Climatic pacing of landscape responses to late-Cenozoic Yukon River capture

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Unreferenced introductory paragraph

Late-Cenozoic climate changes are hypothesized to exert fundamental controls on erosion. Geomorphic constraints on the concurrent response of bedrock rivers, which set erosion rates and patterns in most of Earth's landscapes, remain elusive. Here, we use new cosmogenic isotope and luminescence ages of prominent bedrock terraces along the Fortymile River (Yukon River basin) to reconstruct a ~5-million-year (Ma) history of fluvial adjustment to late-Cenozoic climate and capture-triggered base-level lowering. Cordilleran Ice Sheet (CIS)-induced Yukon River capture imposed Fortymile River base-level lowering at 2.6 Ma, but ensuing bedrock incision occurred in pulses from 2.4–1.8 Ma and at ~1 Ma. These pulses of incision disrupted longer intervals of alluviation under near-consistent climate forcing from 4.8–2.4 and 1.8–~1 Ma. The Fortymile River ultimately exports sediment to the Bering Sea, where provenance and accumulation rate changes since 4.3 Ma match variations in Fortymile River incision. Our results link alluviation and incision to steadiness and change, respectively, in the amplitude-frequency

of climatic forcing under externally imposed base-level lowering, and uniquely constrain hypothesized relationships between late-Cenozoic climate, river response, and landscape erosion.

Main Text

Bedrock river incision sets the pace and pattern of landscape evolution over most of Earth's surface, and is thought to tend toward a steady state of rate equilibrium with rock uplift over long (~10^6-yr) timescales[1,2]. Strath terraces cut into bedrock preserve river channel remnants above the active channel and permit measurement of long-timescale histories of bedrock incision and concomitant uplift[3–5]. Terraces also record the fundamental unsteadiness of river erosion over time as they respond to externally imposed base-level lowering (e.g., by tectonic uplift[3,4] or drainage reorganization[6,7]), because strath terrace formation requires intervals of valley-widening and alluviation that temporarily inhibit vertical incision into bedrock[5, 8-10]. Although incision hiatuses may be stochastically triggered (e.g., by mass wasting events)[9], forcing by late-Cenozoic climate change is believed to exert the primary control on the incision of bedrock channels, the timing of terrace formation[4,8,10], and thus related erosion in the drainage network[11-14].

Whether and how climatic change may affect the related processes of erosion, bedrock incision and terrace formation remain contentious[12–16]. Changes in late-Cenozoic climate include evolution of orbitally paced glacial-interglacial cycles and increases in the dominant period and amplitude of these cycles at ~2.6 and ~1 Ma[17,18]. These late-Cenozoic climate cycles forced periodic fluctuations in continental precipitation[19] such that concomitant variations in discharge link climatic forcing to erosional landscape response[20–21]. Climate-forced variations in the ratio of discharge to fluvial sediment flux are thought to drive alternation between intervals of terrace-forming alluviation and bedrock incision across either individual climate cycles[4,8] or increases in the period and amplitude of forcing[12,13,20]. Experimental data imply that bedrock incision may self-suppress by auto-generating sediment flux in excess of fluvial transport capacity, triggering alluvial intervals under constant discharge conditions analogous to steady climatic forcing[Finnegan et al., 2007; sklar and dietrich, 2001].Conversely, increases in the forcing spectrum acutely amplify sediment output from steadily uplifting and uniformly erodible model landscapes[20], consistent with hypotheses of climate-enhanced erosion since ~2–4 Ma inferred from worldwide basin records of terrigenous sedimentation[12,13]. However, observational constraints capable of directly testing whether and how real fluvial landscapes responded to changes in the frequency of late-Cenozoic climate forcing are rare.

The Fortymile River drains the Yukon-Tanana Upland region of eastern Alaska to the Yukon River in Canada, and provides a landscape uniquely suited to test hypotheses of river response to late-Cenozoic climate (Fig. 1A-B). Sediment eroded from the Yukon-Tanana Upland is ultimately deposited in the Bering Sea, where core U1341B (Fig. 1A) records 4.3 Myr of sedimentation rate increases and pulses of Yukon-Tanana-derived sediment[22] concurrent with key changes in climate cyclicity at ~2.6 and ~1 Ma. Temporal variations in efflux related to Yukon-Tanana Upland erosion also reflect base-level lowering of Yukon River tributaries imposed by reorganization and near-doubling of the Yukon drainage area[23-26] induced by the ~2.6 Ma CIS maximum extent[27]. Downstream of the breached Pliocene divide, Yukon River capture initiated the abandonment and deep (≥260 m) incision of a continuous alluvium-mantled strath terrace (here termed T1) along the lower ~200 km of the Fortymile River[26]. The T1 elevation profile grades to the modern West Fork headwaters and reflects equilibrium conditions in the Pliocene Fortymile River[26,28]. Volcanic rocks that re-surfaced part of the Fortymile River headwater landscape at 70 Ma remain well-preserved and thus reflect exceptional geomorphic stability in the basin prior to CIS-related incision[29]. Nearly ice-free conditions during later glaciations[25] allowed preservation of the subsequent fluvial landscape in two lower strath terrace levels that record subsequent hiatal intervals in the capture-triggered incision. Post-35 Ma tectonic quiescence[30] and homogeneous landscape erodibility, implied by predominantly Paleozoic–Mesozoic-aged crystalline bedrock[31], indicate that the Fortymile River terraces directly record the fluvial response to late-Cenozoic climate change and river capture.

We assess Fortymile River response to late-Cenozoic capture and climate change by pairing cosmogenic isotope and luminescence dating techniques with digital topography analysis (Fig. 1B). We delineate the river network, extract channel elevations, and compute normalized channel steepness (k_{sn}, a geomorphic metric proportional to incision rate[32,33]) on a combination of 5 and 50 m/pixel digital topography that spans the Alaska-Yukon international border. We also map and extract elevations for the three terrace levels along the lower 200 km of the Fortymile River from this digital dataset. Cosmogenic isotope techniques quantify landscape erosion rates and sediment deposition timing. To date gravel deposition in the former river channel, we sampled four high terrace sites (T1; three on the West Fork, one on the North Fork) and three middle terrace sites (T2) for cosmogenic $^{26}Al/^{10}Be$ isochron burial dating[34,35]. We sampled alluvium at three floodplain terrace sites within ~5 m of the modern channel elevation for infrared-stimulated luminescence (IRSL) dating of the current river profile[36], which provides a lower vertical and younger temporal datum for unbiased computation of river incision[10] inferred from the higher elevation cosmogenic $^{26}Al/^{10}Be$-dated terrace deposits and strath height measured in the field via laser range-finder. Finally, concentrations of cosmogenic ^{10}Be in quartz from modern sand quantify basin-averaged rates of denudation[37,38] in three North Fork tributaries that ascertain 10^3–10^4 yr landscape response to incision (integration time reflects measured erosion rates). We also re-analyze previously published Fortymile River cosmogenic data, including eight tributary erosion rates and a single $^{26}Al/^{10}Be$ isochron burial age[26].

The Fortymile River strath terraces record fluvial aggradation and bedrock incision since ~5 Ma. Cosmogenic isochron burial ages of the base (4.8±0.7 Ma) and top (2.4±0.2 Ma) of a ~30 m-thick gravel deposit on the deeply incised (≤260 m) T1 date the onset of terrace formation and abandonment, respectively, near the Fortymile-Yukon River confluence (Fig. 1B-C, 2A). These dates mark a change from net Pliocene gravel deposition to early Pleistocene bedrock incision forced by CIS-induced Yukon River capture[23-27]. The equilibrium river profile geometry of the T1 tread[26] implies a balance between fluvial sediment transport and climatic forcing[28,39] during the depositional interval bound by the T1 outlet ages (Fig. 2A), consistent with hypothesized landscape stability under equable Pliocene climate[12,13].

Cosmogenic isochron burial ages of the T1 gravel decrease monotonically upstream of the Fortymile-Yukon River confluence and mark the latest timing of gravel deposition on the high terrace at 2.4±0.2 Ma near the Fortymile outlet, 2.1±0.2 Ma near the river midpoint at the North and West Fork confluence, and 1.8±0.1 and 1.8±0.2 Ma in the North and West Fork headwaters, respectively (Fig. 1B-F, 2A). Viewed as maximum constraints on channel abandonment, the upstream-decreasing T1 ages imply headward propagation of bedrock incision at an average horizontal pace of ~270 km/Myr throughout the basin from 2.4 to 1.8 Ma. The implied kinematic wave pattern of T1 incision matches model-based expectations of detachment-limited incision[39]. In contrast, isochron burial ages of the near-uniformly incised (~30-40 m above the floodplain) T2 near the outlet (0.8±0.1 Ma), midpoint (1.1±0.2 Ma), and West Fork headwaters (1.0±0.1 Ma) all cluster around 1 Ma. Although we date T2 only in the West Fork, this terrace also flanks the North Fork. In both cases, T2 grades to the 1.8 Ma upstream extent of

T1 (Fig. 2A), bracketing an interval of aggradation that stalled incision from 1.8–1 Ma. Alluviation recorded by T2 implies that sediment flux from the adjacent eroding landscape exceeded Fortymile River transport capacity under consistent 40-kyr climatic forcing, consistent with independent experimental results[Finnegan et al., 2007; Sklar and Dietrich, 2001]. Abandonment of T2 at 1 Ma coincides with the globally recognized mid-Pleistocene climatic transition from 40 kyr cycles to high-amplitude 100 kyr glacial-interglacial cycles and implies concomitant increases in precipitation and runoff[19,20] sufficient to convert T2 alluvium from channel armor to erosive tools [Finnegan et al., 2007; Sklar and Dietrich, 2001]. Unlike T1, the pattern of T2 incision implies spatially near-uniform channel lowering consistent with expectations of transport-limited incision[39]. IRSL ages of sand on the minimally incised (<5 m) floodplain terrace (2.4±0.2, 4.8±0.9, and 5.0±0.3 ka) demonstrate the mid–late-Holocene age of the modern channel profile.

Headwater–knickzone partitioning of tributary erosion rates and k_{sn} on both Forks indicates that the Fortymile River landscape continues to adjust to the pulse of mid-Pleistocene incision implied by the T2 ages (Fig. 2A-B). Basin-averaged tributary erosion rates integrate ^{10}Be production over 20-40 kyr and increase by a factor of 2.5 from the low-relief, low-k_{sn} headwaters (10 mm/kyr) to the deeply-incised, high-k_{sn} knickzone (25 mm/kyr). Tributary k_{sn} and erosion rates are generally higher above the confluence along the North Fork than the West Fork, and a rounded knickpoint divides the West Fork headwaters from its knickzone, whereas no knickpoint occurs on the North Fork (Fig. 2A). These profile patterns imply that headward migration of West Fork incision stalled at 1.8 Ma below the low-relief, low-k_{sn}, slowly eroding headwaters, where T1 grades to the modern landscape. In contrast, the modern North Fork channel cuts ~50 m into the 1.8 Ma upstream extent of T1 and T2 in the comparatively higher-relief, higher-k_{sn}, more rapidly eroding headwaters, indicating that incision lowered this part of the system after the ~1 Ma abandonment of T2. We suggest that *in-situ* basin topography preconditioned different stream power responses to enhanced climatic forcing at 1 Ma; unlike the high-relief North Fork headwater landscape, the low-relief West Fork headwaters may simply not have been steep enough to incise[e.g.,Montgomery and Brandon, 2002].

Pliocene-Pleistocene proxy records show contemporaneous changes in Fortymile River incision, efflux, and late-Cenozoic climate in four phases (Fig. 3A-D). Initially, under equable Pliocene climate[12-14], alluvial Fortymile River conditions covered T1 in ~22 m of gravel near the headwaters of the Pliocene Yukon River (Fig. 1A) while locally derived sediment accumulated slowly and steadily in the Bering Sea[22]. Subsequently, intensified Northern Hemisphere glaciation across the ~2.6 Ma Pliocene-Pleistocene transition[17,18] led to CIS-maximum-induced Yukon River capture[23-27], which abruptly triggered rapid and deep (308±3 mm/kyr) Fortymile River incision into Yukon-Tanana Upland bedrock from 2.4–1.8 Ma, concurrent with a tripling of Bering Sea sedimentation and provenance shift toward a Yukon-Tanana source[20]. Fortymile River incision then stalled from 1.8 to ~1 Ma; T2 aggraded during this non-incising interval, implying sediment flux in exceedance of the river's transport capacity under consistent ~40 kyr early-Pleistocene climate cycles[15,16,18]. Accordingly, during the 1.8–1 Ma incision hiatus marked by T2 aggradation, Bering Sea sedimentation slowed ~fourfold with equivalent local and Yukon-Tanana Upland source provenance[20]. Finally, T2 abandonment occurred following the globally recognized ~1 Ma mid-Pleistocene transition to high-amplitude 100 kyr climate cycles[15,16], likely in response to concomitant discharge enhancement[18]. Subsequent 29±7 mm/kyr Fortymile River incision (~30-40 m) to within ~5 m of the current channel paced a transient threefold increase in Bering Sea sediment accumulation, and a sharp increase in Yukon-Tanana Upland provenance[20]. Together, these records document shifts between (1) non-incising, low-efflux intervals of

Fortymile River alluviation under steady climatic oscillations, and (2) high-efflux intervals of bedrock incision timed with increases in the amplitude and period of climatic oscillation under Yukon River capture-driven base-level lowering.

Using sensitive cosmogenic and luminescence chronometers, we have directly quantified the tempo and style of fluvial processes since ~5 Ma in the well-preserved, tectonically inactive and consistently erodible Fortymile River landscape; an ideal environment for isolating river response to changing climate and base level. Our data show profound synchronous shifts in fluvial process (i.e., alluviation to incision), rate, and sediment export[22] that occur across key frequency changes in late-Cenozoic climate (Fig. 3). Following cumulative aggradation and equilibrium profile development[26] across the climatically equable Pliocene, Fortymile River incision initiated at 2.4 Ma in response to Yukon River capture (Fig. 1A) and progressed rapidly as a kinematic wave for ~0.6 Myr (Fig. 2A) during the onset of 40-kyr-period climate forcing[15,16,18] (Fig. 3). Sediment flux from concomitant erosion of the adjacent landscape initiated a non-incising interval of alluviation from 1.8 to ~1 Ma under consistent 40-kyr climate forcing. The mid-Pleistocene climatic transition to high-amplitude 100-kyr-period forcing triggered incision at ~1 Ma that rejuvenated landscape response to Yukon river capture. Far outlasting the mid-Pleistocene incision pulse, 10^4-yr basin-averaged erosion of the deeply incised landscape occurs twofold faster than in the minimally incised headwater landscape at ≤25 and 10 mm/kyr, respectively (Fig. 2B). Consistent with globally measured sedimentation[12,13], experimental[Finnegan et al., 2007; Sklar and Dietrich, 2001], and modeling results[8,20], our Fortymile River field data show tight coupling between terrace formation, fluvial incision, sediment dynamics, and late-Cenozoic climate change. Our dataset provides the first empirical demonstration of increased river incision across the mid-Pleistocene climatic transition, and generally supports hypotheses of erosional landscape evolution dependence on the frequency of climatic forcing[8,12,13,20,28].

Methods

The isochron method[34,35] requires sampling quartz-bearing sedimentary material archiving a range of pre-burial isotope concentrations at a single depth horizon (indicative of a common burial history) buried by several m of sediment (enough to suppress post-burial production and permit isotope decay). We sampled four shallow pits (sample horizons 2-5 m depth), one deep (~25 m) quarry in the high Fortymile River terrace gravels, and three shallow pits in the middle Fortymile River terrace gravel (Data S1, Figs. S1-7). We prepared samples at the University of Vermont and measured $^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ ratios at the Purdue Rare Isotope Measurement Laboratory (Data S2-3). We correct each isotope measurement for background isotope levels by subtracting the average of all blank measurements from each measurement (Data S4-5), and formally propagate the standard deviation of the blank measurements into concentration uncertainties (Data S2-3). Resulting concentrations are equivalent within 1.5% to concentrations based on batch-specific blank corrections (Fig. S9). The isochron method involves fitting a line to measured nuclide concentrations and analytical uncertainties, with ^{10}Be and ^{26}Al on the x- and y-axes, respectively[34,35]. Samples with a common pre-burial history contain ^{10}Be and ^{26}Al concentrations that reflect post-burial decay away from the surface production $^{26}Al/^{10}Be$ ratio; a line thusly fit to these concentrations can be used to both (a) quantify the duration of post-burial decay and (b) identify and omit samples with dissimilar pre-burial history (i.e., outliers). We use a MATLAB implementation of the isochron approach[35] that applies a linearization factor to correct post-burial production among the ^{10}Be concentrations; the y-intercept reflects post-burial isotope production, but the linearization of ^{10}Be preserves the slope associated with decay of the inherited pre-burial concentrations. We identify two of 47 total isotope concentration pairs as outliers $>2\sigma$ below the regression and omit these from the final linear fits to sample suites 17ALR306 and 16ALR233 (Fig. 1D and I). We quantified basin-averaged erosion rates using ^{10}Be concentrations measured in quartz from modern river sand (250-850 μm) at ten tributary outlets on the Fortymile River (Data S1). ^{10}Be accumulates in quartz at Earth's surface to depths commensurate with cosmic ray e-folding length (~0.6 m in rock), at rates determined largely by latitude and altitude and inversely proportional to erosion rate (*21*). Dividing the ^{10}Be production depth by a given measured erosion rate thus estimates the duration of erosion at the measured rate. Given similar rock type and durability throughout the

Fortymile River basin and minimal lithologic variation within the sampled tributary catchments[31], we assume that quartz sampled at the 250-850 μm grain size range is well-mixed and represents erosion throughout the tributary catchment upstream. We use a MATLAB likelihood estimation routine to compute the most likely elevation and latitude from pixel values within each sample catchment and use the CRONUS online calculator (https://hess.ess.washington.edu/) to assess erosion rates based on ^{10}Be concentrations measured in quartz sand from each outlet (Data S6-7). Topographic shielding minimally impacts Fortymile River ^{10}Be production rates because topography is relatively open in the basins we sample[38], with average hillslopes of 5° to 20°. Similarly, the mean winter snow depth of <50 cm measured at Fortymile Basin SNOTEL sites 1275 and 1189 (https://wcc.sc.egov.usda.gov/nwcc/) confers shielding effects equivalent to a 1-3% reduction in ^{10}Be production[40]. Consequently, we assume minimal snow and topographic shielding effects on ^{10}Be production rate, and report uncertainties computed by CRONUS that reflect these assumptions (i.e., shielding factor = 1; Data S6-7). We collected luminescence dating samples from the modern floodplain at three locations (Data S1) on the West Fork Fortymile River within 5 m elevation of the active channel (Figs. S10-12). We used opaque metal pipes to sample silt and sand from shovel-excavated cutbank exposures; mineralogy of the samples proved suitable for feldspar infrared stimulated luminescence (IRSL) dating. IRSL sample processing and analysis was conducted at the Utah State University Luminescence Lab following standard procedures[36]. We used Topographic Analysis Kit[32] and Topotoolbox[33] MATLAB codes to compute k_{sn} averaged on 1-km river distance bins for the Fortymile River network in a mosaic of 5 m/pixel digital elevation models (DEMs) in Alaska and a 50 m/pixel DEM in Yukon. For this computation we resampled the entire DEM mosaic to 50 m/pixel to absorb potential biases in k_{sn} that might result from discrepant DEM resolutions across the international border. Figure 2B plots km-averaged k_{sn} sampled from the channel network (trunk and tributaries) within a 20 km-wide river-parallel swath[32] shown on Figure 1B.

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Competing interests: Authors declare no competing interests.

Data and materials availability: Cosmogenic and luminescence data generated in this study are available in the supplementary materials and online at doi.org/10.5066/P9XVMTAK. We modified a MATLAB code developed by D. Granger to compute cosmogenic isochron burial ages. IfSAR-based Alaska DEMs are available by searching earthexplorer.usgs.gov/. Yukon DEMs are available by searching viewer.nationalmap.gov/advanced-viewer/.

Supplementary Materials:

Figures S1-S12

External Databases S1-S8 as a single Excel file.

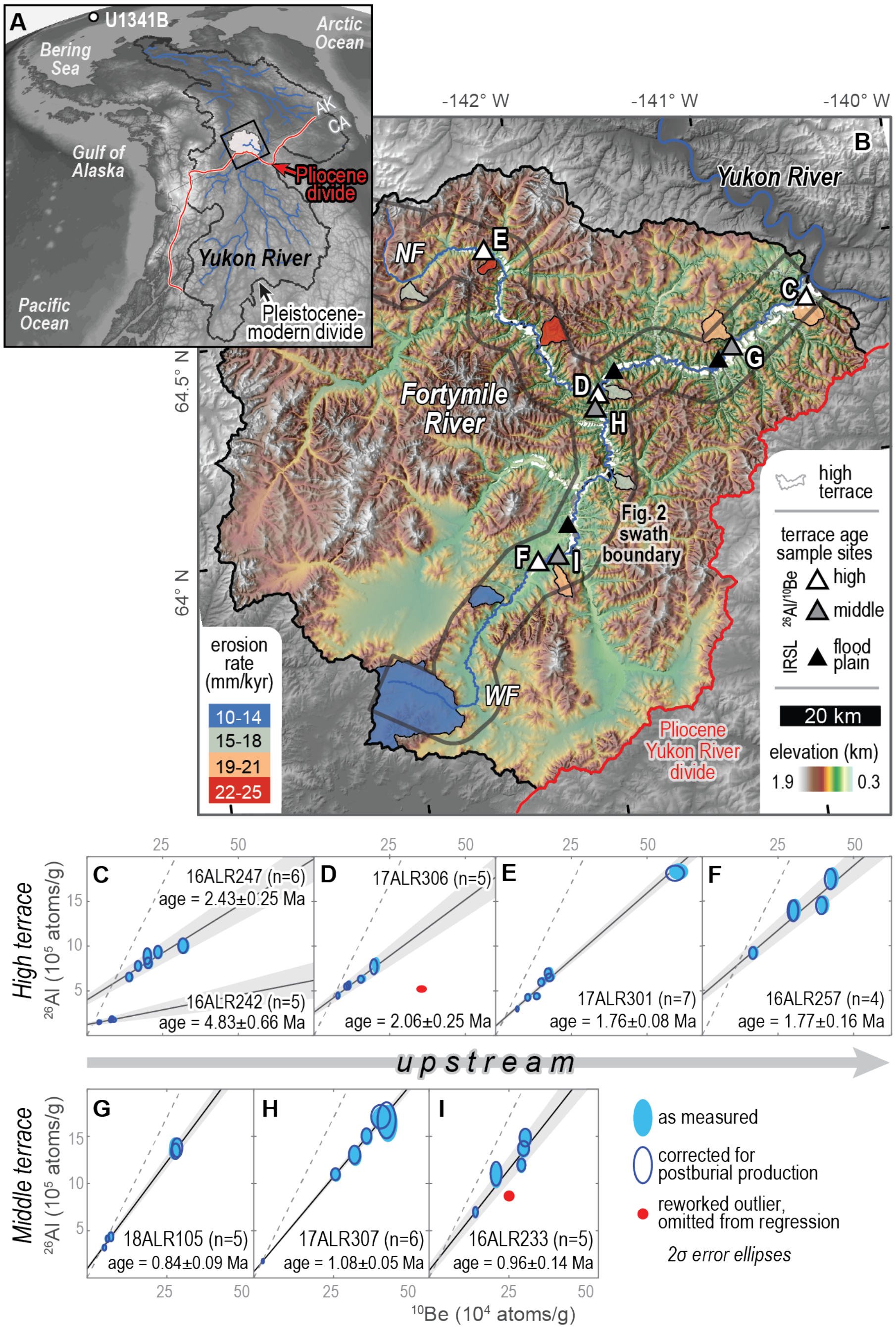

Fig. 1. Fortymile River setting and cosmogenic results. (A) Oblique northwest view of Fortymile River basin (white polygon), Yukon River basin and captured Pliocene divide[23-25], and adjacent ocean basins. (B) Fortymile River geomorphic map, sample locations, and cosmogenic ^{10}Be-based erosion rates. IRSL ages of floodplain sand range from 2-5 ka. (C-I) Cosmogenic ^{26}Al/^{10}Be isochron burial age plots. Dashed grey line is ^{26}Al/^{10}Be surface production ratio and ~zero age. Regression uncertainties are 1σ.

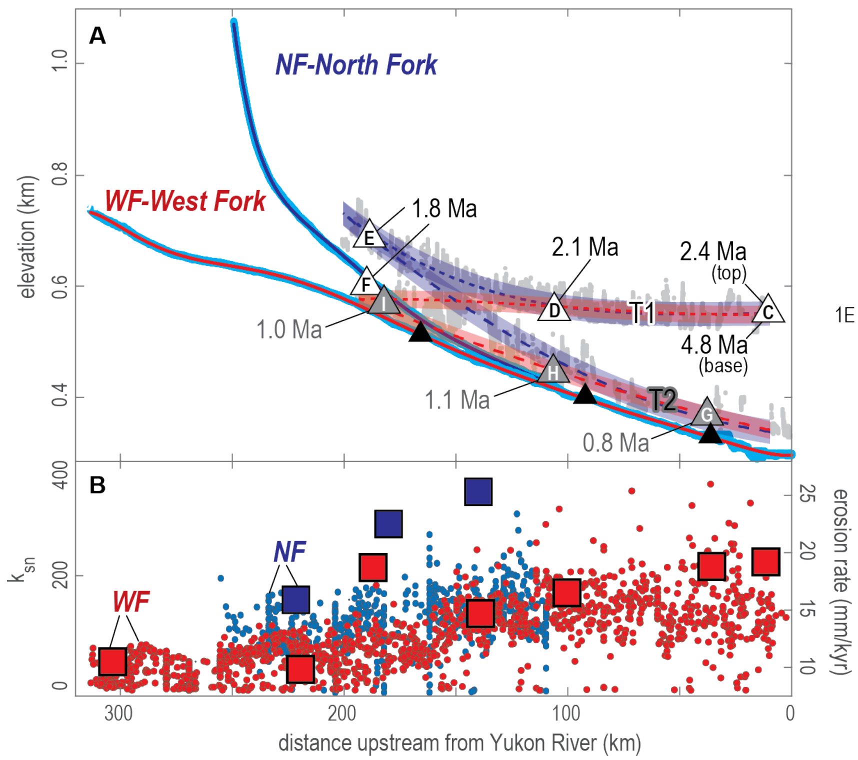

Fig. 2. Fortymile River profiles. (A) Fortymile River channel elevations (cyan line) and polynomial fits, terrace pixel elevations, sample locations, and polynomial fits to highlight terrace form and continuity. Grey dots are pixel elevations within terrace surfaces mapped on Fig. 1; dotted line fit high terrace T1; dashed line fit middle terrace T2; envelopes represent root mean square error of polynomial fit. Age sample locations symbolized and lettered as in Figure 1, cosmogenic $^{26}Al/^{10}Be$ isochron burial ages listed. (B) ^{10}Be-derived tributary erosion rates (large boxes) and km-averaged normalized channel steepness (k_{sn}, small dots; blue = North Fork, red = West Fork) sampled within the 10 km-wide swath profile depicted in Figure 1B. Erosion rate uncertainties are <10%; boxes obscure error bars.

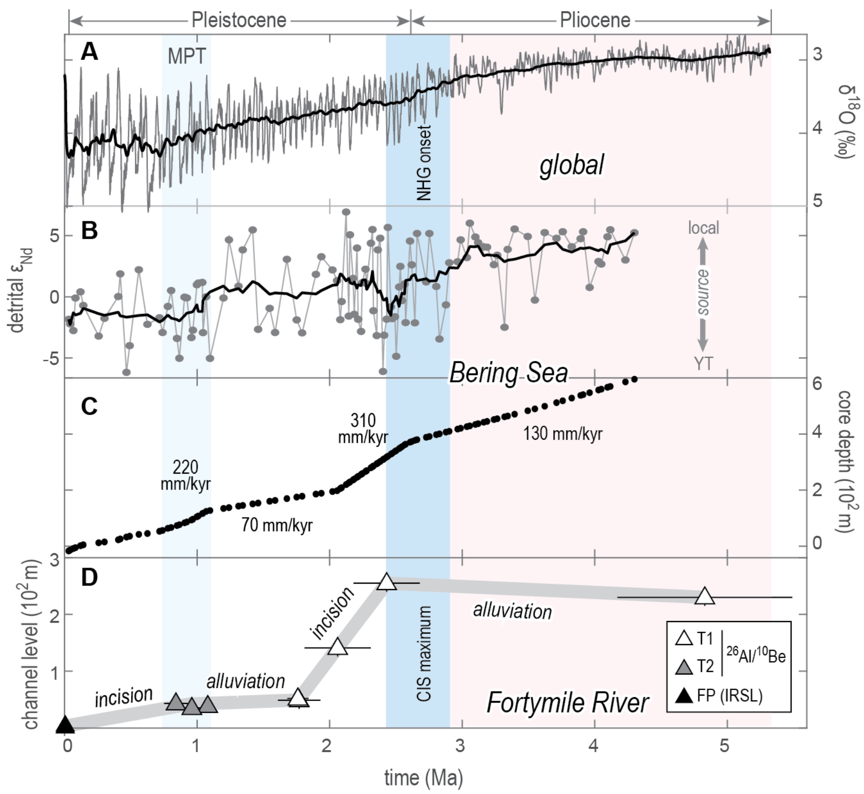

Fig. 3. Late-Cenozoic variations in climate, Bering Sea sedimentation, and Fortymile River incision. (A) The LR04 stack[17] of global benthic $\delta^{18}O$, black line depicts 10^5 year moving average. (B) Detrital ε_{Nd} values from Integrated Ocean Drilling Program (IODP) Site U1341B in the Bering Sea; more negative values reflect increased Yukon-Tanana Upland (YT) sedimentary provenance[22]. (C) Age-depth model for IODP Site U1341B[22] from biostratigraphy, magnetostratigraphy, and astronomically-tuned chemostratigraphy; detrital sediment fraction is ~40 weight %. (D) Cosmogenic $^{26}Al/^{10}Be$ isochron burial ages and infrared-stimulated luminescence (IRSL) ages plotted against height above the mid-late Holocene aged floodplain (FP)[10]. Cordilleran Ice Sheet (CIS) maximum extent[27] coincides with the onset of widespread Northern Hemispheric Glaciation (NHG) and marks the timing of Yukon River capture[23-26]; mid-Pleistocene climate transition (MPT) from ~40 to ~100 ka glacial-interglacial cycles.