Final Technical Report

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AGE CONTROL FOR SLIP RATE AND PALEOEARTHQUAKES ON ACTIVE THRUST FAULTS IN THE NORTHERN FOOTHILLS FOLD-THRUST BELT, ALASKA RANGE

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SUMMARY

The objective of this study was to provide age control for ongoing investigations into Quaternary behavior and paleoearthquake characteristics of active faults in the northern foothills of the Alaska Range. Studies over the past 8-10 years have recognized >10 previously unknown faults with demonstrable Quaternary activity in this region (Figure 1), but these and the few previously recognized active faults remained uncharacterized for their earthquake behavior. Our studies sought to determine sub-surface fault geometries, slip rates, and paleoearthquake chronologies for 5 faults and this grant provided support for radiocarbon dating of buried stratigraphy, terrestrial cosmogenic nuclide dating of fluvial terraces, and additional surveying of deformed surfaces associated with these faults. This report presents a summary of our findings for each fault and concludes with a summary of implications for the broader Quaternary tectonic behavior of this portion of Alaska. This grant provided major support for graduate student Sean Bemis and partial support for undergraduate student Samuel Castonguay.

All radiocarbon dates reported here are calibrated ages (cal BP) unless otherwise noted. Details on pretreatment procedures, AMS results, and calibration methods are provided in Bemis (2010).

Healy fault

The Healy fault is an ~45° north-dipping reverse fault that forms a prominent linear scarp as it crosses several terraces correlated with the Riley Creek glacial advance (~22-28 ka; Wahrhaftig, 1970; Thorson, 1979; Bemis and Wallace, 2007; Dortch, 2006) south of the town of Healy (Figure 2). This fault can be traced from the west bank of the Nenana River westward to moraine deposits correlated with the Healy glacial advance (~60 ka, Dortch, 2006). Because the fault produced a south-facing scarp on terraces that slope gently north, it blocks local drainage that beavers have utilized to construct networks of dams on each of the terrace surfaces that further prevent surface drainage and facilitates the accumulation of fine-grained sediments (Figure 3). The dam on the highest terrace level was abandoned sometime within the past 20 years, draining the pond and making this portion of the scarp the target for paleoseismic trenching. We excavated 3 trenches across this scarp at this location, with each targeting different levels of the stratigraphy. Detailed locations and dimensions of individual trenches provided in Table 1.

Each trench exposed 2-3 discrete ruptures of the fluvial gravel – basal fine sand contact. An additional rupture breached higher in the scarp and is well-defined in trenches T1 and T2. The cumulative brittle offset of these faults is less than ~1.5 m, indicating that much of the deformation recorded by the offset of

the terrace tread is manifest as folding that produced the northward tilts of units along the base of the scarp. The cumulative offset across this fault is recorded by the offset up the top of the fluvial terrace gravels, as shown schematically in Figure 4. This offset as measured indicates a slip rate of ~0.25 mm/yr across the Healy fault. Only one fault rupture is uniquely bracketed in the trench stratigraphy. Due to its position at the base of the modern scarp and the relative youth of the offset stratigraphy, this records the most recent event (MRE) on the Healy fault. This event occurred sometime during the years 1,528-1,176 cal BP (at 2σ confidence) (Bemis, 2010). Additional offsets and soft-sediment deformation occurs within trench stratigraphy, but we are unable to constrain these deformational events in more detail than to divide deformation into Holocene and pre-Holocene events.

Healy Creek fault

The Healy Creek fault is a near-vertical to steeply north-dipping reverse fault with greater than 1 km of cumulative offset (Wahrhaftig, 1970; Bemis and Wallace, 2007). The surface trace of the fault is expressed by an east-west trending scarp that begins east of the Nenana River on a fluvial terrace and can be traced for about 16 km east (Figure 4). General trench details are provided in Table 1. The first trench on this fault (HCF-T1) was excavated by the Usibelli Coal Mine for us across the main scarp on the high fluvial terrace (Figure 2 and 5). To achieve greater depth without shores, a benched trench was dug with a 1.5-2.5 m tall upper wall and a 1-1.5 m tall lower wall separated by an ~2 m wide step. The total exposure was ~40 m long, and the lower walls separated by ~8-10 m. A second trench (HCF-ST) was excavated by hand across a small step in a channel incised across the scarp Figure 5. This trench encountered frozen ground below ~0.5 m, but a low ice content enabled excavation of up to ~1.2 m depth and 6 m long.

In general, the sediments in HCF-T1 are overwhelmingly fluvial gravels and very coarse sand. Bedding within the gravels is common and typically defined by grain size variations and degree of matrix vs. clast support. Large-scale packages of gravel can be traced across the scarp face to where they are disturbed at both the crest and base of the scarp. A thin (10-20 cm) deposit of loess blankets the entire exposure immediately below the modern organic mat except above the crest of the scarp, where there is a thick, wedge-shaped block of reworked silt and gravel below ~1 m of loess. Numerous steeply-dipping shear zones cut the fluvial gravel stratigraphy in HCF-T1, but the only dateable offset stratigraphy is a wedge-shaped block of loess within the crest of the fault scarp. An angular unconformity within the loess deposit that corresponds with a thin colluvial deposit offers secondary evidence for a prehistoric surface rupture. Radiocarbon dates on a charcoal above this unconformity of 11,719-12,640 cal BP and on a suite of manganese oxide nodules from below the unconformity of 14,085-18,484 cal BP constrains a possible earthquake near the end of the Pleistocene. Discussion of the radiocarbon dates on manganese oxide nodules is provided by Bemis (2010).

The shallow exposure of HCF-ST encountered a sequence of loess and peat that is very strongly sheared. The youngest, least-deformed beds are generally 1-4 cm thick and blanket the topography. Intact plant macrofossils are abundant within the frozen deposits and consist of wood, grasses, and mosses. The slope-parallel, isoclinal, imbricate shearing within HCF-ST is clearly non-tectonic. The age of 6,546-6,830 cal BP from a plant macrofossil near the base of the trench indicates that this channel is at least 7,000 years old, possibly much older because the base of the fine-grained section is not exposed. The origin of the channel is unclear, but the lack of a tectonic scarp within the channel suggests that this portion of the fault has not experienced a surface rupture for at least 7,000 years.

Northern Foothills thrust

The Northern Foothills thrust represents the basal thrust of the northern foothills fold-thrust belt near the Nenana River, and is a gently south-dipping, relatively planar thrust fault (Bemis and Wallace, 2007; Bemis 2010). We have identified a semi-continuous fault scarp on the ground and with air photos from adjacent to the Nenana River eastward to Windy Creek (Figure 6). The terrace adjacent to the Nenana River is correlated with the Healy glacial advance (~60 ka, Dortch, 2006) and is offset 2-4 m. In the east,

near Windy Creek, this fault offsets an alluvial surface of unknown age, resulting in a large complex north-facing scarp. We hand-excavated two small trenches across the prominent break-in-slope at the base of the scarp. The first trench was abandoned due to a lack of coherent stratigraphy below the thin mantle of loess and the modern organic mat. The second trench was ~5 m long and exposed ~1.3 m of section at the deepest point. Additional details of this trench site are summarized in Table 1.

Although there are no obvious primary earthquake ruptures in our trench stratigraphy, we use the correspondence of a colluvial wedge with two minor fault offsets to interpret a paleoearthquake at this site. The colluvial wedge was likely produced following this event and thus we dated the loess deposits occurring above and below the wedge to constrain the timing of the earthquake. A radiocarbon age on charcoal from the base of the overlying loess provides a minimum age of 26,591–25,751 cal BP for this event. We dated 5 samples from the loess below (4 detrital charcoal, 1 wood fragment) and all were >45,000 radiocarbon years, which we consider indistinguishable from infinite age. Field observations from this area did not recognize any additional candidate young fault scarps, which corroborates the lack of offset recorded by the <28 ka terraces west of the Nenana River. Therefore, this portion of the Northern Foothills thrust west of Windy Creek has either a >26 ka recurrence interval, more recent earthquakes occurred as distributed deformation and are undetected, or the fault is now inactive. Future efforts on this fault are warranted to attempt to differentiate between these options, as deeper excavations should readily encounter older loess deposits. Therefore any future investigations should also be prepared to employ luminescence dating techniques.

Stampede fault

The Stampede fault is a north-dipping thrust fault on the south flank of the Stampede anticline (Figure 2). It has a well-defined surface trace from the Teklanika River eastward for ~22 km, and likely extends another 30 km west to the Kantishna Hills (Figures 1 and 2). There is no scarp where the Stampede fault projects into the late Pleistocene terraces adjacent to the Nenana River, but this corresponds to a complex zone where the Stampede fault appears to step south and transfer displacement to the Healy Creek fault. We performed differential GPS surveys across several mid and late Pleistocene terraces along the Savage and Teklanika rivers (Figure 2) to constrain the progressive offset across this fault and to determine slip rates (Figure 7). The Stampede fault scarp in this area is obvious on the late Pleistocene terraces, but having a smooth scarp surface and broad (scarp width being 3-5 times the scarp height) suggested that the most recent event did not rupture the surface, or occurred prior to the late Holocene.

Bemis (2010) developed a Quaternary structural cross-section for the Nenana River valley region from the progressive deformation of geomorphic surfaces preserved along the major rivers (Figure 8). This cross-section defines range of kinematically consistent subsurface dip values for the Stampede fault and Northern Foothills thrust, which we use to calculate slip rates as defined by the individual offset surfaces. Figure 9 illustrates the slip rates for the Stampede fault as defined for each surface offset, defining a slip rate of between 0.25 – 1 mm/yr throughout the Quaternary.

Gold King fault

The Gold King fault occurs 10 km north of the ~400 m tall, relatively sinuous range-front escarpment that forms the boundary between the northern foothills and the Tanana basin (Figure 1). We interpret it as a complex splay from the Northern Foothills thrust and is composed of both north-vergent and south-vergent surface traces. Bemis (2010) mapped the Quaternary geology of this region, and defined Quaternary deformation from Pleistocene terraces, Holocene fault scarps, and the Pliocene Nenana Gravel. Differential GPS surveys along terrace treads parallel to Gold King Creek demonstrate a self-consistent pattern of tilting and uplift (Figure 10) that we used to define the subsurface geometry of this fault. The surface trace of the Gold King fault near Gold King Creek is manifest by a fault scarp that is progressively taller on older surfaces, and has a morphology suggestive of at least one Holocene surface rupture. We dated one terrace deformed in the hanging-wall of this fault using an in-situ cosmogenic

nuclide exposure depth-concentration profile, resulting in a modeled minimum age of 82.0 +/- 7.3 ka. However, the present loess cover and evidence of prior loess stripping and redeposition from this and other terraces in the region suggest that this is certainly older, and due to stratigraphic position and this modeled minimum age, we correlate this terrace with marine isotope stage 6, or roughly ~150 +/- 20 ka. Using the dip-slip offset for this terrace indicated by our cross-section interpretation, we suggest a preliminary slip rate of approximately 1.0 +/- 0.2 mm/yr for the Gold King fault.

Derivative Projects:

This grant contributed to our project producing a 1:25,000 scale map of the Quaternary geology and active faulting of the Japan Hills – Gold King Creek area on the northern margin of the Alaska Range. This mapping identified two major thrust faults and a right-lateral fault that trends oblique to the thrust faults. The topography of the region has developed through the progressive uplift on these structures, which, combined with Quaternary glacial cycles, produced a sequence of fluvial terraces that record the uplift. We used the geometry of progressive deformation to define the subsurface geometry of the faults (i.e. Figure 10). This study demonstrated both the activity of this portion of the northern margin of the Alaska Range, and the utility of using landforms for geologic studies in tectonically-active regions of poor geologic exposure.

Another project, and a goal of the preceding NEHRP award, was to understand how the faults in a fold-thrust belt balance thickening and foreland propagation through time to maintain critical taper of the orogenic wedge. Without complete paleoearthquake histories on faults across the fold-thrust belt of the Alaska Range north of the Denali fault, we used the slip rates as recorded by progressive offset/deformation of fluvial terraces to constrain patterns of fault activity. We found that critical taper in this system is predominantly maintained by simultaneous activity on all the major faults of the system.

Bemis (2010) and Bemis et al. (in preparation) integrate the insights into the geometry of Quaternary thrust faulting from these studies with other recent studies (Carver et al., 2008; in review) of active faulting in the Alaska Range. These results show that the Denali fault partitions the NW-directed strain imposed from the far-field collision of the Yakutat microplate into Denali fault-parallel strike-slip and fault-normal compressional components. This strong partitioning of transpressional strain exerts the primary control on the distribution of crustal deformation and mountain growth in central Alaska. Similar shortening rates across the northern Alaska Range thrust system from east to west require that the Southern Alaska Block rotates counterclockwise, shortens internally, and migrates to the NW. Because the Denali fault accommodates the fault-parallel component of strain, the vertical-axis rotations of crustal blocks inferred from seismicity patterns north of the Alaska Range (Page et al., 1995) cannot be driven by a large dextral shear zone between the right-lateral, sub-parallel Denali and Tintina faults. Instead, the same Denali fault-normal maximum compressive stress (Bemis, 2010; Ruppert, 2008) that drives the northern Alaska Range thrust system drives shortening between the Denali and Tintina faults. This shortening is accommodated by left-lateral slip on the NNE-trending Fairbanks and Salcha seismic zones. Similar NNE-trending structures observed in the bedrock geology east of these seismic zones do not accommodate active deformation, because they are unfavorably oriented to the Denali fault-normal maximum compressional stress as the Denali fault curves to the SE.

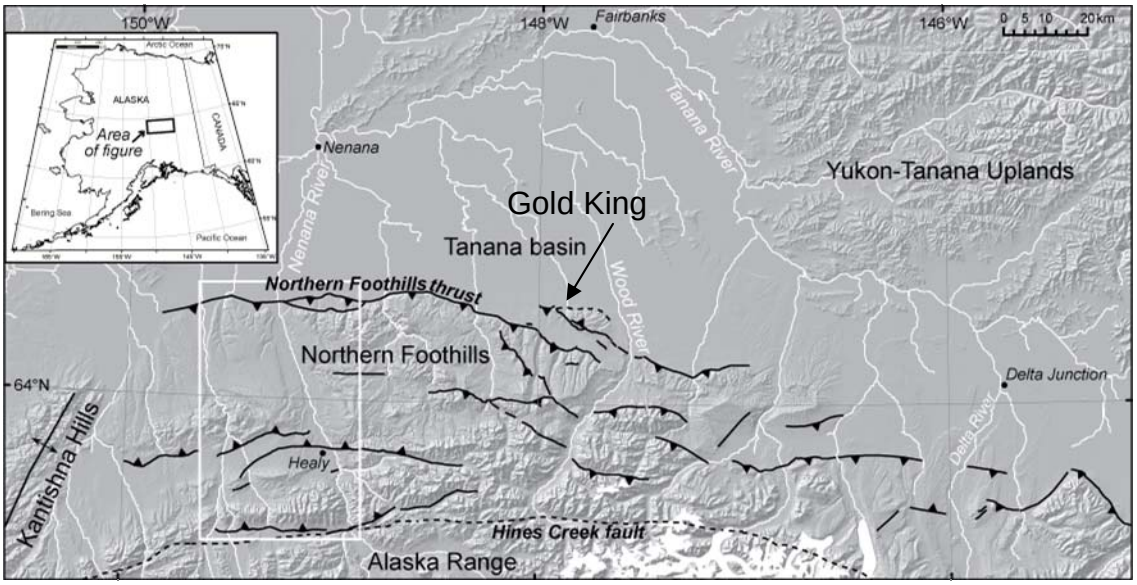


Figure 1. Shaded-relief digital elevation model (DEM) of east-central Alaska (location shown on inset). Structures shown with solid lines are faults with known Quaternary displacement, and these appear to accommodate most of the recent topographic growth of the Alaska Range. The Nenana River valley study area is shown by the white rectangle, and the Gold King fault study area is labeled.

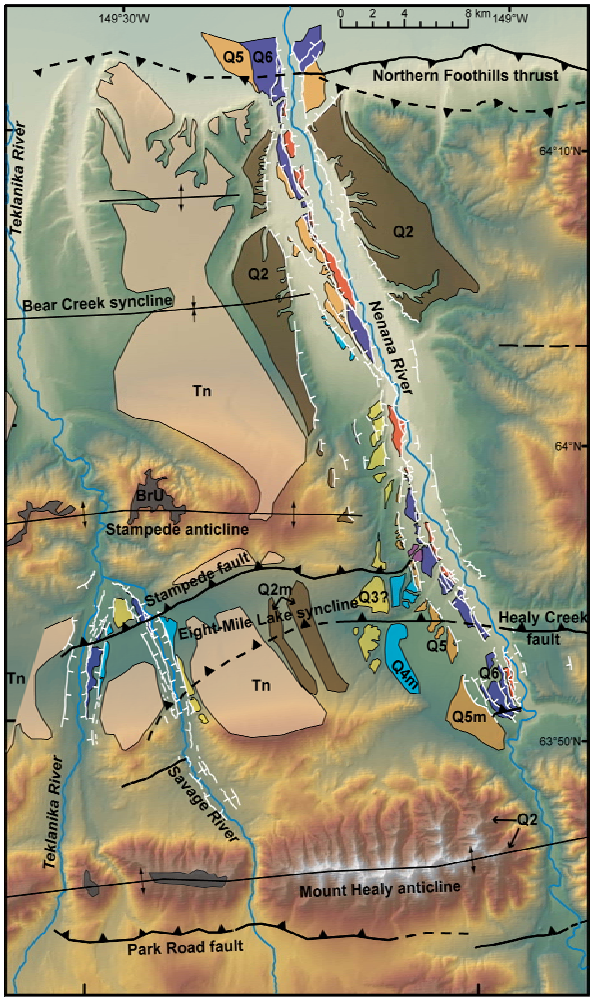


Figure 2. Mapped terraces and geomorphic surfaces shown on a DEM of the Nenana River valley study area (area of figure shown as white rectangle on Figure 1). Terrace sequence informally named with increasing numbers indicating younger surfaces, with the Tn representing the oldest surface which is interpreted to represent the former basin surface prior to uplift.

Table 1. Locations and basic characteristics of Nenana River valley paleoseismic trenches.

Trench Name	Coordinates*	Fault Type	Length / Width (m)†	Depth Range (m)	Paleoseismic Results§
Healy fault T1	402,348 E, 7,081,533 N	Reverse, 45° N dip	5 / 1	0.8 - 2	2 discrete fault offsets, 1 event (MRE) well-constrained, secondary extensional faults
Healy fault T2	402,345 E, 7,081,536 N	Reverse, 45° N dip	24.5 / 1	1.2 – 2.5	4 discrete fault offsets, 1 event (MRE) well-constrained
Healy fault T3	402,355 E, 7,081,532 N	Reverse, 45° N dip	6 / (1.5 – 3)	2 - 2.4	5 discrete fault offsets
Healy Creek fault T1	403,898 E, 7,086,783 N	Reverse, 60° N to near vertical dip	45 / (8 – 16)	3 – 4.5	Numerous minor shear zones and minor offsets, 1 complex deformation zone, deformation focused at crest and base of scarp
Healy Creek fault ST	403,678 E, 7,086,777 N	Reverse, 60° N to near vertical dip	6 / 1	0.6 – 1.2	Fault not exposed, scarp not tectonic
Northern Foothills thrust WC2	398,221 E, 7,122,594 N	Thrust, <30° S dip	5 / 1	0.7 – 1.3	Small, probably secondary offsets, 1 probable event (MRE)

* UTM zone 6, WGS 84, measured with differential GPS, horizontal precision <1 m, surveyed location is the NW corner of the trench over the northernmost vertical grid line.
† Width in parentheses indicates width between lower and upper bench walls, respectively.
§ Age constraints and additional evidence discussed in text.

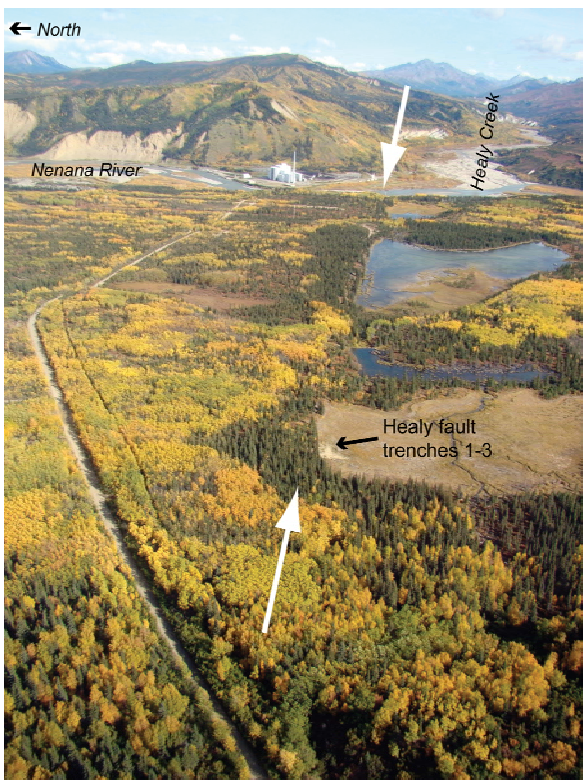
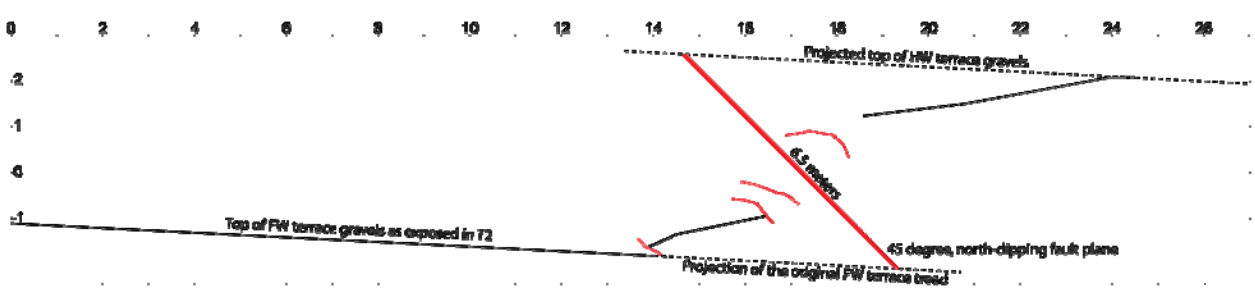


Figure 3. Oblique photo along strike of the Healy fault, showing the linear scarp (between white arrows) and the beaver ponds on the footwall terrace tread. The three trenches were excavated where indicated on the uppermost, drained pond.

Figure 4. Diagram illustrating the dip-slip offset of the terrace tread across the Healy fault. The 45° N dip is determined from the average dip of the down-dip fault traces mapped in the trenches, which also corresponds with the dip of bedding in the underlying Usibelli Group (Wahrhaftig, 1970; Bemis and Wallace, 2007). As this terrace tread is the highest of the flight of outwash terraces correlated with glacial advances of ~22-28 ka, and an ~24 ka date from within the upper 10 cm of the fluvial gravels indicate the slip rate for this fault is ~0.25 mm/yr.



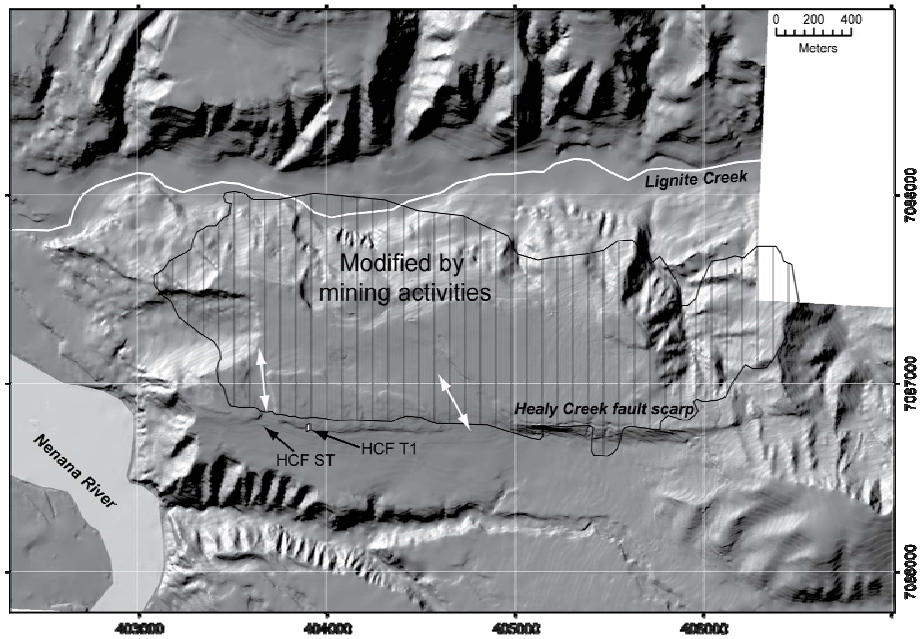


Figure 5. Shaded-relief DEM of pre-mining topography at the Healy Creek fault study area on the Usibelli Coal Mine property. The vertical-lined region indicates the area that has been mined and reclaimed since this topography was originally surveyed. Trench locations are indicated by the black arrows and double-ended white arrows indicate channels incised across the scarp.

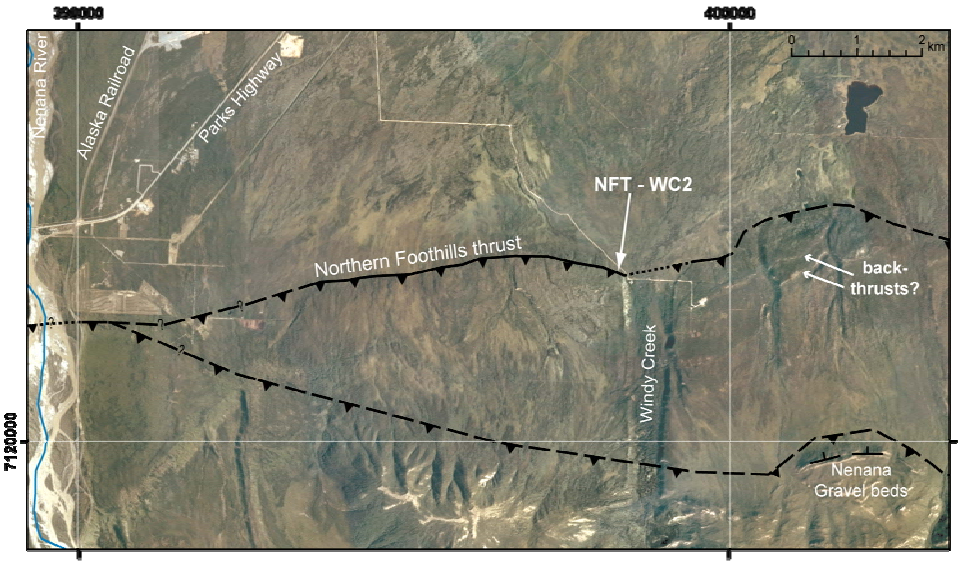


Figure 6. Satellite image of the Northern Foothills thrust trace east of the Nenana River. The northerly strand is the most recently active trace as it consists of semi-continuous scarps across multiple geomorphic surfaces, whereas the southern strand is recognized based on the deformation of older, pre-Pleistocene deposits.

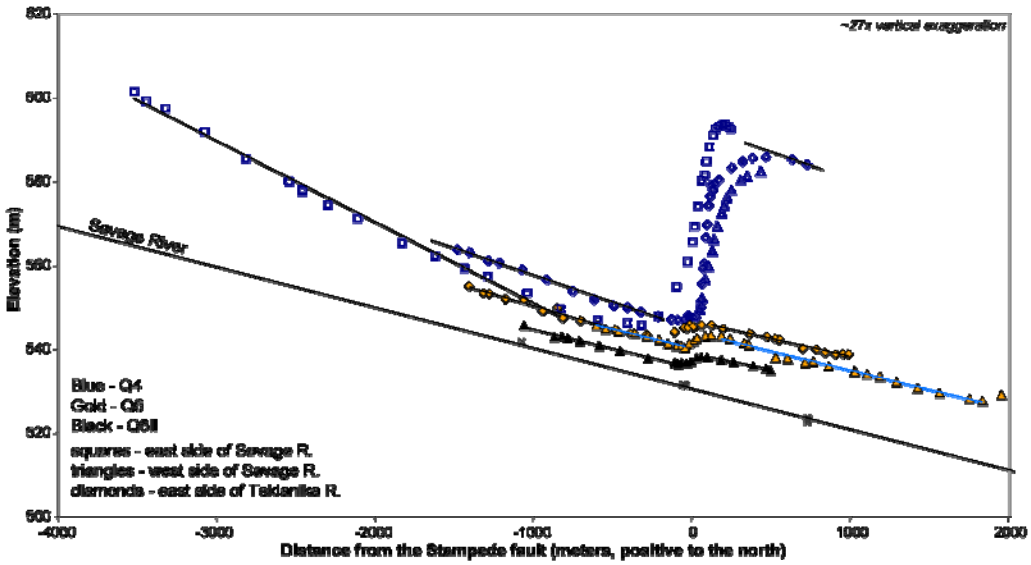


Figure 7. Surveyed profiles of mid-late Pleistocene terraces offset across the Stampede fault adjacent to the Savage and Teklanika rivers.

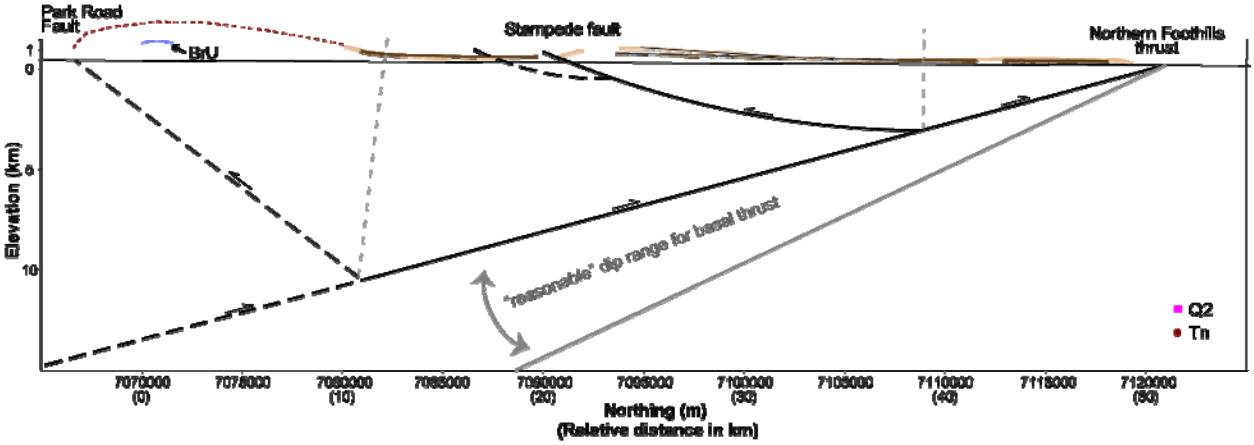


Figure 8. Cross-section of major active Quaternary faults along the Nenana River valley, covering the area shown in Figure 2. Interpretation of subsurface fault geometry is derived from the style of deformation of the Quaternary geomorphic surfaces and is described in detail by Bemis (2010).

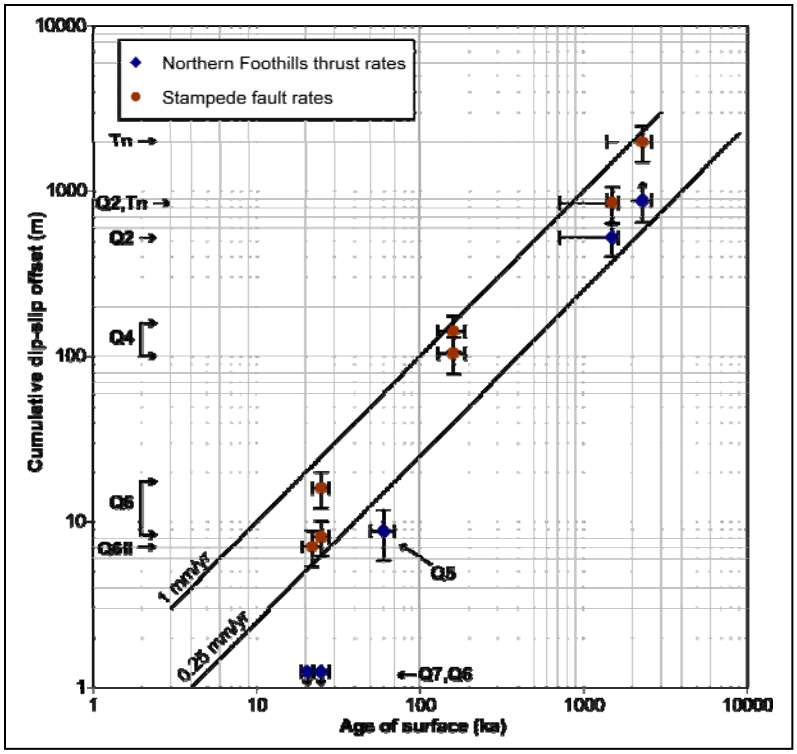


Figure 9. Slip rates for the Stampede fault and Northern Foothills thrust as defined by the sequence of offset surfaces across each fault.

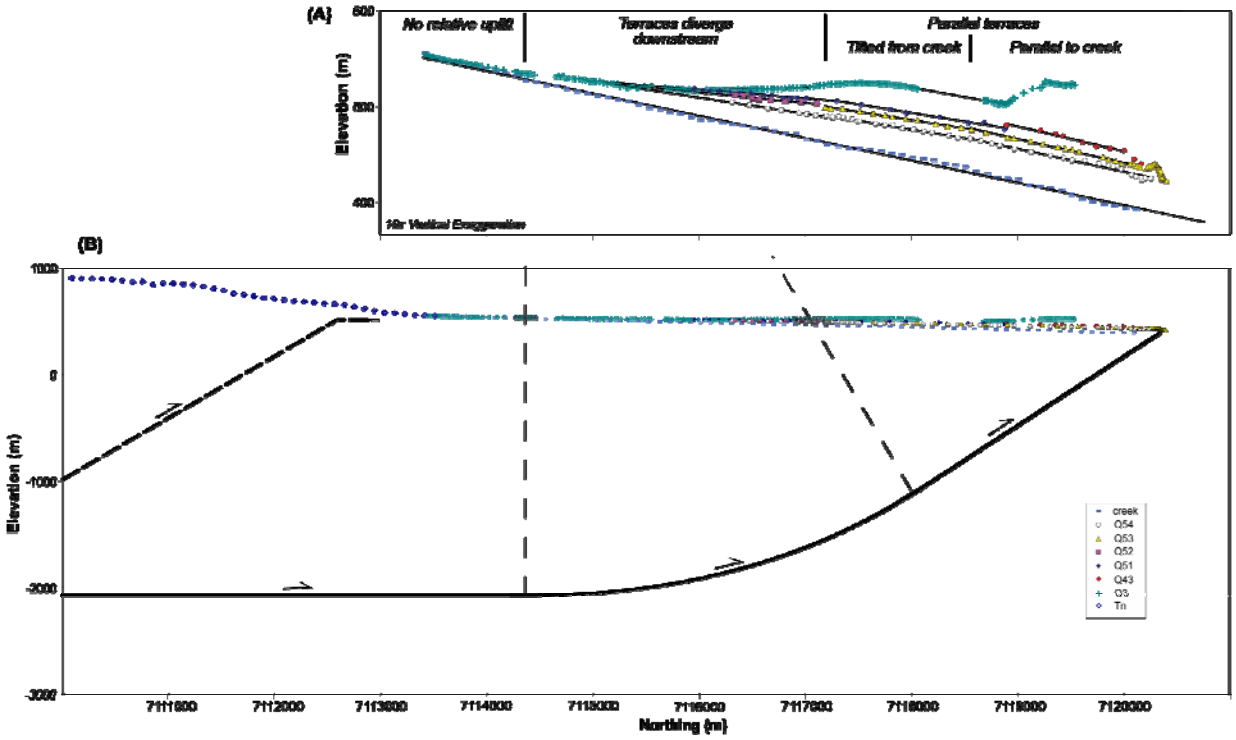


Figure 10. Surveyed terrace profiles (A) and subsurface fault geometry (B) for the Gold King fault. The subsurface geometry is constrained by the style of progressive deformation recorded by the mid-late Pleistocene surfaces, and this cross-section is described in more detail by Bemis (2010).

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Bemis, S.P., Weldon, R.J., Progressively deformed geomorphic surfaces constrain the balance between thrust wedge thickening and foreland propagation in a basement-involved fold- thrust belt [in preparation for submission to Lithosphere].

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Bemis, S.P., Weldon, R.J., Thoms, E.E., and Burns, P., Quaternary geology and neotectonics of the Japan Hills - Gold King Creek area, central Alaska: Identification of active thrust faults and related late Cenozoic deformation [in preparation for Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report]

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