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Recurrence and Flow Direction of Glaciers Across the Kawdy Plateau, Northern British Columbia

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Recurrence and flow direction of glaciers across the Kawdy Plateau, northern British Columbia

By
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Class of 2010

Submitted in partial fulfillment of Honors Requirements for a Bachelor of Science degree from the Department of Earth Sciences

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ABSTRACT

Linear features observed on the Kawdy Plateau (KP) in northwestern British Columbia are indicative of multi-stage continental glaciation before, during, and after the last glacial maximum. The grooves, which cluster into three different groups at unique orientations, indicate that at least two and probably three separate continental ice sheets flowed over the KP, separated by enough time to allow the previous glacier to melt entirely. Linear features on the plateau floor and on top of two volcanoes indicate that all three of these glaciers flowed east/northeast-west/southwest, striking between 21-55°, 87-169°, and 56-86°, oldest to youngest. This evidence for multi-stage continental glaciation has important implications for the reconstruction of the history of the Cordilleran ice sheet, as well as for paleoclimate factors that influenced its development and retreat.
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I. INTRODUCTION AND HYPOTHESIS

The Pleistocene Epoch, which began 2.6 Ma and lasted up until 12,000 years ago, is a period in geologic time characterized by the development and retreat of continental ice sheets across much of the northern hemisphere (Marshak, 2005; Harris, 1994). Most of northern North America was covered by the Laurentide ice sheet (LIS), which stretched from the Rocky Mountains all the way to the east coast, while the Cordilleran ice sheet (CIS) covered the western coast of the continent from Washington State north into Alaska. While extensive research has constrained the timing of advances and retreats of the Laurentide ice sheet, much less is known about the development and fluctuations of the Cordilleran ice sheet, or the specific influences of glaciers on the topography of northwestern British Columbia. Analyzing glacial features located on the Kawdy Plateau, northwest of Dease Lake in northwestern BC, will allow us to construct the general history of the CIS in the area, including type of glaciation (alpine or continental), relative timing, minimum ice thickness, and ice flow direction. The focus of this research attempts to help answer a broader question about the Pleistocene climate in the North American Cordillera: was the northern part of the CIS permanent, or did it melt and reform multiple times during the Pleistocene? Analysis of the orientations and quality of preservation of glacial features has indicated that the features in the in the study area cannot be explained by a single glaciation event, and are therefore indicative of multiple glaciations events on the Kawdy Plateau.

A number of features are considered to be indicative of previous glaciation, and are commonly used to identify an area that has been modified by alpine or continental glaciers. Features indicative of alpine glaciations include cirques, cirque moraines, arêtes, and horns, while features related to continental glaciation include erratics, fluting, drumlinoids, and tuyas. Tuyas are steep-sided, flat-topped volcanic edifices formed by eruptions into and through overlying glaciers (Mathews 1947, Hickson 2000, Komatsu et al 2007, Watson & Mathews 1944, Figure 1). They are particularly useful for constraining the timing and minimum ice thickness of continental ice sheets. Tuyas comprise volcanic breccias and hyaloclastite, with pillow basalts at the base of the edifice and topped by a flat-lying, subaerial lava cap (Figure 2a-b) (Mathews 1947, Hickson 2000, Watson & Mathews 1944). The transition from the dipping hyaloclastite beds and pillow lavas to the relatively distinct subaerial lava cap forms a sharp boundary termed the “passage zone,” which can be used to
constrain the exact elevation of water at the time of eruption. Tindars and subglacial mounds are also volcanic features associated with volcano-ice interactions. Hickson (2000) describes tindars as fissure eruptions dominated by hyaloclastite, breccias, and pillow lavas, most commonly identified by their elongated, ridge-like shape. Subglacial mounds are made of the same material, but are conical in shape and form due to cinder cone eruptions. It is unclear whether tindars and subglacial mounds are the result of eruptions that occurred through the same process of tuyas, and simply never broke through the surface of the glacier above, or if they are created by a different process altogether.

Because pillow lavas and passage zones form due to contact with water and occur at high elevations, it is clear that water must have existed at these elevations at the time of eruption. Since the areas containing tuyas are far inland, the only way to have water at such a high elevation would be to have it confined by ice sheet surrounding the edifice as it erupted (Figure 3). Therefore, subglacial edifices can be used to determine a minimum ice thickness of the ice sheet present at the time of eruption, since the ice must have been at least as thick as the walls of the edifice are tall. Due to their volcanic composition, subglacial edifices can also be dated, providing a numerical age constraint on the timing of glaciation.

The Kawdy Plateau (KP) (Figure 1), therefore, is an ideal place to study the timing and behavior of the CIS, and, due to the ability of the volcanic deposits to withstand glacial erosion, is perhaps one of the only remaining areas that might contain records of glaciations prior to the Last Glacial Maximum (~22-19 ka) (Yokoyama et al., 2000). The KP is a flat, 956-1126 km² plateau in northwestern British Columbia where a number of researchers have recognized the presence of glacial features (Ryder & Maynard, 1991; Gabrielse, 1998; Ryder, 1986; McCuaig & Roberts, 2002; Watson & Mathews, 1944; Mathews, 1947; Hickson, 2000; Edwards & Russell, 2002; Dickson et al., 2002; Fiesinger & Nicholls, 1977; Souther, 1977). Features observed here include cirques, moraines, erratic, drumlinoids, and linear erosional features. At least four tuyas have been identified on the plateau: Horseshoe Tuya, Isspah Butte, Kawdy Mountain, and an unnamed mountain called Tanker Tuya (Watson & Mathews 1944). Tuyas have also been identified in the nearby Cassiar Mountain Range, immediately north of the KP (Allen et al., 1982; Mathews, 1947). The presence of erosional features such as cirques and linear features, as well as volcanic, may provide a more complete picture of ice sheet behavior and interaction during the Pleistocene.
II. METHODS AND EXPERIMENTAL DESIGN

The testing of the hypothesis proposed above comprised three stages. The first stage was, through analysis of field data and aerial photos, to verify that the features observed on the tuyas are in fact produced by glacial erosion, and consequently that dating them will indeed provide insight on the movement and developmental history of the CIS. This included describing in detail the characteristics of the observed features (Table 1) and comparing their characteristics to those in the glaciological literature. This helped to determine if an observed feature matched the description of a recognized glacial feature, and served as a guide for determining the type of measurements to make to quantitatively characterize indentified glacial features.

The second stage included general characterization and quantification of features identified as having glacial origins, including noting cross-cutting relationships, measurement of features’ characteristics (length, orientation, spacing), location, and quality of preservation. Features were then examined to help construct a preliminary glacial history of the area by:

1. Comparing the azimuths of linear features with statistical tests to see if distinct groups exist,
2. Analyzing cross-cutting relationships between linear features based on differences in orientation and preservation,
3. Examining patterns of distribution through the use of rose diagrams, and
4. Looking for features like drumlins or grooves that may be ice flow direction indicators.

This analysis of the KP began with a two-week field study conducted during July of 2009. The azimuths of linear features were measured when encountered in the field (e.g. Tutsingale Mountain, Figure 1), and the structure and composition of the linear features were observed in close detail. The greatest value of the field observations was to collect photographs and gain a first-hand sense of the features’ shape and scale to be able to better interpret similar features on the aerial photographs.
The primary analysis of the observed features on the plateau was done using aerial photographs and Digital Elevation Model (DEM) files. A variety of different methods were tested to determine the best way to measure the features. These methods included: overlaying the aerial photograph on a hillshade map in ARC GIS, overlaying the photographs on the landscape in Google Earth, and making measurements by hand on the aerial photographs, or tracing the features in Adobe Illustrator. Using ArcGIS would have been the preferred method of measurement, but ArcGIS and Google Earth were unsuitable because of inadequate referencing points to position the aerial photographs. Adobe Illustrator was determined to be the most accurate and efficient method available, however required correcting measurements at the edge of the photographs for distortion by the camera lens. Working with the photographs as Illustrator files was preferable to working with them by hand, because specific areas of interest could be enlarged without having to adjust the scale every time a new measurement was made. Since the scale of the aerial photographs is not the same as what is observed on the ground, all measurements had to be converted to length-scale on the ground.

**Measurements**

To conduct measurements of the linear features across the KP, five aerial photographs (BC5616 063, BC5616 064, BC5616 067, BC82015 120, and BC82015 172) were analyzed using Adobe Illustrator. For each photograph, at least three layers were created:

A. One layer including all linear measurements which were eventually color-coded for orientation,

B. Another layer containing potential flow indicators such as drumlinoids, and

C. One containing spacing measurements.

On the linear features layer, lines were drawn using the pen tool, tracing visible linear features on the aerial photos (Figure 4A). When possible, the lines were drawn along the crest of the feature, though in some cases only one side of the feature was clearly visible in the photograph, in which case that lineation was measured. When a drumlinoid feature was encountered, it was notated in a different color for easy relocation.

These features were then measured using the ruler tool to determine their orientations and lengths (Figure 5). This was done by clicking on the bottom left corner of the drawn
line, then the bottom right corner, and recording the measurement generated by Adobe Illustrator. Since Adobe Illustrator automatically measures orientation from a horizontal axis with a value of 0°, a simple equation (90-x) was used to convert the orientation measurements into azimuths. The scale of each aerial photograph was used to convert the length measurements to their actual size (Table 2). Each photograph was examined a minimum of three times, and each time, a random selection of the measured features was checked to ensure that, a) no major features were missed, and b) that the lines drawn were accurate and reproducible. Once different groups of lineations were identified, the features belonging to each group were color-coded by orientation (Figure 4B).

Lengths were sometimes difficult to measure with a great deal of certainty. The resolution of the photographs (Table 2) inevitably limited the accuracy of the measurements. However because that limitation exists for all measurements taken in this study, they are still useful for comparative purposes. In most cases the lineations are clearly defined, but some appear to have been modified by subsequent erosion. In some places, two linear features appear on either side of a tributary or creek bed. Their adjacent position and parallel orientation make it very tempting to say that the features were once connected and have been modified by subsequent erosion, but adequate data is not available to substantiate that claim. Therefore, in the interest of being consistent and conservative, when collecting measurements, the features were delineated as continuous only when their continuity was undeniable. If there was a clear break, even if the two pieces were at the same orientation, they were notated and measured as separate features (Figure 4C). Despite these complications, differences in length are important in order to characterize the features, and if found to correlate with differences in orientation, may help to define unique populations of features.

To measure the spacing between the features, an area with a dense population of parallel grooves was selected. When possible, measurements were taken between grooves that were identified as well-preserved sets, assuming that these locations were most likely to reflect the original spacing of the features. A new line was then drawn over the features, perpendicular to their orientations (Figure 4C). Measurements were then taken from northern trough to northern trough of each feature that the new line intersected. Differences in spacing, if found to correlate with differences in orientation, may help to define unique
populations of grooves or may be characteristic of the process that created the features. Again, it is impossible to know how much the spacing between the features has been modified by subsequent erosion, so the primary purpose of these measurements is to describe and characterize the features.

**Data Analysis**

*Identification of unique groups*

To determine whether individual groups of lineations existed, three primary factors were considered:

A. Quality of preservation, including prevalence and lateral extent,
B. Morphology, and
C. Azimuth.

Differences in azimuths alone would not be enough to determine whether the features were created by different, individual ice sheets, or by a single glacier that may have changed flow direction. Similarly, differences in quality of preservation would not be strong enough evidence to distinguish between a single event and several events, since features can be created and destroyed under a single ice sheet (McCabe 1999, Erickson 1996, Shaw and Freschauf 1973). However, if differences in quality of preservation and morphology are observed to correlate with differences in orientation, that may be more indicative of multiple ice sheet events. On the other hand, if differences in orientation and preservation quality are found to cluster in particular areas on the plateau, this would be more consistent with the interpretation of a single ice sheet changing flow direction as it progressed or regressed across the region.

First, the linear features were split into domains based on geographic location on the plateau to see if any correlation emerged. Using Stereonet 6.3.3 Software, rose diagrams were generated with bin sizes of 10°, the smallest bin size permitted by the percent error, and were used to look for relationships between and within geographic domains and areas of different elevation. Even tiny populations observed on the rose diagrams were considered in detail, since older populations could presumably be very small due to preservation biases (Woolfe et al 2000, Lawson 1996).

The linear features were also examined for trends based on numeric differences. A histogram was generated to illustrate the frequency and distribution of azimuths across the
plateau. Using a bin size of 1°, a master histogram was created to illustrate the frequency patterns of groove at all measured orientations from 21-169° to identify any patterns within the distribution of orientations (Figure 6). Based on the observed differences in frequency, the data was subsequently divided into a series of different “domains” (Table 3) and compared to the total data set to see if they were statistically different enough to be defined as independent groups.

On the histogram, one large, relatively normalized peak encompasses 89% of the measurements taken in the study, while the rest are distributed between two smaller groups on either side of the peak. Two different statistical analyses were used to determine if the medians and means of these apparent groups are statistically different. The first, a One-way ANOVA statistical test, performs a one-way analysis of variance on normalized data, comparing the responses of each measured feature with its factor to produce a confidence interval. In this case, the measured orientation of the groove is the response, while the factor is the group identified by geological indicators. The confidence interval (P), a value between 0.0-1.0, indicates how likely it is that the means of the two groups are statistically different (a smaller P value indicates a higher confidence interval). If the P value is less than 0.05, the means are considered statistically different (Forrester 2010, Sullivan 2007).

The second test, a Kruskal-Wallis test, compares the response and factor to determine the equality of the medians of the groups, and is used when data is not normally distributed within the identified groups. Because two of the three groups do not show a normal distribution of data, this test was used to verify the confidence interval calculated using the One-way ANOVA test. The Kruskal-Wallis test assumes that, “the samples from the different populations are independent random samples from continuous distributions, with the distributions having the same shape” (Minitab, 2010). Again, a calculated P value of less than 0.05 is considered indicative of groups with statistically different medians (Forrester 2010, Sullivan 2007). Both tests were conducted using Minitab Statistical Software. These tests consider only numerical values and do not account for observations such as length, spacing, and cross-cutting relationships, which may also be useful indicators for identifying distinct subsets of data.

Relative ages
When estimating the relative ages of different groups of lineations, quality of preservation and cross-cutting relationships were the primary factors considered. Once groups were identified using statistical and graphical analyses, it was assumed that older features would be much less prevalent and poorly preserved, since they would have been modified or obliterated by more recent glaciation events.

Possible sources of error

While conducting measurements two primary sources of error were identified: distortion and measurement error. One concern was that the distortion at the edges of the air photos, created by the rounded lens of the camera, would alter measurements. Therefore, measurements taken of the same topographic features at the center (least distorted) and the edge of two air photos (BC5616 064 and BC5616 063) were compared. To do this, two distinct lakes, which are located in the center of one photograph and at the very edge of another, were selected and compared. Length measurements of the lakes’ sides, as well as angles measurements of their corners, were taken six times each on each photo and compared. The differences here indicated an average 2.95% error for orientation measurements and a 4.74% error in length measurements for measurements taken on the very edge of an aerial photograph. To account for human error, the measurements of the Potential Flow Indicators (an arbitrary group) were repeated six times each at intervals at least two hours apart, and compared the differences between them, concluding that the error was 7.7% for orientation measurements and 13.35% for length measurements (Table 4).

III. RESULTS

Measurements conducted in this study were designed to characterize the features on the KP to determine whether they belong to one or multiple groups, and to distinguish whether they are indicative of one glacial phase or multiple ones. At least three different kinds of linear features occur on the plateau and the mountaintops: drumlinoids, glacial grooves, and depositional linear features. There are also three tuyas at various stages of erosion. These features were measured, characterized, and identified to determine whether they are indicative of one or more glaciation events across the plateau.

A number of features observed here are believed to be indicative of glacial activity in the area, including:
- Glaciovolcanic edifices (Horseshoe Tuya, Tutsingale Mountain, Tanker Tuya, Kawdy Mountain, Tuya Butte, Isspah Butte)
- Dumlinoids on the plateau floor, Tutsingale Mountain, and Horseshoe Tuya
- Glacial grooves on the plateau floor
- Depositional drumlinoids on Tutsingale Mountain and Horseshoe Tuya
- Cirque on Horseshoe Tuya
- Moraine at the mouth of Horseshoe Cirque
- Absence of obvious glacial till across the KP
- Glacial erratics on Tutsingale Mountain and Tanker Tuya

**Kawdy Plateau**

The Kawdy Plateau is a raised, flat-topped, 956-1126 km² plateau with a peak elevation of 1742 m and a total relief of 550 m (Figures 7a-b). It is comprised of flat-lying volcanic deposits underlain by alluvial and glacial sediment (Gabrielse, 1998), sits on top of highly folded Paleozoic rocks, and has undergone erosion. Most of the deposits consist of alkaline olivine basalt in close proximity to hyaloclastite, pillow basalt, and volcanic breccias. The volcanic activity observed in this study is believed to be the result of tectonic extension (Edwards & Russell, 2002). A gradual slope rises continuously from the southern KP into the Cassiar Mountain Range to the north. The French Range borders the plateau to the east, and the wide, flat Nahlin River Valley loops around the southern edge before flowing north on the western side of the KP (Watson & Mathews 1944, Gabrielse 1998, Figures 7a-b).

**Tuyas**

At least six subglacial edifices have been identified on the KP: Tanker Tuya, Horseshoe Tuya, Tutsingale Mountain, Nuthinaw Mountain, Meehaz, and Kawdy Mountain. Horseshoe Tuya and Tanker Tuya are believed to be mature, fully-formed tuyas, sites where the volume of material erupted was great enough to surpass the passage zone and create a flat-lying subaerial lava cap. Horseshoe Tuya stands 366 m above the plateau surface and is relatively circular except for a large erosive cavity on the northern side of the mountain, which extends down to the plateau floor and accounts for nearly 1/3 of the volume of the edifice. Tutsingale Mountain, on the southern edge of the plateau, is comprised of pillow
lavas and therefore interpreted as a subglacial volcanic feature, although it does not have the classic circular, flat-topped shaped typical of a tuya. This may be due to extensive erosion post-formation, or it may be due to the features’ eruptive history. Tutsingale may have never erupted enough material to form a subaerial lava cap like the ones visible at Tanker Tuya and Horseshoe Tuya, or it may have been a fissure eruption instead of a point-source eruption.

The only feature that has been dated on the plateau is Tanker Tuya, dated at 1.8 Ma and worth a brief description for comparison purposes. Tanker is a ~12 km$^2$ mountain standing 346m above the plateau. Roughly 75% of the mountain has a classic tuya profile, with dipping hyaloclastite beds and capped by at least one and probably two jointed lava caps. These lava caps are believed to indicate the paleo-height of meltwater lakes. The southern third of the mountain is comprised mostly of palagonitized lapilli tuff, possibly related to another eruption event after the formation of the original tuya. No grooves are visible across the top of the feature, and grooves near its base appear to be covered by the talus fan covering the mountains’ slopes and the surrounding plateau. Assuming it originally formed with a classic circular tuya shape, the mountain has been extensively eroded (Figure 8). Our observations at the interior walls of this mountain included sloping hyaloclastite beds, which appear to have originated from roughly the center of the observed hole, as well as at least three dikes, suggesting that we were observing the inner compartments of a volcanic edifice.

**Linear features**

Across the KP surface, particularly surrounding Horseshoe Tuya and Tutsingale Mountain, swarms of macro-scale linear features are visible (Figure 9a-b). They range in length from 15 to 222 m and are approximately 0.5-2m high. On the plateau surface, these features, observed during helicopter flights, appear mostly barren, with very little visible weathered material such as rubble or sediment (Figure 10a-b). Bedrock is exposed in a few places, but the smooth, shallow features are mostly covered by a short, patchy layer of grass. The features are also visible on top of Tutsingale Mountain and Horseshoe Tuya, where they have greater amplitudes and are composed of angular rubble (Figure 11). At this scale, it is difficult to see the small elevation differences that help distinguish the shape, since the differences are too small to quantify on a DEM. Therefore, field observations and photographs of the features on the plateau and on Horseshoe and Tutsingale Mountains were
used to determine their shapes. Most are roughly symmetrical in width and length, maintaining a constant elevation along their length. However, 9 out of the 845 features measured are drumlinoid in shape, having steeper, wider northeast ends and lower, narrower, gently-sloping southwestern tails (Figure 12a-b).

Measurements were made on aerial photographs to characterize the orientation, length and spacing of the features on the plateau surface (Appendix 2). They are most densely populated in the center of the plateau, immediately north and southeast of Horseshoe Tuya, but are prevalent all the way south to the area surrounding Tutsingale Mountain (Figure 13). They trend between 21-169°, but the vast majority of them (89%) fall between 56-86° (Table 6). The features have an average orientation of 74° (±5°), an average length of 263 m (±189 m) and an average spacing of 77 m (± 45 m) (Table 7). They range in length from 63-682 m. Five features have a drumlinoid profile, with a wide, rounded northeastern end and a narrow tail sloping southwest. Most, however, are linear, low-amplitude, rounded features composed of bedrock or covered by what appears to be a very thin veneer of sediment.

**Horseshoe Tuya**

Feature 4 (Figure 1), informally known as Horseshoe Tuya, is a steep-sided, flat-topped edifice situated near the center of the KP (Figure 14a-b). Rising 366 meters above the plateau floor to an elevation of 1760 m, it is roughly circular in shape, with an adjacent ridge on its east flank that trends NNW-SSE, creating a wide, V-shaped erosive feature along the northern edge of the mountain (Figure 15). The relationship between the mountain and the ridge is uncertain, although both appear to be volcanic (Gabrielse, 1998). The flat top of the mountain is coated with a layer of dark, angular, weathered basalt of volcanic origin. It is difficult to tell at what depth intact bedrock begins.

A large, circular erosive feature dominates the NW side of the mountain, consuming about a third of its entire volume (Figures 8, 15). This feature is 950 m wide at its mouth and 250 m deep, approximately 598,264 m² in volume (Figure 16a-c). It has a 66,462 m² tongue-shaped lobe of talus in the center of the feature, which does not extend to the mouth of the feature. The feature is surrounded on three sides by a steep (36-55° slope) curving wall.
Observations of the exposed material in that wall were limited by extensive talus cover, but showed some dipping breccias beds and a lava cap on the top of the edifice (Figure 17).

A series of roughly parallel grooves span the southwest side of the mountain (Figure 18). These features have an average orientation of 86° (±4°) and range in length from 40 m to 175 m, each being between 0.5 and 1 meters in height. The average spacing from trough to trough is 8 m. At least two are relatively long (392 m and 265 m) and linear, maintaining the same height along their entire length. They are the only two that are continuous across the entire width of the corner. Several of the shorter features have a drumlinoid profile, with a wider, truncated side facing east and a narrower, streamlined tail to the west. These drumlinoids were oriented between 85-90°, and were approximately 40-70 m long. Faint traces suggest that grooves parallel to the western grooves may have been present across the rest of the tuya, but the features are too slight be conclusive.

Similar linear features are visible on top of the northeast side of the mountain. These grooves trend 32-41° and range in length from 120 m to 390 m, with an average spacing of 59 m. These features are more regularly spaced than those on the west side and are all within 9° of each other, spanning the entire slope of the mountain. A perpendicular erosive trough bisects two sets of otherwise continuous lines (Figure 19). They do not have the same classic drumlin formation, but remain the same roughly-symmetrical shape down their length, stopping at either end in truncations.

**Tutsingale Mountain**

Tutsingale Mountain is located 20 km southeast of Horseshoe Tuya, on the southeastern edge of the KP. This mountain is longer (NS) than it is wide (EW), rising 350 m above the KP. The well-vegetated west side slopes abruptly up at ~40°, while the east side drops away more steeply and is covered with brown, gravel-sized talus. The northern end rises steeply of the plateau while the southern end slopes down more gently (Figure 20). The top of the mountain has a relatively flat section that mirrors the shape of the whole feature (Figure 21).

While working in the field, small outcrops of vertical columnar basalt and pillow basalts were observed at the top of the mountain. Fist-sized, weathered chunks of basalt were located at the base of the outcrops and on the north, east, and south slopes of the
mountain. Weathered pieces were less frequent on the west side, which is covered by a thin, even coating of short grass. A few non-basalt clasts were observed, including small (4-6 cm) pieces of granite and limestone, and at least one meter-long limestone boulder on the southeast flank of the mountain.

Trending widthwise across the top and west side of the mountain are a series of roughly parallel, relatively straight grooves approximately 15m apart (Figure 22). They trend between 90° and 109° with an average orientation of 96°, and follow the natural slope of the mountain’s west side. They are composed of angular rubble ~ 2-5 cm long, and are less 0.5-1.0 m in amplitude with a triangular morphology (Figure 23). They are more distinct and regular on the highest part of the mountain, and are not visible, perhaps due to vegetation cover, at the base.

IV. DATA ANALYSIS

No pattern emerged from the examination of length and spacing measurements. To illustrate the distribution of features at different orientations across the KP, a histogram of all orientation measurements was generated. The histogram illustrates one clear peak beginning at 56-63° and ending at 86-98°. This peak accounts for the vast majority (89-97%) of the measurements taken on the KP. It is therefore clear that the dominant trend of features across the KP is within this peak. However, the histogram does not account for geologic indicators and considerations. If some of these features are related to older glaciations events, they are likely to have been extensively modified or obliterated by more recent glacial activity. Features like these may be the only indicators of pre-LGM ice activity. Because Tanker Tuya has been dated at 1.8 Ma, there must have been ice active on the KP 1.8 million years ago, well before the LGM. Therefore, despite the small prevalence and poor preservation, they cannot be thrown out as “background” or random measurements. Their presence indicates that at some point in the history of the KP ice flowed in these directions. Therefore, in the interest of understanding the complete glacial history of the KP, they are considered significant.

Upon first examination of the histogram, seven potential groups were identified (Figure 24): 1 peak, possibly subdivided into 4 mini peaks, each comprising 2-10° ranges, and two groups encompassing ~20-50° ranges. Defining the exact extent of the peak
included both numeric and geologic indicators, including quality of preservation. The break on the left side of the peak could arguably begin at 54°, 56°, or 63°, though it is important to note that due to the standard deviation of the measurements, it is only possible to pinpoint this breaking point within 5°. No geologic indicators indicate any reason not to define this side of the peak at the earliest place of increasing population. Therefore 56° was selected as a best-guess estimate of the earliest value at which the peak is beginning to rise. On the right side of the histogram, the division could occur at 86°, 82°, or 98° (the same standard deviation applies).

The value of 86° was eventually selected based on geologic input, since numerical data alone was insufficient to define the boundary. In analyzing the morphology of the features, it became clear that no drumlinoids existed at an azimuth greater than 86°. In order for these drumlinoids to survive the influence of glaciations, they are likely to be among the younger features on the KP. Because the 56-86° group is considered to be the youngest group, for reasons later explained, 86° appeared to be the most likely separation point between the two groups.

Statistical testing of the three larger groups indicate that they are statistically unique from one another and from the total data set. Testing of the four small peaks within the larger peak proved inconclusive. The One-way ANOVA and Kruskal-Wallis tests indicated that they are statistically-unique from each other, but the standard deviation of the data set (±5°) is too large to state with confidence that the 2-10° ranges of the four smaller peaks are significant. If the data set were more accurate, the groups may have slightly different values. Therefore, the data is sufficient only to indicate the presence of at least three unique groups of linear features.

If the One-way ANOVA or Kruskal-Wallis tests had indicated no statistical differences between the means and medians of the groups, that may have supported the interpretation of one single group of lineations on the KP. However, since the two tests both indicated high confidence intervals that the means and medians are statistically different, so the two smaller groups cannot be excluded in the interest of understanding the complete glacial history of the KP. In summary, through the use of statistics, and examination of a histogram, three statistically-unique groups of linear features, orientated at 21-55°, 56-86°, and 87-169°, have been identified.
Geographic Distribution

The linear features were then analyzed using rose diagrams to observe any major trends based on geographic distribution. Diagrams were generated based on lateral location, as well as location at different elevations (Figure 25). These included six diagrams:

- Entire KP (Figure 26)
- Northern KP surface (Figure 27a)
- Northern KP, including lineations on Horseshoe Tuya (Figure 27b)
- Southern KP surface (Figure 28a)
- Southern KP, including lineations on Tutsingale Mountain (Figure 28b)
- Mountaintops (Figure 29)

The trends indicated by these diagrams were then compared to see if any differences in trends were visible based on geographic location.

A rose diagram of the whole area illustrates a single dominant trend between 56-86°, (Figure 26). The dominant trend is therefore very clear, oriented between 56-86°. However, the diagram also shows a tiny group, barely distinguishable on the graph, at the 21-55° orientation, and another very tiny set between 87-169°. As discussed before, the small groups, though tiny in comparison to the 56-86° group, cannot be discounted.

Diagrams representing the northern half of the plateau show trends almost identical to the trends of the whole KP (Figures 27a, 27b). The overwhelming majority of lineations fall within the 56-86° group, with a tiny percentage (< 4%) of features existing within the 21-55° or 87-169° groups. Diagrams of the southern half of the plateau are still vastly dominated by the 56-86° group, but a larger group of the 87-169° group is visible. The 21-55° group is indistinguishable (Figures 28a, 28b).

The group of features on the mountaintops, however, show a different distribution of trends (Figure 29). The less prevalent groups, 21-55° & 87-169°, are much more prevalent on the mountaintops, while the 56-86° group is indistinguishable. This suggests a different series of glacial modification on the mountaintops than on the plateau surface, and supports the conclusion that the 21-55° and 87-169° groups are important features to consider in
reconstructing the glacial history of the KP. Without them, there would be no way to infer the glacial history of these two tuyas, and details of the history would be indeterminable.

V. DISCUSSION

Horseshoe Tuya

The morphology, composition, and features on Horseshoe Tuya are indicative of a subglacial origin and subsequent glacial modification by at least two stages of glaciation. The volcanic composition and classic tuya shape of the mountain strongly suggests it is a tuya, and therefore subglacial in origin. The presence of linear features, including drumlinoids, as well as extensive frost-wedging indicates subsequent glacial deposition and shaping. The fact that these grooves are present at three different orientations, as well as the absence of material at Horseshoe Cirque, suggests that the mountain has been modified by at least two and potentially three separate ice sheets.

Horseshoe Tuya, with its steep-sided, flat-topped profile and lava cap, fits the classic morphological description of a tuya (Mathews 1947; Watson & Mathews 1944). Standing alone at such high elevation off the valley floor, it is difficult to account for its sudden relief in any other way. It is also composed of pillow lavas, dipping breccias beds, and a flat-lying lava cap, which is consistent with the interpretation of the mountain being a tuya. Assuming that its original shape was approximately circular, its overall form appears to have been well maintained, with the obvious exception of the large eroded area on its NW side. This is consistent with other identified tuyas, including nearby Tuya Butte and Herdubreith in Iceland.

Assuming it is a tuya, we can tell that is has been extensively eroded, losing nearly a third of its volume. The rounded erosive feature, with its distinct circular shape, steep wall, and talus lobe, has all the characteristics of a feature made from erosion by a cirque glacier. It may be possible to remove such a volume of material through mass wasting alone, but most mass wasting processes (i.e. landslides) are unlikely to incise into the heart of the edifice and create such a particular shape. More likely, mass wasting processes would erode material off the sides. If the feature were the result of mass wasting events alone, talus would probably be deposited in a smooth, relatively straight slope from the base of the eroded wall to the toe of the lobe. Instead, the feature has a steep headwall (Hooke, 1991)
and a lobe with a rounded rim of slightly higher elevation, a feature consistent with clasts being moved downslope by a process that stopped at one specific location and dropped more of its load there, at that rim, than in other areas. A retreating or stagnant cirque glacier would account for why the talus stopped moving downslope at this specific place. This talus lobe, therefore, has been interpreted as a terminal moraine.

The volume of the material in this moraine (66,462 m$^2$), however, is clearly not great enough to account for the volume of material that has been removed from this mountain (~589,264 m$^2$). Likewise, although the steep walls at the mouth of the cirque indicate erosion, no talus deposits are presently located at the base of the walls. A considerable volume of eroded material is, therefore, missing. Since there is no evidence for current or previous fluvial processes at this cirque, the only known mechanism in the area that could transport that volume of material so far away that we see it nowhere on the KP is an ice sheet.

This interpretation strongly implies that an interglacial period must have occurred. It is also difficult to account for the missing material if assuming only one glacial stage on the KP. Cirques, at higher elevations than the plateau, freeze earlier and remain longer than ice sheets, insulating their talus deposits from ice sheet transport, continuing to produce morainal material after the ice sheets have retreated. In order for that material to be transported, it must have at some point been exposed, meaning the cirque glacier must have melted to allow a second ice sheet to flow by and pick up all the morainal material. It is likely that a cirque glacier formed on the north side of Horseshoe, producing the large hole in the tuya via erosion, then melted entirely, allowing for mass wasting to transport the rubble beyond its mouth, exposing it to the second generation of glaciers (Figure 30). This explanation accounts for the absence of adequate moraine deposits immediately north of Horseshoe Tuya. If the glacier flowed southwest across the KP and into the Nahlin River Valley, it may have shifted its flow direction north, following the topography and carrying its sediment load well beyond the study area. This is compelling evidence for at least two distinct glacial periods separated by an interglacial period where conditions were sufficient to melt ice sheets entirely.

The presence of linear features at three different orientations on top of Horseshoe Tuya is also consistent with multiple glaciations. The features' morphologies and
compositions are consistent with fluting (Gordon et al 1992, Solheim et al 1990). It is possible, since tuyas are dike-fed, that the ridges could be eroded remnants of dikes, but it is unlikely that dikes would form at this peripheral location on the tuya, and parallel to one another. If these were exposed dikes, we would also expect to see more erupted material to the north and west of this location. Since we do not, the grooves visible on the top of Horseshoe Tuya are most consistent with a glacial origin.

The exact glacial origin of the lineations on top of Horseshoe Tuya is uncertain. On the west side of Horseshoe Tuya, the ridges are composed entirely of loose, angular chunks of basalt, consistent with frost wedging (Ritter 2002, Walder & Hallet 1985, Eyles 1983, Hooke 2001, Marshak 2005). Whether the features are depositional, the result of sediment being squeezed up underneath a glacier (Shaw & Freschauf, 1993), or were eroded into bedrock and subsequently weathered by frost-wedging is unclear. The northeastern end of the mountain was not visited while in the field, and the resolution of the aerial photos makes speculation on the composition of the grooves on the north side of the mountain difficult.

It is also uncertain why the two corners of this mountain display such distinct linear features while the rest of the tuya top does not. Gabrielse (1998) noted that this may indicate the tuya was only partially hit by an ice sheet, however grooves on the plateau surface surround all sides of the edifice, indicating that the mountain sits right in the middle of an area that once was covered by an ice sheet. It is therefore unclear why only part of the edifice would have been affected. One possibility is that the sudden relief of the mountain was too great for the ice sheet to overcome. However, ice depth estimates suggest that the CIS was over 2 km thick (Tushingham & Peltier, 1991) more than high enough to cover the top of Horseshoe. Furthermore, the presence of the lineations on the top of the mountain indicates that ice did cover at least parts of the top of the mountain. It is therefore uncertain why more than half of the tuya top shows no evidence of glaciation when ice left such distinct markings at some locations.

Horseshoe Tuya displays all three groups of linear features noted on the KP. The quality of preservation of the three groups were compared to determine the age sequence of the groups, which should indicate the sequence of glaciations if they are indeed related to separate ice sheets. On Horseshoe, the 87-169° group is the most prevalent, occurring on the southwest corner of the mountain. Of the 32 lineations on Horseshoe Tuya, 10 are between
87-169°, 7 are between 56-86°, and 13 are between 21-55°. No notable differences in spacing and length were observed.

The only drumlinoids present are in the 56-86° group. In order for these to be preserved, it seems the 56-86° group must be the youngest. The 21-55° group, on the northern corner of the mountain, is the best preserved, containing some of the clearest features on the KP. In this situation, the recurrence and quality of preservation seem to give conflicting ages. For instance, the absence of the 21-55° group on the plateau suggests they were wiped out by subsequent glaciers, meaning they were one of the older, if not the oldest of the grooves. But the excellent quality of preservation of this group on the top of Horseshoe Tuya seems to contradict that interpretation, suggesting that they may be the youngest of the groups. This contradiction is not clearly understood, but the 21-55° group is present only on the northern side of Horseshoe Tuya, which is the only location where the grooves are visible on a slope. Because of this complication, it is possible that the grooves have been accentuated by erosion, or were made by an entirely different process altogether. Therefore, it seems more reliable to use the age sequence indicated by the plateau floor, which suggests that the 21-55° group is the oldest on the KP.

**Tutsingale Mountain**

A number of features observed on Tutsingale Mountain are indicative of glacial origin and modification. The composition of the mountain, primarily intact and crumbled pillow lavas, indicates a subglacial origin, despite its elongate shape and the absence of a flat lava cap on the top. The drumlinoid morphology of the edifice and the presence of linear grooves across the top are also indicative of glacial modification.

Tutsingale Mountain is a subglacial edifice that is roughly oval in shape, oriented with its longer axis northeast to southwest (Figure 21). It is composed almost entirely of intact and crumbled pillow lavas, though at least one area of jointed lava flows was observed on the top of the northern end of the mountain. It stands slightly less than 400 m above the plateau at its highest point, though most of the edifice is lower in elevation due to its slopes. The southwest to northeast profile of the mountain demonstrates a vaguely drumlinoid shape (Figure 20), with the northeast side being steeper and shorter than the southwest side, which slopes more gently down to the plateau at about 30°. Across this gentler, southwest slope are
numerous parallel grooves oriented between 87-169°, spaced an average of 15 m apart and an average of 161 m long (Figure 22).

Tutsingale Mountain’s relief above the plateau, as well as the basaltic pillow lava and massive lava on top, are consistent with a volcanic origin. Additionally, the pillow lava observed on the mountain’s top at 1,727 m elevation above sea level indicates that the mountain must have been entirely beneath water at the time of the eruption. It is possible that the valley floor once sat at that elevation, and has since eroded away to its present level, but to erode the entire plateau 350 m to such a flat, consistent elevation, leaving Tutsingale elevated at 350 m above the plateau, within 2 Ma is a difficult argument to substantiate. To have water at such a high elevation on this plateau, at least 350 m higher that the plateau floor today, is most readily explained by the presence of a continental icesheet to confine the water. A glacial origin is consistent with the tuya process identified as the creator of other mountains in the area, and would explain Tutsingale’s existence more simply.

Tutsingale’s elongate shape does not match the classic, circular shape expected of a tuya (Jones 1969, 1970). At least two hypotheses, both based on the presence of ice, can explain the origin of Tutsingale Mountain. The first hypothesis asserts that Tutsingale formed by subglacial eruption and still maintains roughly its original shape. The absence of a lava cap would then indicate that too little material erupted to form a full-fledged tuya, instead creating a tindar (Jones 1969, 1970). The second hypothesis is that Tutsingale originally formed as a much larger, full-fledged tuya, with a relatively round shape and an intact lava cap. If true, this would indicate that Tutsingale is one of the older mountains on the plateau, having undergone extensive erosion due to glacial and mass wasting processes. Without clear evidence of a large volume of removed material having been transported somewhere else, there is not enough evidence to determine whether or not this is the case.

The mountain’s profile, which mirrors the profile of the grooves across its top, is drumlinoid, which is consistent with morphological alteration by glacial processes. Tutsingale is almost certainly not a depositional feature, due to its composition of intact pillow lavas and jointed basalt, but the across-width profile of the mountain is drumlin-like, with a steep eastern side and a more gently sloping western side (Figure 20). No obvious change in bedrock composition or difference in vulnerability to weathering on the two sides accounts for the non-symmetric shape, and if the mountain formed by eruption into ice, as
believed, there is no clear reason why one side would form a steeper slope than the other. Since its shape is consistent with glacial erosion having shaped the whole feature, it seems most likely that a subsequent glacier is to blame. The glacier would have encountered the eastern face of the mountain first, grinding up and over it, eroding that face through frost-wedging while tapering the west side of the mountain.

The grooves across Tutsingale are also best explained by the presence of a continental ice sheet. It is possible that these grooves could be dike-controlled, however the uniform spacing, straight, linear manner, and parallel orientation of these features makes that unlikely. Additionally, no dikes were observed protruding out of the east side of the mountain. Since the dikes would have to be at least slightly younger than the pillow lavas to have cut through them, more resistant jointed flows should be exposed on the eroded side amidst the talus, however no such features were observed. Despite extensive erosion into the side of the edifice, the grooves are visible only on the top surface of the mountain, suggesting that they formed by geomorphic processes. The shape of the grooves, with a wider, steeper east end and a sloping, narrowing west tail, is also consistent with the description of drumlinoid “inverted spoon” shapes. Since they are so close to parallel, continuous across the structure, and at too high an elevation to be caused by rivers, a continental ice sheet is the most likely explanation.

**Plateau surface**

The presence of parallel, evenly-spaced grooves that are continuous across the plateau surface and found at both high and low elevations strongly suggests glacial modification. No other process is known to create sets of parallel, evenly-spaced, continuous grooves. Lineations like these are common in glacial till and sediment all over the world (Gordon et al 1992, Solheim et al 1990), and on bedrock (Bradwell 2005, Bradwell et al 2007, Andreassen et al 2007). The presence of the tuyas further substantiates the interpretation that these features are related to glaciers, since ice is known to have been active in this area. These features are also shaped slightly differently than the grooves on the mountaintops, being generally lower amplitude and more rounded across their tops, which is consistent with the interpretation that the grooves on the plateau surface have an erosive origin while those on Tutsingale Mountain and Horseshoe Tuya are depositional. The occurrence of grooves at
three uniquely-oriented groups on the plateau surface suggests that the KP has undergone modification by at least three ice sheets flowing in different directions.

**Formation of Glacial Grooves**

The morphologies, composition, and size suggest that all these features were formed by glacial processes. However, the differences in morphologies and composition of the features on the mountaintops and the features on the plateau surface indicate that the two groups may have formed due to different glacial processes.

The absence of any morphological or sedimentological evidence suggesting a river valley on the plateau, as well as the lateral extent of the area covered, indicates that these grooves are likely not related to river processes, which would be confined to a narrower area and would not commonly erode or deposit such straight, symmetric, and continuous features. This, as well as their presence on the mountaintops, more than 400m above the plateau, suggests that whatever process formed them was acting at both elevations. The only documented, reasonable explanation in this area for features of this type across such a broad area and at both elevations is the influence of a continental ice sheet. The shape, location, and behavior of the grooves on the mountaintops match descriptions of glacial fluting described in Flint (1971), USGS (2009), and Boulton (1976), while the features on the plateau floor are consistent with the descriptions of glacial grooves (Karlen 1981, Sharpe 1989, McCabe et al, 1999).

Based on observations of these features on the plateau, it is unclear whether they are depositional features composed of glacial sediment, or if they are composed of a bedrock core with only a thin layer of sediment on top (flutes, by definition, can be depositional or erosional) (Shaw and Freschauf, 1973). The KP is mapped by Gabrielse as composed primarily of glacial and alluvial sediment, however, observations of the grooves on the plateau were not so conclusive. The sediment layer on the plateau floor, at least between Horseshoe and Tanker Tuyas, is either extremely thin or entirely absent, and in specific locations to the east, the grooves are not composed of sediment, but eroded into Paleozoic bedrock (Figure 31). It is therefore difficult to determine if the adjacent grooves are composed of a thin layer of sediment which was shaped into a flutes through depositional processes at the base of a glacier, or if all the grooves on the plateau surface are in fact
eroded into bedrock. Even the features that sit on the area mapped as alluvial and glacial sediment are bare of all but a very thin layer of sediment, as indicated by the absence of any vegetation except for very short, sparse grass. The grooves which exist on the areas mapped as alluvial and glacial sediment are virtually identical to the features on the Paleozoic bedrock, suggesting that the formation process is the same on both types of material. Therefore, since observations indicate that at least some of the features are composed of bare bedrock, it is the tentative opinion of this study that the grooves on the plateau surface are composed of bedrock and covered by a thin veneer of sediment, the rest of the sediment having been removed by the flowing glacier.

According to studies conducted in Norway, Scotland (Bradwell 2005, Bradwell et al. 2007), Canada (Patterson 1998), and Antarctica (Sawagaki & Hirakawa 1997, Sharpe & Shaw 1989), streamlined bedrock features are thought to be the geomorphological signature of high energy subglacial meltwater erosion. If the linear features on the plateau are indeed eroded into bedrock, a large-scale meltwater event or ice stream may explain their absence on the tops of the mountains. The KP may have undergone a large-scale meltwater flood event, supported by the observation of at least one jokulhaup deposit northwest of Tanker Tuya, or at least one recent period of high-velocity meltwater flow (Bradwell et al. 2007).

In contrast to the grooves on the plateau surface, the features atop Horseshoe Tuya and Tutsingale Mountain are definitely composed of angular, fragmented material, suggesting a depositional origin. It is possible that these features have bedrock cores and are covered by material weathered in-situ (the angular fragments observed on both mountaintops, are consistent with frost-wedging), however, observations from the field indicate no compelling reason to believe they are not composed entirely of fragmented material. As far as this study could tell, they are composed entirely of fragment material, thus, in contrast to the features on the plateau surface, these are more likely depositional features. These features have a greater amplitude (Figure 18) and a more triangular, less rounded profile (Figure 23).

The actual process of forming flutes is still widely speculated and poorly understood, and this study will not delve into the formation process in great detail. However, the morphology suggests that the depositional features on the mountaintops did not form due to a streamlined deposition of sediment behind an upstream impediment. It is unlikely that every
single impediment to over 50 flutes would have been removed since their formation, and even less likely that impediments would find their way onto the tops of the mountains in the first place. It is possible they formed, instead, by the squeezing of sediment into channels under the ice. This may explain the triangular morphology of some of the features on Tutsingale Mountain (Figure 13), though this still fails to explain the straight and evenly-spaced nature of the features.

Evidence for multiple periods of glacial erosion

Linear features

To evaluate whether the linear features indicate multiple glaciations or one glacier changing flow direction, two main factors were considered: orientation and quality of preservation, include prevalence and morphology.

The presence of three statistically-unique groups across the KP suggests differences in ice flow direction over time. It would be unusual for a single advancing glacier to account for features at such a range of orientations (21-169°), but there are two potential ways that a single glacier could account for all of these features:

a) Local topography caused the glacier to flow southwest, then to rotate and flow north up the Nahlin River Valley (Figure 32), or,

b) the regression of the glacier created lineations at different orientations.

The local topography of the area, with the Cassiar and French mountain ranges to the north and east and the Nahlin River Valley to the southwest, is consistent with this interpretation. However the distribution of orientations across the KP is not consistent with this interpretation. The number of features between 87-169° does increase on the southern half of the plateau, but the southern plateau is still dominated by the 56-86° group (Figures 25, 28, 32). If all the linear features on the KP were created by a single advancing, rotating glacier, the 87-169° group should become dominant across the southern half of the plateau. Since that is not the case, the single advancing glacier interpretation does not appear to be consistent with the distribution of linear features.

The regression of the glacier could account for some of the features observed on the KP. Glacial retreat is often associated with large-scale melt-water flows and ice streams, which are known to erode linear grooves into bedrock across a wide area (Andreassen &
The 56-86°, which is deemed the youngest group, and which dominates the low-elevation areas and is absent on the mountaintops, could readily be explained by ice-stream erosion. However the elevation and geographic distribution of the sparse features between 87-169° and 21-55° are not consistent with that interpretation. If these smaller groups were created by a regressing glacier, the mountaintops seem to be the least likely location for features caused by regression to be present, since at this time, the glacier is presumably shrinking vertically as well as horizontally. For these reasons, meltwater flow or ice-streams triggered by glacial regression could account for the youngest group on the plateau (56-86°), but not the older groups present on the mountaintops.

The differences in quality of preservation also suggest that some sets of lineations may be older than others. If the differences in quality of preservation were due to a single glacier, the features at the northeast corner of the plateau should be the best preserved, but this correlation was not observed. Since the differences in frequency correlate, instead, with the orientations of the groups, it seems likely that the differences may have a preservation bias based on temporal differences, not differences in geographic location. Therefore, the single, rotating glacier interpretation does not seem consistent with the orientations or differences in quality of preservation of the linear features on the KP.

Cirque

The most compelling evidence for multi-stage glaciations is the absence of extensive talus cover at the base of Horseshoe Cirque. Assuming Horseshoe Tuya was originally circular, like most tuyas, the current moraine is far too small to account for the volume of material that has been eroded from the mountain. The volume of material missing, and the fact that the missing clasts are not visible anywhere on the plateau, indicates that some large-scale process must have removed the eroded material prior to the deposition of the talus visible there today. Due to the absence of a large river bed or topographic gradient to allow for gravitational transport, it is most likely that these were removed by a moving glacier. No other mechanism is available in the area to transport so much material so far away that it is not visible anywhere on the KP.

If true, this means that the moraine at Horseshoe Cirque must have at some point been exposed to transport by a moving ice sheet. The original cirque glacier that created the cirque and moraine would have insulated the eroded material from transport by the first ice
sheet, so must have melted entirely to expose the moraine to transport by a second ice sheet. Since the cirque glacier that created the moraine would be some of the last ice to linger, due to its higher elevation, this suggests that the original ice sheet would have to melt almost entirely to allow for this mechanism of transport to occur. Therefore, in order to account for the missing material from the moraine at Horseshoe Cirque, the KP must have experienced interglacial periods, where the continental ice sheet melted almost entirely. This supports the theory that the KP has been modified by multiple glacial events with interglacial periods in between. This is also consistent with the large temperature fluctuations derived from Oxygen isotope data over the last 2 million years (Bowen et al, 1986).

**Tuyas**

Another observation supporting the multi-stage continental glaciers is the presence of tuyas at significantly different stages of erosion. Observations of Horseshoe Tuya, Tutsingale Mountain, and Tanker Tuya note the absence of glacial grooves on Tanker, while there are numerous grooves on Horseshoe and Tutsingale. Tushingham & Peltier (1991) estimated that the thickness of glaciers in this area was between 2-3 km. Ice of this thickness should have left its mark on all of the mountains on the KP, thus, the absence of the grooves on Tanker may indicate that Tanker formed after the passing of the glaciers that carved the grooves on the plateau, Horseshoe, and Tutsingale. From the observations made here, this study can state only that the regional glaciers must have been at least 450m thick at the time the tuyas were created.

**Relative Age of Glacial Erosion Events**

The quality of preservation and cross-cutting relationships of these groups can be used to estimate a relative age sequence of the three ice sheets that created these grooves (Figure 33). Therefore, the mountains must either be younger than the glacier that created those lineations, or the process that created these lineations must not have been active on the mountaintops. Tuyas that erupted when the ice sheets were stagnant or retreating may not exhibit grooves on their surfaces at all, but since Horseshoe Tuya has well-preserved grooves in different orientations, we would expect it not only to show signs of the 56-86° group, but to be dominated by features striking 56-86°.
The rose diagrams of the whole KP and the plateau surface show that the area is dominated by the 56-86° group. Is it also the only group that contains drumlinoid features, which suggests that this group is the best preserved. These features are therefore interpreted to be the youngest group. It is unclear why the latest ice age would leave no mark on Tutsingale and so few features on Horseshoe Tuya. As the youngest, they should also dominate the local tuyas that are old enough to have seen the most recent stage of advancing ice sheets.

The best possible explanation of the features observed on the KP is that differences in formation processes may explain the apparent contradiction. As noted before, based on observations from the plateau surface, the 56-86° group appears by far the youngest and best preserved, yet its absence on the mountain tops contradicts that interpretation. One way to explain this apparent contradiction is if the 56-86° group formed during the onset of a glacial ice stream or a meltwater flood. Ice streams are known to erode similar features (Andreassen & Winsborrow 2009, Bradwell et al. 2007, McCabe et al. 1999, Patterson 1998, Sharpe & Shaw 1989), and would be active only on the areas of lowest elevations, leaving the mountaintops unaffected. This may explain why the 56-86° group dominates the low-elevation areas of the plateau and had little influence on the tops of Horseshoe Tuya and Tutsingale Mountain. It is important to note that ice streams would also carve the grooves parallel to the direction of ice flow, legitimizing their primary use as indicators of ice flow direction in this study.

Regardless of which glacial processes created this group on the plateau floor, it is difficult to argue that it is not the youngest set of features. The presence of dumlinoid features in this group further substantiates that hypothesis.

From the plateau floor data, the 20-62° groove set appears to be the oldest, due to its tiny representative population. It is curiously well-preserved on the northern side of Horseshoe Tuya, making it impossible to confidently determine that it is the oldest and least-prevalent group on the KP. However, the fact that this group is best represented by a small population on the slope of the tuya, not on a flat surface like all the other grooves, raises doubts about its actual origin. Its absence on the plateau is too noticeable to ignore, and since it appears only on a slope, its apparent high quality of preservation may be due to drainage channel extenuating topographic lows originally created by glacial activity,
deepening the troughs and making them appear better-preserved. Therefore it is most likely that this is the oldest group on the KP.

Finally, the 87-169° group, being better preserved and more numerous across the mountains and plateau floor than the 21-55° group, is consistent with a middle generation of glaciation (Table 8).

**VI. CONCLUSION**

The glacial features observed on the Kawdy Plateau, including multiple groups of glacially-carved linear features and a moraine that is too small for its cirque, suggest that the KP has undergone at least two and probably three separate glaciation events, with ice sheets flowing across the plateau at different directions.

Based on their composition and morphology, the parallel, linear features on the KP are interpreted to be glacial. The grooves on the plateau floor are composed of a bedrock core and carved by continental ice sheets flowing over the area, while the features on the mountains are depositional, loose material probably squeezed up into ridges at the bottom of a flowing ice sheet. Geological indicators and statistical testing show that the grooves exist in three statistically-unique groups with unique orientations, encompassing a 91° range of orientations. It would be highly unlikely for a single ice sheet flowing from a single accumulation center to create linear features at such a wide variety of orientations, and the difference in the prevalence and quality of preservation of the three groups suggests that they are different ages. Statistical testing using the One-way ANOVA and Kruskal-Wallis tests indicate that the means and medians of these three groups are statistically different. The distribution of orientations is not consistent with the single, rotating glacier hypothesis, suggesting that three separate ice sheets flowed across the KP, accounting for the three groups.

The absence of morainal material at Horseshoe’s Cirque supports this conclusion, since this study can identify no other reasonable mechanism for transporting ~531,802 m² of eroded material beyond the plateau. Its absence also suggests that during at least one of the interglacial periods, the previous ice sheet must have disappeared almost entirely in order to expose eroded material from the mountain to transport by the next ice sheet. This means that shifts in accumulation zones alone cannot account for all the features on the KP, and that
temperature fluctuations on the KP must have at times been significant enough to melt and
reform ice sheets.

The crosscutting relationships and quality of preservation of the three groups indicate
that the 56-86° group is youngest, and the 20-62° and 87-169° groups are both older. The
87-169° group is thought to be related to the second generation glacier due to its quality of
preservation (better than the 21-55° set, and worse than the 56-86° set. The extremely poor
preservation quality of the 20-62° set suggests that it is the oldest set, and that the excellent
preservation of these features on the north side of Horseshoe is the result of preferential
erosion along the troughs of the features, since they are on a slope. It is unclear why this
group is so sparse on the mountaintops. One possible explanation is that this group may be
related to ice stream activity and meltwater flows. This may account for their different
morphology and sparse representation on the high-elevation areas of the plateau.

VII. Further Research and Implications

Test the multiple-glaciation hypothesis:

The absolute dates derived from the tuyas on the KP will be instrumental in
continuing to test the multiple-glaciation hypothesis. These dates, expected in December
2010, will indicate the age differences between Horseshoe, Tanker, and Tutsingale Tuyas.
These age differences, as well as the sequence of ages, will enable further testing of this
hypothesis.

If afforded the time and monetary funds, additional field research would include
further observation of the features on the ground, specifically the grooves observed on the
northern and western sides of Horseshoe Tuya. Further observations of the grooves on the
western side of Horseshoe Tuya would try to determine the composition (bedrock or rubble)
of the features in specific areas. Further analysis of the grooves on the northern side of
Horseshoe Tuya would test the hypothesis that these are in fact glacial grooves carved by the
same process identified elsewhere on the KP. Finally, research would continue to determine
why the relative age sequence of glacial striations appears to be different for the plateau than
the mountaintops.

Relative age dating of tuyas:
The methods used in this study may have further implications for dating tuyas in this area and less accessible areas around the world and on Mars. At a later date, this relative ages estimated in this study may be used to establish the relative age of the tuyas based on the extent of erosion they have each undergone. By estimating the approximate original shape of selected tuyas and comparing it to the current shape of the features, it may be possible to estimate the extent of modification for each tuya and determine relative age dates of the tuyas in the area. Assuming that the more extensively modified features are the oldest, the features can be compared to determine a relative age sequence of the volcanoes in the area. Previous unpublished research by B. Edwards has produced tentative ages for one of the selected lava flows, which will act as a reference point and, with the relative ages determined in this study, help constrain the timing of variations in ice characteristics of the CIS in two ways: First, the structure of the volcanic features in the area indicates whether they erupted under glaciers (pillows, tuyas, subglacial mounds) (Mathews 1947, Watson & Mathews 1944), or independent of glaciers (cones, unconfined lava flows). The eruption age, therefore, indicates the condition of the CIS when each feature formed. Second, the extent of erosion on each feature may indicate the density of glaciers post-eruption phase. By noting which volcanic features appear at what times, we could then speculate as to when glaciers were present and how their thickness varied over the lifespans of these volcanoes.

_Evaluating the reliability of relative dating by extent of erosion:_

Lava samples collected during field research in Summer 2009 are to be dated using 40Ar/39Ar geochronology by this time next year. Therefore, in addition to studying the KP and the history of the CIS, completing this study and the estimation of age based on extent of erosion will help to evaluate the method of relative dating by quantifying extent of erosion of tuyas. If the ages determined in this study match the radiometric dates, it would suggest that relative dating based on extent of erosion is a reliable way to date tuyas, and may consequently be useful for studying tuyas in other, less accessible locations such as Russia, Antarctica, and Mars. Thus, the results of this work could enable some lower cost projects to make more confident age estimates of their research areas until further funding for geochronometric data is available. Conversely, if the dates attained in this study do not match the geochronometric results next year, it would indicate that this may not be a reliable
dating method, and therefore researchers should not waste time, money, or confidence on comparing the extent of erosion of tuyas for dating purposes.
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26 no. 7, pg. 643-646.
Figure 1. A) Location map and B) map of the Kawdy Plateau, northern British Columbia. 1. Tutsingale Mountain; 2. Nuthinaw Mountain; 3. Kawdy Mountain; 4. Horseshoe Tuya; 5. Tanker Tuya; 6 Ispaah Butte.
Figure 2a. Dipping hyaloclastite beds at Tanker Tuya.

Figure 2b. Profile of Horseshoe Tuya illustrating the steep walls and flat top of a classic tuya edifice (looking southeast). Tuyas like Horseshoe are believed to have formed by eruption under a continental glacier (Mathews 1947, Edwards 2002, Hickson 2002). Photograph by Edwards, 2009.
Figure 3. Schematic illustrating the formation and components of a mature tuya. Edwards, per. comm. 2009.

Figure 4. Illustrating the process of measuring the lineations in Adobe Illustrator. A) The features were first traced all in the same color and measured. B) Once statistically-different groups had been identified using the rose diagrams and statistical tests, the One-way ANOVA and the Kruskal-Wallis, the features were then color-coded for orientation. On this aerial photograph, BC5616 063, blue indicates features between 56-86°; red shows features between 87-169°, and green illustrates features between 21-55°.
Figure 4C. Aerial photograph BC5616 063, showing the final draft of a measured, color-coded photograph. The spacing measurements are indicated by the red circles.
Figure 5. General features observed on the Kawdy Plateau and considerations while taking measurements. A. Many features have clear lineations on their north sides, and less clear lines on their south sides, making it difficult to determine the width of the features. In an attempt to attain the most consistent and reliable spacing data possible, I always measured features from north side to north side, as that was the most consistent visible part of the features. B. Some features appear to strike at the same orientation, but are not continuous, raising the question of whether or not to count them as one long feature or two shorter ones (the blue lines illustrate the two different ways that the length of this feature could be measured). C. Some features are so poorly preserved that it is difficult to be certain that they even truly exist, while others, like the one shown in D., are clear, well-defined, and continuous across a long distance. Images taken from aerial photos BC5616-063, BC6516-064, and BC5616-067.
Figure 6. Histogram for the total data set illustrating the density of grooves at different orientations (bin size 1°).

Figure 7a. Topographic profile of the KP, looking north.
Figure 7b. Topographic profile of the KP, looking west.

Figure 8. Profile of the cirque on Horseshoe Tuya.
Figure 9a. Aerial photo BC5616-064, showing the linear features across the Kawdy Plateau north of Horseshoe Tuya.
Figure 9b. Grooves visible across the Kawdy Plateau between Tanker and Horseshoe Tuyas.
Figure 10a. Photograph of the grooves looking southwest across the Kawdy Plateau, Tanker on the immediate right.

Figure 10b. Photograph of grooves from the air, looking northeast.
Figure 11. Photographs of grooves on Tutsingale Mountain (top) and Horseshoe Tuya (bottom).
Figure 12a. Locations of potential flow direction indicators on aerial photograph BC5616-067.
Figure 12b. Drumlino id features observed on the Kawdy Plateau. A-E) Features on the plateau surface; F) Features on the western corner of Horseshoe Tuya. The dimensions of these particular features are not statistically different from the others on the plateau, but these appear to have the inverted spoon shape typical of drumlins and some grooves. The shape can be used to estimate ice flow direction, since the steeper sides of the features are known to point up river (Flint 1971, USGS 2009).
Figure 13. Google Earth image showing distribution of grooves across entire KP.
Figure 14a. Profile of Horseshoe Tuya, illustrating the steep sides, sudden, lonely relief, and flat top. View looking southeast; cirque visible on the NW sides. Photograph by Edwards, 2009.

Figure 14b. Profile of Horseshoe Tuya, illustrating sudden relief, steep sides, and flat plateau.
Figure 15. Horseshoe Mountain, a circular, flat-topped volcanic edifice with a large circular erosive feature cut all the way to the valley floor in its NW side. Google Earth image taken at ~21,000 ft.

Figure 16a. Showing the locations of profiles drawn across Horseshoe Tuya.
Figure 16b. Topographic profile A, across the mouth of the cirque on Horseshoe Tuya.

Figure 16c. Topographic profile B, from the mouth of Horseshoe Cirque across the top of the tuya.
Figure 17. Looking northeast at the north wall of the cirque at Horseshoe Mountain. The erosion has exposed a flat-lying lava cap over volcanic breccias layers and deposited a large, tongue-shaped lobe of talus, interpreted to be a moraine, at the center of the feature. The amount of talus present in that moraine is not enough to account for the amount that has been removed in the formation of this cirque.

Figure 18. Linear features observed on the western corner of Horseshoe Tuya. These features are composed of angular rubble, suggesting extensive frost-wedging of the lava cap of Horseshoe. It is unclear if the linear features are depositional, having been created by squeezing underneath a glacier into linear forms, or if they were originally eroded into bedrock and have been subsequently weathered by frost-wedging. Note Everett for scale.
Figure 19. Close-up aerial view of the grooves on the north end of Horseshoe Tuya. This set are particularly well-defined and strike at a significantly different orientation than the rest of the data set (average azimuth: 37°).

Figure 20. Profile of Tutsingale Mountain, illustrating the drumlinoid shape, looking northwest.
Figure 21. Bird’s-eye view of Tutsingale Mountain, showing linear ridges across the top. Taken from aerial photograph BC82015-172.
Figure 22. Grooves running east to west across the top of Tutsingale.
Figure 23. Photograph of the author on Tutsingale Mountain beside one of the observed linear drumlinoids. Note the triangular shape of the feature to the right, and the apparent fragmental composition.
Figure 24. Notated histogram showing the numeric divisions tested using the One-way ANOVA and Kruskal-Wallis statistical tests. The red lines and bold numbers (1,2,3) indicate the final defined groups and their boundaries, while the other numbers (4-7) indicate the smaller peaks that were tested. The standard deviation of the measurements (±5) is too great to determine if these groups are statistically unique.
Figure 25. Geographic domains of linear features observed on the KP. Rose diagrams were generated for the entire study area, then to compare the northern plateau (yellow) to the southern plateau (blue), and the mountain tops (red) to the plateau surface as a whole. The rose diagrams indicated an overwhelming trend of 56-86°, with small outlier groups of between 87-169° and 21-55°. The trends observed indicated no significant difference between the northern and southern plateau, but showed statistically-different distributions of orientations on the mountain tops than on the plateau surface.
Figure 26. Rose diagrams illustrating the distribution of the 827 linear features across the whole KP. Bin size on the left is 10°, and due to the standard deviation of this data set, is the most accurate bin size that is reasonable. The diagram on the right has a bin size of 5° for comparison. A single trend is clearly dominant, but tiny groups at statistically different orientations remain essential for interpreting the glacial history of the plateau. Features created by older stages of glaciation may have been almost obliterated by younger glacial activity.
Figure 27. Rose diagrams showing the distribution of linear features across the northern half of the plateau (Figure 25). Bin size for both diagrams is 10°. A) features on the plateau surface. B) features on the plateau surface and across the top of Horseshoe Tuya.

Figure 28. Diagrams showing the distribution of linear features across the southern half of the plateau (Figure 25). A) Distribution across the plateau surface. B) Including the features on top of Tutsingale Mountain.
Figure 29. Rose diagram illustrating the distribution of the linear features across the mountaintops (elevation greater than 100m above the plateau surface).
Figure 30. Reconstruction of the interpreted history of Horseshoe Cirque: A. Inferred shape of Horseshoe's original lava cap, derived from comparison to other younger tuyas like Tuya Butte. With a point source of heat, a melting glacier should create an approximately circular hole in the ice for the erupting lava to fill. B. Stage 2 erosion, where ice accumulated on the northern slopes of the mountain and erodes, depositing a moraine. C. Stage 3 erosion, where continued cirque glaciation has removed a large chunk of material from the side of Horseshoe. A continental glacier scours away the moraine that had been transported beyond the mouth of the cirque. D. Horseshoe Tuya as it appears today, missing approximately 1/3 of its original volume, but displaying only a tiny glacial moraine.
Figure 31. Aerial photographs overlain on top of a bedrock geology map of the Kawdy Plateau. The pink areas are areas of Paleozoic bedrock, while the tan show areas of alluvial and glacial sediment and the yellow areas indicate the volcanic edifices. Most of the study area is mapped as being underlain by alluvial and glacial sediment by Gabrielse, 1998, but at least one area, indicated by the red circle, contains glacial grooves eroded directly into the Paleozoic bedrock.
Figure 32. A possible interpretation for the glacial groove on the KP. It is possible that the three groups of grooves are indicative of a glacial fulcrum, where a glacial tongue coming from the northeast meetings the Nahlin River valley and stalls on the KP, rotating to flow northwest, down the river gradient. This may explain why there is a greater presence of the 87-169° group on the southern half of the plateau. However, the 56-86° group is still overwhelmingly dominant across the plateau, so the rotating glacier theory does not account for the distribution of features observed on the KP. A rotating glacier also would not explain the missing material from Horseshoe’s cirque, and therefore is deemed unlikely.
Figure 33. Reconstruction of the glacial history of the Kawdy Plateau, based on quality of preservation and prevalence of the three identified groups of glacial grooves. Time 1 (yellow): 21-55° depositional features created when an ice sheet flows over the plateau from northeast to southwest. Time 2 (red): 87-169° depositional features created when a second glacier flows from east to west, obliterating most evidence of the southwest-flowing glacier. Time 3 (blue): 56-86° group created when an ice stream or meltwater flood, flows across the area, overprinting the other linear features and carving grooves into the bedrock.
### Tables

**Table 1. Quantified characteristics of glacial features on the Kawdy Plateau**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Azimuth, length, spacing, prevalence</td>
</tr>
<tr>
<td>Cirque</td>
<td>Depth, width, headwall height, headwall slope volume, orientation</td>
</tr>
<tr>
<td>Moraine</td>
<td>Depth, volume</td>
</tr>
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</table>

**Table 2. Scales used to interpret aerial photographs.**

<table>
<thead>
<tr>
<th>Aerial Photograph</th>
<th>Scale (cm:m)</th>
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<tbody>
<tr>
<td>BC5616 063</td>
<td>1:297</td>
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<tr>
<td>BC5616 064</td>
<td>1:374</td>
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<tr>
<td>BC5616 067</td>
<td>1:291.23</td>
</tr>
<tr>
<td>BC82015 120</td>
<td>1:394</td>
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<tr>
<td>BC82015 172</td>
<td>1:403</td>
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Table 3. Potential domains observed.

<table>
<thead>
<tr>
<th>Domain tested</th>
<th>Average Orientation</th>
<th>Standard Deviation</th>
<th>P value (&lt;0.05 indicates statistical uniqueness)</th>
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<tbody>
<tr>
<td><strong>Geographic:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern plateau</td>
<td>74°</td>
<td>8</td>
<td>0.58</td>
</tr>
<tr>
<td>Southern plateau</td>
<td>74°</td>
<td>12</td>
<td>0.58</td>
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<tr>
<td>Mountaintops</td>
<td>81°</td>
<td>24</td>
<td>0.002</td>
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<tr>
<td><strong>Numeric:</strong></td>
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</tr>
<tr>
<td>21-55°</td>
<td>37°</td>
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<td>87-169°</td>
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Table 4: Calculated error for azimuth and length measurements, including human error, rectifying error, and distortion error from the edge of the aerial photographs.

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<tr>
<th>Azimuth</th>
<th>StDev</th>
<th>Average</th>
<th>% error</th>
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<td>14.85</td>
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<tr>
<td>0.79</td>
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<tr>
<td>1.17</td>
<td>9.09</td>
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<td>1.26</td>
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<td>1.86</td>
<td>16.54</td>
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<tr>
<td>0.58</td>
<td>13.3</td>
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</table>

Average % error 7.65

<table>
<thead>
<tr>
<th>Length</th>
<th>StDev</th>
<th>Average</th>
<th>% error</th>
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<td>0.89</td>
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Average % error 13.35
Table 5. Statistical Analysis

**A. Comparing the 21-55°, 56-86°, and 87-169° groups**

**One-way ANOVA: Response versus Factor**

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<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
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<td>Factor</td>
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<td>69492.6</td>
<td>34746.3</td>
<td>850.02</td>
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<tr>
<td>Error</td>
<td>841</td>
<td>34377.7</td>
<td>40.9</td>
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<tr>
<td>Total</td>
<td>843</td>
<td>103870.3</td>
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S = 6.394 R-Sq = 66.90% R-Sq(adj) = 66.82%

**Individual 95% CIs for mean based on pooled StDev**

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
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<td>1</td>
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<td>45.710</td>
<td>13.564</td>
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<tr>
<td>2</td>
<td>737</td>
<td>74.352</td>
<td>4.962</td>
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<td>3</td>
<td>48</td>
<td>95.577</td>
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<td></td>
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<td>45</td>
<td>60</td>
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**Kruskal-Wallis Test: Response versus Factor**

<table>
<thead>
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<th>N</th>
<th>Median</th>
<th>Av Rank</th>
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<td>59</td>
<td>45</td>
<td>30.0</td>
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<td>2</td>
<td>737</td>
<td>.00</td>
<td>428.0</td>
<td>1.72</td>
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<tr>
<td>3</td>
<td>48</td>
<td>74.18</td>
<td>820.5</td>
<td>11.65</td>
</tr>
<tr>
<td>Overall</td>
<td>844</td>
<td>93.71</td>
<td>422.5</td>
<td></td>
</tr>
</tbody>
</table>

H = 281.25 DF = 2 P = 0.000
H = 281.25 OF = 2 P = 0.000 (adjusted for ties)

**B. Comparing the small peaks between 60-67°, 68-73°, 74-78°, 78-80°, 81-82°, and 83-85°.**

**One-way ANOVA: response versus factor**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>5</td>
<td>16995.47</td>
<td>3399.09</td>
<td>1618.53</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>732</td>
<td>1537.28</td>
<td>2.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>737</td>
<td>18532.75</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 1.449 R-Sq = 91.71% R-Sq(adj) = 91.65%

**Individual 95% CIs For Mean Based on Pooled StDev**

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>82</td>
<td>64.873</td>
<td>1.981 (*)</td>
</tr>
<tr>
<td>2</td>
<td>248</td>
<td>71.007</td>
<td>1.602 (*)</td>
</tr>
<tr>
<td>3</td>
<td>269</td>
<td>75.743</td>
<td>1.411 (*)</td>
</tr>
<tr>
<td>4</td>
<td>64</td>
<td>79.347</td>
<td>0.529 (*)</td>
</tr>
</tbody>
</table>

69
5  45  81.486  0.600
6  30  83.624  0.797

---+-----------+-----------+-----------+---------
| 65.0 | 70.0 | 75.0 | 80.0 |

Pooled StDev = 1.449

Kruskal-Wallis Test: response versus factor
Kruskal-Wallis Test on response

<table>
<thead>
<tr>
<th>factor</th>
<th>N</th>
<th>Median</th>
<th>Ave Rank</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>82</td>
<td>65.56</td>
<td>41.5</td>
<td>-14.78</td>
</tr>
<tr>
<td>2</td>
<td>248</td>
<td>71.25</td>
<td>206.5</td>
<td>-14.78</td>
</tr>
<tr>
<td>3</td>
<td>269</td>
<td>75.68</td>
<td>465.0</td>
<td>9.22</td>
</tr>
<tr>
<td>4</td>
<td>64</td>
<td>79.38</td>
<td>631.5</td>
<td>10.29</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>81.42</td>
<td>686.0</td>
<td>10.28</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>83.59</td>
<td>723.5</td>
<td>9.29</td>
</tr>
<tr>
<td>Overall</td>
<td>738</td>
<td>369.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

H = 671.63  DF = 5  P = 0.000
H = 671.64  DF = 5  P = 0.000 (adjusted for ties)

C. Comparing the northern and southern halves of the KP, as well as the mountaintops.
One-way ANOVA: response versus FACTOR

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td>1</td>
<td>2290</td>
<td>2290</td>
<td>10.00</td>
<td>0.002</td>
</tr>
<tr>
<td>Error</td>
<td>324</td>
<td>74243</td>
<td>229</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>325</td>
<td>76534</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 15.14  R-Sq = 2.99%  R-Sq(adj) = 2.69%

Individual 95% CIs For Mean Based on
Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>265</td>
<td>74.44</td>
<td>12.34</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>81.24</td>
<td>23.82</td>
</tr>
</tbody>
</table>

Pooled StDev = 15.14

Kruskal-Wallis Test: response versus FACTOR
Kruskal-Wallis Test on response

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>N</th>
<th>Median</th>
<th>Ave Rank</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>590</td>
<td>74.83</td>
<td>459.7</td>
<td>0.18</td>
</tr>
<tr>
<td>2</td>
<td>265</td>
<td>72.97</td>
<td>405.2</td>
<td>-3.89</td>
</tr>
</tbody>
</table>
Table 6. Distribution and characteristics of linear features on the KP.

<table>
<thead>
<tr>
<th>Location</th>
<th>Composition</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>21-55° (23 features)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 on north side of HS</td>
<td>Unclear</td>
<td>Linear</td>
</tr>
<tr>
<td>11 dispersed on plateau surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>56-86° (751 features)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 on SW side of HS</td>
<td>Depositional</td>
<td>Drumlinoid</td>
</tr>
<tr>
<td>739 on plateau surface</td>
<td>Erosive</td>
<td>Linear</td>
</tr>
<tr>
<td><strong>89-169° (53 features)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31 on Tutsingale Mtn</td>
<td>Depositional</td>
<td>Linear</td>
</tr>
<tr>
<td>22 on plateau surface</td>
<td>Erosional</td>
<td>Linear</td>
</tr>
</tbody>
</table>
Table 7. Characteristics of Domains

<table>
<thead>
<tr>
<th>Domain</th>
<th>Azimuth</th>
<th>Length (m)</th>
<th>Spacing (m)</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Av</td>
<td>St Dev</td>
<td>Av</td>
<td>St Dev</td>
</tr>
<tr>
<td>21-55°</td>
<td>37°</td>
<td>10</td>
<td>135</td>
<td>44</td>
</tr>
<tr>
<td>56-86°</td>
<td>74°</td>
<td>5</td>
<td>164</td>
<td>201</td>
</tr>
<tr>
<td>87-169°</td>
<td>94°</td>
<td>10</td>
<td>277</td>
<td>186</td>
</tr>
<tr>
<td>Total</td>
<td>74°</td>
<td>11</td>
<td>263</td>
<td>189</td>
</tr>
</tbody>
</table>

Table 8. Tentative Glacial Timeline of the Kawdy Plateau

5. Very warm. All glaciers melt, revealing the landscape visible today. Landslides and salufluction lobes continue the erosion begun by the glaciers.

4. Not that cold. Meltwater flow/s occur under the ice sheet as the glacier begins to retreat. The youngest event washes across the plateau surface, leaving grooves between 56-86° on the low-elevation areas of the KP. Glacier transports away all the talus from Horseshoe cirque.

3. Pretty cold. Ice sheet 2 flows across the area, transporting moraine material form Horseshoe Cirque southwest into the Nahlin River Valley. Linear features between 87-169° form. Many of the 21-55° features are obliterated. Horseshoe cirque is further eroded.


1. Very cold. Ice sheet one flows across the KP; 21-55° group is formed. Horseshoe cirque begins to form.