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Glacial isostatic adjustment shifted early Holocene river hydrology in Maine, USA

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ABSTRACT

Glacial isostatic adjustment produces crustal deformation capable of altering the slope of the landscape and diverting surface water drainage, thereby modulating the hydraulic conditions that govern river evolution. These effects can be especially important near the margins of ice sheets. In Maine, USA, post-glacial changes in sedimentation within major river systems have been interpreted as the result of regional tilting and drainage rerouting due to glacial isostatic adjustment. In this study, we model isostatic adjustment driven by retreat of the Laurentide Ice Sheet, quantify the associated tilting and drainage rerouting, and explore how these changes impacted sediment transport in Maine's rivers. Through an analysis of changes to river slope and drainage area produced by glacial isostatic adjustment, we show that ice sheet retreat altered the median sediment grain size that rivers could entrain. We also find support for previous estimates of the timing and direction of drainage reversal at Moosehead Lake, Maine's largest lake. Our results suggest that the history of sedimentation in Maine's rivers reflects time-dependent effects of glacial isostatic adjustment that are superimposed on any changes in runoff associated with deglaciation. Further, our case study demonstrates that isostatic adjustment affects alluvial channel evolution and sediment delivery to the coastline for several millennia after an ice sheet retreats.

INTRODUCTION

Topography controls the movement of sediment through river systems. A river's ability to erode and transport sediment depends on channel slope and water discharge, which in turn depend on upstream drainage area (Howard et al., 1994). Both slope and drainage area change as topography evolves. Tectonic uplift governs million-year evolution of topography; however, on glacial time scales, solid Earth deformation in response to the growth and decay of ice sheets can outpace background tectonic signals by one to two orders of magnitude (e.g., Whitehouse et al., 2007; Pico et al., 2022). A growing body of research suggests that glacial isostatic adjustment (GIA) influences the evolution of river systems. Diverted channels (Wickert, 2016; Pico et al., 2018), enhanced rates of incision (Pico et al., 2019; Wickert et al., 2019) and meandering (Kodama et al., 2023), and altered delta construction (Whitehouse et al., 2007) document rivers' interactions with isostatically displaced topography.

Rivers in Maine (USA) likely experienced large changes due to GIA. Ice retreat across Maine between 16 ka and 13 ka (Koester et al., 2017; Dalton et al., 2020) exposed a landscape formerly depressed under >1.6 km of glacial ice (Bierman et al., 2015). Postglacial uplift was recorded by a 60 m drop in relative sea level (Belknap et al., 1987; Barnhardt et al., 1995) and by the levelling of lake basins formerly tilted toward the ice mass (Balco et al., 1998). By ca. 11 ka, runoff from residual ice melt had diminished (Borns et al., 2004; Hooke et al., 2017), but GIA was ongoing (Fig. 1).

Several lines of geologic evidence suggest that GIA impacted Maine's major rivers, the Kennebec and Penobscot Rivers. Maine's largest lake, Moosehead Lake, forms the headwaters of the modern Kennebec River. At northern Moosehead Lake, an abandoned drainage outlet—now elevated 4.5 m above lake level—provides evidence of a past connection to the Penobscot River (Balco et al., 1998; Fig. S1 in the Supplemental Material[1]). Outflow ceased ca. 9.6 cal k.y. B.P. (Kelley et al., 2011). A 20 m lowstand shoreline at southern Moosehead Lake coincides chronologically with drainage through the now-elevated northern outlet, together implying that Moosehead Lake was tilted to the NW during the early Holocene (Balco et al., 1998).

Kelley et al. (2011) hypothesized that switching Moosehead Lake drainage between Maine's largest rivers initiated a transition in these rivers' ability to transport coarse sediment. Their hypothesis is grounded in sedimentary evidence: abrupt coarse deposition in the upper Kennebec River valley with no Penobscot analogue (the North Anson Formation; Borns and Hagar, 1965) and the termination of sandy paleodelta construction at the Penobscot River while the Kennebec paleodelta continued to build (Barnhardt et al., 1997; Belknap et al., 2005).

Changes in river discharge driven by drainage basin reconfiguration would have been accompanied by GIA effects on channel slope. Borns and Hagar (1965) speculated that glaciation decreased the slope of the Kennebec River, and Hooke et al. (2017) hypothesized that the

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[1]Supplemental Material. Additional detail on methods, Figures S1–S9, and Tables S1–S3, measurements of riverbed grain size. Please visit https://doi.org/10.1130/GEOL.S.28462277 to access the supplemental material; contact editing@geosociety.org with any questions.

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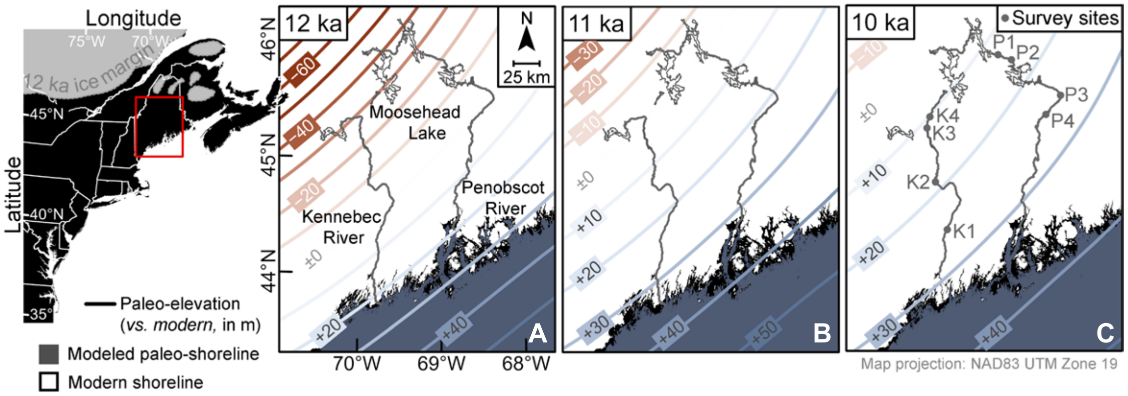

Figure 1. Modeled paleo-elevations relative to modern topography in Maine at (A) 12 ka, (B) 11 ka, and (C) 10 ka. Uplifted topography shown with blue contours; depressed topography with red contours. Grain size survey sites are labeled in (C). The left panel shows ice extent at ca. 12 cal. ka per Dalton et al. (2020).

slope of the lower Penobscot River was reduced to near zero. Lowered channel slopes could alter depositional behavior by trapping bed material and limiting sediment throughput.

This study evaluates whether GIA modulated sediment transport in Maine's watersheds by redirecting fluvial drainage and changing river channel slope. Further, we assess whether a rerouting of Moosehead Lake discharge can explain shifts in river behavior. We use this case study to quantitatively examine how isostatic rebound can impact river evolution in recently deglaciated regions, independent of changes in precipitation or meltwater runoff.

DRAINAGE BASIN REORGANIZATION AFTER DEGLACIATION

We reconstructed topographic change due to GIA across the early Holocene. During the last deglaciation, ice retreat produced a complex spatiotemporal pattern of topographic change. Our GIA simulations are based on the sea-level algorithm of Kendall et al. (2005) and incorporate the influence of load-induced rotational changes (Milne and Mitrovica, 1996), evolving shorelines, and grounded marine-based ice migration (Lambeck et al., 2003; Kendall et al., 2005). GIA calculations require two components: a model of Earth's viscoelastic structure and a history of global ice cover. We chose an Earth model within a range of parameters identified by Baril et al. (2023) for fitting Maine's relative sea level history (96 km lithospheric thickness; upper and lower mantle viscosities of 0.3×10^{21} and 1.5×10^{22} Pa s, respectively). We paired this Earth model with a modified version of the global ice history ICE-6G (GI-31-ICEPC2; Farmer et al., 2023; Supplemental Material) and ran our GIA simulation from 122 ka to present. As Maine deglaciated, isostatic rebound associated with the collapse of the Laurentide Ice Sheet was under way. Our model estimates that the Moosehead Lake region uplifted ~40 m between 12 ka and 10 ka (Fig. 1). We tested the sensitivity of our GIA calculations to the choice of Earth model by comparing our results to GIA simulations with an alternate Earth model, VM2 (Peltier, 2004). The regional isostatic deformation gradient is similar with both models, though slight differences in isobase orientation result in subtle (<k.y.) variations in uplift timing at Moosehead Lake (Fig. S2). With our model, uplift concludes slightly later and is more compatible with Kelley et al.'s (2011) ^{14}C dates (Fig. S3). Nevertheless, variations in local uplift timing across the tested Earth models do not substantially alter estimates of the net change in landscape gradient (Fig. S4).

To reconstruct paleotopography and map paleo-drainage paths, we subtracted GIA from a 1 arc-s digital elevation model (DEM) of modern topography (Supplemental Material). Our method assumes that tectonic contributions to relative sea level are negligible during the Holocene, an appropriate assumption along the North American Atlantic passive margin (e.g., Karegar et al., 2016). Our topographic reconstructions predict an early Holocene drainage divide shift at Moosehead Lake, consistent with geologic evidence. During the interval of regional ice retreat, isostatically depressed topography tilted Moosehead Lake to the NW (at a gradient of 0.65 m/km at 14 ka) relative to its modern elevation (Fig. S5). Lake outflow was directed through the now-abandoned northern channel draining to the Penobscot River (Figs. 2A and 2B). Between 12 ka and 10 ka, isostatic uplift slowed from ~30 mm/yr to ~10 mm/yr. By 10 ka, the NW tilt was reduced to 0.2 m/km relative to present, sufficient to redirect lake drainage southward toward the Kennebec River (Fig. 2C). Drainage divides established by 10 ka persist to the present (Fig. 2D).

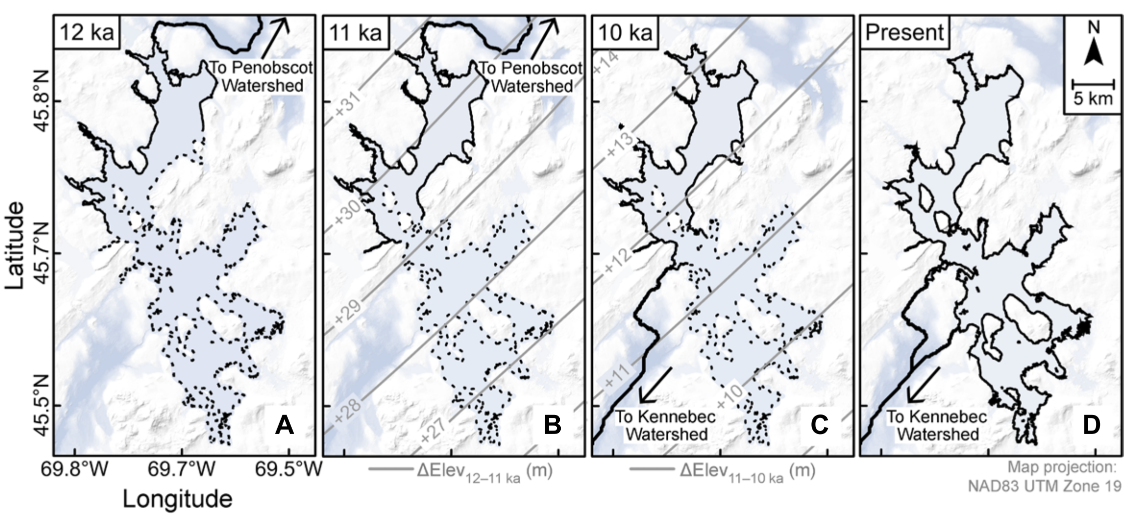

Figure 2. Reconstructed drainage from Moosehead Lake at (A) 12 ka, (B) 11 ka, with gray contours showing elevation change from 12 ka to 11 ka, (C) 10 ka, with gray contours showing elevation change from 11 ka to 10 ka, and (D) present. Solid shorelines follow the topographic contour of the lake outlet elevation. Dotted lines show the modern shoreline in areas where submerged paleo-shorelines cannot be traced due to inadequate bathymetric data. Note the drainage direction shift from 11 ka to 10 ka.

EFFECT OF GLACIAL ISOSTATIC ADJUSTMENT ON SEDIMENT TRANSPORT IN RIVERS

Topographic change due to GIA would have altered the capacity of Maine's rivers to entrain and transport sediment. Drainage reorganization would have altered the upstream area contributing water discharge to each point along the rivers in affected drainage basins. Isostatic deformation and rebound would have altered the slopes of channels flowing perpendicular or oblique to GIA contours in Figure 1. River channel width and depth would have adapted to these imposed changes in discharge and slope. Accounting for these effects, we calculated proxies for GIA-induced changes in sediment entrainment capacity and bedload sediment transport rate.

In gravel-bedded rivers, the shear stress exerted on the riverbed (τ_b) at bankfull flow typically corresponds to the entrainment threshold of the median grain size on the bed (D_{50}) (Parker et al., 1982). We calculate the change in D_{50} (ΔD_{50}) as a proxy for the impact of GIA on sediment entrainment capacity.

The sediment entrainment threshold is generally written in terms of the dimensionless shear stress (the Shields number, τ^*):

$$\tau^* = \frac{\tau_b}{(\rho_s - \rho) g D_{50}}, \quad (1)$$

where ρ_s and ρ are the densities of sediment (2650 kg/m^3) and water (1000 kg/m^3) and g is the acceleration due to gravity. In gravel-bedded rivers, τ^* typically falls between 0.03 and 0.07 (Buffington and Montgomery, 1997), and a particle tracer study by Snyder et al. (2009) found that this expectation holds for gravel entrainment in Maine rivers.

During steady, uniform flow in wide channels, the bed shear stress can be approximated as

$$\tau_b = \rho g H_{bf} S, \quad (2)$$

where H_{bf} is the bankfull flow depth and S is the channel slope. Substituting this approximation for τ_b into Equation 1 and solving for D_{50} yields a predictive relation for bed sediment size (D_{pred}) in terms of H_{bf} and S, which can be estimated from GIA-corrected DEMs:

$$D_{pred} = \frac{\rho g H_{bf} S}{(\rho_s - \rho) g \tau^*}. \quad (3)$$

We estimated H_{bf} using hydraulic geometry relations calibrated for Maine (Dudley, 2004), which relate upstream drainage area (A) to channel geometry, assuming a constant terrestrial runoff rate. Our estimates therefore isolate the effect of drainage basin rearrangement on channel morphology, onto which spatiotemporal variability in runoff (e.g., due to climate or vegetation) would be superimposed. We adopted a reach-averaging approach to estimate S, dividing each river into reaches based on channel orientation (excluding dams and mainstem lakes; 30 km average reach length; Fig. S6). We calculated S as the elevation change over a river reach divided by horizontal reach length. By averaging across reaches, we eliminate effects of localized aggradation from estimates of ΔS. To evaluate the sensitivity of our approach to the specific hydraulic geometry relation used, we repeated our calculations with an alternative solution for D_{pred}, which uses bankfull channel width (W_{bf}) instead of H_{bf} (Supplemental Material). Trends in ΔD_{pred} are consistent across both approaches (Tables S1 and S2).

The sediment transport rate is likewise influenced by upstream drainage area and local channel slope. In addition to D_{pred}, we calculated the fractional change in bed load sediment flux ($\Delta Q_s/Q_s$) driven by GIA, which provides an additional means of testing hypothesized connections between GIA and fluvial sedimentation:

$$\frac{\Delta Q_s}{Q_{s,i}} = \frac{A_f^a S}{A_i^a S} - 1, \quad (4)$$

where the subscripts i and f denote initial and final conditions and $a = 1.05$ in Maine (Dudley, 2004).

Snyder et al. (2013) demonstrated that Equation 3 successfully predicts D_{50} in coarse-bedded rivers in Maine using estimates of S and H_{bf} derived from DEMs (within a factor of two at 80% of their 276 survey sites). Analogous bed material, channel morphology, longitudinal profiles, and deglacial history suggest that Equation 3 should also hold in the Kennebec and Penobscot Rivers. To test this expectation, we surveyed the grain size distribution of bed sediment at eight sites (four per river). Using the Wolman (1954) technique, we measured the intermediate axis of 100 randomly selected clasts along transects perpendicular to the riverbank. Our predicted and measured D_{50} match within 1 cm at seven of eight sites (Fig. 3, Table S3). At all eight sites, predictions meet Parker et al.'s (2007) criterion for predictive success ($D_{pred}/D_{50} = 0.5$–2).

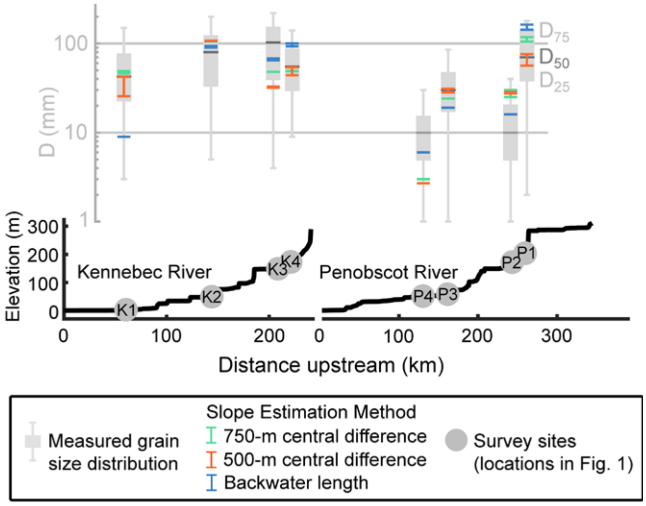

Figure 3. Measured bed grain size distributions compared with predicted median diameter using three methods to estimate channel slope. Box plot whiskers display the range of grain size measurements at each site, excluding outliers (see Supplemental Material). Prediction ranges show values within ±1 digital elevation model raster cell of each site.

Our calculations suggest that GIA influenced D_{pred} throughout the Holocene through the effects of altered drainage basin geometry on H_{bf} and W_{bf} and of crustal deformation on S. The drainage divide shift at Moosehead Lake is associated with a 28% increase and 14% reduction in total area of the Kennebec and Penobscot watersheds, respectively (Fig. 4F). The fractional change is greatest in the upper watersheds, where Moosehead Lake drainage represents a larger proportion of total discharge. GIA increased overall channel slope since 11 ka (17% across the entire Kennebec River, and 19% across the Penobscot). Local slope changes are controlled by river orientation relative to the crustal deformation gradient. GIA steepened reaches flowing south- and eastward by 5%–44% while reducing the slope of reaches flowing westward by 16%–33% (Fig. 4E).

Drainage reconfiguration increased sediment transport capacity in the upper Kennebec River while hampering sediment transport through the Penobscot River West Branch. Our findings support interpretations that the North Anson Formation represents a "change of regime" in the Kennebec watershed (Borns and Hagar, 1965, p. 1246) related to Moosehead Lake drainage (Kelley et al., 2011). At the North Anson Formation, flows carrying newly mobilized, coarse sediment (Fig. 4C) encountered low-relief, still isostatically depressed topography where aggradation was favored (Fig. 4D).

We also find that reduced sediment delivery to the lower Penobscot River may have contributed to the end of sand deposition at its paleodelta. The loss of Moosehead Lake drainage reduced sediment flux through the upper Penobscot watershed, likely reducing its overall sediment load (Fig. 4D). Lower rates of oceanward sediment transport may have been superimposed on a depletion of glacial sediment

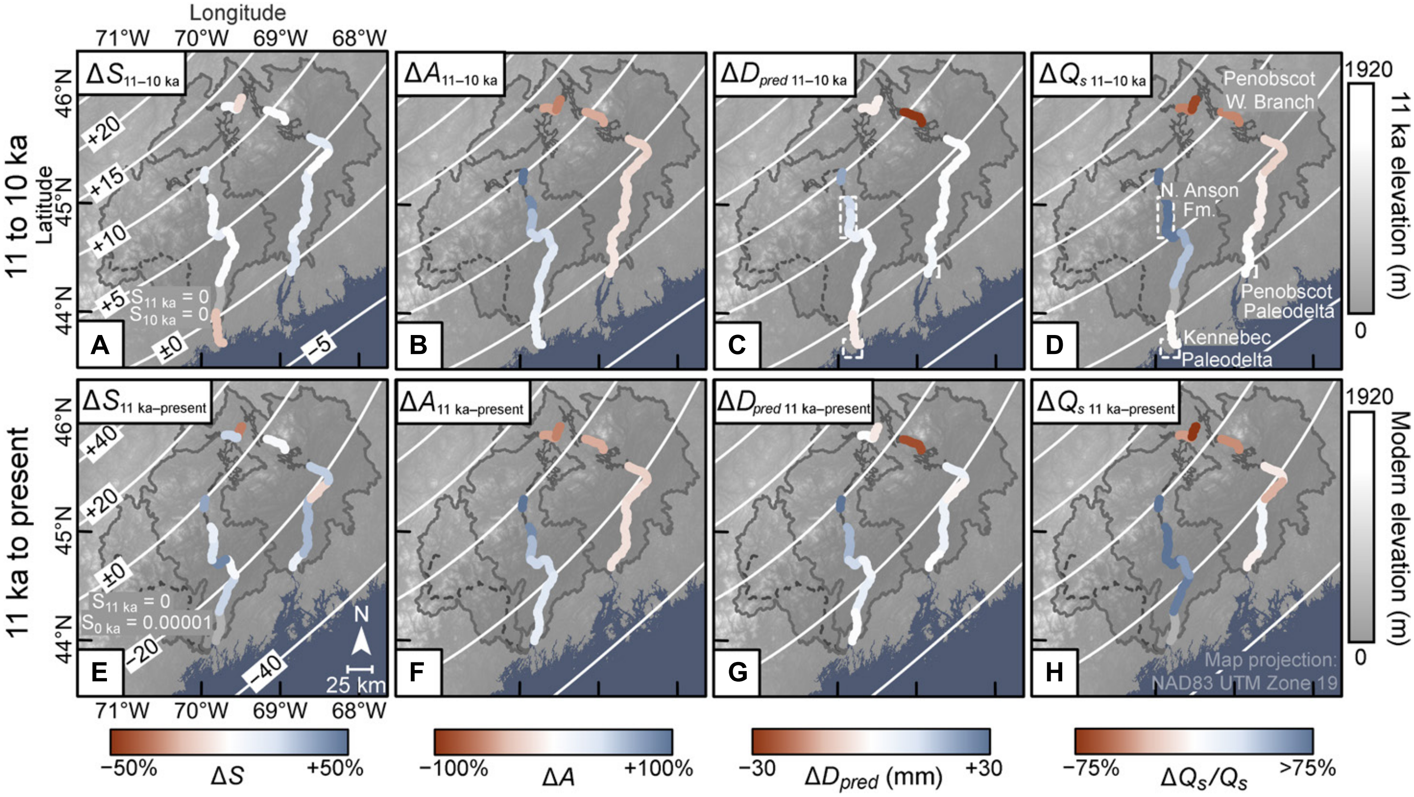

Figure 4. Glacial isostatic adjustment (GIA)-driven changes in (A, E) channel slope, *S*; (B, F) drainage area, *A*; (C, G) the median grain size of mobile sediment, D_{pred}; and (D, H) bed load sediment flux, Q_s. Top row (A–D): changes from 11 ka to immediately after Moosehead Lake drainage reversal; bottom row (E–H): net change since 11 ka. Contours show elevation change due to GIA during the specified time interval. Sites that recorded changes in fluvial deposition are indicated with white dashed boxes in C and D and labeled in D.

sources, base level interactions (as tens of meters of fluvial relief were submerged between 11 ka and 9 ka), and/or a drier precipitation regime.

Since the early Holocene, GIA enhanced sediment mobility in the Kennebec River, while the combination of reduced drainage and channel slope change driven by differential uplift produced variable effects on sediment transport along the Penobscot River (Figs. 4G and 4H). In general, early Holocene drainage area exchange influenced ΔD_{pred} less than did slope, but its impact on $\Delta Q_s/Q_s$ persists today in both watersheds.

CONCLUSIONS

In Maine, GIA in response to Laurentide Ice Sheet retreat reconfigured drainage basins and steepened the gradients of river reaches flowing perpendicular to the crustal deformation gradient. We demonstrate that the magnitude of isostatic rebound since 11 ka was sufficient to redirect drainage at Moosehead Lake from the Penobscot to the Kennebec River, changing their drainage areas by –20% and +30%, respectively. Channel slope increased (up to +40%) or decreased (up to –30%) depending on river orientation relative to differential uplift. By modulating the capacity of rivers to entrain and transport sediment, GIA influenced the reworking of glacially deposited sediment for several millennia after ice retreat. These estimates isolate the effect of GIA on watershed topography, which was superimposed on changes in runoff. Our results highlight that the sedimentary composition of Maine's rivers reflects a time-dependent control on sediment transport that was altered over the course of isostatic rebound, operating alongside any changes in sediment supply. More generally, our results suggest that rivers record the effects of solid Earth deformation on sediment transport, in addition to variations in sediment supply and climate-induced changes in water flux.

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