Supplemental File S1

Site Descriptions for Features Offset Along the Denali Fault System

This file gives a description for each of the sites studied along the Denali fault system. All sites were chosen for having features that show long term offsets across the fault. This supplemental file follows the order sites are listed in Table 1. Some of the site descriptions repeat Data Repository 1 of Matmon et al. (2006) as noted below.

All site names have a 4 letter code. The first two letters are DF, as this work is related to the Denali fault system. The next two letters usually relate to a local geographic name.

The Denali fault trace is marked by a red line in all the photos.

There are various sources of the photographs, and here we show the ones that we consider best show the feature and the offset. Most of the black and white air photos were taken during August 1973 with an intended scale of 1:12,000. Colored air photos were taken during November 2002 with an intended scale of 1:6000. However, scales differ from photo to photo and within each photo. Scale can be calculated from given offset. Oblique photos were taken during our fieldwork. For some sites, we show the 'restored' offset, in which we have sliced the photo along the fault trace and then unslipped the photo to show the offset we measured in the field. This sometimes reveals additional offset features that were difficult to assess in the field.

Offset was measured in several ways:

1. Measuring tape. The error expresses the uncertainty in identifying the piercing point. The magnitude of the error is related to the size of the correlated element. For example: in order to correlate a 10 meter wide channel, a ±5 meter offset is attributed to the location of each point. The total uncertainty of ±7 meters which is attributed to the offset measurement is derived from the addition of uncertainties:

$$\sigma_{sum} = \sqrt{\sigma_i^2 + \sigma_j^2} \qquad (1)$$

2. GPS locations. A ±10 meter error is attributed to each measured point to account for the uncertainty in the GPS measurement. Therefore, a total uncertainty of ±14 meter is attributed the offset measurement (see eq. 1 above). Additional error was sometimes added and expresses the uncertainty in identifying the piercing point. The magnitude of the error is related to the size of the correlated element (as explained in 1 above).
3. Accurate determination of the air photo scale in the area of the offset. The error expresses the uncertainty in identifying the piercing point. The magnitude of the error is related to the size of the correlated element (as explained in 1 above).

Uncertainties of average ages were calculated using the root mean square approach. This is a useful method for describing the reliability of an average (*Error analysis,* Taylor, 1997):

$$\sigma_{\bar{m}} = \sqrt{\frac{1}{N}\Sigma\sigma_i^2} \qquad (2)$$

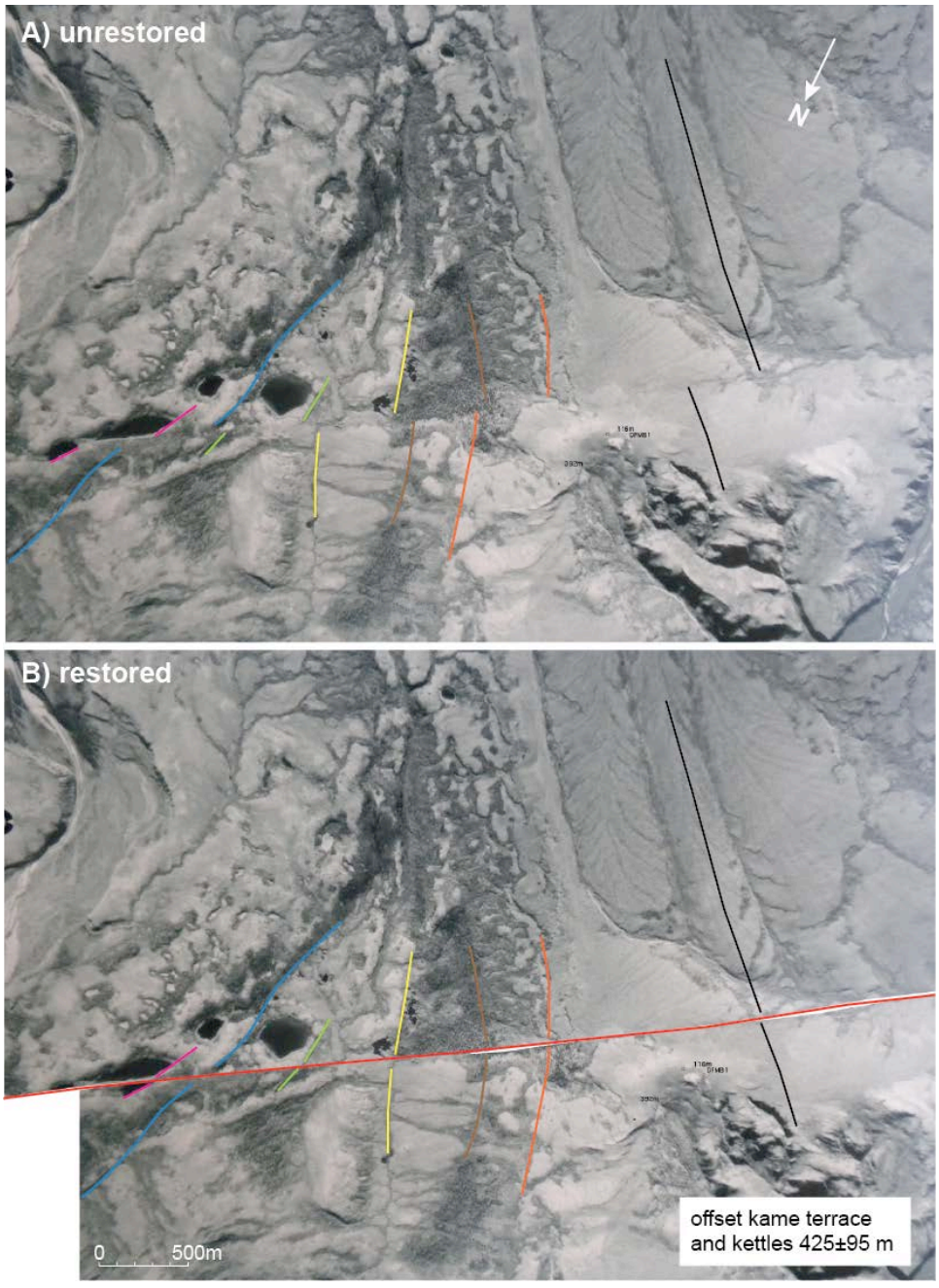
Uncertainties of slip rate were derived from the multiplication of uncertainties:

$$\sigma_S = S\sqrt{(\frac{\sigma_{age}}{age})^2 + (\frac{\sigma_{offset}}{offset})^2} \qquad (3)$$

where S is the slip rate.

Site DFMB – Middle Fork of the Big River

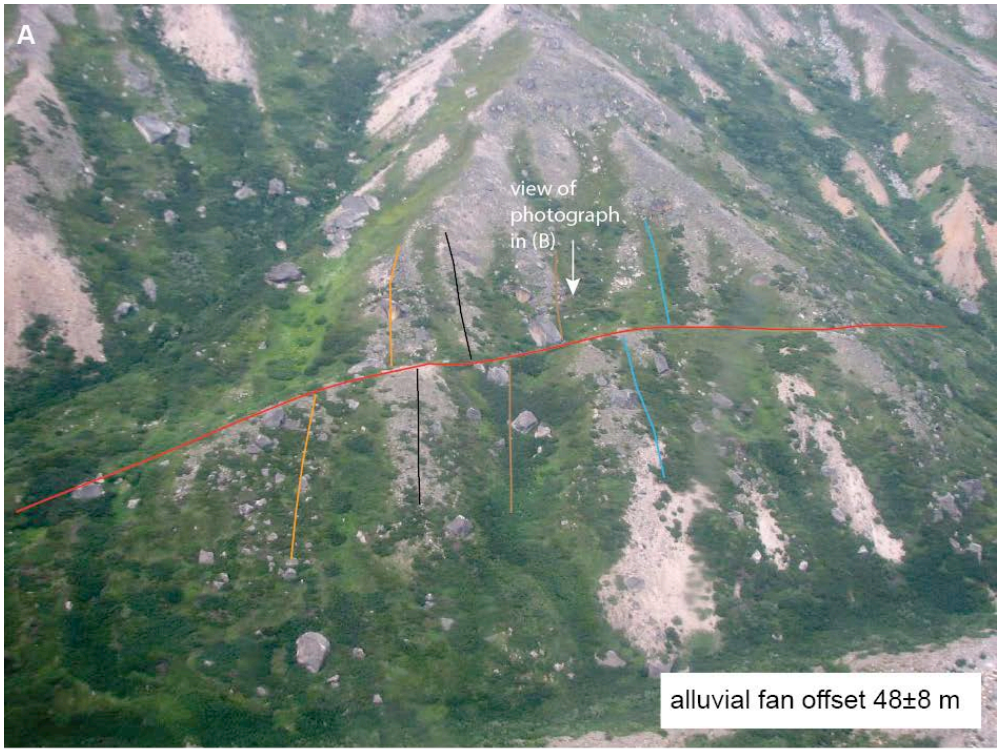
Location: N62°15.994', W154°34.186'



This site is on a broad ridge between two valleys, which was glaciated and then offset along the Denali fault. The offset at this site is best shown by comparing (A) unrestored, and (B) restored, or unslipped, aerial photographs. Linear kame terrace and kettle features were offset and then measured by transferring control points measured on the ground to air photos, and then digitally cutting the air photo along the trace of the Denali fault and restoring the features to their original position. The older moraine crest (black line) is broad and does not provide a precise offset, but recessional kettle lake margins (pink and green lines), kame terrace margins (brown and orange lines), and kame terrace drainage (yellow line) and recessional moraine margin (blue line) provide robust piercing points. The uncertainty is related to the scale of the photographs.

Site DFRC – Ripsnorter Creek

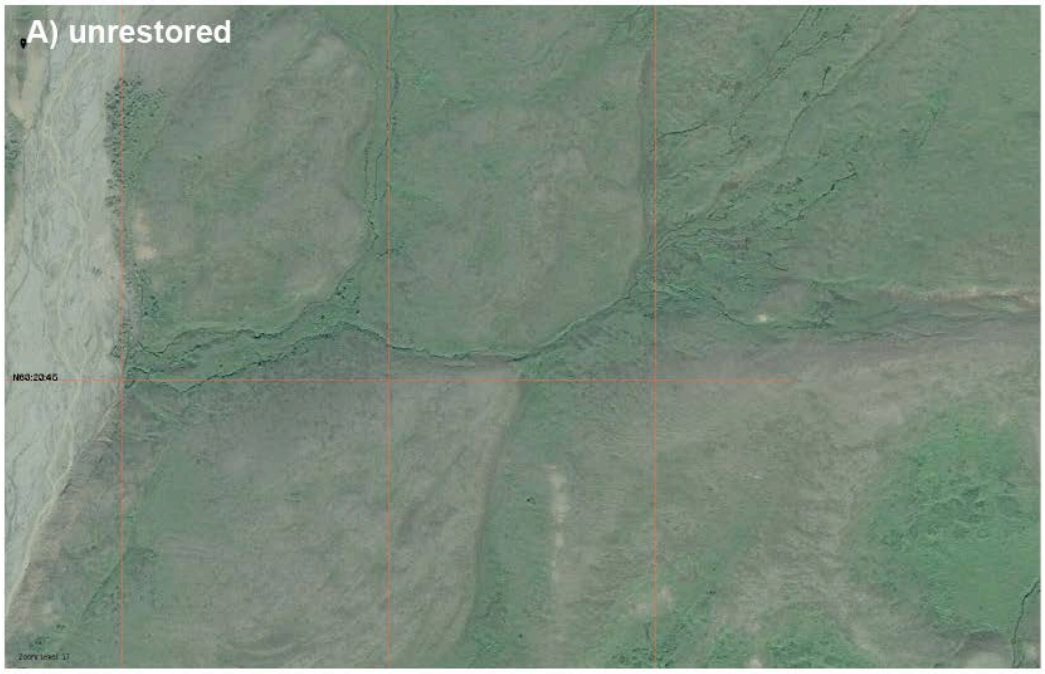
Location: N62°47.456', W152°10.927'

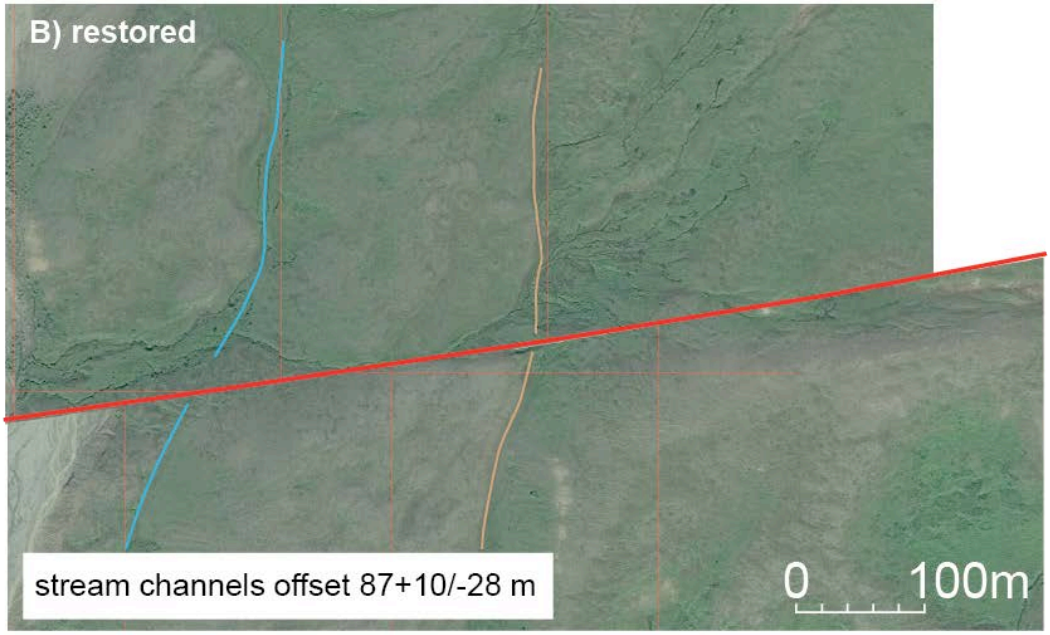


This site is a steep alluvial fan that accumulated below a glacier that has now retreated above the field of view of the photograph in (A). Large granitic boulders fell down the slope from the moraine at the toe of the glacier, perhaps caused by ancient earthquakes. This fan was then incised and the gullies and interfluves offset along the Denali fault. Giant boulders were sampled, as shown in (B). The uncertainty in the offset is related to the broadness of the gullies and interfluves. Correlated ridges and swales are shown by the colored lines in (A). We measured the offset of both the gullies and swales on the ground and averaged those measurements for the offset measurement used.

Site DFBU – Bull Creek

Location: N63°23.909', W149°25.139'

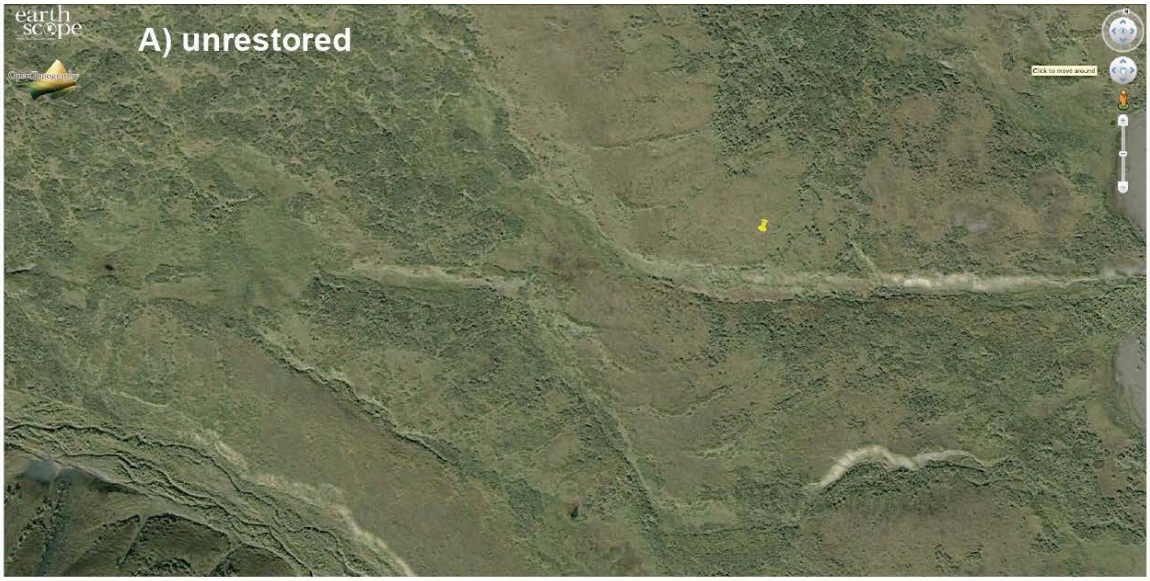


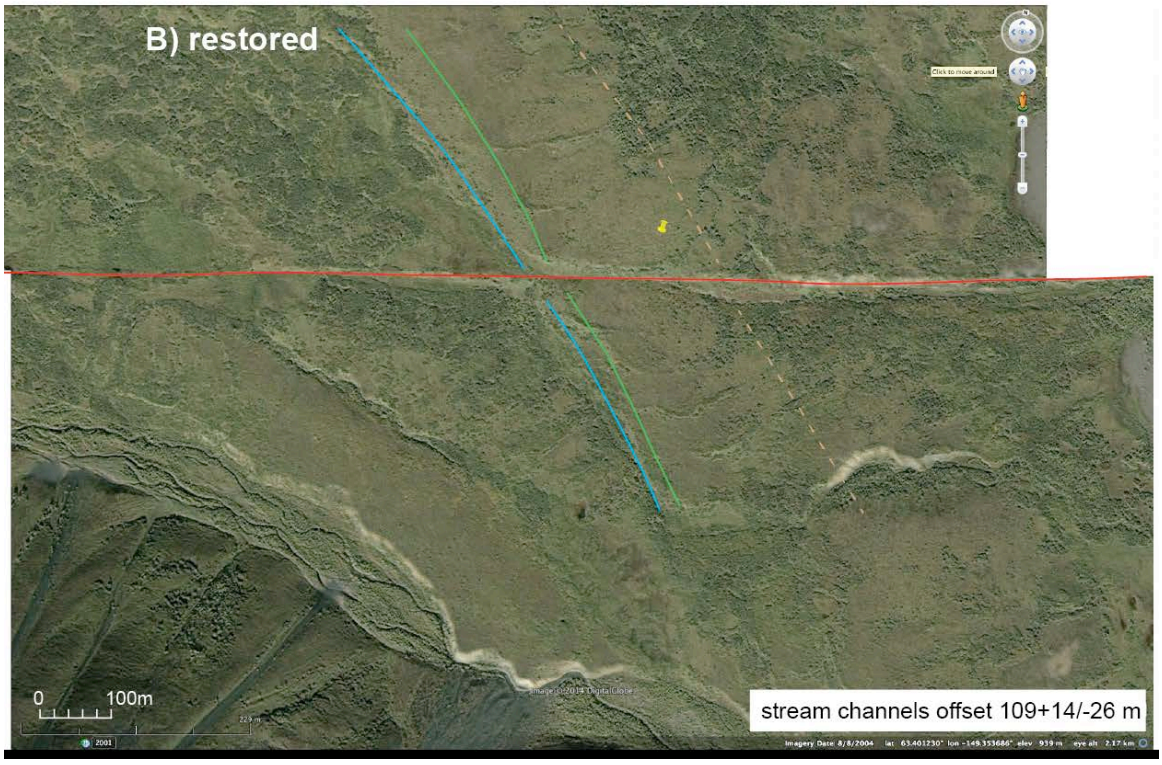


This site is on the south flank of the Alaska Range, where high-gradient braded streams are flowing down the mountainsides. A braided stream is on the left side of this image, but there are also relict drainages that formed soonafter deglaciation. Two such stream channels incised into a moraine and are clearly offset a similar amount across the Denali fault. On the south side of the fault, the margins of the two channels are sharp and provide excellent piercing points. North of the fault, the channel margins are clear 40 meters or more from the fault, and projecting their orientation toward the fault is the principle uncertainty in the offset measurement. We find the best estimate of offset from this satellite imagery, confirmed by measurements taken on the ground. A) Unrestored view of offset channels, B) restored, or unslipped, view of channels.

Site DFCA – Cantwell River

Location: N63°24.188', W149°20.982'

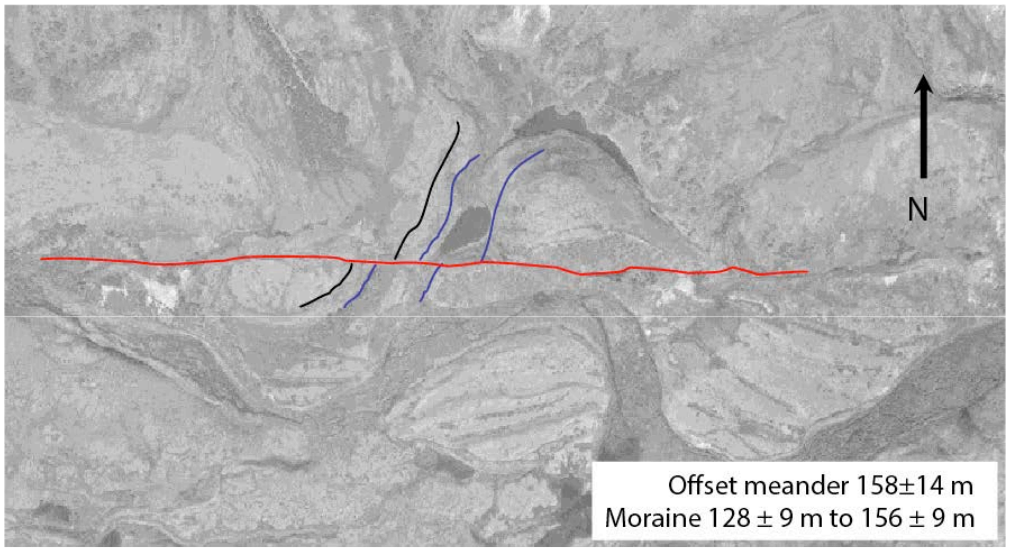




This site is like DFBU, in that it was glaciated and then subsequently incised by fluvial channels soonafter deglaciation. These are now abandoned and then offset along the Denali fault. The main channel thalweg (green line) is well defined, and the western channel wall is also well defined (blue line). These features were more difficult to see on the ground, and thus we use the Google Earth image. The principal uncertainty comes from the scale of the imagery and the broadness of the features.

Site DFSC – Schist Creek

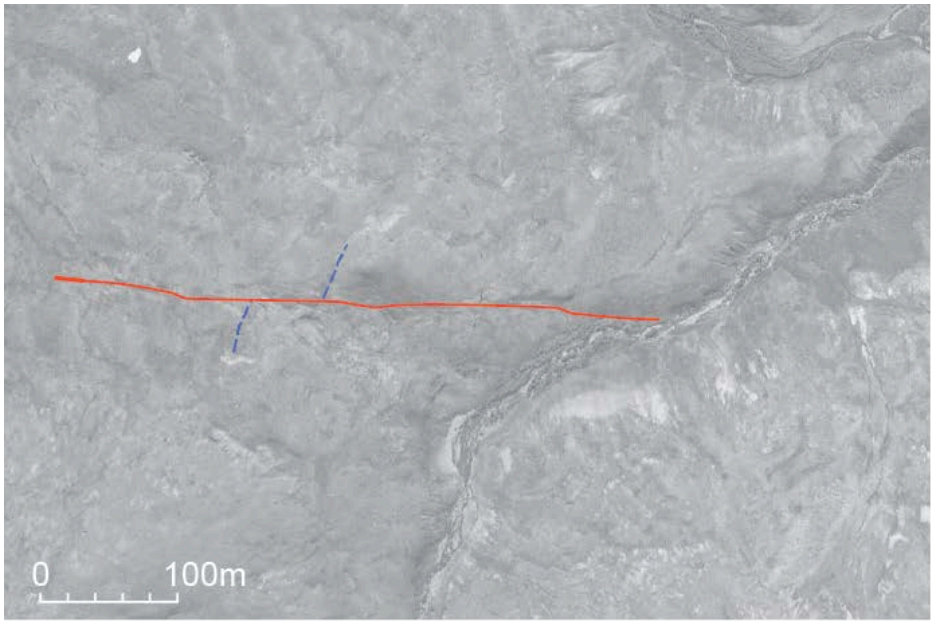
Location: N63°27.777', W148°38.888'

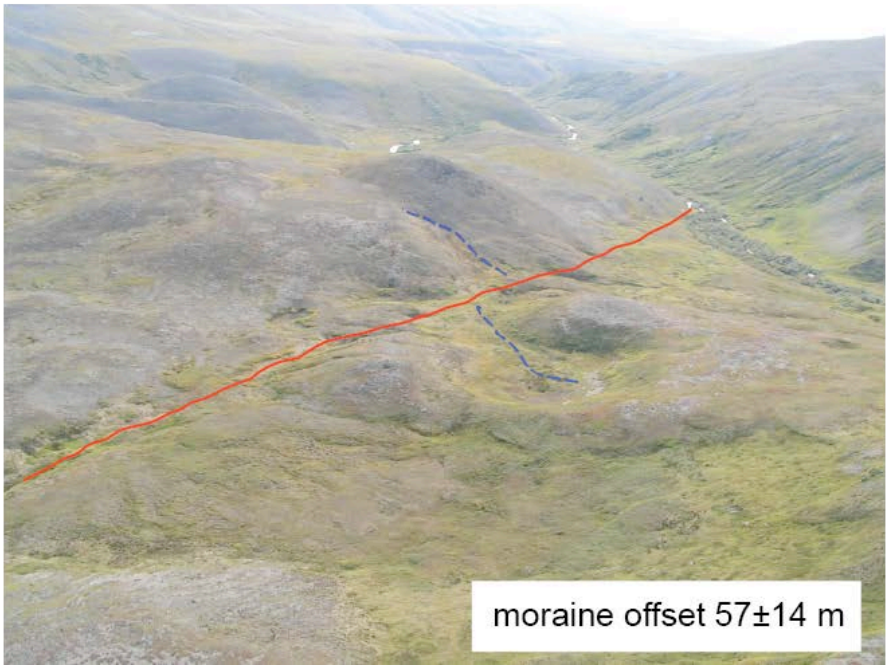


The present day Schist Creek is oriented parallel to, and located about 500 m to the south, of these paleodrainages. They likely formed soon after deglaciation, and given their high position on the this south facing slope, they likely formed while there was still glacial ice in the valley bottom. The meander offset is measured by correlating the base and crest of the meander's banks (blue lines). The error expresses the uncertainty in identifying the exact location of the slope-river valley contact. Moraine – offset is measured by correlating the moraine's crest (black line). The uncertainty in the measurement is expressed both by the range of measured offsets (there were two possibilities of crest identification) and by the uncertainty on the location of each piercing point. Offset was measured both by GPS locations of piercing points and measuring tape. Description modified from Matmon et al. (2006).

Site DFPP – Pyramid Peak

Location: N63°28.207', W148°25.572'

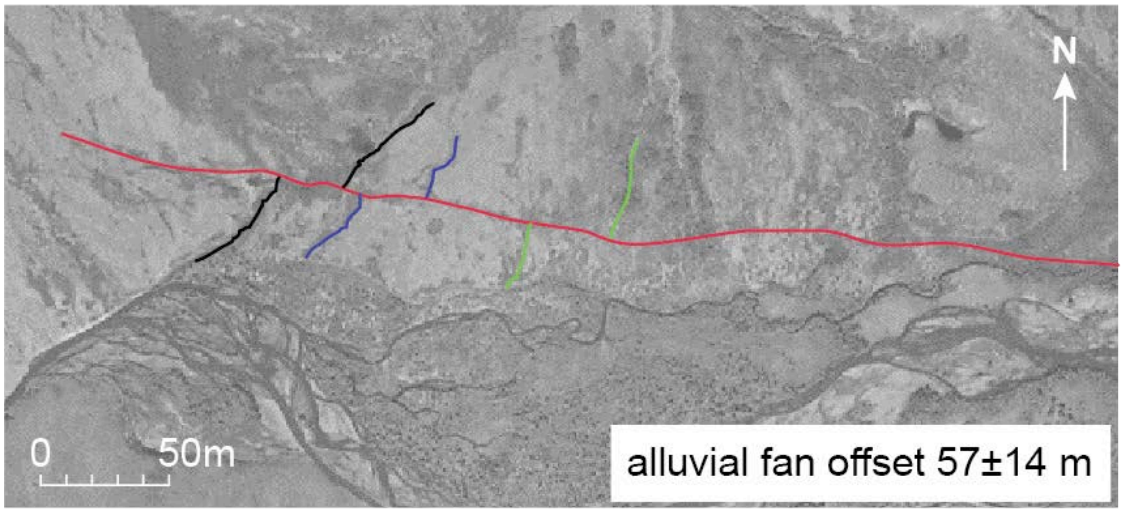


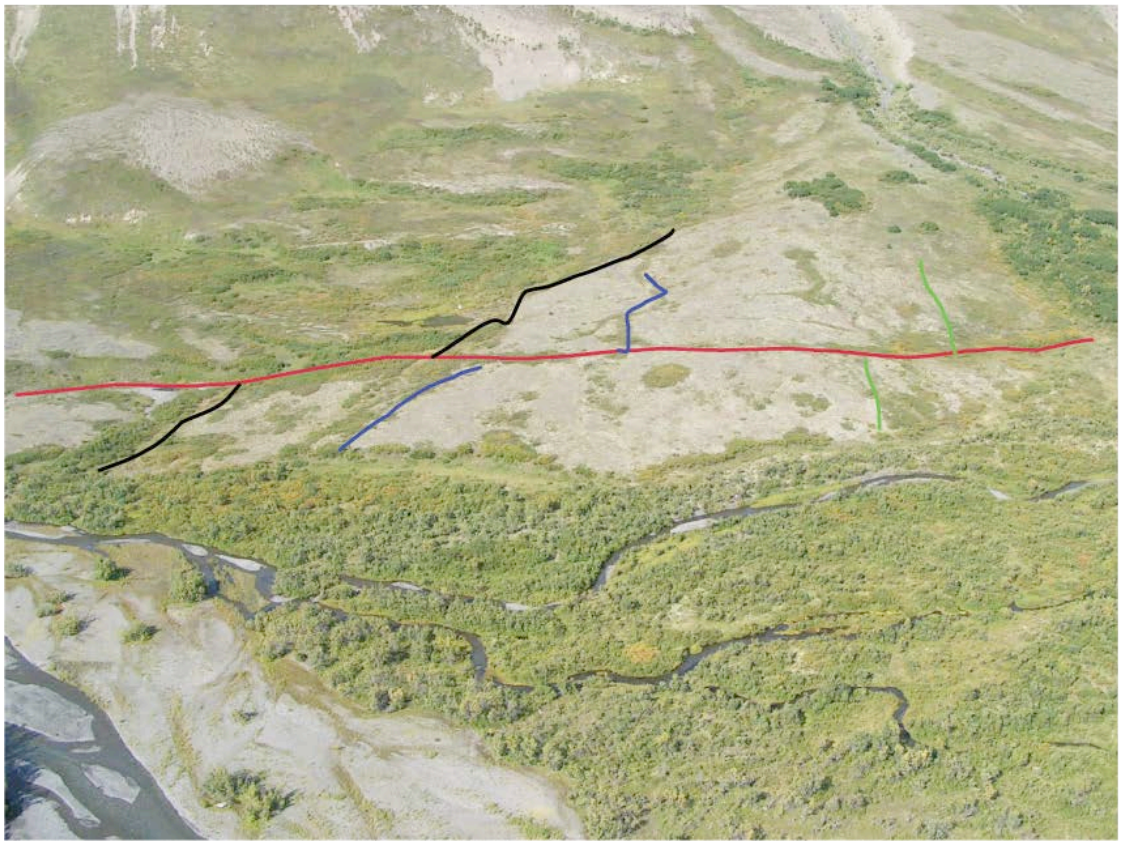


Like other sampling localities, this site lies on the south flank of the Alaska Range. At Last Glacial Maximum time, a large valley glacier filled the axial valley along the Denali fault with ice. It was fed by glaciers flowing from side valleys. These glaciers subsequently retreated, leaving moraines and till behind. Here a broad ridge likely originated as a medial moraine between the valley glacier and the main trunk glacier. This moraine is offset along the Denali fault (red line). The east edge of the morainal ridge is shown by the dashed blue lines. The error expresses the uncertainty in extrapolating the moraine edge to the fault, particularly on the north side of the fault, where its linear expression is weak. Offset was measured both by GPS locations of piercing points and measuring tape.

Site DFWC – Wells Creek

Location: N63°29.382', W148°05.064'

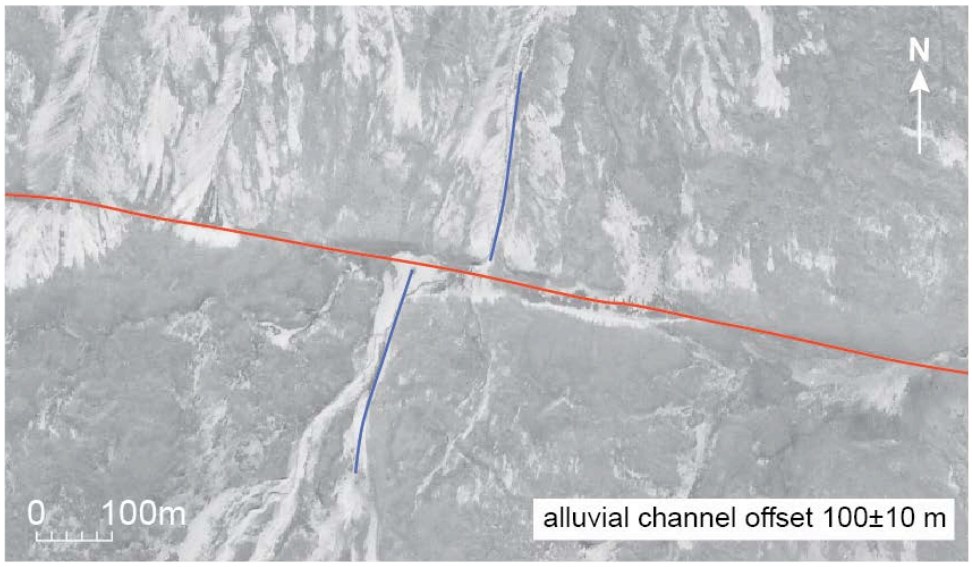


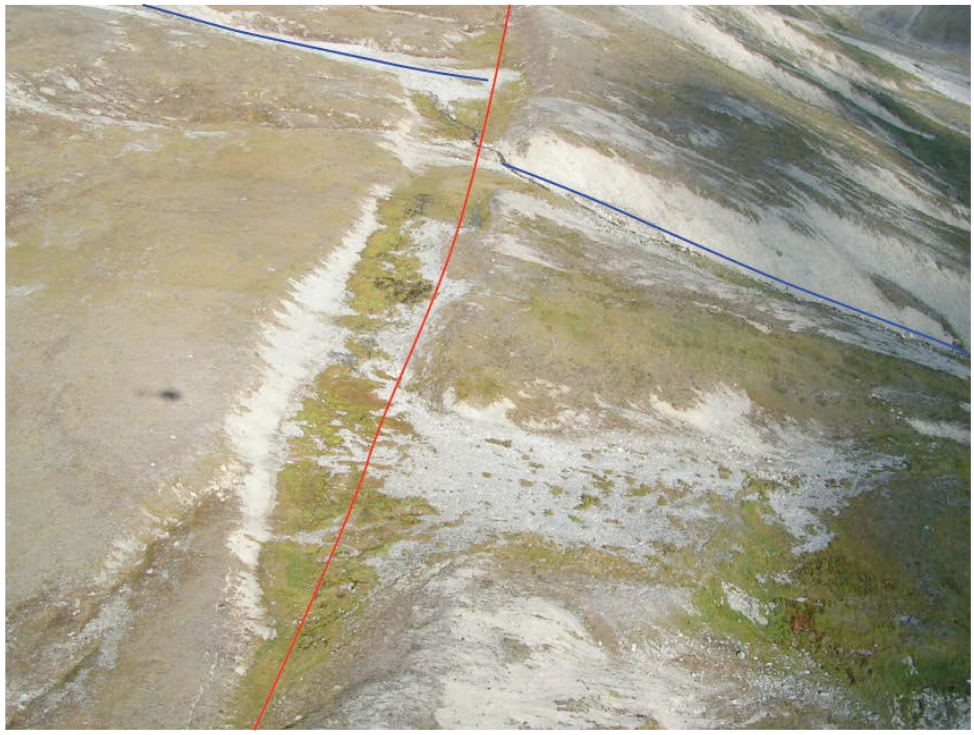


This site is on the south flank of the Alaska Range on an alluvial fan. A series of alluvial fans along this range front have indications of being offset by the Denali fault, but this relationship is the clearest. Here the alluvial fan offset is measured by correlating eastern edge of the fan (green line), the western edge of the fan (black line) and a small channel within the fan (blue line). The uncertainty in the measurement is expressed both by the range of measured offsets and by the uncertainty on the location of each piercing point. Offset measurements were made with a measuring tape. Description from Matmon et al. (2006).

Site DFNR – Nenana River

Location: N63°30.545', W147°37.924'

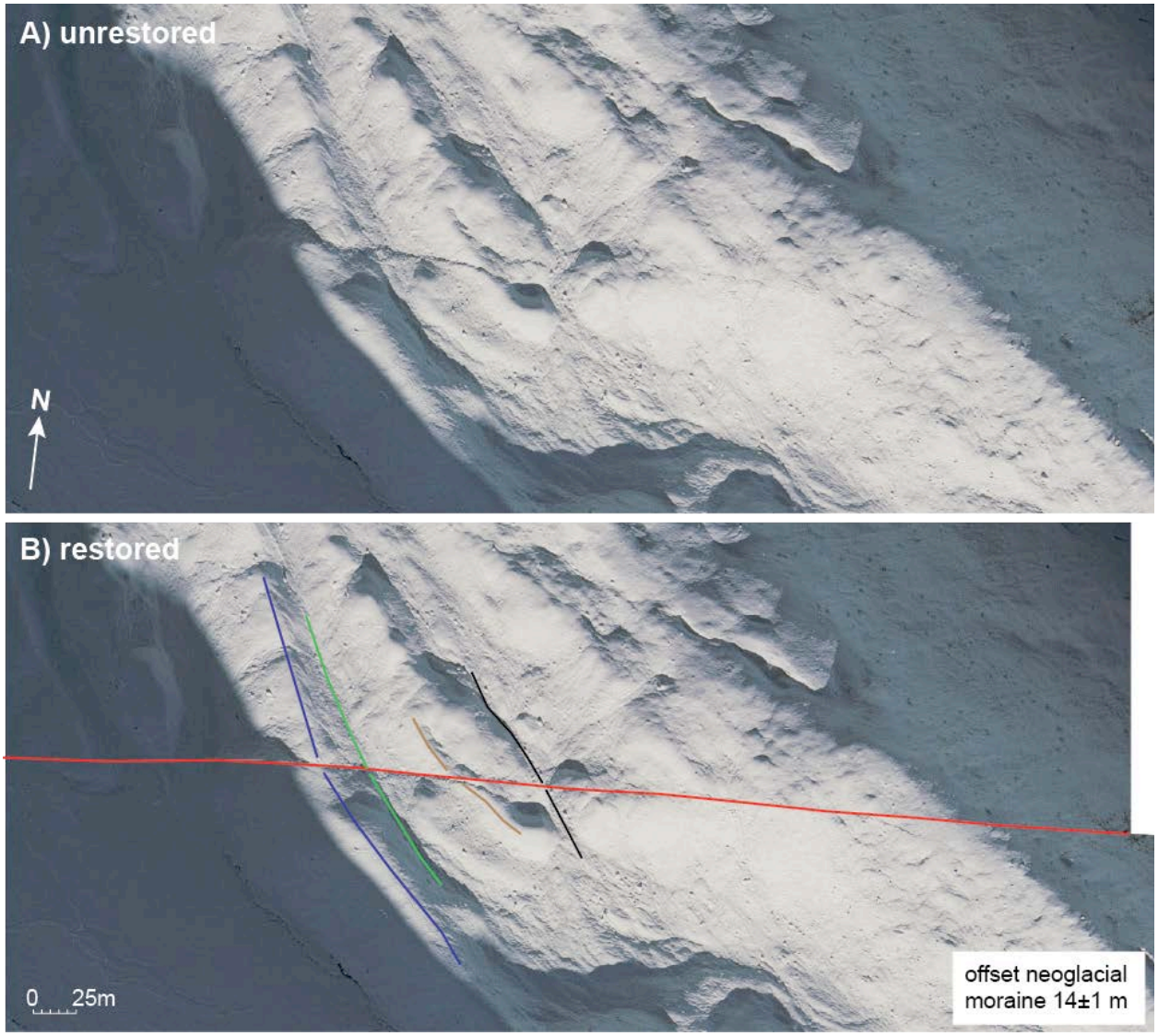




The site is on the south flank of the Alaska Range. A large valley glacier filled this valley, retreated, and then the surface was incised as fluvial processes became dominant. This stream channel was offset across the Denali fault. The offset of this channel was measured by projecting the thalweg of the the channel (blue lines) to the Denali fault trace (red line). We also assessed offsets at the upper edge of the bank to the stream, but these are rather broad, and the thalweg provided a more precise piercing point, with more certainty in its projection to the fault trace. The error in the measurement comes from uncertainty in knowing the position of the downhill channel within the larger eroded area adjacent to the stream. Offset was measured both by GPS locations of piercing points and measuring tape.

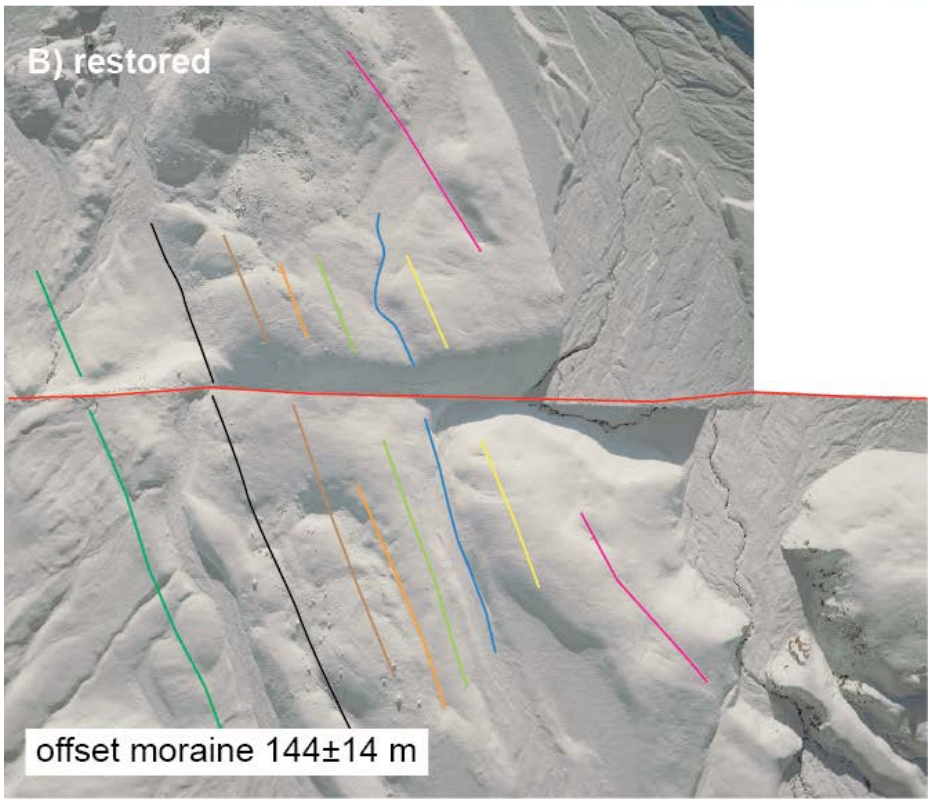
Site DFTH – Headwaters of Susitna River

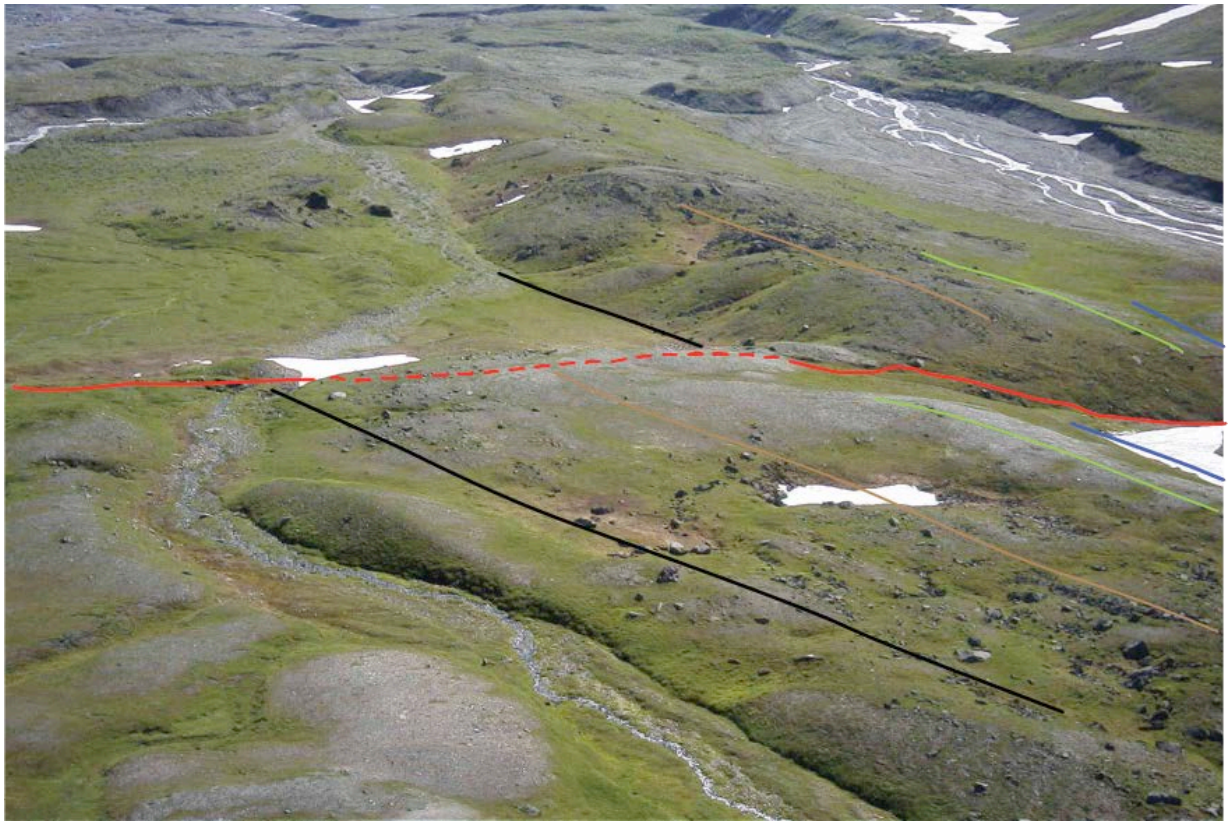
Location: N63°31.679', W147°03.737'



This site is on the south flank of the Alaska Range on a mountainous ridge that crosses the Denali fault between two major valley glaciers. Uphill from this site is an alpine glacier that used to completely fill this valley. It retreated, possibly readvanced, and then produced this sharp crested and well defined neoglacial moraine (blue line), which was then offset by the Denali fault. The adjacent drainages to the east (green line and black line) are also sharp features with little modification of the original geometry by erosion. A ridge on the adjacent moraine (brown line) is somewhat broader. The best measure of offset comes from on-the-ground measurements using a tape measure. These were confirmed by digital photogrammetric measurements (see Haeussler, 2009). Given all the offset features, there is little uncertainty. Note that individual strands of the 2002 surface rupture are oriented slightly clockwise of the longer term fault trace, which can be seen in the airphoto taken (A) above in November of 2002.

Site DFCR – Chistochina River
Location: N63°12.623', W144°49.905'





This site is on a south-facing slope of the Alaska Range. The large Chistochina Glacier used to fill this valley, and it remains a large trunk glacier, just 1 km to the southeast. Tributary glaciers met with the Chistochina Glacier in this region, and as all glaciers retreated, they left behind moraines, which were then incised by fluvial processes. These moraines were offset by the Denali fault. Measurement of offset along this moraine is based on three measured features: a channel flowing within the moraine (blue lines) which is offset 139±7 meters, the eastern moraine crest (brown lines) which is offset 135±17 meters, and the eastern moraine boundary (black lines) which is offset 157±14 meters. The similarity in offset of the three measured elements provides confidence in the offset determination. The errors express the uncertainty in determining the exact location of the piercing point. The average offset is 144±14 meters. The red dashed line in the bottom photo indicates the trace of the fault hidden by the moraine. Offsets were measured both by GPS and a measuring tape. Description modified from Matmon et al. (2006).

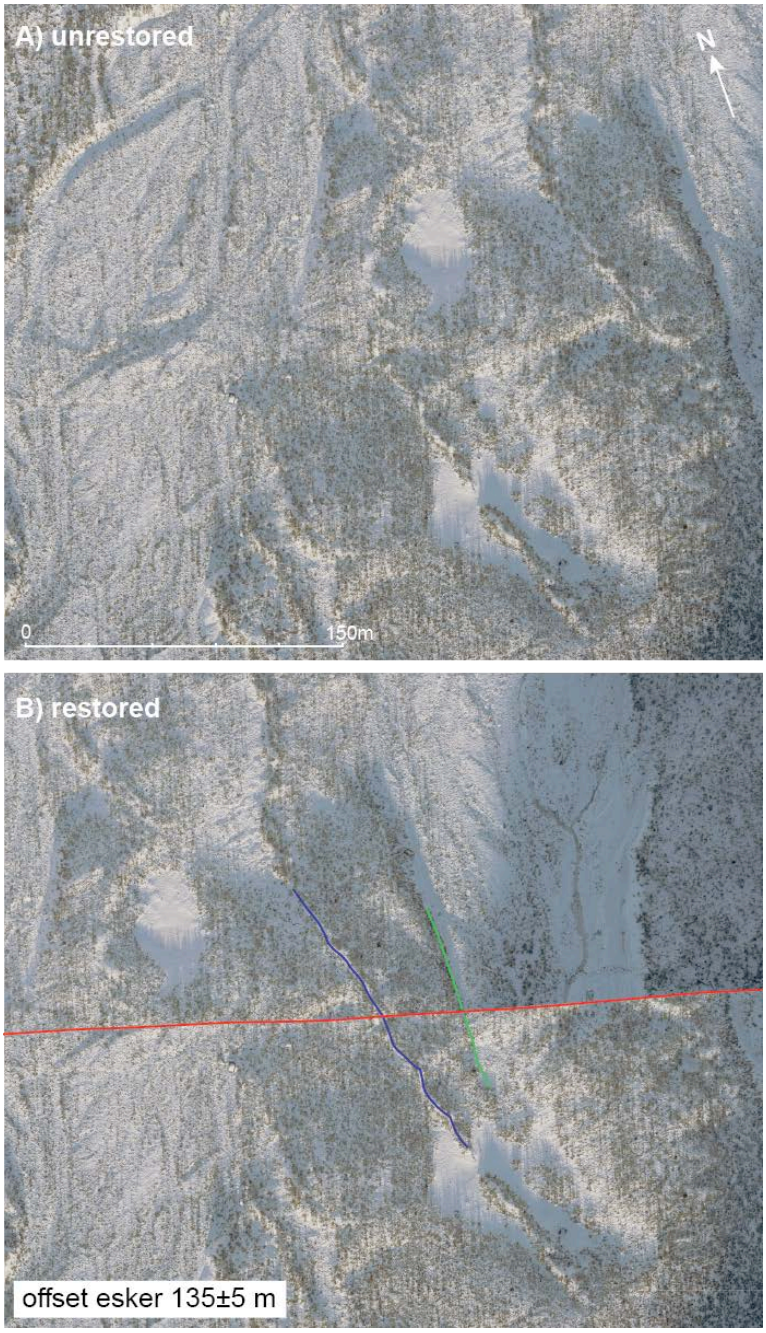
Site DFMF – Middle Fork of Chistochina River

Location: N63°09.246', W144°35.411'

This site is located on a south-facing slope near the headwaters of the Chistochina River. The valley used to be filled with glacial ice, and large valley glaciers remain in adjacent valleys 1.5-2 km to the east and west. Glacial retreat exposed this ridge of morainal material, which was subsequently offset on the Denali fault. Modern alluvial fans have subsequently filled in the valley floor. Measurement of offset along this moraine is based on two measured features: a channel flowing along the western edge of the moraine (blue lines) which is offset 171±4 meters, and the moraine crest (black lines) which is offset 136±17 meters. The errors express the uncertainty in determining the exact location of the piercing point. The average offset is 154±12 meters. Dashed black line in upper photo marks the interpolation of the moraine crest where it was washed out by a landslide. Offsets were measured both by GPS and a measuring tape. Description from Matmon et al. (2006).

Site DFES – Esker east of Chistochina River

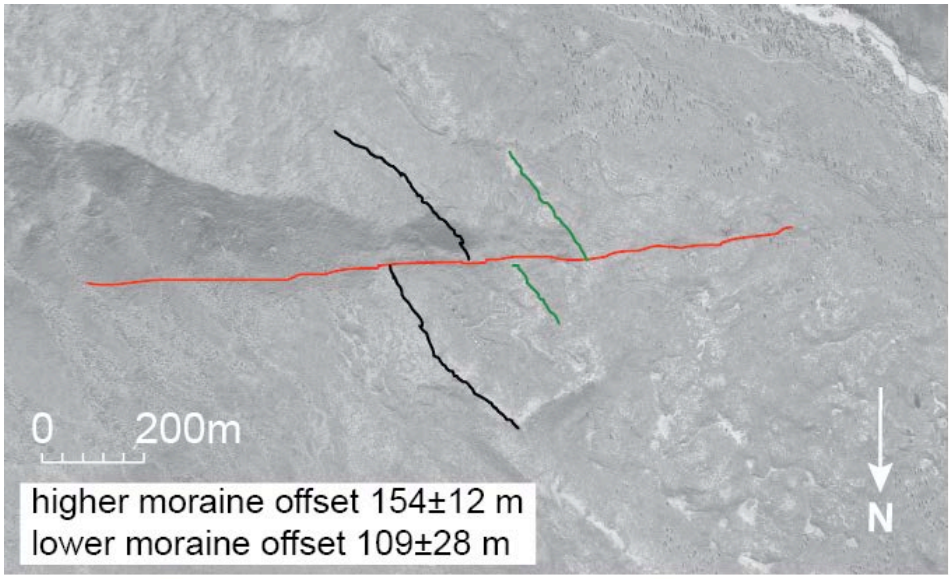
Location: N63° 08.794', W144° 34.219'

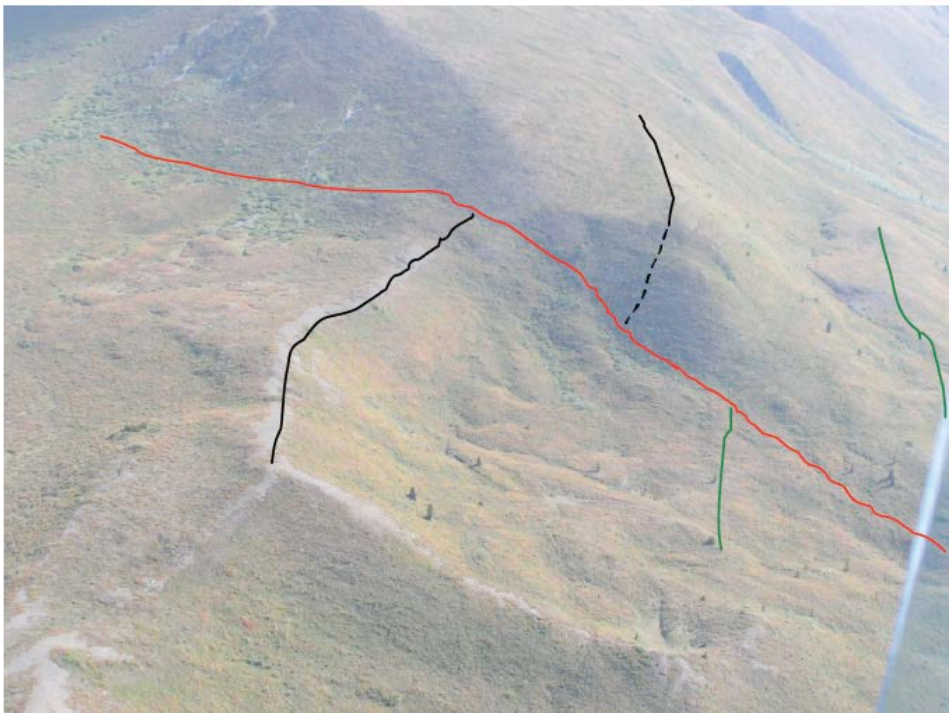


This site is located just 1.25 km east of the previous site, DFMF, 1.3 km in front of a large and nameless valley glacier exiting mountains of the Alaska Range. on a south-facing slope near the headwaters of the Chistochina River. The valley used to be filled with glacial ice, which stagnated and left behind eskers and kettle lakes. Modern braided rivers subsequently modified the valley floor. Here, a sharp and linear esker is offset 135±5 m along the Denali fault. The crest of the esker (blue line) is well defined. North of the fault, the margin of the modern stream channel to the east (green line) is well defined, and it lines up with a channel margin south of the fault, consistent with the esker offset. Uncertainty in the offset is related to the rounded edge of the esker. The offset was measured using digital photogrammetric methods (Haeussler, 2009).

Site DFTR – Tetlin River

Location: N62°40.515', W142°48.401'

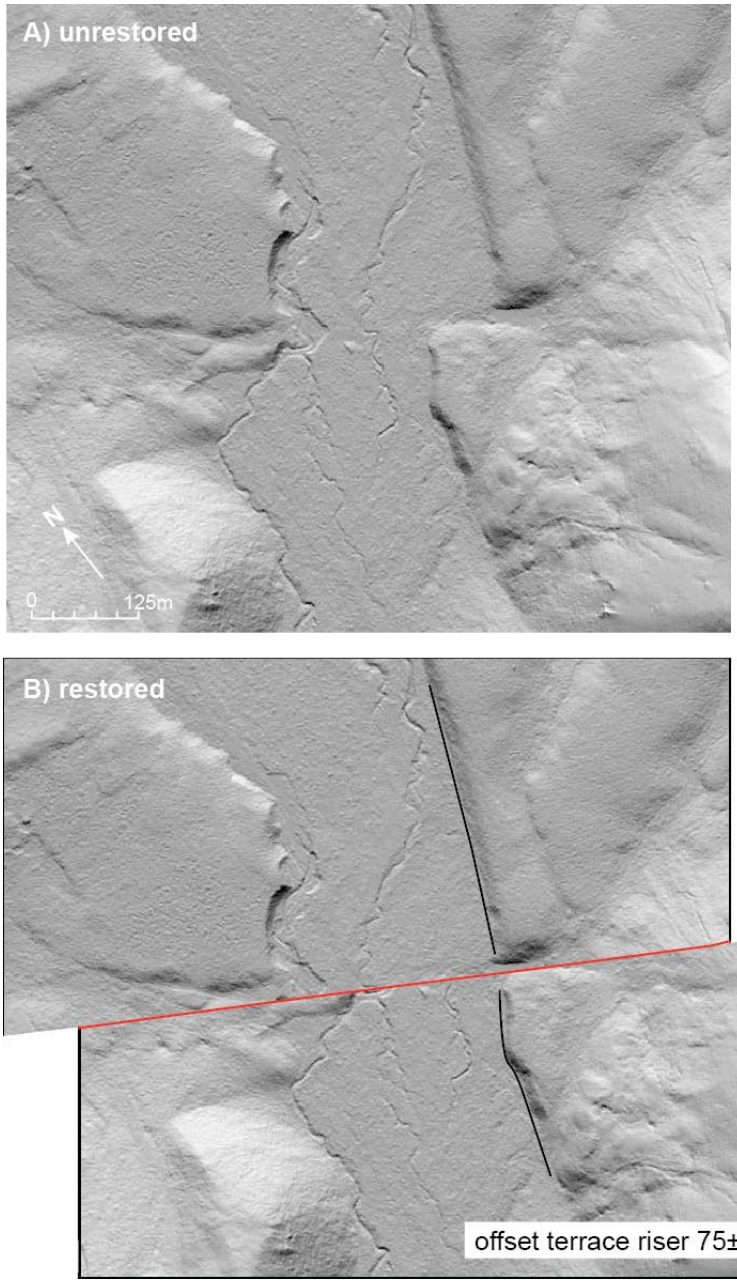




This site is located along the eastern Denali fault, on a medial moraine and kame terrace complex, where glaciers once flowed northward out of the Alaska Range. Modern valley glaciers lie about 6 km up the drainage to the south. After glacial retreat, fluvial processes modified the landscape. Two offset moraines were measured and dated at this site. The offset of both moraines was determined by the displacement of their crests. South of the fault, the high moraine crest (black lines) is eroded and the large error reflects the uncertainty in extrapolating the crest orientation to the fault trace (dashed line). The crest of the low moraine (green lines) is not well defined and the large error reflects the uncertainty in determining the piercing point. Offset was determined by GPS locations and on the air photo after determining the scale of the air photo in the field. Description from Matmon et al. (2006).

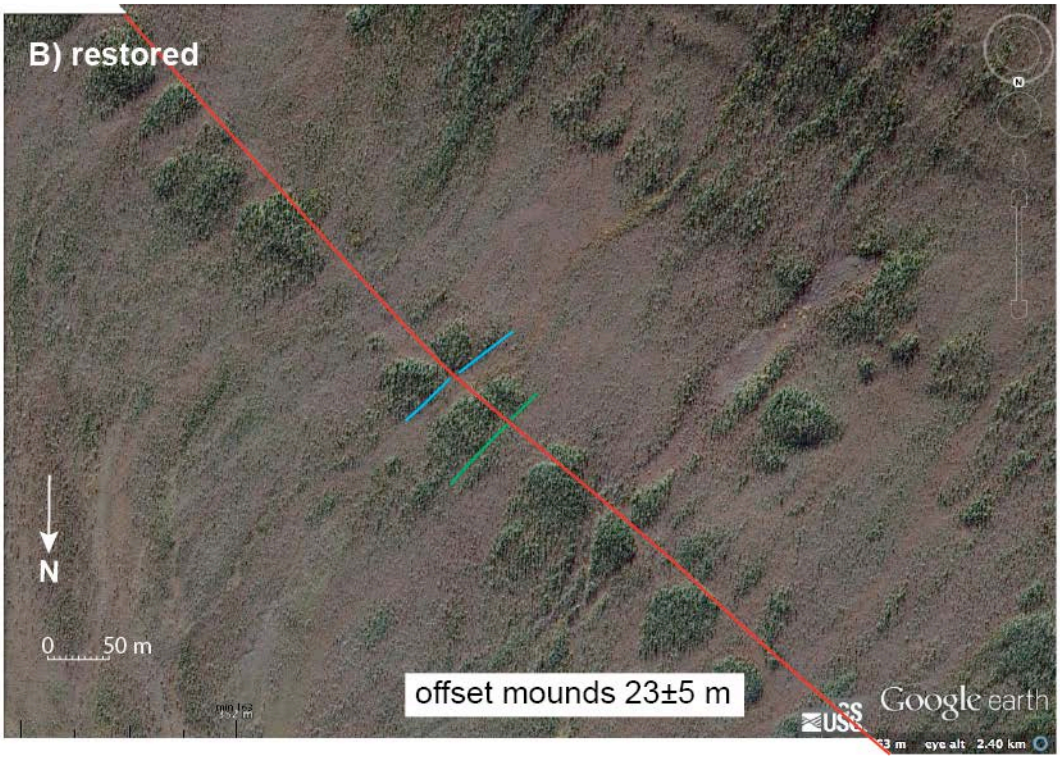
Site DFPB – Buck Creek

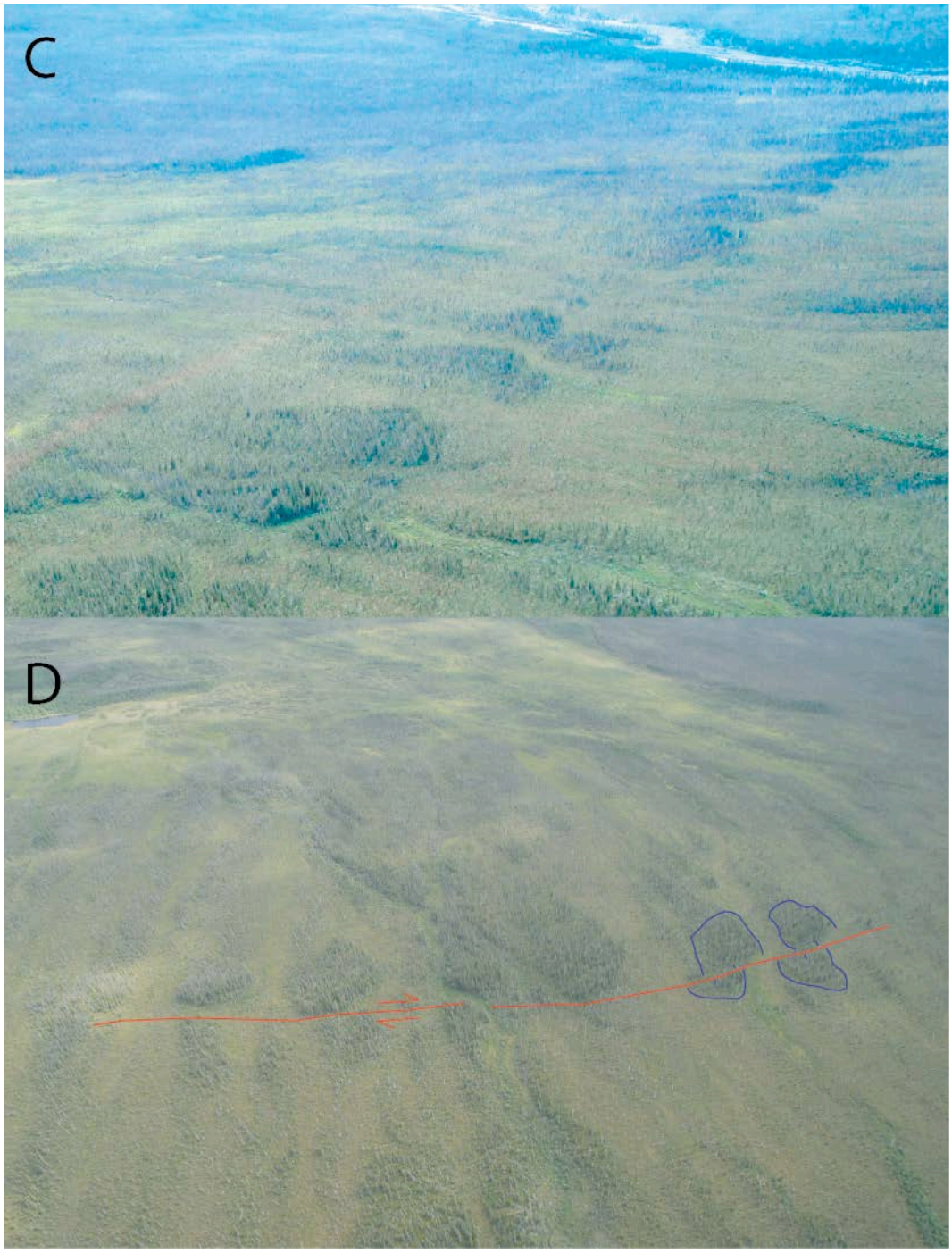
Location: N62°44.984', W143°04.065'



This site is located in the Mentasta Mountains along the axial valley of the eastern Denali fault. This valley was filled by glacial ice at some point in the past, and then the landscape modified by fluvial processes. This site is located on an alluvial fan that was deposited at the mouth of this branch valley, which was incised by the modern stream, and subsequently offset along the eastern Denali fault. The very linear terrace riser at a right angle to the fault makes this an ideal feature. There could have been some modification of the base of the riser south of the fault due to fluvial processes, causing the offset to be a minimum. However, the linearity of the feature indicates modification is minimal. We utilized both EarthScope lidar data and field observations for measuring the offset of this sharp north-trending terrace riser base (black line) and crest. The principal uncertainty comes from the how to project the slightly curving riser south of the fault toward the fault trace.

Site DFKL – Kluane Lake
Location: N61°18.600', W139°00.599'

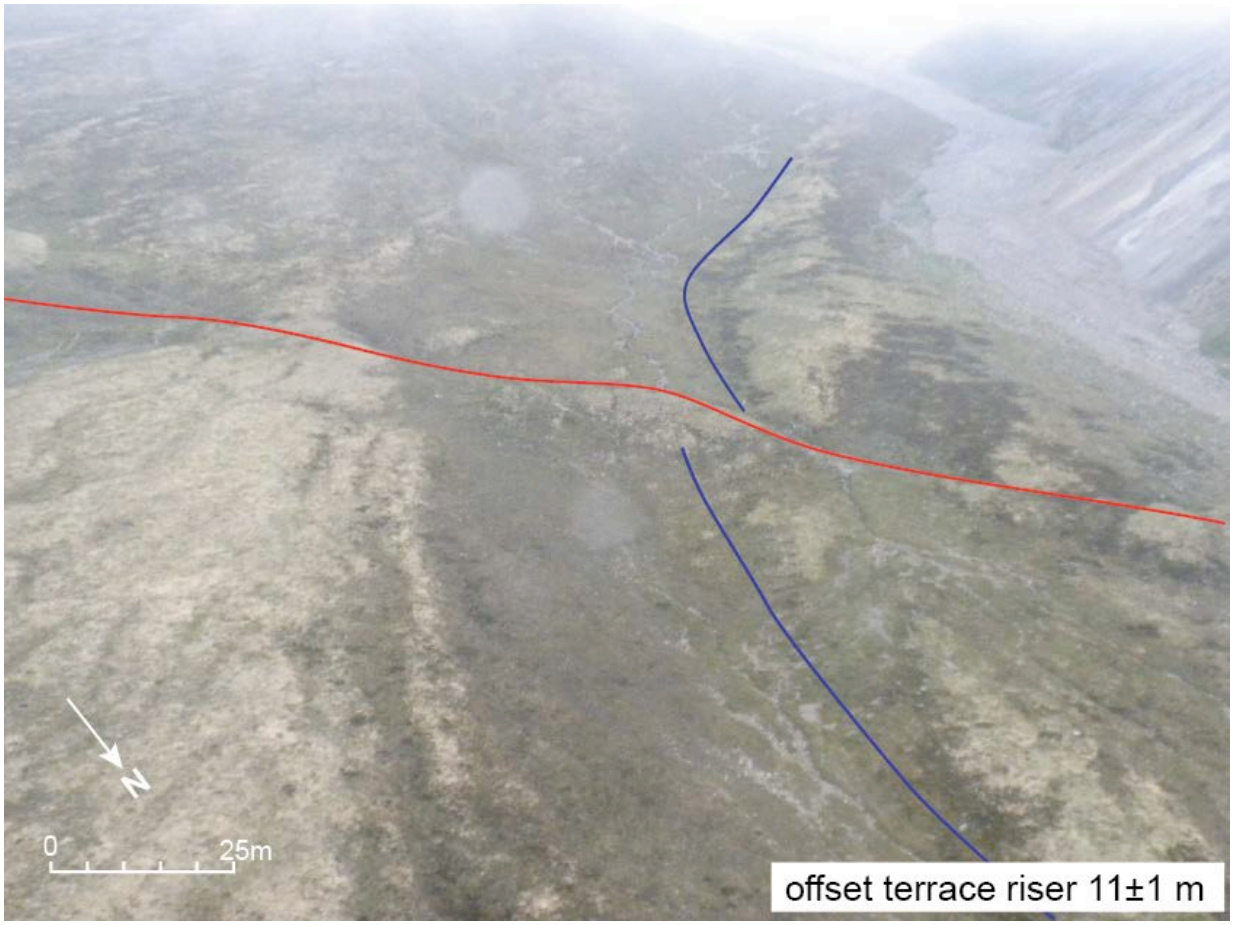




Photographs and development of the eastern Denali fault trace (see also Seitz et al., 2008). A) View of mounds on a Digital Globe image in Google Earth. B) Same image as in (A) but restored to offset of 23 m, as measured in the field and reproduced using these images. The margins of the mounds (black and green lines) are clearly seen. The uncertainty relates to the uncertainty in the margin of the tree lines. C) Oblique photograph of the eastern Denali fault showing that the fault is expressed as a series of mounds, which appear to be uplifts along the fault line. D) View of offset mounds along the fault trace. The mounds are better drained and thus have larger black spruce trees growing along them.

Site DFCM – Copper Mountain

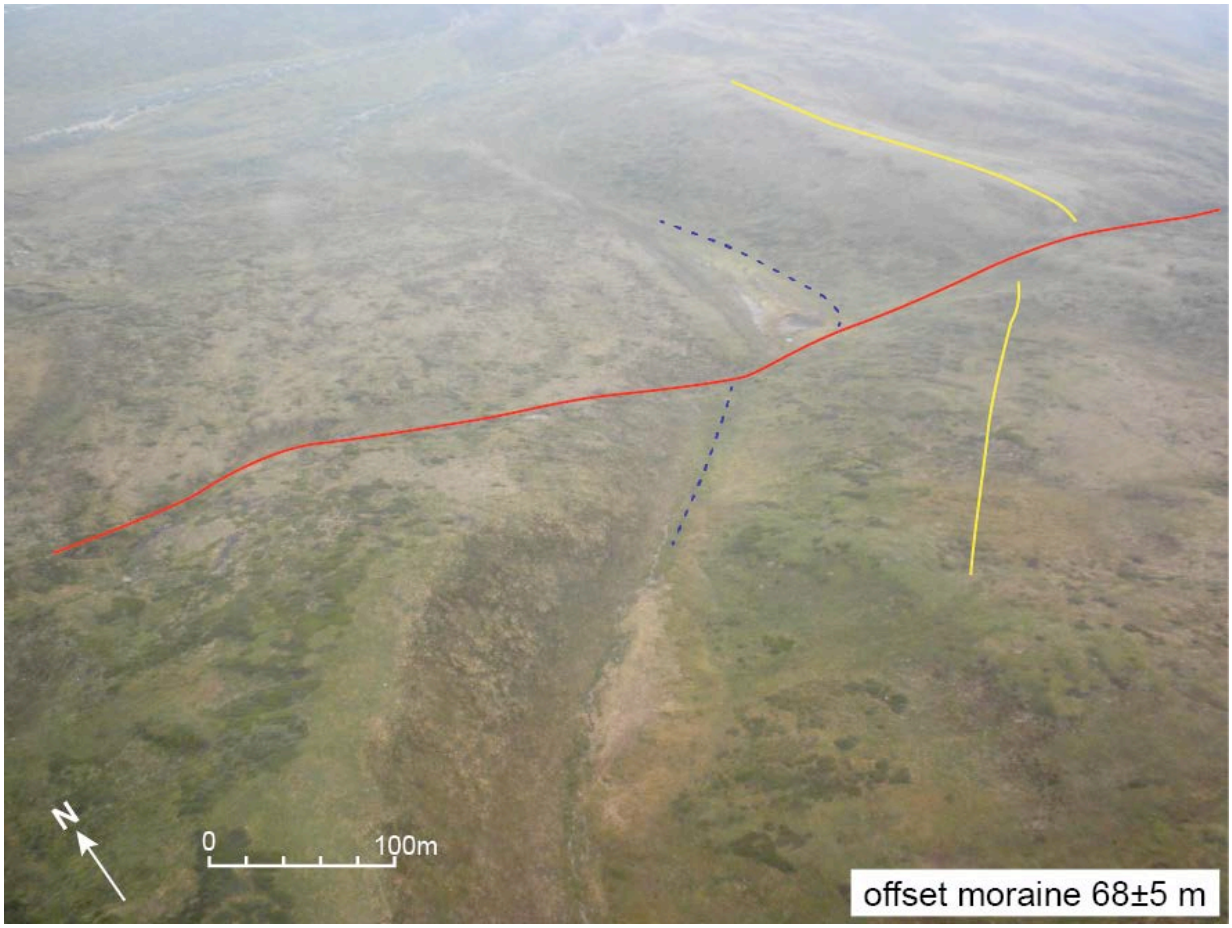
Location: N62°15.877', W142°31.263'



This site is located on a north-facing slope in the Nutzotin Mountains. At some point a large valley glacier filled the valley below this site. Since retreat of the glacier, fluvial processes have moved sediments down the alpine valleys. This site is appxoimately 30 m elevation above the valley bottom. A large allvual fan developed at the base of this valley, and it was subsequently incised by younger or modern streams. This stream course has mostly been abandoned for the course on the right side of the photo. The terrace riser was offset by the Totschunda fault. Measurement of offset of this terrace riser (blue lines) is based on projecting the riser toward the fault trace (red line). The principal uncertainty is related to projecting the riser inflection point toward the fault trace on the northeast side of the fault. Offsets were measured both by GPS and a measuring tape, and uncertainty was low due to the linearity of the rise and the high angle to fault.

Site DFNC – Notch Creek

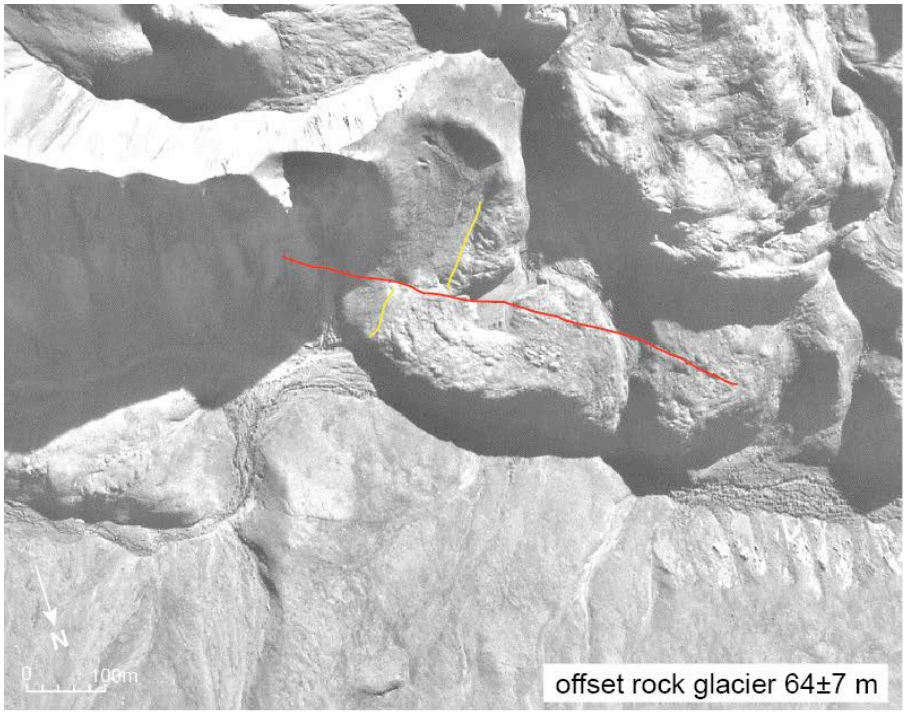
Location: N62°14.877', W142°30.177'



This site is on a northeast-facing slope of the Wrangell Mountains. The area was glaciated, and a large unnamed valley glacier lies about 2 km to the southwest. The surface was cut by the Totschunda Fault and offset. The surface has a set of weakly defined lateral moraines, one of which is shown by the yellow line. A stream (dashed blue line) incised into the till-covered surface and is offset by the fault (red line). Although some water still flows along the stream channel, the modern stream is underfit with respect to the channel — it likely had much greater flow soon after deglaciation. The principal uncertainty comes from projecting the trace of the stream into the fault trace on the northeast side of the fault, as the stream bends in this region. Offsets were measured both by GPS and a measuring tape.

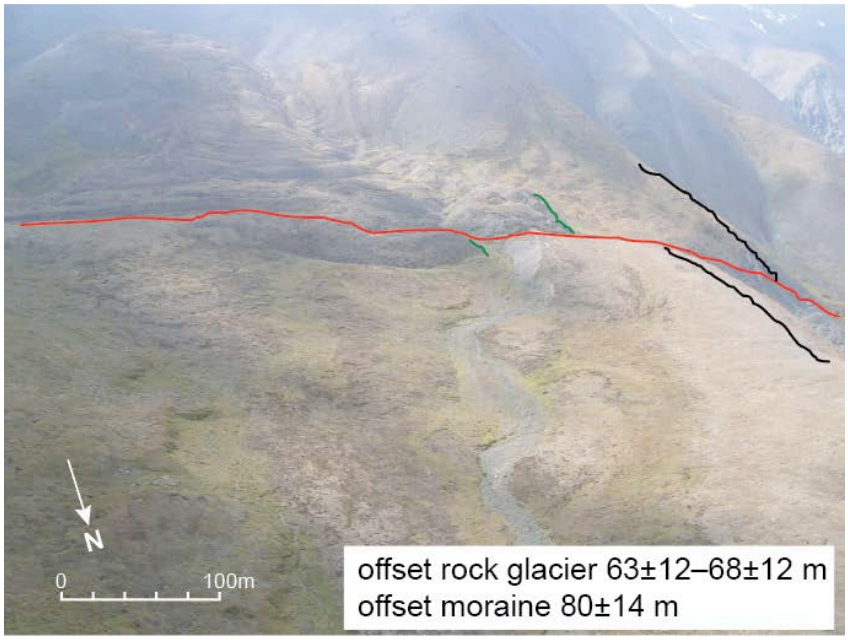
Site DFDP – North of Noyes Mountain

Location: N62°40.457', W143°09.359'



This site is on a northeast-facing slope in the Mentasta Mountains. There area had been glaciated, but more recently a rock glacier flowed to the northeast off the ridge of mountains to the southwest. Although part of the rock glacier remains active to the west, this part of the rock glacier ceased being active, decayed, and then was offset along the Totschunda fault. Offset was determined by the measured displacement of the southeastern boundary (yellow lines) of the inactive rock glacier. The error expresses the uncertainty in determining the piercing point. Offset was measured with a measuring tape. Description modified from Matmon et al. (2006).

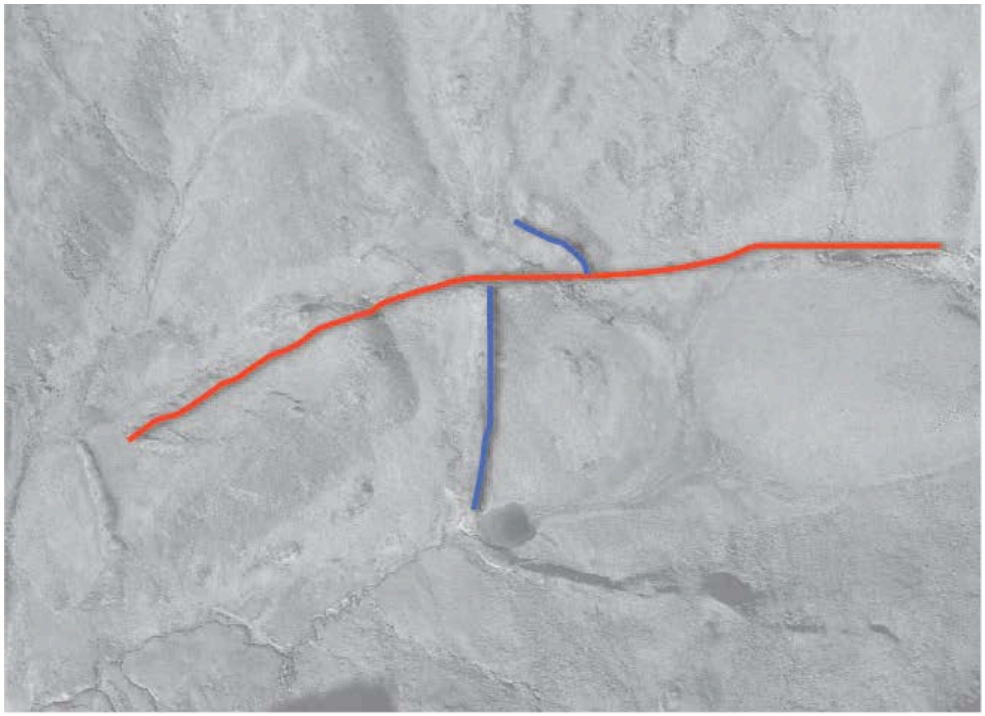
Site DFNM – Noyes Mountain
Location: N62°37.132', W143°01.905'

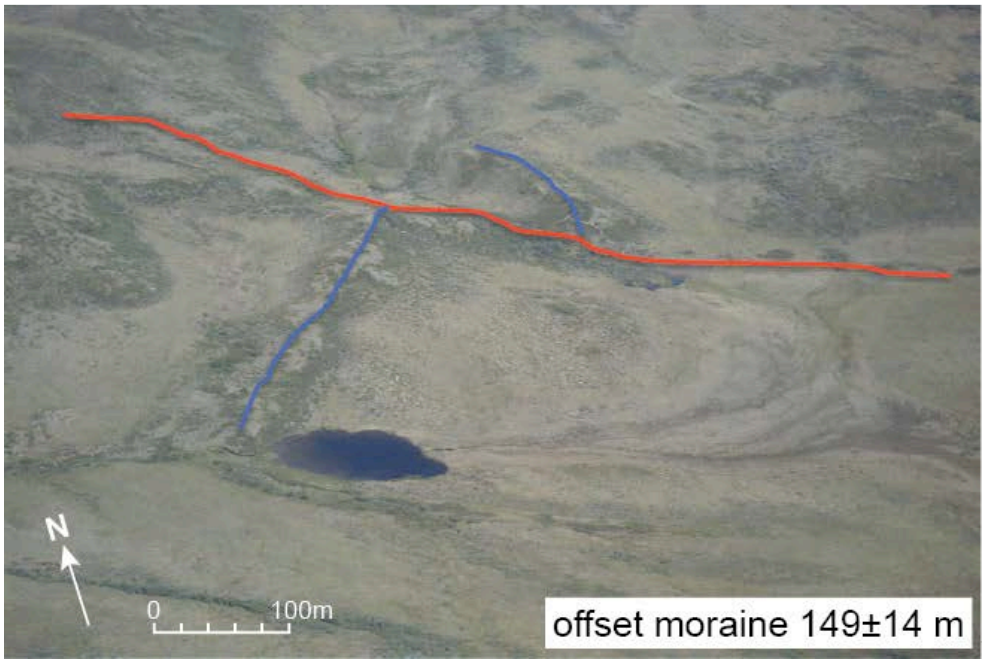


This site is located to the east of Noyes Mountain in the Mentasta Mountains along the Totschunda fault. This is located in a large glacial valley, which glaciers have retreated out of. This site is located on the toe of a rock glacier deposit. The rock glacier remains active further uphill, but there is no evidence that this part of the rock glacier is still moving, as it is well vegetated. Two offset features were measured and dated at this site and cross the Totscunda fault at a high angle. The offset of the inactive rock glacier (green lines) was measured three times and the measurements range between 63±12 meters and 68±12 meters. The offset was determined by the measured displacement of the western boundary of the rock glacier using GPS locations and a measuring tape. The offset of the moraine (black lines) was determined by the measured displacement of the moraine's crest. The eroded part of the moraine crest is extrapolated and marked with a dashed black line. Description modified from Matmon et al. (2006).

Site DFTC – Totschunda Creek

Location: N62°31.996', W142°51.140'





This site lies in a glacially carved valley on a south-facing slope in the Mentasta Mountains. There are no active glaciers nearby today. Retreat of glaciers left behind various glacial features, including moraines. This moraine crest (blue line) intersects the Totschunda Fault (red line) at a high angle, and the offset was determined by measuring tape and GPS. The error expresses the uncertainty in determining the piercing point, particularly for the moraine crest on the north side of the fault, which is curving toward the fault trace.