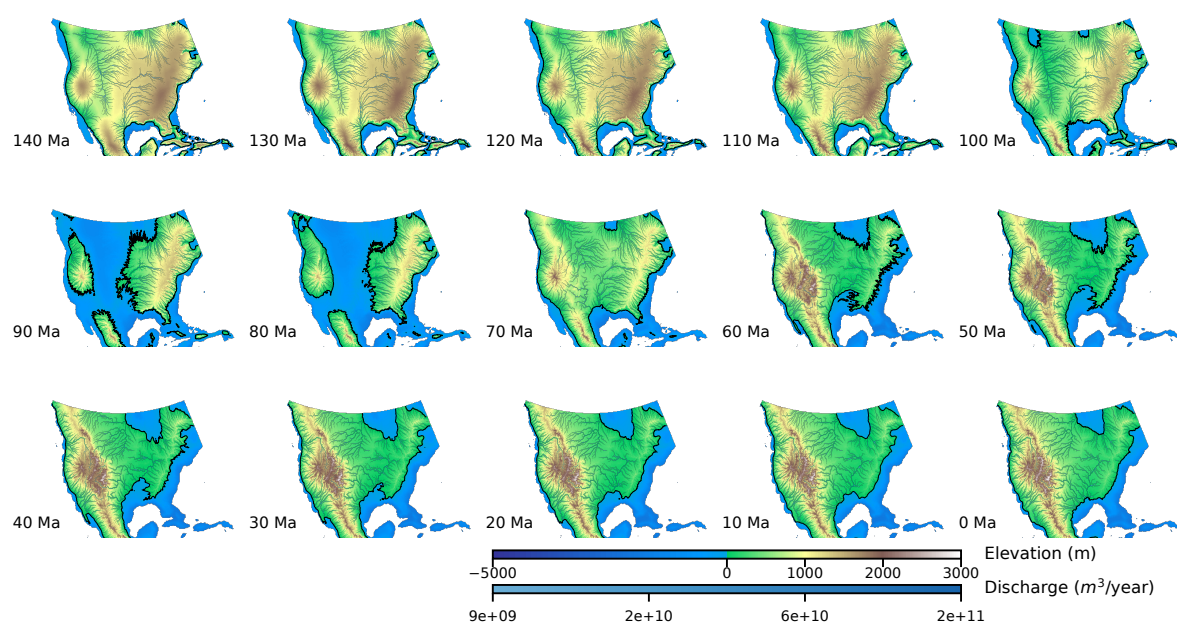


Figure S9. Modeled temporal evolution of topography and drainage networks

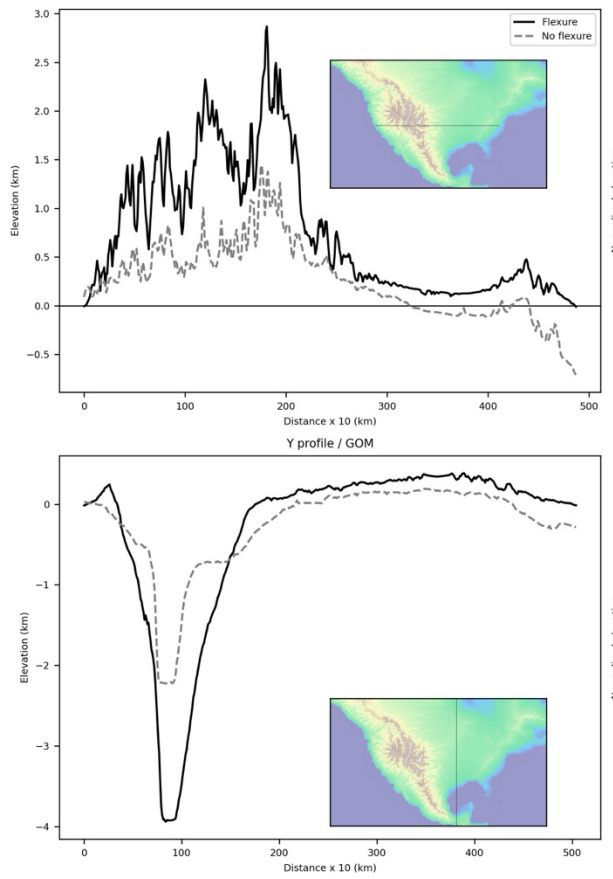


Figure S10. Comparison of topographic cross-sections from models with (solid) and without (dashed) flexural isostasy.

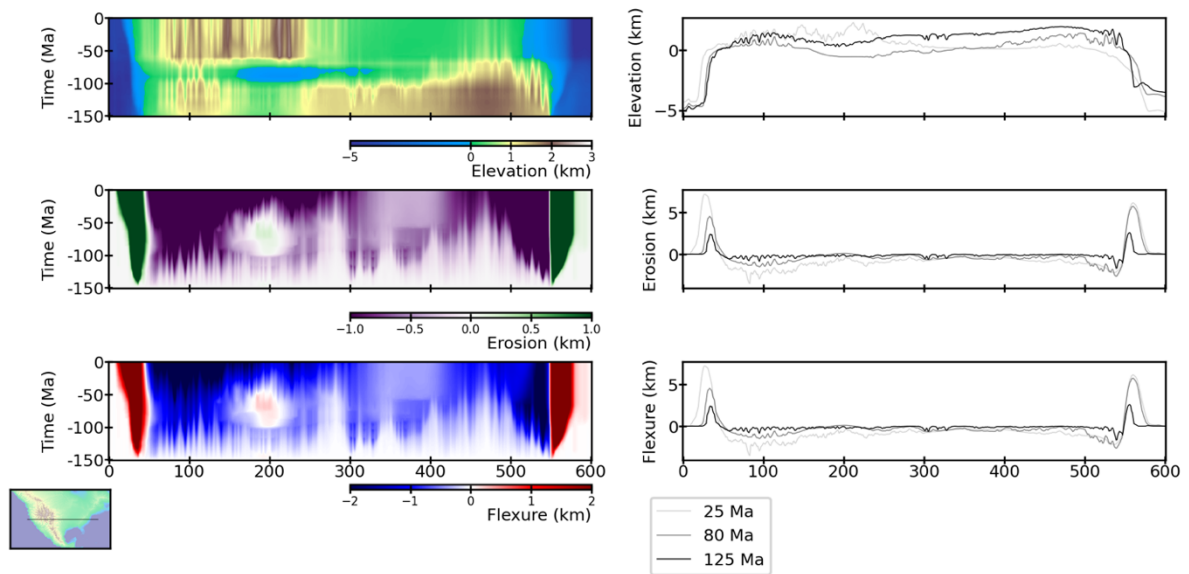


Figure S11 left: Vertical stack of a cross-section showing the temporal evolution of elevation, erosion and flexural deflection. Right: Cross-section at selected times showing elevation, erosion and flexural deflection.

- 1 Rainbird, R. H., Hearnan, L. M. & Young, G. Sampling Laurentia: Detrital zircon geochronology offers evidence for an extensive Neoproterozoic river system originating from the Grenville orogen. *Geology* **20**, 351-354 (1992). [https://doi.org/10.1130/0091-7613\(1992\)020<0351:Sldzgo>2.3.Co;2](https://doi.org/10.1130/0091-7613(1992)020<0351:Sldzgo>2.3.Co;2)
- 2 Riggs, N. R., Lehman, T. M., Gehrels, G. E. & Dickinson, W. R. Detrital Zircon Link Between Headwaters and Terminus of the Upper Triassic Chinle-Dockum Paleoriver System. *Science* **273**, 97-100 (1996). <https://doi.org/doi:10.1126/science.273.5271.97>
- 3 Patchett, P. J., Ross, G. M. & Gleason, J. D. Continental Drainage in North America During the Phanerozoic from Nd Isotopes. *Science* **283**, 671-673 (1999). <https://doi.org/doi:10.1126/science.283.5402.671>
- 4 Gehrels, G. E. *et al.* Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona. *Lithosphere* **3**, 183-200 (2011). <https://doi.org/10.1130/1121.1>
- 5 May, S. R. *et al.* Detrital zircon geochronology from the Bighorn Basin, Wyoming, USA: Implications for tectonostratigraphic evolution and paleogeography. *GSA Bulletin* **125**, 1403-1422 (2013). <https://doi.org/10.1130/b30824.1>
- 6 Laskowski, A. K., DeCelles, P. G. & Gehrels, G. E. Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America. *Tectonics* **32**, 1027-1048 (2013). <https://doi.org/https://doi.org/10.1002/tect.20065>
- 7 Dickinson, W. R. & Gehrels, G. E. U-Pb ages of detrital zircons from Permian and Jurassic eolian sandstones of the Colorado Plateau, USA: paleogeographic implications. *Sedimentary Geology* **163**, 29-66 (2003). [https://doi.org/https://doi.org/10.1016/S0037-0738\(03\)00158-1](https://doi.org/https://doi.org/10.1016/S0037-0738(03)00158-1)
- 8 Allred, I. J. & Blum, M. D. Early Pennsylvanian sediment routing to the Ouachita Basin (southeastern United States) and barriers to transcontinental sediment transport sourced from the Appalachian orogen based on detrital zircon U-Pb and Hf analysis. *Geosphere* **18**, 350-369 (2021). <https://doi.org/10.1130/ges02408.1>
- 9 Blum, M. & Pecha, M. Mid-Cretaceous to Paleocene North American drainage reorganization from detrital zircons. *Geology* **42**, 607-610 (2014). <https://doi.org/10.1130/g35513.1>
- 10 Blum, M. D. *et al.* Detrital-zircon records of Cenomanian, Paleocene, and Oligocene Gulf of Mexico drainage integration and sediment routing: Implications for scales of basin-floor fans. *Geosphere* **13**, 2169-2205 (2017). <https://doi.org/10.1130/ges01410.1>
- 11 Wahbi, A. M., Blum, M. D. & Doerger, C. N. Early Cretaceous continental-scale sediment routing, the McMurray Formation, Western Canada Sedimentary Basin, Alberta, Canada. *GSA Bulletin* **135**, 2088-2106 (2022). <https://doi.org/10.1130/B36412.1>
- 12 Allred, I. J., Blum, M. D., Frederick, B. C. & Wahbi, A. M. There and Back Again: Recycling of the Appalachian Signature in DZ U-Pb Records of Phanerozoic North America. *Lithosphere* **2023**, 8478638 (2023). <https://doi.org/10.2113/2023/8478638>
- 13 Fisher, W. L. & McGowen, J. H. Depositional Systems in Wilcox Group (Eocene) of Texas and Their Relation to Occurrence of Oil and Gas. *AAPG Bulletin* **53**, 30-54 (1969). <https://doi.org/10.1306/5d25c591-16c1-11d7-8645000102c1865d>
- 14 Galloway, W. E. Depositional systems of the lower Wilcox Group, north-central Gulf Coast Basin. *Gulf Coast Association of Geological Societies Transactions* **18**, 275-289 (1968).
- 15 Edwards, M. B. Upper Wilcox Rosita Delta System of South Texas: Growth-Faulted Shelf-Edge Deltas. *AAPG Bulletin* **65**, 54-73 (1981). <https://doi.org/10.1306/2f91976f-16ce-11d7-8645000102c1865d>

- 16 Crabaugh, J. P. *Nature and growth of nonmarine-to-marine clastic wedges: Examples from the Upper Cretaceous Iles Formation, Western Interior (Colorado) and the lower Paleogene Wilcox Group of the Gulf of Mexico Basin (Texas)* Laramie, University of Wyoming, (2001).
- 17 Brown, L. F., Jr., & Loucks, R. G. Chronostratigraphy of Cenozoic depositional sequences and systems tracts: A Wheeler chart of the northwest margin of the Gulf of Mexico Basin. 28 (University of Texas at Austin Bureau of Economic Geology 2009).
- 18 Meyer, D., Zarra, L. & Yun, J. From BAHA to Jack, Evolution of the Lower Tertiary Wilcox Trend in the Deepwater Gulf of Mexico. *The Sedimentary Record* **5**, 4-9 (2007).
- 19 Zarra, L. in *The Paleogene of the Gulf of Mexico and Caribbean Basins: Processes, Events and Petroleum Systems* Vol. 27 (eds Lorcan Kennan, James Pindell, & Norman C. Rosen) 0 (SEPM Society for Sedimentary Geology, 2007).
- 20 Snedden, J. W. *et al.* Validation of empirical source-to-sink scaling relationships in a continental-scale system: The Gulf of Mexico basin Cenozoic record. *Geosphere* **14**, 768-784 (2018). <https://doi.org/10.1130/ges01452.1>
- 21 Thomas, W. A. *et al.* Detrital zircons and sediment dispersal in the Appalachian foreland. *Geosphere* **13**, 2206-2230 (2017). <https://doi.org/10.1130/ges01525.1>
- 22 Pecha, M. E. *et al.* in *Tectonic Evolution of the Sevier-Laramide Hinterland, Thrust Belt, and Foreland, and Postorogenic Slab Rollback (180–20 Ma)* Vol. 555 0 (Geological Society of America, 2022).
- 23 Mackey, G. N., Horton, B. K. & Milliken, K. L. Provenance of the Paleocene–Eocene Wilcox Group, western Gulf of Mexico basin: Evidence for integrated drainage of the southern Laramide Rocky Mountains and Cordilleran arc. *GSA Bulletin* **124**, 1007-1024 (2012). <https://doi.org/10.1130/b30458.1>
- 24 Galloway, W. E., Whiteaker, T. L. & Ganey-Curry, P. History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin. *Geosphere* **7**, 938-973 (2011). <https://doi.org/10.1130/ges00647.1>
- 25 Winker, C. D. Cenozoic shelf margins, northwestern Gulf of Mexico. *Gulf Coast Association of Geological Societies Transactions* **32**, 427–448 (1982).
- 26 Swinehart, J. B., Souders, V. L., Degraw, H. M. & Diffendal, R. F., Jr. in *Cenozoic Paleogeography of West-Central United States* (eds R. M. Flores & S. S. Kaplan) 209-229 (SEPM (Society for Sedimentary Geology), 1985).
- 27 Larson, E. E. & Evanoff, E. in *Depositional Environments, Lithostratigraphy, and Biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America)* (eds Dennis O. Terry, Jr., Hannan E. LaGarry, & Robert M. Hunt) 0 (Geological Society of America, 1998).
- 28 Fan, M., Mankin, A. & Chamberlain, K. Provenance and Depositional Ages of Late Paleogene Fluvial Sedimentary Rocks In the Central Rocky Mountains, U.S.A. *Journal of Sedimentary Research* **85**, 1416-1430 (2015). <https://doi.org/10.2110/jsr.2015.87>
- 29 Bell, R. A great pre-glacial river in northern Canada. *Scottish Geographical Magazine* **11**, 368 (1895).
- 30 McMillan, J. N. Shelves of the Labrador Sea and Baffin Bay, Canada. **1**, 473-515 (1973).
- 31 Duk-Rodkin, A. & Hughes, O. L. Tertiary-quaternary drainage of the Pre-glacial Mackenzie basin. *Quaternary International* **22-23**, 221-241 (1994). [https://doi.org/https://doi.org/10.1016/1040-6182\(94\)90015-9](https://doi.org/https://doi.org/10.1016/1040-6182(94)90015-9)
- 32 Gillis, E., Wright, R., Mitchell, V. & Montevecchi, N. Definition of the Churchill River Delta and its petroleum potential, offshore Labrador, Canada. *Interpretation* **8**, SH19-SH32 (2020). <https://doi.org/10.1190/int-2019-0091.1>

- 33 Thrane, K. Provenance study of Paleocene and Cretaceous clastic sedimentary rocks from the Davis Strait and the Labrador Sea, based on U-Pb dating of detrital zircons. *Bulletin of Canadian Petroleum Geology* **62**, 330-396 (2014). <https://doi.org/10.2113/gscpgbull.62.4.330>
- 34 Sears, J. W. & Beranek, L. P. The Great Preglacial “Bell River” of North America: Detrital Zircon Evidence for Oligocene–Miocene Fluvial Connections Between the Colorado Plateau and Labrador Sea. *Geoscience Canada* **49**, 29–42 (2022). <https://doi.org/10.12789/geocanj.2022.49.184>
- 35 Corradino, J. I. *et al.* Ancestral trans–North American Bell River system recorded in late Oligocene to early Miocene sediments in the Labrador Sea and Canadian Great Plains. *GSA Bulletin* **134**, 130-144 (2021). <https://doi.org/10.1130/b35903.1>
- 36 Craddock, W. H. & Kylander-Clark, A. R. C. U-Pb ages of detrital zircons from the Tertiary Mississippi River Delta in central Louisiana: Insights into sediment provenance. *Geosphere* **9**, 1832–1851 (2013). <https://doi.org/10.1130/ges00917.1>
- 37 Davis, S. J. *et al.* The Paleogene California River: Evidence of Mojave-Uinta paleodrainage from U-Pb ages of detrital zircons. *Geology* **38**, 931-934 (2010). <https://doi.org/10.1130/g31250.1>
- 38 Salles, T., Ding, X. & Brocard, G. pyBadlands: A framework to simulate sediment transport, landscape dynamics and basin stratigraphic evolution through space and time. *PLOS ONE* **13**, e0195557 (2018). <https://doi.org/10.1371/journal.pone.0195557>
- 39 Divins, D. Total sediment thickness of the world’s oceans & marginal seas. *NOAA National Geophysical Data Center, Boulder, CO* (2003).
- 40 Cook, T. & Bally, A. (Princeton, Princeton University Press).
- 41 Sawyer, D. S. Total tectonic subsidence: A parameter for distinguishing crust type at the U.S. Atlantic Continental Margin. *Journal of Geophysical Research: Solid Earth* **90**, 7751-7769 (1985). <https://doi.org/https://doi.org/10.1029/JB090iB09p07751>
- 42 Dickinson, W. R. *et al.* Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region. *GSA Bulletin* **100**, 1023-1039 (1988). [https://doi.org/10.1130/0016-7606\(1988\)100<1023:Papsol>2.3.Co;2](https://doi.org/10.1130/0016-7606(1988)100<1023:Papsol>2.3.Co;2)
- 43 Fan, M. & Carrapa, B. Late Cretaceous–early Eocene Laramide uplift, exhumation, and basin subsidence in Wyoming: Crustal responses to flat slab subduction. *Tectonics* **33**, 509-529 (2014). <https://doi.org/https://doi.org/10.1002/2012TC003221>
- 44 Delworth, T. L. *et al.* GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. *Journal of Climate* **19**, 643-674 (2006). <https://doi.org/https://doi.org/10.1175/JCLI3629.1>
- 45 Seton, M. *et al.* Global continental and ocean basin reconstructions since 200Ma. *Earth-Science Reviews* **113**, 212-270 (2012). <https://doi.org/https://doi.org/10.1016/j.earscirev.2012.03.002>
- 46 Wickert, A. D. Open-source modular solutions for flexural isostasy: gFlex v1.0. *Geosci. Model Dev.* **9**, 997-1017 (2016). <https://doi.org/10.5194/gmd-9-997-2016>
- 47 Hyndman, R. D., Currie, C. A., Mazzotti, S. & Frederiksen, A. Temperature control of continental lithosphere elastic thickness, T_e vs V_s . *Earth and Planetary Science Letters* **277**, 539-548 (2009). <https://doi.org/https://doi.org/10.1016/j.epsl.2008.11.023>
- 48 Bahr, D. B., Hutton, E. W. H., Syvitski, J. P. M. & Pratson, L. F. Exponential approximations to compacted sediment porosity profiles. *Computers & Geosciences* **27**, 691-700 (2001). [https://doi.org/https://doi.org/10.1016/S0098-3004\(00\)00140-0](https://doi.org/https://doi.org/10.1016/S0098-3004(00)00140-0)