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Early Pleistocene climate-induced erosion of the Alaska Range formed the Nenana Gravel

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ABSTRACT

The Pliocene-Pleistocene transition resulted in extensive global cooling and glaciation, but isolating this climate signal within erosion and exhumation responses in tectonically active regimes can be difficult. The Nenana Gravel is a foreland basin deposit in the northern foothills of the Alaska Range (USA) that has long been linked to unroofing of the Alaska Range starting ca. 6 Ma. Using ^{26}Al/^{10}Be cosmogenic nuclide burial dating, we determined the timing of deposition of the Nenana Gravel and an overlying remnant of the first glacial advance into the northern foothills. Our results indicate that initial deposition of the Nenana Gravel occurred at the onset of the Pleistocene ca. 2.34 Ma and continued until at least ca. 1.7 Ma. The timing of initial deposition is correlative with expansion of the Cordilleran ice sheet, suggesting that the deposit formed due to increased glacial erosion in the Alaska Range. Abandonment of Nenana Gravel deposition occurred prior to the first glaciation extending into the northern foothills. This glaciation was hypothesized to have occurred ca. 1.5 Ma, but we found that it occurred ca. 0.39 Ma. A Pleistocene age for the Nenana Gravel and marine oxygen isotope stage 10 age for the oldest glaciation of the foothills necessitate reanalysis of incision and tectonic rates in the northern foothills of the Alaska Range, in addition to a shift in perspective on how these deposits fit into the climatic and tectonic history of the region.

INTRODUCTION

The Pliocene-Pleistocene transition represents a dramatic shift in global climate to cooler temperatures and widespread glaciation, particularly in the high latitudes (e.g., Shackleton and Opdyke, 1977; Lisiecki and Raymo, 2005). In tectonically active regimes, disentangling this climate signal can be challenging, since tectonic activity can either mute or amplify the effects of climate on erosion and exhumation (e.g., Raymo and Ruddiman, 1992; Yanites and Ehlers, 2012). In southern Alaska, USA, growth of the Alaska Range coincided with global cooling, beginning in the late Miocene (ca. 6 Ma) and continuing until the present (Fig. 1). Unsurprisingly, development of the Alaska Range had a marked effect on the climate of interior Alaska, blocking moisture originating in the Gulf of Alaska and increasing continentality north of the mountain range (Fitzgerald et al., 1995; White et al., 1997). However, while evidence of glaciation is widespread for portions of Alaska and its surroundings spanning the Pliocene-Pleistocene transition (Fig. 1A; Westgate et al., 1990; Krissek, 1995; Preece et al., 1999; Duk-Rodkin et al., 2001; Takahashi et al., 2011; Melles et al., 2012; Brigham-Grette et al., 2013; Hidy et al., 2013; Bender et al., 2020), the only evidence of the effect of global cooling on the Alaska Range itself is a pulse of exhumation in the eastern range ca. 3 Ma (Benowitz et al., 2011).

The Nenana Gravel is one of the few deposits that could provide a record of the history of the Alaska Range during this period. The ~1200-m-thick foreland basin deposit spans the northern foothills of the Alaska Range and has long been interpreted as recording the unroofing and erosion of the adjacent Alaska Range since the late Miocene (Fig. 1B; Wahrhaftig and Black, 1958; Wahrhaftig et al., 1969; Wahrhaftig, 1970, 1987; Ridgway et al., 1999, 2007; Thoms, 2000). However, the lack of a precise chronology for the deposit complicates interpretations of climate-tectonic interactions in southern Alaska during the Pliocene-Pleistocene transition. We present cosmogenic nuclide burial ages along a stratigraphic transect of the type locality of the Nenana Gravel and an overlying glacial deposit at Suntrana Creek (Fig. 1B; see also Fig. S1 in the Supplemental Material[1]). Our results indicate that the Nenana Gravel is the product of Pliocene-Pleistocene cooling and glaciation of the Alaska Range.

NENANA GRAVEL AND BROWNE GLACIATION

The base of the Nenana Gravel denotes an abrupt transition in both paleoflow direction and depositional environment (Thoms, 2000). The underlying Usibelli Group exhibits low-energy fluvial and lacustrine sedimentology and southward paleoflow markers, whereas the Nenana Gravel is dominated by alluvial fan and braidplain deposits and contains northward paleoflow markers. The lower portion is made up of mostly stream-flow strata, which coarsen and shift

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[1]Supplemental Material: Expanded methods, discussion of outliers, sample data and supplemental figures. Please visit https://doi.org/10.1130/GEOL.S.15138579 to access the supplemental material, and contact editing@geosociety.org with any questions.

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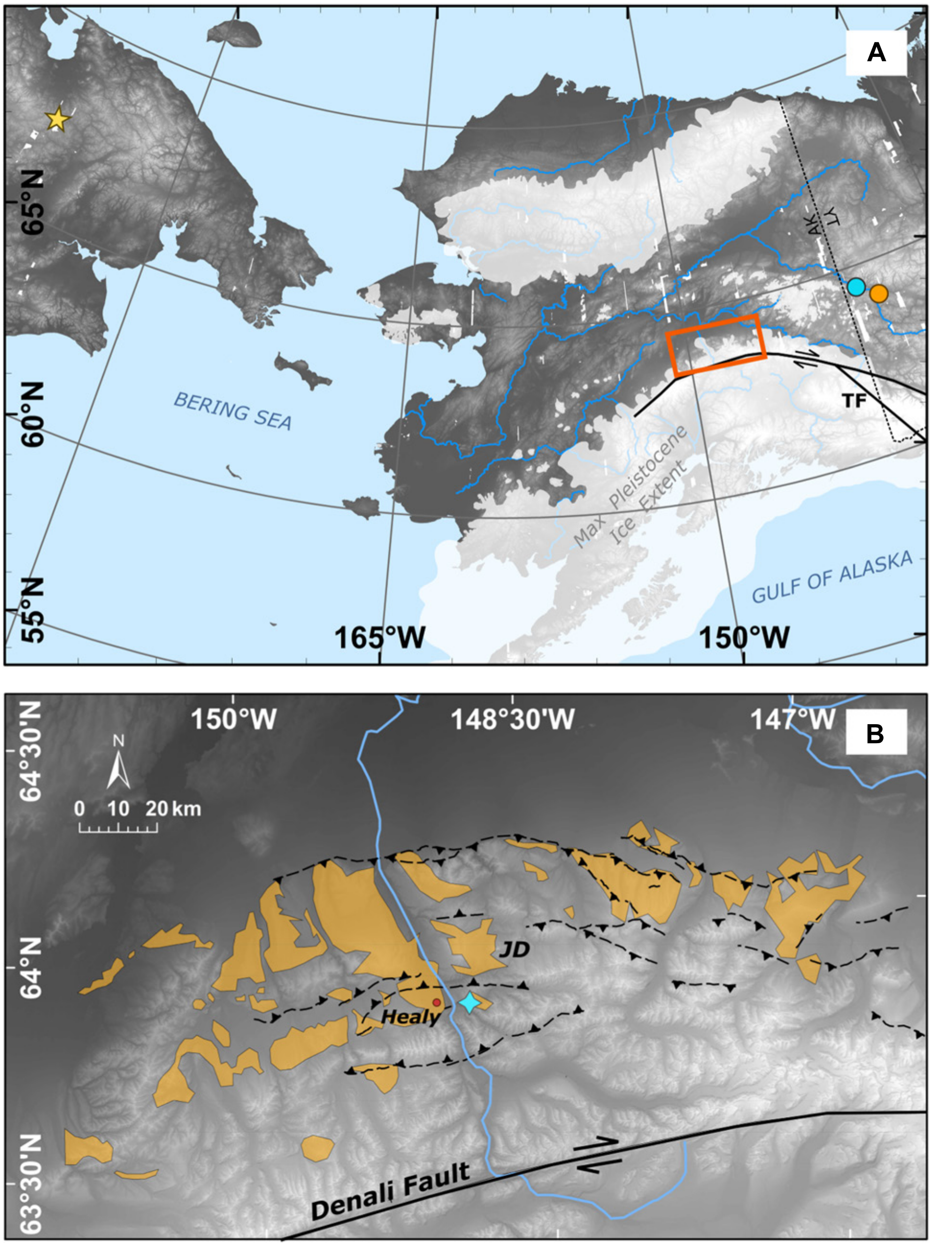

Figure 1. (A) Regional map of northeast Russia, Alaska, and western Yukon Territory with North American maximum Pleistocene ice extents from Kaufman et al. (2011). Black dashed line—border between Alaska (AK) and Yukon Territory (YT). Yellow star—location of Lake El'gygytgyn Arctic climate record. Blue and orange circles—locations of constraints on early Pleistocene glaciation of region from past studies (Bender et al., 2020; Hidy et al., 2013, respectively). Orange box—extent of Nenana Gravel deposits preserved by Northern Foothills fold-and-thrust belt and area of Figure 1B. Solid black line—location of Denali fault and Totschunda fault (TF). (B) Orange polygons highlight extent of Nenana Gravel in the region (Wilson et al., 1998). Red dot—location of the town of Healy; teal diamond—location of Suntrana Creek. Jumbo Dome (JD) is located north of Suntrana Creek. The northern Alaska Range thrust system is shown as black dashed lines (from Bemis et al., 2012).

to sheet-flow facies up-section (Thoms, 2000; Ridgway et al., 2007). Suntrana Creek is the thickest known section of the Nenana Gravel, suggesting it contains the most complete sedimentologic record of this period of aggradation. Current age constraints for the Nenana Gravel are based on ^{40}Ar-^{39}Ar dates of 6.7 ± 0.1 Ma from a tephra in the top-most portion of the underlying Grubstake Formation within the Usibelli Group (Triplehorn et al., 2000) and deformation of the upper Nenana Gravel at 1.026 ± 0.057 Ma by the nearby Jumbo Dome andesite plug (Fig. 1B; Athey et al., 2006). A paraconformity separates the base of the Nenana Gravel from the Usibelli Group, and it is unclear how much time, if any, is missing from the section.

The glacial deposit overlying the Nenana Gravel at Suntrana Creek is thought to be a remnant of the oldest preserved glacial advance into the northern foothills of the Alaska Range, referred to as the Browne glaciation (Wahrhaftig and Black, 1958). The Browne glaciation is estimated to have occurred in the middle Pleistocene, as determined by relative dating, and is described as high-elevation deposits perched on terraces above the Nenana River with large (~12-m-diameter) granitic erratics (Wahrhaftig and Black, 1958; Thorson, 1986). The till sheets are heavily deflated, leaving mainly the large erratics to distinguish the surface from its surroundings (Capps, 1912).

METHODS

We used ^{26}Al/^{10}Be cosmogenic nuclide burial dating to determine ages for the Nenana Gravel deposit. Samples ($n = 19$; Table S1) were collected from exposures along stream cutbanks and interfluve ridges at five locations: four sample horizons broadly spaced stratigraphically within the Nenana Gravel, and a fifth at the base of the overlying till deposit (Fig. 2). A minimum of three samples were collected from each horizon, with individual samples consisting of one or more ~5–15-cm-diameter cobbles of granitic, quartzite, or cherty lithologies, from which pure quartz was isolated. Samples were processed in the Tulane University Cosmogenic Nuclide Laboratory (Louisiana, USA). Al and Be isotope ratios were measured at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab, Indiana, USA). Expanded methods can be found in the Supplemental Material, along with full analytical details.

We used two different approaches to calculate burial ages. At horizons where three or more samples were measured, we employed a Bayesian linear regression code to fit an isochron. This code tests the likelihood of modeled linear fits to the given data, the output of which is a probability distribution of the slope and intercept of the best-fit line representing the burial age (Balco and Rovey, 2008). If a horizon either produced fewer than three samples, or the spread of the sample ratios did not allow for isochron fitting, simple burial ages and uncertainties were calculated using a boot-strap Monte Carlo method (Fig. S2). Simple burial ages are presented as median ages and uncertainties, which are based on the half-width of the interquartile range reported for horizons containing multiple samples.

RESULTS

Four cobble samples collected from directly above the Nenana Gravel–Usibelli Group contact (~560 m above sea level [a.s.l.]) yielded an isochron age of 2.34 ± 0.27 Ma (Figs. 2 and 3). All other stratigraphic horizons were dated using simple burial dating. Samples collected from the middle of the Nenana Gravel (708 m a.s.l.) produced a burial age of 2.23 ± 0.29 Ma. One sample collected mid-deposit at 778 m a.s.l.

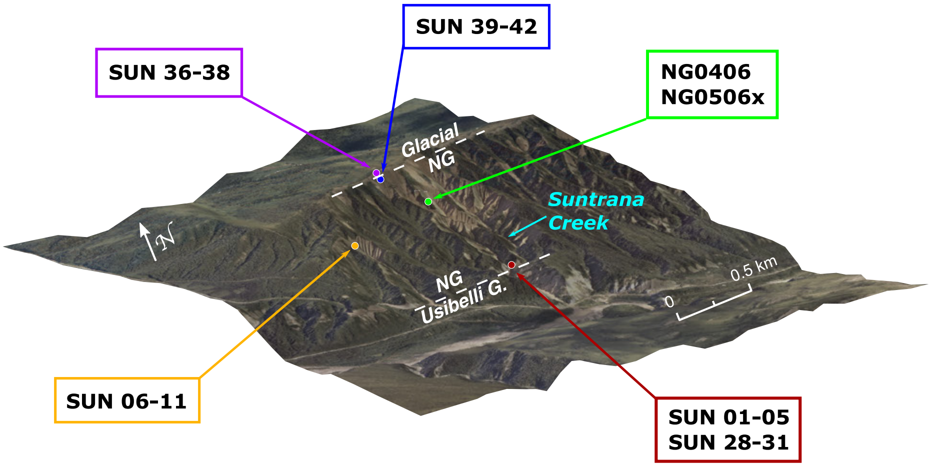

Figure 2. Oblique view of sample locations at Suntrana Creek, Alaska (teal diamond in Fig. 1B). Contacts between units are denoted by white dashed lines. Marker colors correspond to sample ages in Figure 3. NG—Nenana Gravel.

was dated to 1.06 ± 0.96 Ma. Samples collected from the upper section of the Nenana Gravel (909 m a.s.l.) yielded an age of 1.72 ± 0.71 Ma. The overlying glacial unit (919 m a.s.l.) was dated to 0.39 ± 0.32 Ma. Simple burial ages with 2σ uncertainties are presented in Table S1. Several outliers throughout the transect, notably with modern ^{26}Al/^{10}Be isotope ratios, are discussed in the Supplemental Material.

DISCUSSION

Our results indicate that initiation of Nenana Gravel deposition occurred in the early Pleistocene, ca. 2.34 Ma, and continued through at least ca. 1.72 Ma. Our data indicate that the Nenana Gravel is the product of increased glacial erosion and sediment production in the Alaska Range associated with the marked climate transition at the beginning of the Pleistocene, and that deposition ceased before the first glacial advance into the northern foothills ca. 0.39 Ma.

Initial Deposition of the Nenana Gravel

Our new age for the Nenana Gravel is significantly younger than the original maximum-limiting age estimate of ca. 6.7 Ma, yet it is correlative with both cooling of the Arctic and the timing of Cordilleran ice sheet expansion (Fig. 4; Brigham-Grette et al., 2013; Hidy et al., 2013; Bender et al., 2020). Initial deposition also occurred shortly after the substantial pulse of exhumation in the eastern Alaska Range at ca. 3 Ma, which was interpreted by previous researchers as glacial erosion (Benowitz et al., 2011). The established model for Nenana Gravel deposition presumes a correlation with tectonically driven exhumation of the Alaska Range ca. 6 Ma, where northward propagation of deformation resulted in a transition from the low-energy lacustrine deposits found in the upper Usibelli Group to the coarse-grained alluvial deposits that make up the Nenana Gravel (Thoms, 2000; Ridgway et al., 2007). However, our results show that the paraconformity between the Nenana Gravel and Usibelli Group spans ~4.4 m.y. Reconciling our ca. 2.34 Ma age with the established model requires an extremely long sediment transport time from the Alaska Range to Suntrana Creek. We can confidently rule this out because the low ^{26}Al and ^{10}Be nuclide concentrations measured in samples from the Nenana Gravel–Usibelli Group contact suggest that the sediment was eroded, transported, and buried in rapid succession. The apparent lag between exhumation of the Alaska Range and deposition of the Nenana Gravel instead suggests that foreland denudation dominated the region as it transitioned from a lower-relief landscape to one with greater erosive potential.

Furthermore, estimated deformation and fluvial incision rates in the Nenana River corridor were previously based on the late Miocene age of the Grubstake Formation. Our early Pleistocene age for the base of the Nenana Gravel necessitates a reassessment of these rates in future work, as they are likely underestimated (e.g., Wahrhaftig, 1987; Bemis, 2010).

Abandonment of the Nenana Gravel

Deposition of the Nenana Gravel continued at Suntrana Creek from ca. 2.34 Ma through at least ca. 1.72 Ma. We observed a weak oxidation horizon between the upper Nenana Gravel and the glacial deposit at Suntrana Creek, indicating that the Nenana Gravel may have been exposed for a significant duration before glaciation of the region at ca. 0.39 Ma (Fig. S1; Thoms, 2000). We note that the timing of Nenana Gravel abandonment (between ca. 1.72 Ma and ca. 0.39 Ma) is consistent with the prior minimum age limit of ca. 1.03 Ma (Athey et al., 2006).

Evidence for increased glacial erosion associated with the middle Pleistocene climate transition is documented in southern coastal Alaska, west-central Yukon Territory, and the Gulf of Alaska in Ocean Drilling Program Site 887 cores (e.g., Krissek, 1995; Gulick et al., 2015; Bender et al., 2020), and this event occurred within our temporal constraints for abandonment of the Nenana Gravel. However, the increased erosion/basin aggradation observed in these studies contrasts with the incision at Suntrana Creek during this time frame. Rather, we suggest that northward propagation of tectonic shortening associated with the development of the northern Alaska Range thrust system was the probable cause for the abandonment of the Nenana Gravel (Fig. 1B; Bemis and Wallace, 2007; Bemis et al., 2012). Between 1.72 and 0.39 Ma, regional uplift of the thrust system above the base level of the foreland basin to the north likely drove the

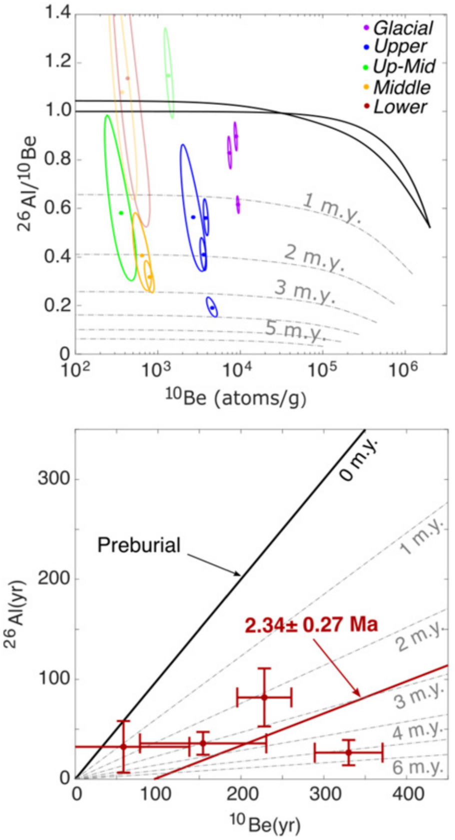

Figure 3. Sample concentrations from Nenana Gravel (Alaska) transect plotted with 2σ error ellipses. Colors correspond to sample locations in Figure 2. Outliers are represented by faded symbols. Gray dashed lines signify theoretical sample positions at different burial times. (Top) ^{26}Al/^{10}Be two-nuclide diagram of transect. ^{26}Al and ^{10}Be nuclide concentrations for each horizon were normalized to ^{26}Al/^{10}Be production ratio of 1 to allow for presentation on a single plot. Solid black lines portray a surface with constant exposure (top curve) and a surface with constant erosion (bottom curve). (Bottom) ^{26}Al-^{10}Be isochron plot for samples from the Nenana Gravel–Usibelli Group contact. Solid black line has a slope of 6.87 and represents the modern ^{26}Al/^{10}Be production ratio at Suntrana Ridge. Slope of best-fit isochron (solid red line) was used to calculate an age of 2.34 ± 0.27 Ma for initiation of Nenana Gravel deposition.

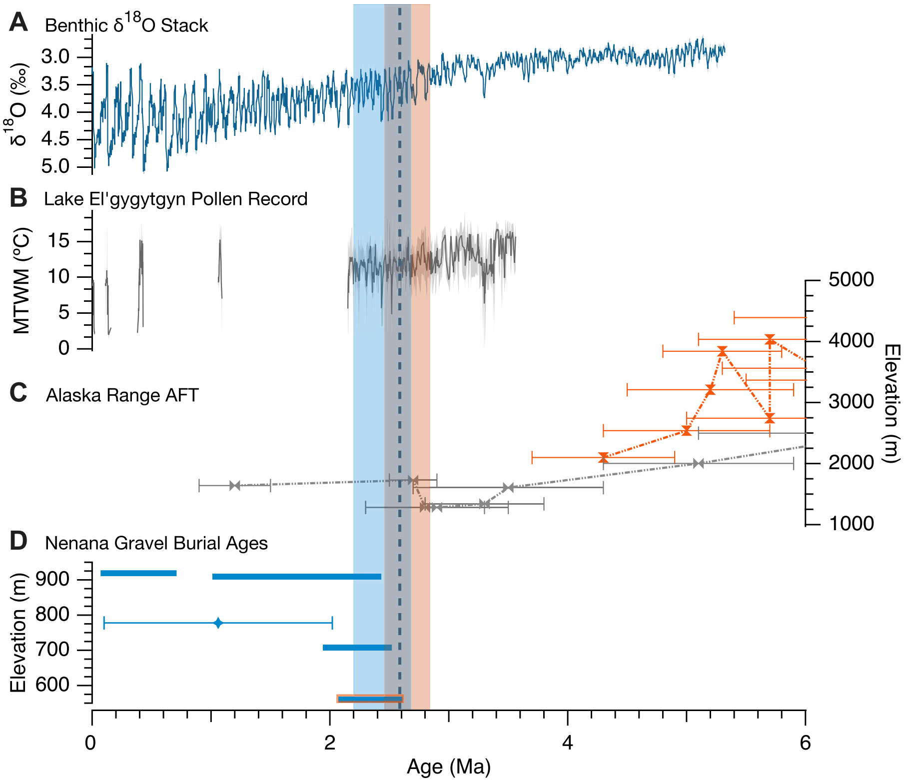

Figure 4. (A) Benthic $\delta^{18}O$ stack from Lisiecki and Raymo (2005). (B) Mean temperature warmest month (MTWM) derived from Lake El'gygytgyn pollen record in northeast Russia (Brigham-Grette et al., 2013). (C) Apatite fission-track (AFT) age versus elevation profiles from the central (gray; Fitzgerald et al., 1995) and eastern (orange; Benowitz et al., 2011) Alaska Range. (D) Median $^{26}Al/^{10}Be$ burial age for each horizon (blue bars). Blue diamond with error bar represents horizon with only a single data point. Isochron age with 1σ error is denoted by the blue box with orange outline. Orange vertical bar represents 1σ age of outwash gravel in western Yukon Territory (Hidy et al., 2013). Blue vertical bar represents glacial damming at the border of central Alaska and Yukon (Bender et al., 2020).

incision that led to abandonment of the Nenana Gravel at Suntrana Creek.

Glacial Unit Overlying Nenana Gravel

Geologic mapping indicates that the first expansion of ice out of the Alaska Range and into the northern foothills occurred during the Browne glaciation (Wahrhaftig and Black, 1958). This advance was previously estimated to have occurred ca. 1.5 Ma (Wahrhaftig and Black, 1958; Thorson, 1986), but our age for the till overlying the Nenana Gravel at Suntrana Creek is ca. 0.39 Ma, coinciding with a particularly large glaciation in Alaska and Yukon Territory at the onset of marine isotope stage (MIS) 10 (Brigham-Grette, 2001).

CONCLUSIONS

Cosmogenic nuclide burial ages from our transect of the Nenana Gravel at Suntrana Creek indicate that initial deposition of the Nenana Gravel occurred ca. 2.34 Ma, coincident with global cooling and Cordilleran ice sheet expansion. The ca. 4 m.y. lag in erosion after initial exhumation of the Alaska Range indicates that the Nenana Gravel is not linked to unroofing of the mountain range as previously hypothesized. Tectonic activity and incision rates in the northern foothills based on the previous maximum age limit (ca. 6.7 Ma) of the underlying Grubstake Formation are underestimated, considering our new findings, and will need to be recalculated. The age estimate for Nenana Gravel abandonment (ca. 1.72 Ma to 0.39 Ma) from the transect agrees with the prior minimum age limit (ca. 1.07 Ma) from deformational relationships with the Jumbo Dome pluton. We conclude that the Nenana Gravel deposit at Suntrana Creek was likely abandoned due to tectonic uplift from ongoing shortening within the northern Alaska Range thrust system. Additional efforts to date the preserved top of the Nenana Gravel at other locations along strike of the Alaska Range would establish valuable constraints on the recent tectonic evolution of the region and the balance between climate, erosion, and sediment dynamics.

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