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Decoding 150 million years of continental-scale sediment transfer and drainage evolution across North America

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Abstract

Sediment transfer from continents to oceans is a fundamental component of the silicate-weathering thermostat, through which chemical weathering consumes atmospheric CO₂ and regulates climate over geological timescales. Yet understanding how and why sediment transfer evolves over geological timescales remains challenging because of the complex interactions between tectonics, mantle dynamics, drainage reorganization and sea-level change. Here, we integrate detrital zircon U–Pb age datasets with geologically constrained landscape and basin evolution models to reconstruct 150 million years of North American drainage evolution and sediment transfer. Our reconstruction reveals how the dominant controls on continental sediment

transfer shift through time. Fluxes were lowest during the Late Cretaceous, when widespread continental flooding suppressed relief. Tectonic reorganization and uplift subsequently drove an order-of-magnitude increase in sediment flux through the Cenozoic. Erosional unloading induced further flexural uplift, amplifying relief and sustaining sediment production beyond active orogenesis, while offshore depositional loading drove basin subsidence and created accommodation for long-term sediment storage. Together, these findings establish a process-based, quantitative history of continental sediment transfer and river reorganization, significantly advancing our understanding of their potential links to long-term climate and carbon evolution.

Main

The fate of eroded sediments—and the rivers that transfer them to the oceans—ultimately determines how landscapes evolve, how sedimentary basins fill, and how silicate weathering regulates climate and the long-term carbon cycle. In fact, carbon cycle models rely on mountain building and erosion as key drivers of the silicate-weathering feedback, and modern rivers show that ~40% of chemical denudation occurs on the steepest 10% of Earth's surface^{1, 2}. Equally important is the burial of terrestrial organic carbon, in deltas and shallow marine shelves, which accounts for 70–90% of global accumulation³. Continental-scale rivers, such as the Amazon and Ganges–Brahmaputra, deliver a substantial share of this flux to the oceans⁴ and underscore the importance of large drainage networks in linking erosion to long-term carbon storage. These observations show the importance of tectonics, erosion, and sediment burial in the carbon cycle, yet over geological timescales the drivers for silicate weathering, climate and the long-term carbon cycle have been difficult to decode. Moreover, dynamic interactions between mantle processes, surface uplift, flexural responses and sea-level change make links between these

processes difficult to isolate. These challenges are reflected in longstanding questions that remain important to debate^{5, 6}: For example, can positive feedbacks between erosion and flexural uplift sustain elevation during tectonic quiescence? And does continental flooding suppress erosion sufficiently to help explain reduced CO₂ withdrawal during intervals of elevated global temperature in the Cretaceous?

There is also significant debate over long-term global sediment fluxes⁷⁻¹⁰. Some studies argue for stability in erosion and deposition over the past 10 Myr, despite major climatic and tectonic shifts¹⁰. Others highlight dynamic change in sediment recycling and accumulation on the ocean floor⁷. Further complicating this picture is the “Sadler effect”¹¹ where the impact of averages calculated over longer timescales (that include hiatuses and erosion) makes accumulation rates appear to increase toward the present⁹. Resolving these contrasting perspectives requires integrating empirical records with process-based models that capture the interplay between tectonics, erosion, sediment routing and long-term burial.

Here we investigate processes that govern large-scale sediment transfer from orogenic belts to the oceans by exploring the evolution of three continental-scale river systems. We use the basin and landscape dynamics code BADLANDS¹² to quantify system-scale responses and identify the relative contributions of: (1) deformation (uplift and subsidence), (2) flexural isostatic adjustment in response to sediment loading and unloading, and (3) surface processes. We use detrital zircon (DZ) U-Pb ages¹³⁻¹⁷ to constrain the timing of drainage reorganization and provide benchmarks to assess model results. Integration of this data with models shows how sediments are eroded, rerouted and ultimately delivered to the oceans and reveals the interdependence of deformation, flexural isostatic adjustments and sediment transport. The results provide a unique

opportunity for understanding the links between Earth dynamics, silicate erosion and long-term climate regulation.

Testing the controls on the evolution of continental-scale river systems in North America

Our compilation of detrital zircon U-Pb ages of >17,000 grains from >40 samples across the United States and Canada¹³⁻¹⁷ (Supplementary Materials) provides one of the most complete continental-scale perspectives on sediment provenance (Fig. 1d and Table 1). This data provides a robust, empirical record of large-scale sediment transfer from orogenic highlands to the oceans; this allows us to reconstruct the evolution and reorganization of three continental-scale river systems that have drained North America over the past 150 Myr.

Regional to continental-scale drainage networks develop independently in the models and emerge, change and disappear in response to mantle convection, tectonics, global sea-level change and surface processes (Fig. 2a). The temporal changes in these self-generated drainage networks are tracked by calculating their spatial extents through time (Fig. 2b). Models and their boundary conditions are validated through comparison of modelled against reconstructed drainage areas derived from the DZ U-Pb age distributions. The influence of surface uplift and subsidence, flexural isostatic adjustment in response to sediment loading and unloading, and erosion and deposition on the evolution of large-scale sediment transfer to the oceans are isolated by calculating the evolution of each of these processes in five distinct regions: The US Western Cordillera, the Western Interior Foreland Basin, the Appalachian Cordillera, the Gulf of Mexico (GoM) and Hudson Bay (Fig. 3). The models capture the continuous evolution of drainage and sediment flux over the last 150 Myr and show three distinct periods of major reorganization.

91 In the Early Cretaceous, two main drainage systems emerge (Fig. 1b). The primary modelled
92 river system develops two main subcatchments that drain the Sevier Fold and Thrust Belt in the
93 west and the Appalachians in the east. These systems converge into a single northward-flowing
94 axial river that terminates in the Boreal Sea and captures drainage from an area of $\sim 7.4 \times 10^6$
95 km². A secondary drainage system flows southward into the GoM area and captures a drainage
96 area of $\sim 1.1 \times 10^6$ km². The direction, extent and scale of the modelled systems closely match
97 drainages reconstructed from DZ U–Pb data from the Alberta foreland basin^{14,17} and the GoM
98 (Fig. 2b). The development of both modelled drainage systems is closely coupled to inherited
99 paleotopography. Modelled topography in the Appalachian Mountain Belt is ~ 0.5 km higher than
100 in the Western Cordillera foreland basin forcing drainage in the east to flow westward (Fig 1b).
101 In addition, the modelled Mississippi Embayment in the Early Cretaceous is 0.1–0.3 km higher
102 than the central lowlands, creating a drainage divide that separates west-flowing catchments
103 from those directed south into the GoM. During this period the scale and direction of sediment
104 routing from orogenic belts to the oceans is controlled by the inherited topographic features and
105 erosional feedbacks (Fig 3).

106
107 In the Late Cretaceous, from ~ 100 to 70 Ma, modeled drainage systems are significantly reduced
108 in size as the Western Interior Seaway develops. The areas of the two land masses (Laramidia
109 and Appalachia¹⁸) and their associated drainage systems agree closely with drainage areas
110 generated from paleogeographic reconstructions^{18,19} (Fig. 1 a, b) and DZ U–Pb data¹⁴ (Fig. 2).
111 The model generates inundation of the seaway through anomalously high sea level combined
112 with subsidence from low-angle subduction of the Farallon Plate (dynamic topography) while
113 being smoothed by sediment loading; dynamic topography and flexure tend to reduce surface

elevation across western–central North America (Fig. 1), such that with less landmass for erosion, this interval (100–70 Ma) was dominated by subsidence and sediment deposition in the inland sea and coastal depocenters (Fig 3). By the end of the Late Cretaceous (70 Ma), inundation by the Western Interior Seaway ceased as dynamic subsidence diminished and migrated eastward, while the Laramide Orogeny uplifted the continental interior and global sea level fell.

In the Paleocene, the model two main successor drainage systems emerge in the models (Fig. 1b). The first drains the Western Cordillera and flows northeast into present-day Hudson Bay (area: $\sim 4.0 \times 10^6 \text{ km}^2$), which contrasts with the Early Cretaceous system that flowed north and terminated in the Boreal Sea. This first successor drainage corresponds to the Bell River system (Fig. 1a), a hypothesized transcontinental river first inferred from evidence of ice-flow directions across North America²⁰ and later corroborated by the recognition of its submerged delta in the Saglek Basin²¹. The second system flows southward into the GoM (area: $\sim 4\text{--}5.0 \times 10^6 \text{ km}^2$). The direction, extent and scale of these emergent systems broadly agree with drainages reconstructed from DZ U–Pb data obtained from deposits in the Cartwright Formation in the Saglek Basin²⁰ and the Wilcox Group in the GoM¹⁴ (Fig. 2). However, a few discrepancies in the estimated extent of the Bell River system can attributed to: (1) the computational domain being slightly smaller than the northernmost extent of the catchment²⁰ and (2) uncertainties in defining catchment limits from DZ U–Pb data. Detrital zircon U–Pb ages $< 250 \text{ Ma}$ in Paleogene sedimentary units of the Saglek Basin suggest that the Bell River system had headwaters that connected to the magmatic arc in the Canadian Rockies as early as the Paleocene^{15,20}, although the northern limits of the catchment remain difficult to constrain with available data. We also

find a discrepancy in the location of the drainage divide between the Bell River system and the GoM catchment. In the model the western headwaters of the Bell River system include the northern Laramide province, the eastern Sevier Fold and Thrust Belt, and the Canadian Rockies. We note that Hafnium isotopic data in GoM Wilcox fluvial deposits²¹ imply the Coast Mountains batholith in British Columbia was part of the GoM catchment.

Despite small discrepancies in estimating the extent of the Bell River system, the models suggested that it formed as North American migrated west over the subducting Farallon slab. Concurrent eastward translation of dynamic subsidence lowered the eastern North America, as found in inverse models of mantle flow²² as well as the forward mantle flow models integrated with surface processes here²³. Around 63 Ma, this east-directed tilt migrated into the northern part of North America and, together with uplift from the Laramide Orogeny, redirected fluvial pathways and sediment transport to the north-northeast and Hudson Bay. We interpret that this reorganization led to the demise of the McMurray system and formation of the successor Bell River system.

Segmentation of the McMurray system also resulted in Paleocene expansion of drainages that flowed into the GoM (Fig. 2b). The modeled GoM drainage area ($5.0 \times 10^6 \text{ km}^2$) is consistent with DZ U-Pb data and channel-belt scaling relationships¹⁴ but differs from constraints based on Hf isotopes²¹, which represent empirical evidence that the Paleocene catchment was connected to the Coast Mountains batholith in British Columbia²¹. The model does not capture this expansion but instead incorporates the mountain ranges of western British Columbia into the Bell River catchment itself. Future analyses of Hafnium isotopes in Paleocene DZ U-Pb ages from the

Saglek Basin^{15,16} can shed light on this discrepancy, but, regardless, this period of uplift associated with the Laramide Orogeny has been the primary control on sediment routing, driving large river systems to transfer material from the orogenic belts to the coastal oceans. At the same time, dynamic subsidence caused by the basalt-to-eclogite transformation of an oceanic plateau within the Farallon slab depressed the GoM region and generated accommodation necessary to preserve the large volumes of sediment delivered to the continental margins (Fig. 3).

In the Oligocene, modelled drainages capture expansion of the Bell River system (Fig 1b) and the evolution of drainages that flowed to the GoM, including: (1) the central and western branches of the Bell River system, with headwaters in the Western Cordillera and a confluence on the west side of Hudson Bay; and (2) the eastern branch of the Bell River system, with headwaters in the Appalachian Cordillera. The modeled drainage area for the Oligocene Bell River system ($8.1 \times 10^6 \text{ km}^2$) is smaller than reconstructed estimates²⁰ ($9.7 \times 10^6 \text{ km}^2$) but, as in the Paleocene case, the discrepancy arises because DZ U–Pb data is not in itself sufficient to provide confident definition of the northern Bell River system catchment.

Estimating sediment delivery to downstream basins from specific catchments is key to reconstructing sediment routing, making the boundaries of catchments and sub-catchments critical. Uncertainty over the boundaries of the Bell River catchment also raises the question of whether the California River^{20,24} in the southwest US may have been an integrated fluvial system into this basin during the Oligocene. Although DZ U–Pb ages from the Cypress Hills in Alberta have been interpreted as similar to the Colton Formation, neither of these deposits, nor those from the Saglek Basin (Fig. S3), match Colton age spectra. Moreover, Oligocene DZ U–Pb ages

represent >5% in GoM sediments versus <1% in the Saglek Basin, which indicates that only the GoM received sediment from the Central Rocky Mountains²⁵. Together with the model results, these provenance constraints support an Oligocene California River that drained southward into the GoM (Fig. 1) rather than into the Bell River system²⁰. Regardless, during the Oligocene, sediment transfer from orogenic belts to the oceans was governed by the erosion of Laramide terranes. The models show that even in the absence of renewed uplift after 60 Ma (Fig 2b, 2d, Fig. 3), relative elevation and erosion rates were sustained by flexural uplift induced by erosional unloading, while large sediment loads offshore were accommodated by flexural subsidence (Fig. 3).

Mountains to Margins: Sediment Flux, Surface Temperature, and the Carbon Cycle

For North America, our results show pronounced variability in sediment production and preservation over the last 150 Myr, with minimum fluxes during the Late Cretaceous and substantial increases through the Cenozoic driven by drainage reorganization. During the Late Cretaceous, anomalously high global sea level and low-angle subduction of the Farallon Plate promoted marine inundation of the Western Interior Seaway that suppressed topographic relief and limited sediment delivery to adjacent basins. Consequently, the lowest modelled rates of continental erosion and sediment flux occurred during this interval (Fig. 2b). From the Late Cretaceous to the Neogene, modelled sediment accumulation in the GoM increased by an order of magnitude (Fig. 2), reflecting Laramide-related uplift that reorganized drainage networks and enhanced sediment delivery. After Laramide deformation ceased in the Eocene, continued denudation of the Western Cordillera and Colorado Plateau drove flexural uplift through erosional unloading, sustaining relief and sediment supply long after active orogenesis had

ended; this is consistent with evidence that erosional unloading can drive substantial post-orogenic flexural rebound and shape long-term landscape evolution²⁶. Simultaneously, depositional loading in the GoM induced flexural subsidence that generated accommodation for continued sediment accumulation. Together, these coupled flexural responses link mountain denudation to basin accommodation through a long-lived source-to-sink feedback. The magnitude of modelled flexural deflection is comparable to that reported for other continental-scale sedimentary systems^{27, 28}, including the Amazon Fan^{29,30} suggesting that load-induced flexure is a fundamental mechanism for sustaining long-term sediment storage beyond classical syn-tectonic–thermal subsidence models³¹.

To place the results of the North American model developed here in an Earth-system climate context, we compared its sediment fluxes with published reconstructions of atmospheric CO₂ and global surface temperature²⁵ (Fig. 2c). Comparisons between regional geological records and global climate archives have long provided insight into Earth-system evolution, despite differences in spatial scale⁵. Here, although the reconstruction does not capture the global sediment budget, the Mississippi–GoM system is one of Earth's largest siliciclastic source-to-sink systems and so offers an independent, process-based record of how tectonics, drainage integration and continental flooding have influenced sediment delivery through time.

In the Late Cretaceous, minimum modelled sediment fluxes coincided with high global temperatures, yielding an inverse relationship between sediment flux and surface temperature. This correspondence is consistent with widespread continental flooding suppressing relief and silicate weathering and so limiting long-term atmospheric CO₂ drawdown. Previous work has

emphasized the role of palaeogeography²⁶, particularly the concentration of continental landmasses at low latitudes; our results suggest that the geomorphic consequences of continental flooding also warrant consideration. Given the uncertainties associated with Cretaceous CO₂ reconstructions²⁵, independent constraints from Earth-surface processes offer a valuable perspective.

From the Late Cretaceous to the Neogene, increasing sediment fluxes coincided with declining global temperatures, consistent with enhanced denudation accompanying drainage integration and tectonically driven increases in relief. These correlations do not imply direct causation but do support the hypothesis that large-scale changes in continental erosion and sediment delivery influenced long-term silicate weathering and atmospheric CO₂.

Previous comparisons between sediment production and global climate proxies have typically relied on sedimentary compilations that combine multiple depositional processes, including carbonates, contourite-modified siliciclastics and mass-transport deposits³⁰. Instead, the models here isolate the siliciclastic component of sediment flux, resolving the geomorphic and tectonic controls on sediment production directly. This process-based framework offers an independent perspective on long-term CO₂ and temperature records and underscores the role of continental-scale source-to-sink systems in linking tectonics, surface processes and the carbon cycle.

Population name	Age range (Ma)	Primary source	Potential recycled sources
Western Cordillera	<275	Cordilleran magmatic arc distributed in Nevada, Arizona, California and British Columbia	Reworking of Western Cordillera (Sevier) Fold and Thrust Belt or Western Canada sedimentary basin (WCSB) foredeep in Wyoming, Montana and British Columbia
Appalachian and Peri-Gondwanan	280-750	Appalachian-Ouachita cordillera and Pan-African/Brasiliano terranes extending from southern to southeastern United States	Paleozoic-Mesozoic Appalachian-Ouachita foreland basin, U.S. Midcontinent, and western U.S. Laurentian passive-margin strata
Grenville	950-1250	Appalachian cordillera (e.g., Blue Ridge), Llano Province in Texas, and Shawinigan and Ottawan orogenies in the Great Lakes region in Canada	
Midcontinent	1300-1500	S. Midcontinent and plutonic intrusions within the Yavapai-Mazatzal provinces	
Yavapai-Mazatzal	1600-1800	Yavapai and Mazatzal orogens and associated intrusions within the Mogollon Highlands of mid- to southwest United States	
Penokean-Trans-Hudson	1800-2000	Paleoproterozoic Trans-Hudson and Penokean orogens in south-central Canada and U.S. Great Lakes region	Recycling pervasive in North American strata
Wyoming or Superior	>2500	U.S. Midcontinent and the Canadian Shield	

Table 1. Summary of interpreted primary and recycled sources for detrital zircon populations in North America

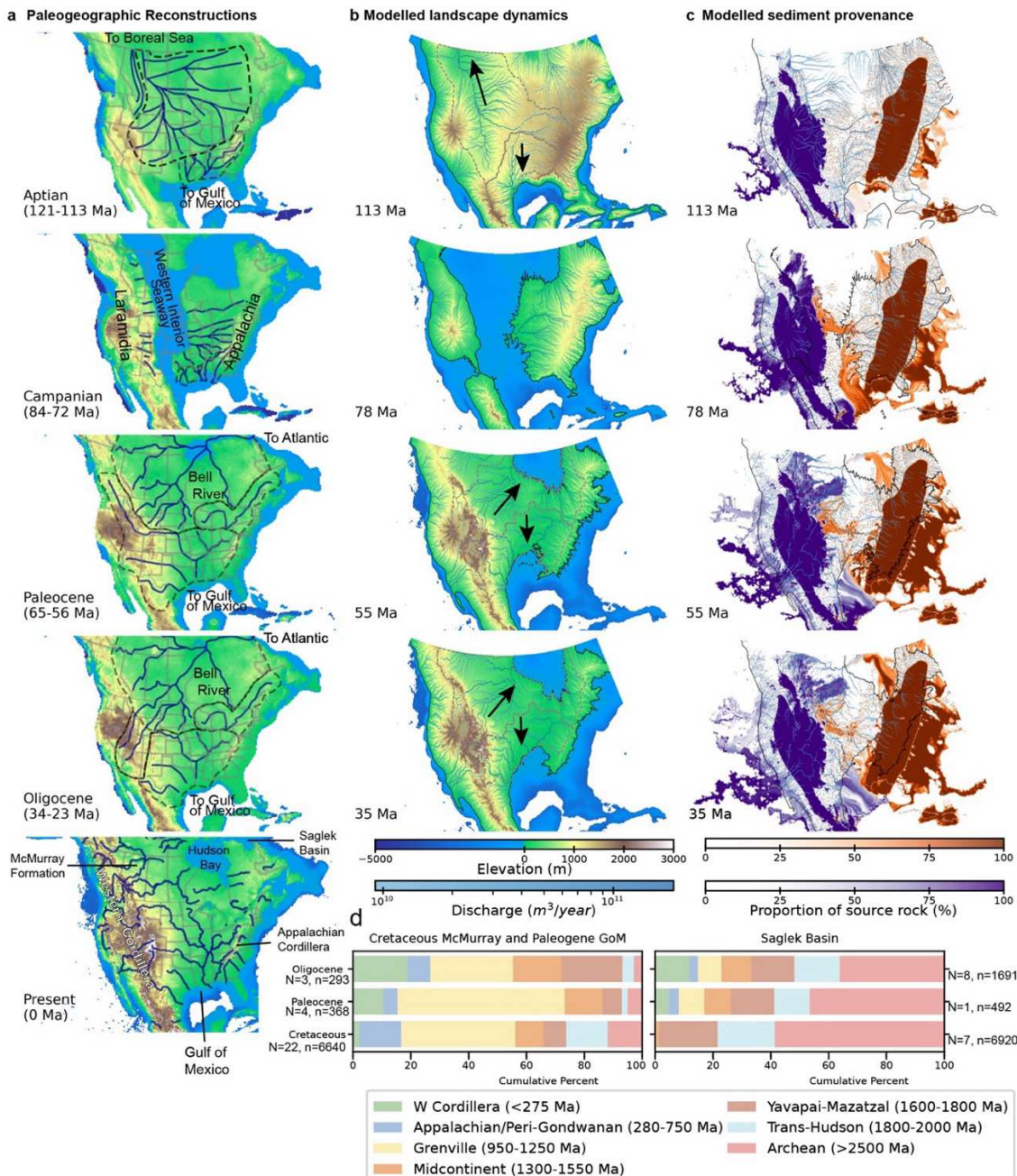


Figure 1. Comparison of observed and modeled continental-scale drainage reorganization of North American Rivers. (a) Paleogeographic¹⁹ and drainage reconstructions for the Aptian, Campanian, Paleocene and Oligocene^{14,15,20,32}. (b) Model outputs showing paleotopography, paleodrainages and modelled catchment boundaries (grey lines). Arrows indicate the principal drainage directions; catchment areas are shown in Fig. 2b (c) Modeled proportion of sediment being transported from a given source to a depocenter. (d) Comparison of the proportions of detrital U-Pb age groups in the fluvial deposits of the McMurray, GoM and the Saglek Basin. See Table 1 for Summary of interpreted primary and recycled sources for detrital zircon populations in North America. The evolution of these three main river systems is consistent with paleogeographic reconstructions based on detrital zircon records.

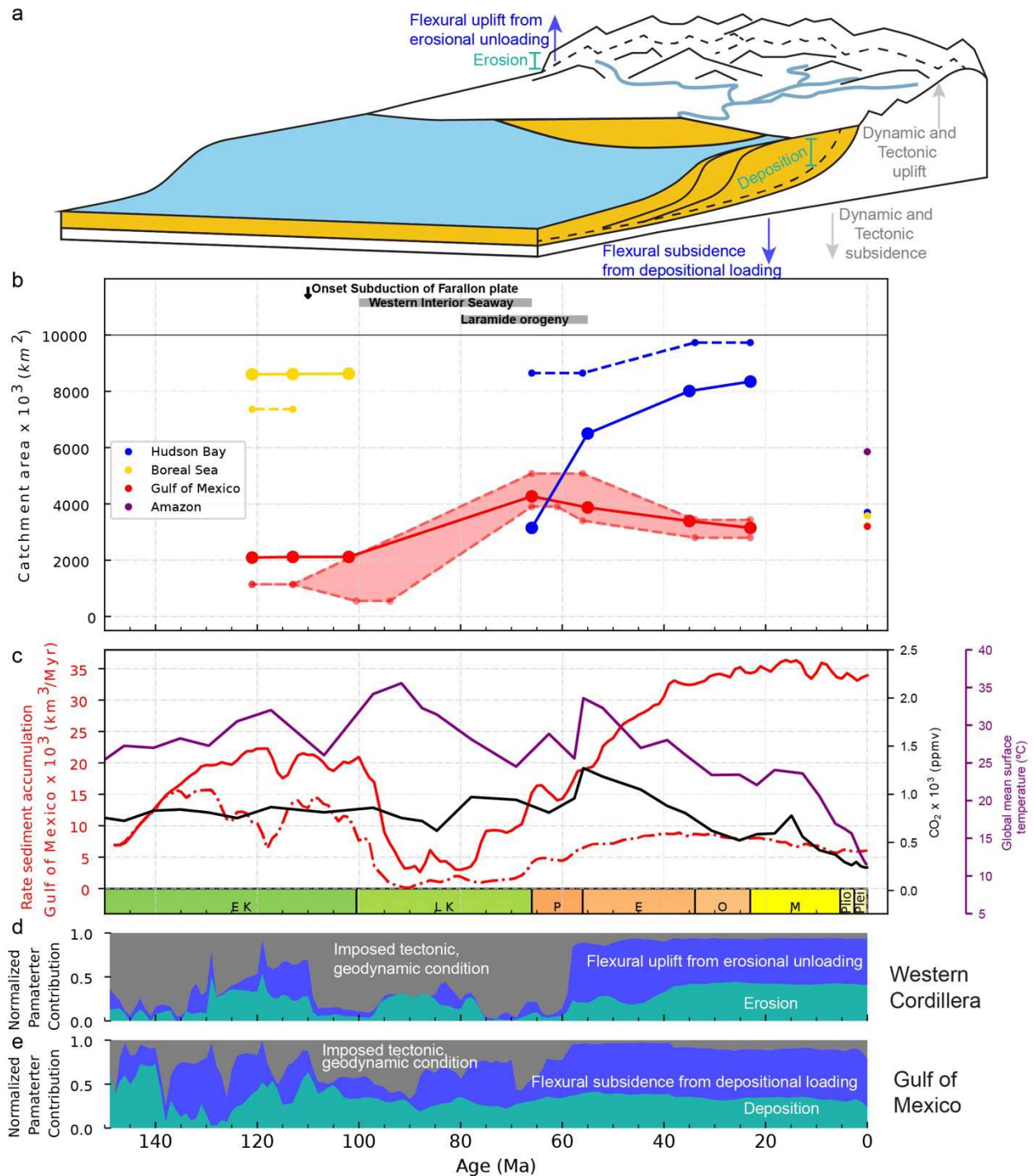


Figure 2. (a) Conceptual diagram showing the components of vertical motions captured in the models presented in this study (b) Temporal evolution of continental-scale catchment areas in North America. The models capture the dominance of the Boreal River systems during the Early Cretaceous, fluctuations in catchment size of the GoM drainages and emergence and expansion of the Bell River system. Solid lines represent the catchment areas derived from the models, while the dashed lines indicate estimations based on detrital zircon data^{14,20,21}, with the envelope reflecting the minimum and maximum values from different studies. Horizontal grey bars denote

272 the duration of the geodynamic and tectonic events imposed into the model. (c) relationship
273 between global temperature, atmospheric CO₂³³ and modelled sediment volume accumulated in
274 the GoM in the flexurally compensated model (solid red) and its non-compensated counterpart
275 (dashed red) (d-e) Normalized rates of imposed and geodynamic and tectonic factors as well as
276 flexural isostasy and surface processes (erosion and deposition) for the Western Cordillera and
277 GoM.
278

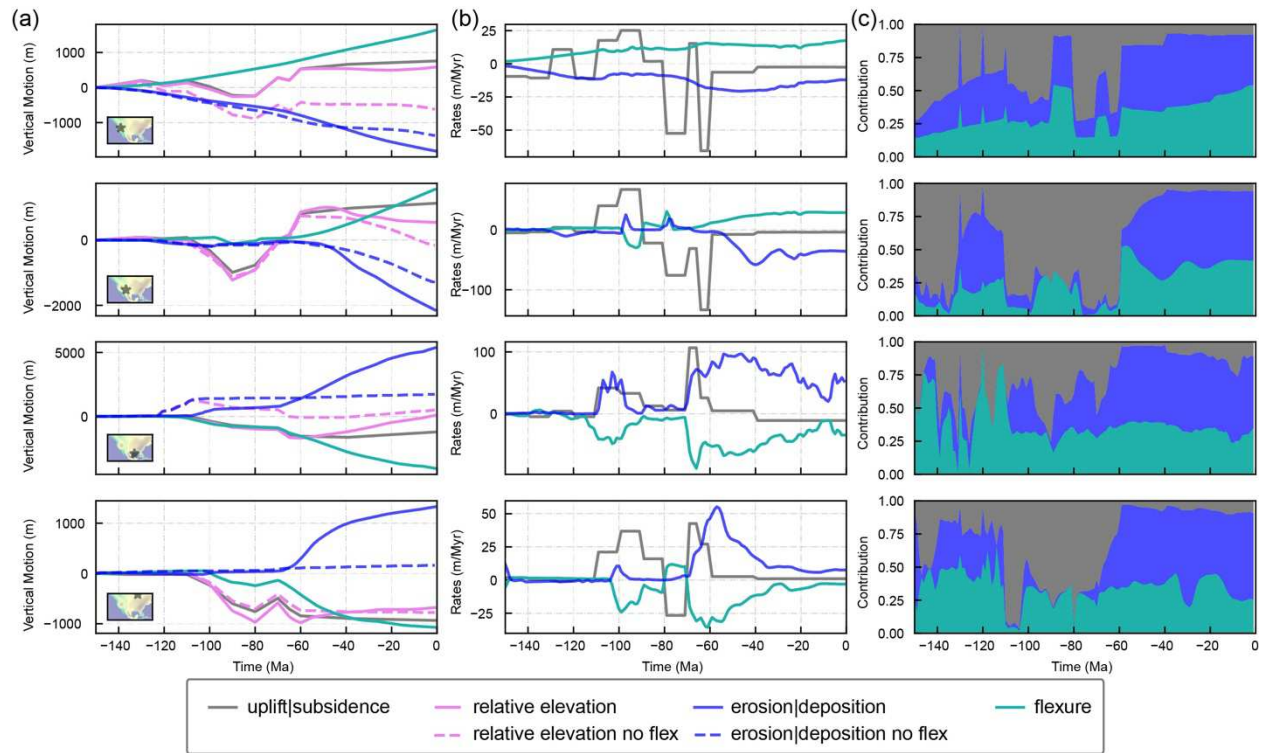


Figure 3. Temporal evolution of (a) cumulative values, (b) rates, and (c) normalized rates of imposed uplift and subsidence, together with modelled relative surface elevation, flexural response, and erosion | deposition, for the Western Cordillera, Western Interior Basin, GoM, and Hudson Bay regions. Dashed lines show the results from models without flexural compensation. Relative surface elevation is defined as the difference between the initial elevation and the elevation at each time step. The inset indicates the locations where the calculations were performed.

297 **CRedit Authorship Statement**

298 SP: Conceptualisation; Data Curation; Formal analysis; Investigation; Methodology;
299 Visualisation; Writing - Original Draft, Review & Editing
300 MB: Conceptualisation; Data Curation; Formal analysis; Investigation; Methodology;
301 Visualisation; Writing - Original Draft, Review & Editing
302 HW: Conceptualisation; Formal analysis; Methodology; Writing - Review & Editing
303 TS: Formal analysis; Methodology; Writing - Review & Editing
304 AT: Formal analysis; Methodology; Writing - Review & Editing
305 MG: Conceptualisation; Data Curation; Formal analysis; Investigation; Methodology;
306 Visualisation; Writing - Original Draft, Review & Editing
307

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317

318 **Data and code Statement**

319 The detrital zircon data, along with the model inputs and boundary conditions presented in this
320 manuscript, are available as Supplementary Data files. The scientific software used in this study,
321 Badlands, is available from <https://github.com/badlands-model/badlands>, and the software
322 documentation can be found at <https://badlands.readthedocs.io/en/latest/>. The detrital zircon
323 analysis software detritalPy is available from <https://github.com/grsharman/detritalPy>. The
324 PALEOMAP paleoelevation reconstruction and related GPlates rotation and geometry files are
325 downloaded from <https://zenodo.org/records/5460860>

326 **Competing Interests Statement**

327 The authors have no competing interests to declare.
328

329 **Ethics Declaration**

330 Not applicable.
331

Methods

Detrital zircon data, analysis and interpretation

The published DZ U-Pb chronological datasets present in this study are listed in the Supplementary data. Visualization and analysis of detrital zircon U-Pb age spectra was carried out with the Python toolset detritalPy³⁴.

DZ U-Pb signatures of North American drainage organization and reorganization

Our compilation of >17,000 grains from >40 samples across the United States and Canada (Fig. S1-S3) provides the first continent-scale perspective on temporal and spatial trends (Fig. 1d), from which we reconstruct the evolution of the McMurray, GoM and Bell River systems. DZ U-Pb data from Aptian McMurray deposits^{14,17} and from the Paleogene and Neogene GoM and Bell River systems¹⁵ (Fig. S1-S2) consistently show a <275 Ma signature linked to arc magmatism in the Western Cordillera. The youngest ages in this group constrain the depositional timing of the McMurray, GoM, and Bell River systems (Fig. S5). We note these ages are generally consistent with independently derived chronological constraints from biostratigraphic criteria¹⁴. The presence of volcanogenic grains that provide constraints indicates the McMurray, Wilcox, Bell River system, and Vicksburg-Frio systems had some portion of their distal headwaters in close proximity to the Mesozoic volcanic arc, which extends from SW Canada to Southern California.

The Early Cretaceous McMurray, the Paleocene and Early Eocene Wilcox, and Paleocene to Miocene Bell River system are also characterized by pre-Mesozoic U-Pb age groups that further differentiate and define parts of their drainage areas. For example, McMurray samples from Alberta, Wilcox samples from the GoM coastal plain, and Bell River system samples from

offshore Canada are dominated by primary and recycled zircon grains with U-Pb ages of ca. 275-1250 Ma that were ultimately derived from the Paleozoic Appalachians and the Mesoproterozoic Grenville orogenic systems^{13,35}. In addition to the primary and recycled Appalachian-Grenville signals, McMurray and Wilcox samples therefore include primary and recycled zircons with U-Pb ages that were ultimately derived from the western United States¹³. By contrast, U-Pb ages representing Paleoproterozoic Trans-Hudson (ca. 1800-2000 Ma) and Archaean (>2200 Ma) sources are common in eastern tributaries of the McMurray system, but are less significant for the Paleocene Wilcox, Oligocene Vicksburg-Frio, and Miocene Fleming GoM systems (Fig. 1d, Fig. S2, S3).

The Eocene to Miocene Churchill delta and subjacent Paleocene strata of the Saglek Basin represent the depocenter for the Bell River system and also include a small component of the diagnostic <275 Ma signature^{15,16}, which are also consistent with independently-derived biostratigraphic data (Bujak Davies Group, 1987). The presence of grains with U-Pb ages <275 Ma links the Saglek Basin with the Western Cordillera magmatic arc source terrain (Fig. 1d). The recycled Appalachian-Grenville signature is also present in the Paleogene and Neogene Saglek Basin, as are DZ U-Pb ages that represent primary and recycled Mesoproterozoic anorogenic granites and the Paleoproterozoic Yavapai-Mazatzal orogen (Fig. 1d). U-Pb ages <1800 Ma generally reflect headwaters, drainage areas, and routing systems that are within the United States but absent from Cretaceous strata in the Saglek Basin (Fig. 1d). These various age groups appear for the first time in the Paleocene to Eocene as the Bell River system becomes fully integrated. However, unlike the McMurray, GoM Wilcox and GoM Vicksburg-Frio systems, Paleocene through Miocene strata of the Saglek Basin are dominated by (>50%) age groups associated with the Trans-Hudson orogen and Archaean age groups of the Canadian

shield, a signature that had much earlier been present in the east-to-west flowing tributary system of the McMurray (Fig. 1d). By comparison, the McMurray, Wilcox, and Vicksburg-Frio systems contained only 25%, 7% and 7%, respectively, of U-Pb ages derived from the Canadian shield (Fig. 1d). The DZ U-Pb signatures of the Bell River-Churchill delta system therefore support the view of a generally southwest to east flowing transcontinental river system with headwaters in the Western Cordillera magmatic arc in the US and Canada and the Sevier Fold and Thrust Belt in the western US; in addition, a contributing drainage area included large parts of the western US and the Canadian shield.

Evolution of continental-scale river systems in North America

In the Early Cretaceous, the primary continental-scale river system was represented by the McMurray Formation in the Alberta foreland basin (Fig. 1), which had a contributing area that extended from the Sevier Fold and Thrust Belt in the southwest United States to the Appalachians in the southeast United States and then north to eastern Canada (Fig. 1). The establishment of the Western Interior Seaway during the mid-Late Cretaceous (Albian-Cenomanian) divided North America into Laramidia and Appalachia (Lyster et al., 2020) and, in doing so, segmented the McMurray system (Fig. 1). Withdrawal of the Western Interior Seaway in the Paleocene then favored the routing of drainages from the Western Cordillera and across the US continental interior to the GoM. This important successor drainage is represented by the Paleocene and Early Eocene Wilcox Group of the GoM coastal plain, shelf and deepwater basin¹⁴. Also in the Paleocene, the Bell River system²⁰ was established as an important continental-scale drainage that originated in the Canadian and US Western Cordillera, and

400 flowed east-northeast across what is the modern Hudson Bay region, to the northeast Canadian
401 Atlantic margin and the Saglek Basin in offshore eastern Canada (Cartwright Formation²⁰).
402
403 In the Neogene, the Bell River system continued to deliver sediment from the Western Cordillera
404 to the Atlantic margin and expanded its drainage to include headwaters in the British Columbia
405 magmatic arc. Southward along the Western Cordillera, tributaries west of the Laramide
406 Rockies, which previously flowed into the GoM, were captured and redirected north-northeast.
407 This expansion of the Bell River system headwaters was likely coincident with, and related to, an
408 approximate 30% reduction (Fig. 2) in drainage area for the GoM drainage system as a whole,
409 which is represented stratigraphically by the Oligocene Vicksburg-Frio and Miocene Fleming
410 Groups of the GoM coastal plain, shelf and deepwater basin³⁶. Previous studies have proposed
411 that at this time there is no connection between the Neogene depocenter in the GoM, the central
412 Rockies, and the ash-rich Eocene to Oligocene fluvial deposits in the northern US Great
413 Plains^{25,37,38}. Instead, Oligocene River systems of the Bell River system in the Rocky Mountain
414 region are interpreted to have flowed to the northern US Great Plains from headwaters in the
415 Sevier Fold and Thrust Belt of western Wyoming, and the volcanic centers further to the south
416 and west in Nevada, Utah, Colorado and New Mexico^{25,39,40} and not to the GoM. We test this
417 hypothesis by revisiting the available DZ data and using numerical models.
418 After the Neogene, the repeated expansion and contraction of Plio-Pleistocene ice sheets likely
419 played a key role in demise of the Bell River system^{15,20}. Much of the interpreted drainage area
420 of the Bell River system across Canada would have been subject to erosion by ice sheets, such
421 that the stratigraphic record of the Bell River system is now mostly preserved in isolated
422 locations within western Canada, and then in the Saglek Basin, more than 4000 km to the

east. Plio-Pleistocene glaciation also played a pivotal role in growth of the modern-day Mississippi River system⁴¹.

Forward modeling

We build ²³ on previous numerical models of the landscape evolution of North America^{23,42} to explore the processes that govern large-scale sediment transfer from orogenic belts to the oceans by exploring the evolution of three continental-scale river systems. The computations are performed using the basin and landscape dynamics code BADLANDS¹². The models develop drainage basins where rivers merge on the coastal plain, then the river mouth acts as a point source for sediment input to the marine domain. Modeled sediment flux is controlled by river incision, governed by precipitation, drainage area, the topographic gradient, and erodibility, and hillslope diffusion, which is dependent on diffusivity and the topographic gradient. Once the sediment load is accumulated in the marine domain, a continental shelf emerges and shelf-margin clinothems are generated. The models start with a paleotopographic surface that provides a first-order representation of the two most significant continental-scale mountain ranges in North America at 150 Ma, that is the pre-existing topography associated with the Sevier Orogeny^{43,44} and the Appalachian Orogeny⁴⁵ (Fig. S5).

To test the role of: (1) the withdrawal of the Western Interior Seaway in the demise of the McMurray River system and the establishment of the Bell River; and (2) uplift associated with the Laramide Orogeny in the establishment and expansion of the Bell and Mississippi River systems, we impose a series of tectonic and subsidence events where timing and deformation is based on geological observations and geodynamic (coupled plate tectonics/mantle convection) models⁴². Precipitation conditions are based on simple temporally- and spatially-dependent rainfall trends;

sea-level fluctuations are accounted for by imposing the sea-level curve of Haq⁴⁶. The flexural isostatic response to changes in water and sediment load is calculated using a two-way coupling between BADLANDS and gFlex⁴⁷, which computes the deflection of the Earth's surface using an elastic plate flexure solution.

To understand how tectonics and surface dynamics distribute the sediment from two distinct sediment sources, the Western Cordillera (<250 Ma plus the cosmopolitan Appalachian signature *sensu*¹³ and the Appalachian Cordillera (950 –1250 Ma, 1600 – 2000 Ma, 2400–3200 Ma), we used the rock-tracking function in BADLANDS to trace the proportion of sediment load that was composed of each source. We clarify that the rock-tracking function does not take sediment recycling into account, but we consider that this function provides useful information to unravel sediment dispersal patterns.

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