Cirque forms and alpine glaciation during the Pleistocene, west-central Yukon[1]

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ABSTRACT

Uplands in west-central Yukon supported alpine ice centres during the pre-Reid glaciations (Early Pleistocene). Subdued cirque forms are thought to be glacial cirques that have undergone degradation by nivation. The paleo-equilibrium line altitude (ELA) dropped as low as 1054 ± 96 m in the Crag Mountain upland (CMU). A pre-Reid age for the CMU cirques is based upon the presence of an Early-Middle Pleistocene paleosol in a moraine feature. Cirques in the Ogilvie Mountains provide proxy ELAs for the Reid (mean 1391 ± 132 m) and McConnell (mean 1488 ± 103 m) glaciations. Cirque glaciers did not form in CMU and most of Dawson Range during these later glaciations due to a decrease in precipitation. It is suggested that the progressive marginality of cirque glaciation through the Middle and Late Pleistocene may be related to the progressive enlargement of precipitation-diverting continental ice sheets east of the Cordillera.

RÉSUMÉ

Les hautes terres dans le centre ouest du Yukon ont été le siège de centres glaciaires alpins durant les glaciations pré-Reid (Pléistocène précoce). Les formes quasi-circulaires estompées seraient des cirques glaciaires ayant subi une dégradation par nivation. L'ancienne altitude de la ligne d'équilibre a chuté à 1054 ± 96 m dans les hautes terres du mont Crag. L'attribution d'un âge pré-Reid aux cirques des hautes terres du mont Crag est basée sur la présence d'un paléosol du Pléistocène précoce-moyen dans une forme morainique. Les cirques dans les monts Ogilvie fournissent des altitudes de la ligne d'équilibre pour les glaciations Reid (valeur moyenne de 1391 ± 132 m) et McConnell (valeur moyenne de 1488 ± 103 m). Aucun glacier de cirque ne s'est formé dans les hautes terres du mont Crag et dans la grande partie du chaînon Dawson au cours de ces glaciations tardives à cause d'une diminution des précipitations. Le caractère marginal progressif des glaciers de cirque pendant le Pléistocène moyen et tardif pourrait être attribuable à l'agrandissement progressif des calottes glaciaires continentales dû à un déplacement des précipitations à l'est de la Cordillère.

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INTRODUCTION

The surficial geology of a large area of west-central Yukon (Stewart River 1:250 000 map area (115N and 115O) and adjacent areas) is currently being mapped as part of the Geological Survey of Canada's Ancient Pacific Margin NATMAP project. Defining the limits of past glacial ice cover is a key component in this endeavour. Bostock (1966) established limits of past regional glaciations. These pertain to areas covered by past Cordilleran ice sheets. However, recent investigation of cirque-like features and glacial landforms in the Sixtymile River basin (Lowey, 2000), mapping of degraded cirques in the Dawson Range (Jackson, 2000), and mapping of landforms and glacial erratics in the Yukon-Tanana Upland of adjacent Alaska (Weber, 1986) have suggested that cirque, valley or small ice cap glaciation may have existed earlier in the Pleistocene at elevations common within uplands of the Stewart River map area.

There are significant problems inherent in gaining more of an understanding of these past local ice centres: most of the deposits of these alpine glaciers have been eroded away or buried, and the cirques from which the glaciers originated have been eroded to suggestive but equivocal bowl-shape alpine landforms.

This paper presents an inquiry into these cirque-like features. It deals with the following questions:

1) Are these bowl-like alpine features really degraded glacial cirques?
2) Do middle or Early Pleistocene glacial deposits related to the purported cirques exist?
3) What is the geographic distribution of these cirque-like features?
4) What do their geographic distributions indicate about climatic factors during these old glaciations and how did they differ from more recent glaciations?

To address these questions, the occurrences of these cirque-like forms were mapped and their distributions and morphometry compiled. A literature review was carried out to investigate the climatic controls determining the occurrence of cirques and similar landforms. Deposits that were suspected as originating from alpine valley glaciers were also investigated.

SETTING

West-central Yukon lies within the Yukon Plateau (Mathews, 1986), a region of accordant summits and broad intervening valley systems. The age of this formerly uplifted surface is uncertain, but probably dates to the Early Tertiary. Elevations of summits generally decrease westward from the Pelly Mountains (elevations up to 2190 m) and southward from the Ogilvie Mountains (elevations up to 2050 m). Relief from mountain summit to valley floors ranges up to 1130 m. Glaciation has caused the most notable differences in the morphology of uplands and drainage patterns. Recently glaciated uplands such as the Pelly and Ogilvie mountains are marked by alpine glacial landforms such as horns, arêtes and cirques. Valley systems are commonly anastomosed due to widening and deepening of pre-existing fluvial drainage by valley glaciers.

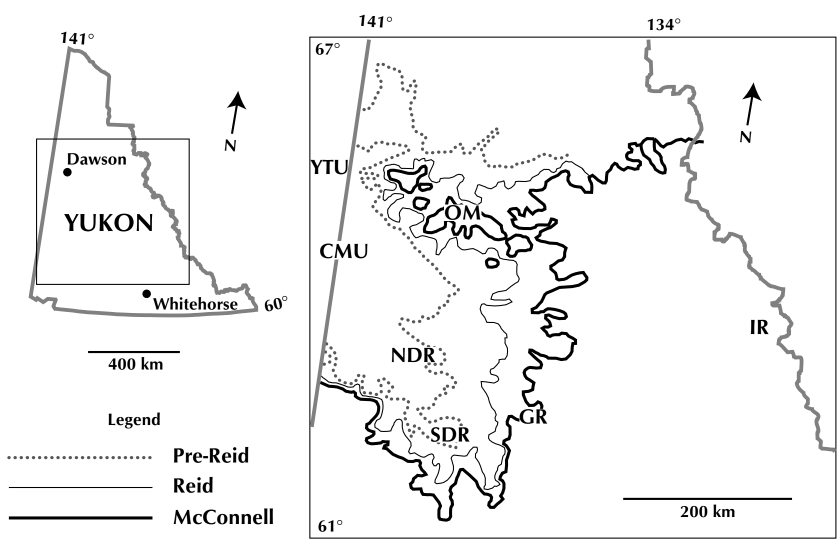


__Figure 1.__ Map showing study areas and generalized Cordilleran glaciation limits, central Yukon Territory (modified from Duk-Rodkin, 1999).
YTU – Yukon-Tanana Upland (Alaska)
OM – Ogilvie Mountains
CMU – Crag Mountain upland
NDR – northern Dawson Range
SDR – southern Dawson Range
GR – Glenlyon Range
IR – Itsi Range

In contrast, areas such as the Klondike Plateau have been described as “gentle undulations rising here and there along converging ridges to culminate in...dome-like eminences or groups of relatively smooth-sloped mountains” (Bostock, 1948, p. 62). Valley systems reflect their fluvial origin, and anastomosing valley systems occur only along the limits of regional glaciation. The cirque-like features, which are the subject of this paper, occur along the dome eminences and the sides of the higher ridges.

Bostock (1966) recognized four glaciations during which an ice sheet formed over eastern and southern Yukon and advanced west and north: the Nansen, Klaza, Reid and McConnell. Each of these glaciations was less extensive than its predecessor (Fig. 1). Hughes et al. (1969) grouped Nansen and Klaza glaciations into the pre-Reid glaciations due to the difficulty in correlating the scattered occurrences of sediments left behind by these glaciations that pre-date the last geomagnetic reversal (*ca.* 0.78 Ma), and may date to *ca.* 2.5 Ma (Froese et al., 2000). The pre-Reid grouping will be used in this paper.

The present climate of the Yukon Plateau is sub-Arctic continental with low relative humidity, and precipitation modified by orographic and rain shadow effects (Wahl et al., 1987). The highest mean annual precipitation, up to 3500 mm, occurs over the presently glacierized Coast Mountains (CM) and Saint Elias Mountains (SEM) (Fig. 2). The Pelly (PM) and Selwyn (SM) mountains form an interior wet belt with precipitation up to 700 mm. The Stewart River map area and adjacent parts of west-central Yukon are particularly arid due to their position in the rain shadow of CM/SEM, with annual mean total precipitation ranging from 300 to 500 mm.

GLACIAL CIRQUES AND SIMILAR FEATURES

A cirque is a topographic hollow, open downstream but bounded upstream by the crest of a steep slope (headwall), which is arcuate in plan around a more gently sloping floor. It is glacial if “the floor has been affected by glacial erosion while part of the headwall has developed subaerially, and a drainage divide was located sufficiently close to the top of the headwall for little or none of the ice that fashioned the cirque to have flowed in from the outside” (Evans and Cox, 1974, p. 151). Glaciers require cold temperatures and sufficient effective precipitation for snow accumulation to exceed ablation (Benn and Evans, 1998). Glaciers erode cirques once the surface gradient of the ice initiates rotational flow (Evans, 1999). Cirque altitudes and aspects provide a “long-term integration of the morphological effect of glacial climate” (Evans, 1977,

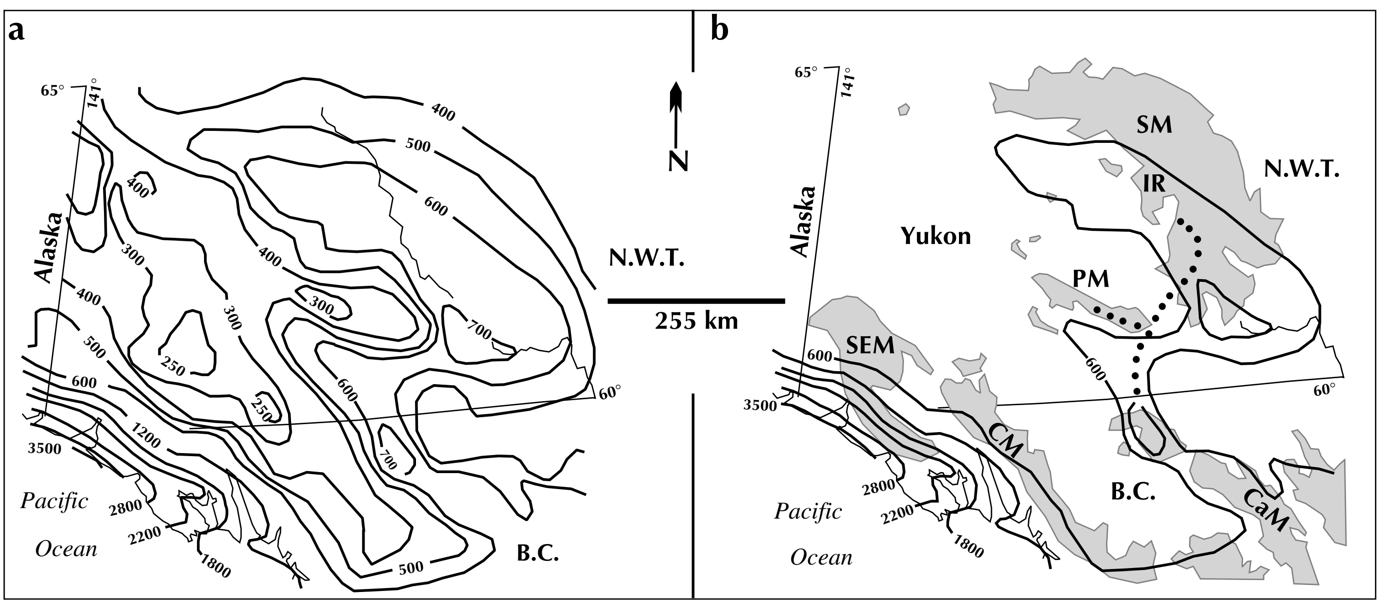


Figure 2. (a) *Isohyet map (mean annual precipitation, mm) of southern Yukon and northern British Columbia;* ***(b)*** *> 600 mm isohyets and areas containing summits with elevations >1900 m (shaded). The generalized ice divide (dotted line) from which the Selwyn and Cassiar lobes advanced into the Yukon River basin (figure after Jackson et al., 1991, his Figure 2; climatic data from Wahl et al., 1987). SM – Selwyn Mountains; IR – Itsi Range; PM – Pelly Mountains; SEM – Saint Elias Mountains; CM – Coast Mountains; CaM – Cassiar Mountains*

p. 151). Where and when climate conditions are marginal for the existence of cirque glaciers, they occur in deep, wide cirques with a narrow pass, or col, upwind (Graf, 1976). This implies that cirque glacier formation is encouraged and perpetuated by pre-existing cirque forms.

A nivation hollow or nivation cirque, as this landform is also called, shares the cirque form; however, it shows evidence of the suite of processes known as nivation taking place under snowpatches, rather than glacial erosion. Nivation processes include freeze-thaw cycles and abrasion by material embedded in mobile snow pack, intensification of chemical weathering through insulation and moisture, and mechanical transport through solifluction and meltwater flow (Thorn, 1988; Christiansen, 1998). The rate of degradation in a snow-covered nivation hollow in the Colorado Rockies has been measured at 0.0074 mm/yr (Thorn, 1976). Definitive criteria for the purely morphometric discrimination between glacial cirques and nivation hollows are absent from the literature. Nivation features, although usually smaller than glacial features, cannot be differentiated by size alone (Evans and Cox, 1974). Large nivation hollows have been studied in northern Quebec (Henderson, 1956), Sweden (Rudberg, 1984; Rapp, 1984; Rapp et al., 1986), Denmark (Christiansen, 1996) and northeast Greenland (Christiansen, 1998). The only definitive way to discriminate between these landforms and glacial cirques, particularly when cirques have been degraded by erosion and periglacial activity, is by demonstrating past flow of glacial ice from cirques into adjacent valleys.

METHODS

Lowey (2000) presented evidence suggesting the existence of degraded cirques, and morainal and related features in the upland south of Sixtymile River (Fig. 3). This upland will be referred to as Crag Mountain upland after one of the few named peaks in that area. The sites discussed by Lowey (2000) were visited during the course of surficial geology mapping in 2001 in order to further investigate the genesis and the age of the glacial features. In the office, cirques and cirque-like landforms between latitudes 62 and 65 degrees North and longitudes 136 and 141 degrees West were inventoried and their morphometric parameters measured. This geographic area includes the broad physiographic regions of the Yukon Plateau and the Ogilvie Mountains. Included in this area are unequivocal glacial cirques from the Late Pleistocene glaciations. Cirques and cirque-like features were compiled from existing surficial geology maps and new air photo interpretation.

FIELD INVESTIGATION OF VALLEY GLACIATION IN UPLANDS BEYOND THE LIMIT OF REGIONAL GLACIATION

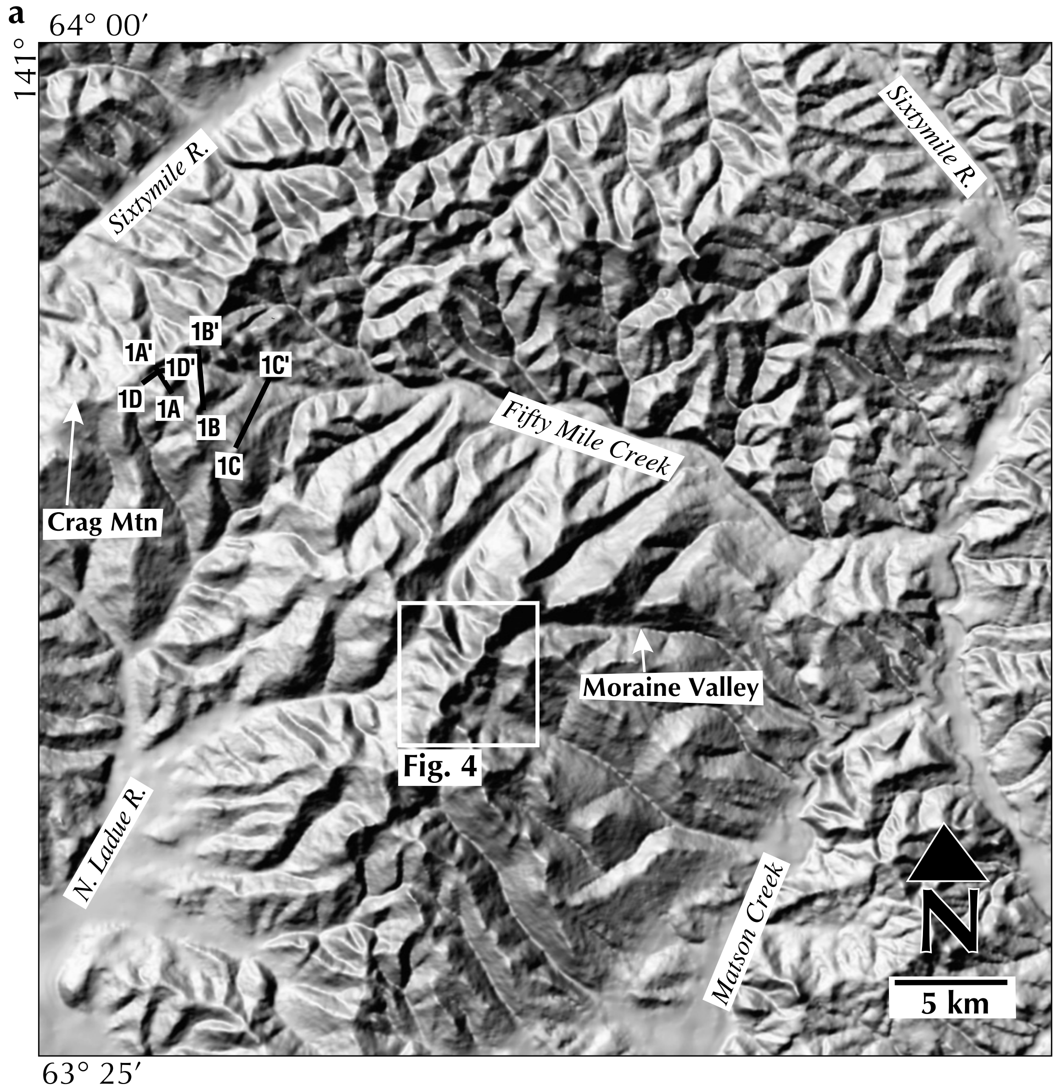
Lowey (2000) noted several features indicative of the past presence of valley glaciers in valleys descending from the Crag Mountain upland: arête-like ridges, U-shaped valleys, truncated spurs, flights of terraces (upper Fifty Mile Creek) and morainal features that lie across valleys. A valley south of Fifty Mile Creek is notable in this regard and will be referred to as Moraine Valley (Fig. 3). Other similar features were noted on air photos and visited in the field. Suspected morainal features were traversed and pits were dug in them in order to determine the depth and type of soils and degree of weathering as an indication of their age. In the lab, a succession of topographic cross-sections was constructed across valleys descending the Crag Mountain upland to compare cross-valley shape changes with distance in a down-valley direction. This was done in order to look for changes indicative of the transition between formerly glaciated upper reaches of valleys and unglaciated lower reaches.

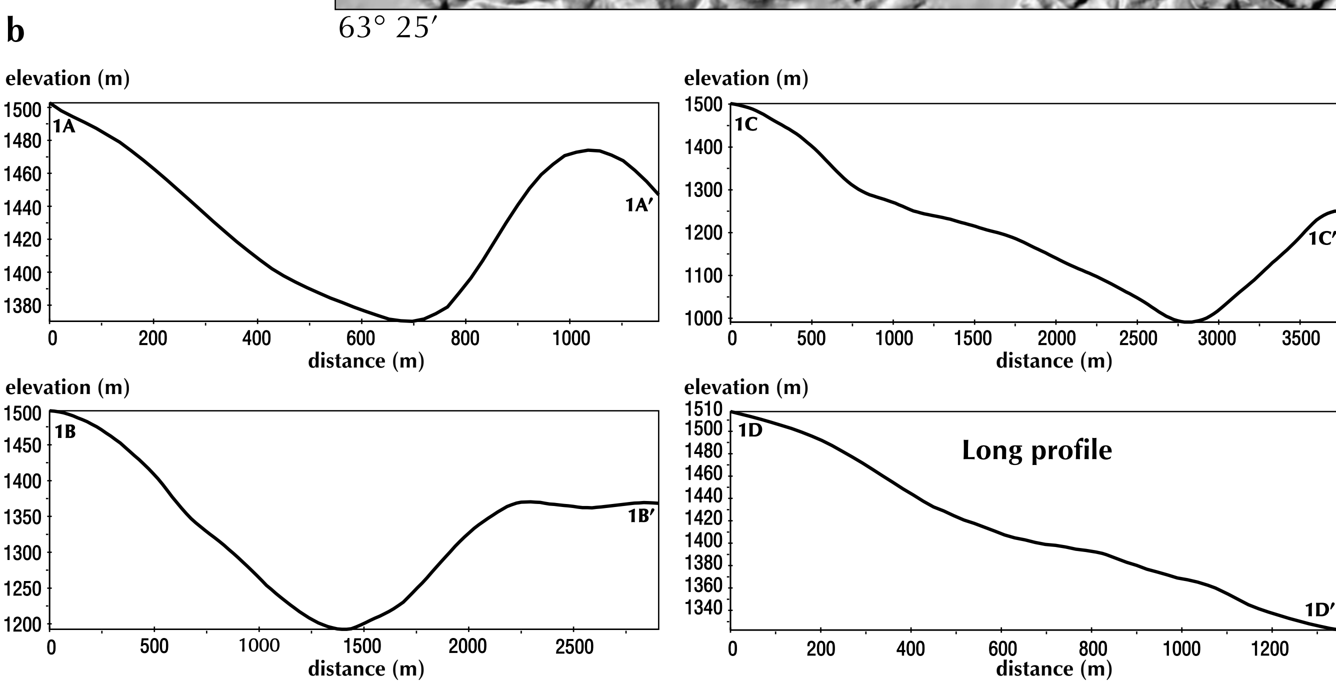
MORPHOMETRIC AND STATISTICAL METHODS

Morphometric characteristics for cirque and cirque-like landforms are measured on 1:50 000-scale NTS maps, with the exception of cirques on sheets 105L/7, L/8, L/1 and 115I/5, which are measured off of 1:100 000-scale base maps assembled from the respective 1:50 000 sheets (Ward and Jackson, 1993; Jackson, 1997). A total of 331 cirque forms were studied in five regions: Crag Mountain upland (115N/15,16,10,9), northern Dawson Range (115J/15,10,9,8), southern Dawson Range (115I/5,6, 4,3), Glenlyon Range (105L/7,8,1) and Ogilvie Mountains (116A/12,11,10,9). The established cirques and cirque-like landforms were divided into four grades based on quality of form, with grade 1 forms closest to the ideal cirque form of Evans and Cox (1974) and grade 4 being still recognizable but different from the ideal (Fig. 4). This is similar to the methodology used by Lowey (2000); however, in this study, subdued cirque forms are grouped within grade 4 rather than a grade 5 (marginal, with cirque status and origin doubtful).

Developing criteria for differentiating between cirques of different ages is problematic because of the many variables involved. Vernon and Hughes (1966) separated glacial features in the Ogilvie Mountains into two classes,

Figure 3. (a) *'Hillshade' model of Crag Mountain area showing locations of cross-sections (1A-1A'; 1B-1B'; 1C-1C'), long profile (1D-1D') and selected features. Location of Figure 4 is indicated.* ***(b)*** *Cross-sections and long profile of a grade 1 cirque in the Crag Mountain upland (UTM E504200, N7081500; NAD 27). Cross-sections are approximately 0.5, 2.5 and 5 km from foot of cirque headwall.*





"glaciated in the last glaciation" and "not affected by last glaciation," on the basis of qualitative geomorphic criteria (rounded arêtes and gully-dissected cirque walls interpreted as older). However, stages of weathering found within cirque forms may be explained by differing rates of erosion within different rock lithologies. Jackson et al. (1996) found this to be the case in the Alberta Foothills and Rocky Mountain Front Ranges.

Cirque-floor altitudes represent a maximum value for the ELA (paleo-equilibrium line) of cirque glaciers and must be used with caution (Meierding, 1982; Benn and Evans, 1998); however, as a relative measure they are thought to be useful. Cirques of all aspects are included in the altitudinal frequency distributions. Descriptive statistics for cirque-floor elevations only include cirque forms facing north, as any calculation involving cirque elevation is biased by including cirques of greatly different orientation (Evans, 1977). Skewness measures the degree of symmetry in a frequency distribution. Kurtosis measures flatness or peakedness of a data set. In order to estimate the amount of depression of snowline during past glaciations relative to the present (Holocene) interglacial periods, the present equilibrium line altitude (ELA) was inferred from glaciers in the Itsi Range ice fields along the Yukon/Northwest Territories border in the Selwyn Mountains (Fig. 1). The ELA was approximated by an accumulation-area ratio of 0.65 (Meierding, 1982). The 'ice field' layer of the digital topographic map (105J/16) was imported into AutoCAD and the ELA was interpolated from contour lines.

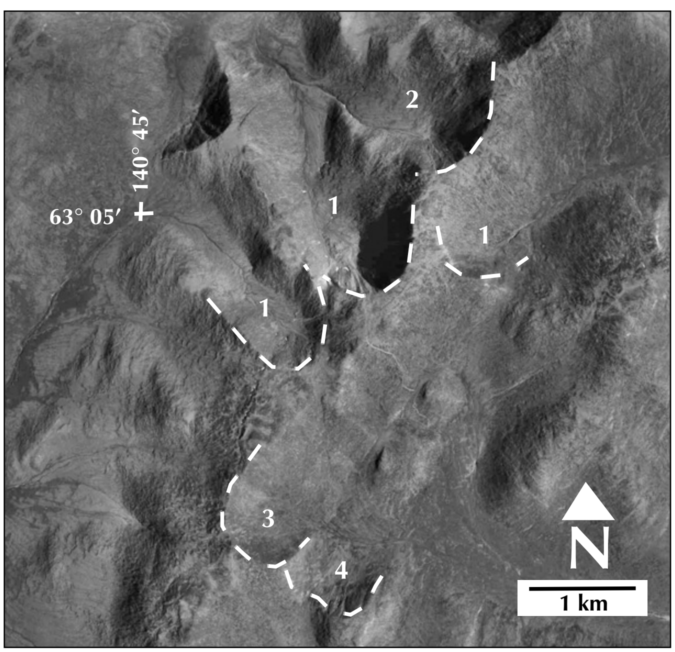


Figure 4. *Detail of air photo showing cirques of varying quality (grade) in Crag Mountain upland. Grade 1 cirques are closest to the ideal cirque form and grade 4 cirques are poorly developed. 1, 2, 3, 4=grade. NAPL A27660-66.*

Ninety-five percent confidence intervals for the mean cirque-floor elevations of cirques and cirque-like features were calculated using VassarStats: Website for statistical computation (R. Lowry, 2002, *http://faculty.vassar.edu/lowryVassarStats.html*). A 95% confidence interval for the mean is calculated by adding and subtracting 1.96 standard errors of the mean. Confidence intervals are used to compare the cirque-floor elevations of high-quality (grade 1 or 2) cirques to those of low-quality (grade 3 or 4) cirque forms. Confidence intervals are viewed as a strong replacement for hypothesis testing (Johnson, 1999).

Cumulative vector diagrams (Evans, 1977) determine the mean orientation of cirques in each geographic area studied. These diagrams depict the resultant vector, the only valid mean for directional data (Curray, 1956). Each individual vector in these diagrams is the sum of the number of cirques within one of sixteen 22.5° divisions of the compass. Evans (1977) suggested that vector strength could be interpreted as the degree of asymmetry of cirque orientation (Table 1). Asymmetry represents the preference to 'best' aspect for glacier formation, and therefore, cirque formation. Evans (1977) found that as snowline falls, the effect of aspect, and therefore asymmetry, is reduced, forming a 'law of decreasing glacial asymmetry with increasing glacier cover.' Cumulative vector diagrams for all regions except the Itsi Range and the Ogilvie Mountains, where cirques could be related to moraines from succeeding glaciations, include cirque aspects from multiple glaciations. Therefore, results must be regarded as composite. Nevertheless, because alpine glaciation may not have occurred in a particular region during every glaciation, the results are thought to be meaningful.

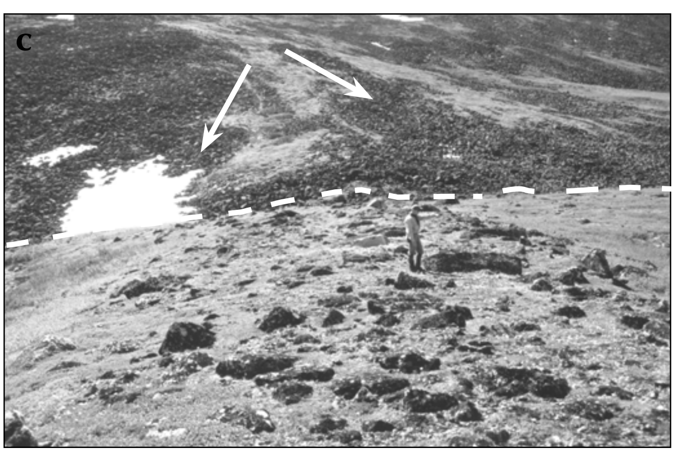
Table 1. *Suggested interpretation of vector strength (after Evans, 1977).*

Vector strength (L)	Degree of asymmetry
>80%	extremely asymmetric
60-80%	strongly asymmetric
40-60%	markedly asymmetric
20-40%	weakly asymmetric
<20%	symmetric

RESULTS

FIELD EVIDENCE OF FORMER VALLEY GLACIERS

Crag Mountain upland yields the best evidence for past valley glaciation in areas beyond the limit of regional glaciation (Bostock, 1966; Duk-Rodkin, 1999), corroborating the conclusions of Lowey (2000) for the Crag Mountain area and those of Weber (1986) for Yukon-Tanana Upland in Alaska. Evidence includes U-shaped valleys (Fig. 5a) and truncated spurs in valleys that originate from cirque-like landforms along divides above 1300 m, as well as corroboration of the glacial origin morainal feature in Moraine Valley. U-shape valleys locally transform into V-shaped valleys downstream. This suggests a former glacial limit similar to canyon transformations seen in valleys at the limits of valley



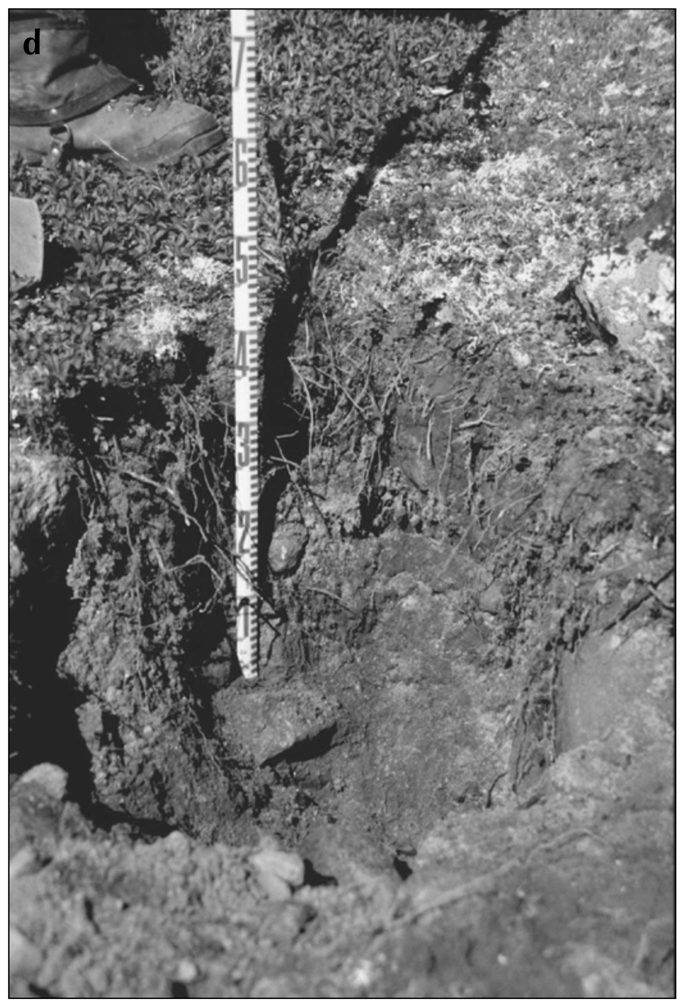


Figure 5. *Glacial features in and around Crag Mountain upland.* ***(a)*** *View of U-shaped valley of Borden Creek. View is to the northwest with summit of the Crag Mountain upland in the background.* ***(b)*** *View looking down valley at three bouldery ridges: distance from X to X′ is 200 m.* ***(c)*** *Looking along morainal ridge in the area of x' toward the slope to the south. Toe of a large rock glacier (dashed line) is seen advancing onto the moraine (flow direction of rock glacier indicated by arrows).* ***(d)*** *Soil pit containing red fossil soil with ventifacts and clasts with clay skins.*

glaciers in unglaciated regions such as the Merced River valley below Yosemite Valley, California (Matthes 1930, his Fig. 4). In other valleys, such as those of Borden, Sven and Pine creeks, the U-shape form persists to the valley of Sixtymile River (Fig. 5a). Unfortunately, a complete lack of exposures and of distinctive erratic rock types prevents the discrimination of glacial deposits in these areas.

Deposits at Moraine Valley

The moraine-like feature in Moraine Valley consists of a complex of elongate boulder ridges transverse to the long axis of the valley (Fig. 5b,c). The largest is 200 m long, 65 m wide with local relief of up to 23 m between the crest and the down-valley side. It is studded with large angular boulders of granitoid plutonic and gneissic lithologies. Although the soil directly underlying the surface is an incipient one (Regosol), excavation of 30-cm-deep pits between boulders on the down valley side of the largest ridge encountered remnants of a fossil soil having Munsell colours in the 7.5 yr 3/4 range (brown), buried ventifacts (wind-sculpted stones), and clay skins (argillans) on stones (Fig. 5d). These are all characteristic of the Wounded Moose paleosol which is developed in the deposits of the Early Pleistocene pre-Reid glaciations (Tarnocai et al., 1985; Smith et al., 1986; Tarnocai 1987, 1990; Tarnocai and Schweger, 1991). The burial of pods of this soil attests to intense cryoturbation following the formation of the soil. The effects of a periglacial climate are further indicated by complexes of rock glaciers which cover the adjacent north-facing slopes and are overrunning the southern margins of these bouldery ridges. The narrow, elongate form of these features precludes a nonglacial origin either as a rock avalanche or as the toe of an inactive rock glacier, (the former forms a hummocky carpet of bouldery debris across a valley, whereas the latter remains as a lobate or spatulate tongue of bouldery debris). Morainal features similar to the ridges in question occur in the headwaters of the Kananaskis River in the Canadian Rocky Mountains, Alberta (Jackson, 1987, p. 19). They originated as a rockfall onto the surface of a retreating valley glacier. The rockfall debris was transported to the terminus and concentrated as transverse ridges and heaps of boulders with reliefs comparable to those in Moraine Valley. The angular, bouldery texture of these ridges has allowed their survival as landforms. Other glacial landforms and deposits that existed in the area presumably have been buried or removed by erosion.

In order for a valley glacier to have deposited these bouldery ridges, it would have had to advance 1.5 km from the cirque at the head of the valley. This is a minimum figure for the length of the former valley glacier. U-shape cross-sections in adjacent valleys persist more than 8 km. Although no detailed calculations were done, it appears that there is a direct relationship between the linear persistance of valley U-shape cross-section and the total area of degraded cirques.

CIRQUE MORPHOMETRY AND CIRQUE-FLOOR ALTITUDES

In west-central Yukon, fresh and degraded cirque forms range from the classic semi-circular armchair-like forms to valley heads with bowl-shaped curvature. North-facing

Table 2. *Descriptive statistics for cirque-floor elevations in five regions of west-central Yukon. Only north-facing cirques are considered.*

Region	Altitude (m)			Standard deviation	Skewness	Kurtosis
	Minimum	Maximum	Mean			
Itsi Range ice fields	1780	2100	1929	84	0.04	-0.08
Ogilvie Mountains						
not active during last glaciation	1036	1646	1391	132	-0.77	0.41
active during last glaciation	1219	1707	1488	103	-0.65	1.05
Glenlyon Range	1402	2012	1667	122	0.67	1.68
Dawson Range						
northern	1189	1676	1433	125	-0.10	-0.42
southern	1128	1515	1451	117	-0.83	0.62
Crag Mountain upland						
minor mode	853	1189	1054	96	-0.76	-0.04
major mode	1219	1515	1346	92	0.10	-0.80

cirque-floor altitudes range from 853 to 2012 m above sea level. Altitudinal frequency distributions for the regional groups are presented in Figure 6. Ninety-five percent confidence intervals comparing the means of high-quality and low-quality cirque forms are presented in Figure 7. Descriptive statistics for cirque-floor elevations are presented in Table 2. Backwall height ranges from 30 to 518 m. Cirque-form width ranges from 91 to 2300 m, and length ranges from 100 to 2700 m. The mean values for a range of characteristics are summarized in Table 3. Most cirque forms are drained by first-order streams and have an outward sloping bottom, with little or no overdeepening. Cumulative vector diagrams depict the mean aspect and degree of asymmetry for each region (Fig. 8).

Itsi Range of the Selwyn Mountains and contemporary ELA

The Selwyn lobe of the Cordilleran Ice Sheet (McConnell Glaciation) originated from an ice-divide in the Selwyn Mountains and pressed into west-central Yukon (Campbell, 1967; Jackson et al., 1991). Ice fields present today in the Itsi Range are thought to be analogous to glacier cover present in Selwyn Mountains during the Reid/McConnell interglacial period (Jackson et al., 1991).

The Itsi Range supports 21 ice fields, with a total area of 18 386 569 m^2 (data from 1976-77 air photos). The mean ice field ELA is 1929 ± 84 m (Table 2) and provides an estimate of the contemporary ELA within the interior of Yukon. It can be used to evaluate the depression of the ELA during past glaciations. The average ice field has a headwall aspect of 28° west of north, and the aspect distribution is weakly asymmetric (Fig. 8). South-facing ice fields have higher ELAs due to the enhanced insolation received by that orientation.

Ogilvie Mountains

The Ogilvie Mountains (OM) have the least complicated glacial history of the formerly glacierized areas inventoried. During the McConnell and Reid glaciations, cirques fed valley glaciers, which in turn locally fed piedmont lobes in adjacent lowlands. Confluence of Ogilvie Mountain glaciers with a lobe of a Cordilleran Ice Sheet that occupied Tintina Trench occurred during the pre-Reid glaciations (Duk-Rodkin, 1999).

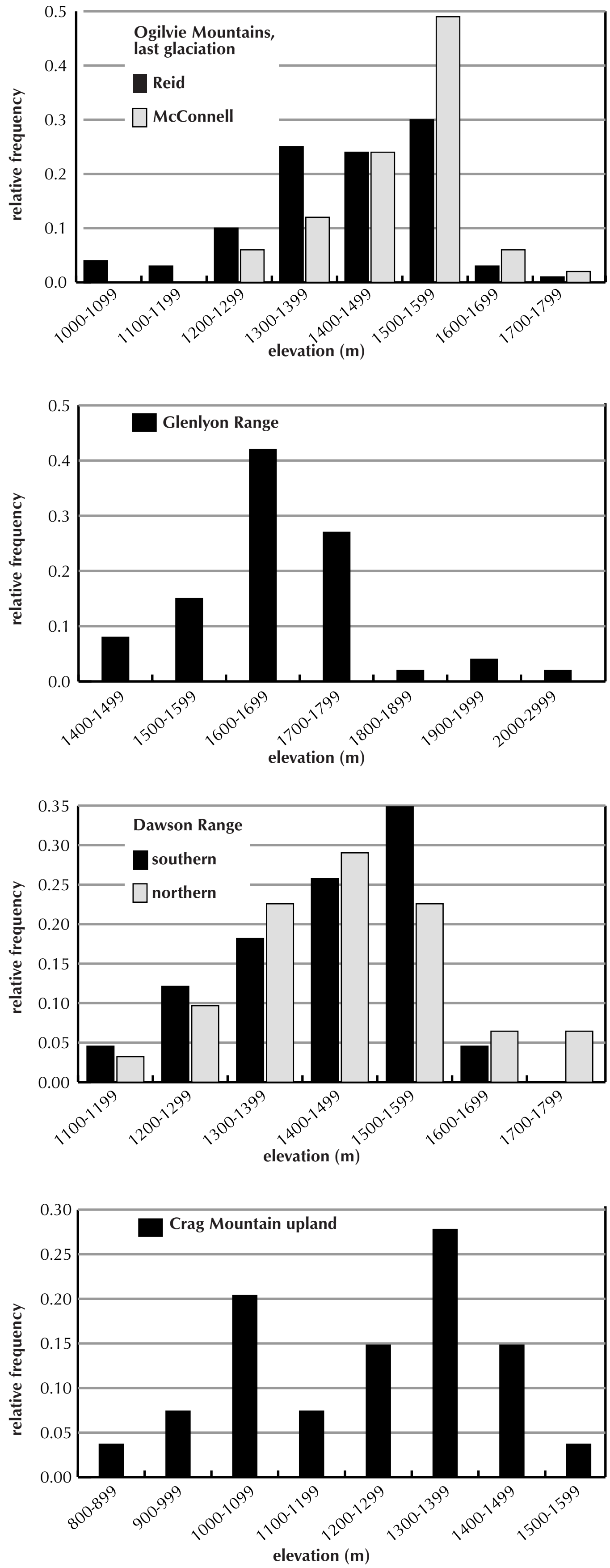


Figure 6. *Relative frequency distributions of cirque-floor elevation (m).*

Table 3. *Mean cirque-form values for various morphometric parameters.*

Area (proposed glaciation(s))[1]	Generalized geology[2]	N	Grade[3]	Altitude[4] (m)	Height[5] (m)	Width[6] (m)	Length[7] (m)	Length: Height Ratio	Length: Width Ratio
Crag Mountain upland (pre-Reid/Reid)	metamorphic/ volcanic	54	3	1232	152	797	985	7.7	1.3
Dawson Range (pre-Reid/Reid)	metamorphic/ volcanic/plutonic								
northern		31	2	1456	168	787	932	6.6	1.2
southern		66	3	1439	135	747	603	4.9	1.8
Glenlyon Range (Reid/McConnell)	plutonic	52	1	1665	214	636	791	4.2	1.7
Ogilvie Mountains									
(McConnell)	sedimentary	49	2	1487	322	732	780	2.5	1.1
(Reid)	sedimentary	79	2	1417	273	718	723	2.8	1.1
All		**331**	**2**	**1449**	**214**	**736**	**802**	**4.8**	**1.4**

[1]Ages from Lowey, 2000; Jackson, 2000; Ward and Jackson, 2000; Vernon and Hughes, 1966.

[2]Summarized from Gordey and Makepeace, 1999.

[3]Follows classification of Evans and Cox, 1995 as used in Lowey, 2000.

[4]Altitude measured as most obvious break in slope denoted by contour lines (to nearest 50 ft (15 m), 100 ft (30 m)contour interval), essentially, the altitude of the cirque-floor, converted to metres (/3.2810).

[5]Height measured from top of headwall to break in slope denoted by contour lines (to nearest 50 ft (15 m)).

[6]Width measured at widest extent of break in slope denoted by contour lines (to nearest 15 m).

[7]Length measured from apex of obvious break in slope denoted by contour lines to where sidewalls abruptly end or drop in altitude (to nearest 15 m).

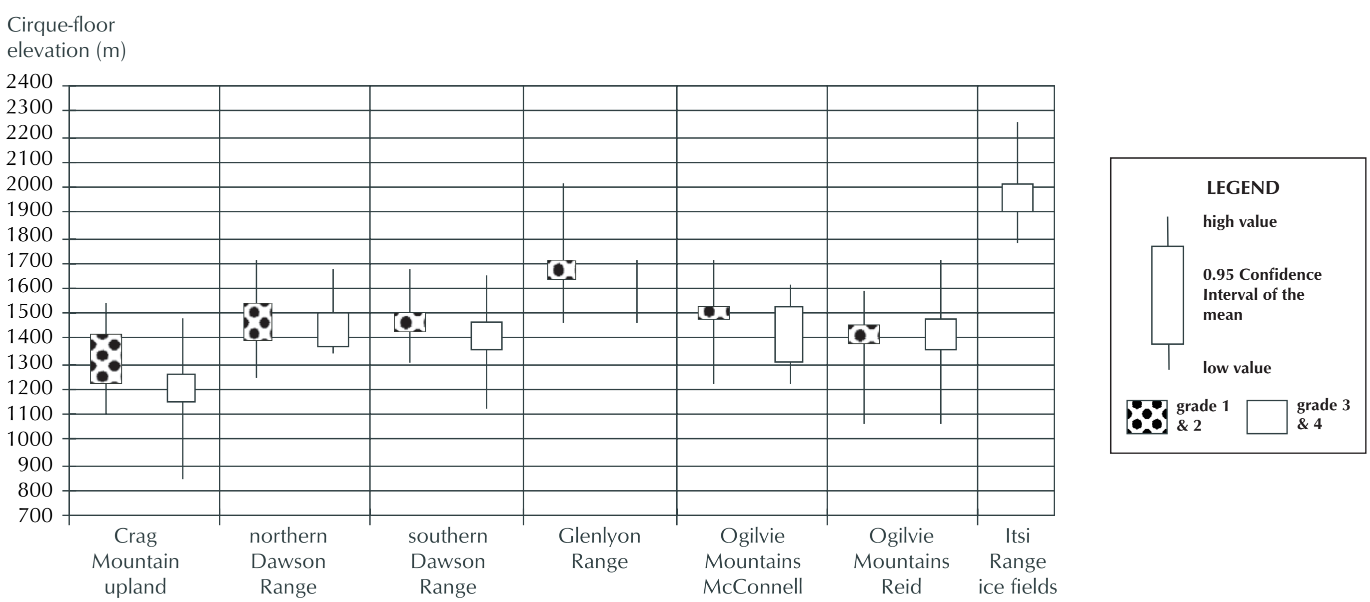


Figure 7. *The 0.95 confidence intervals (CI) for the mean cirque-floor elevation with high and low outliers. The Itsi Range ice fields represent the CI for an interglacial equilibrium line altitude (ELA).*

Inventoried OM cirques comprise a subset of those mapped by Vernon and Hughes (1966). The means of cirque-floor elevations for the two age populations of cirques identified by them, i.e., active during the last glaciation and not active during last glaciation, are 1488 ± 103 m and 1391 ± 132 m, respectively (Table 2). We will refer to the former population as 'McConnell' and the latter as 'Reid.' Both are related to moraine systems. Such moraines are generally lacking elsewhere in areas glaciated only during pre-Reid glaciation. The 'McConnell' altitudinal frequency distribution is leptokurtic: cirque-floor elevations predominantly fall within the 1400-1499 m range. The cirque-floor elevations, of both of Vernon and Hughes' cirque groupings are 440-540 m lower than the contemporary ELA in the Itsi Mountains (1930 ± 84 m). If only the mean cirque-floor elevations for the grade 1 and 2 cirques are compared, 'McConnell' cirques occur at a mean elevation approximately 100 m higher than 'Reid' cirques. The mean cirque-floor elevation for high-quality (grade 1 or 2) 'Reid' cirques is between 1381 and 1452 m whereas for the 'McConnell' cirques it is between 1474 and 1531 m (0.95 confidence interval) (Fig. 7). This is consistent with the view of increasing marginality, as demonstrated by a rise of ELA, with decreasing age between the Reid and McConnell glaciations. Furthermore, 29% of the 'Reid' cirques are

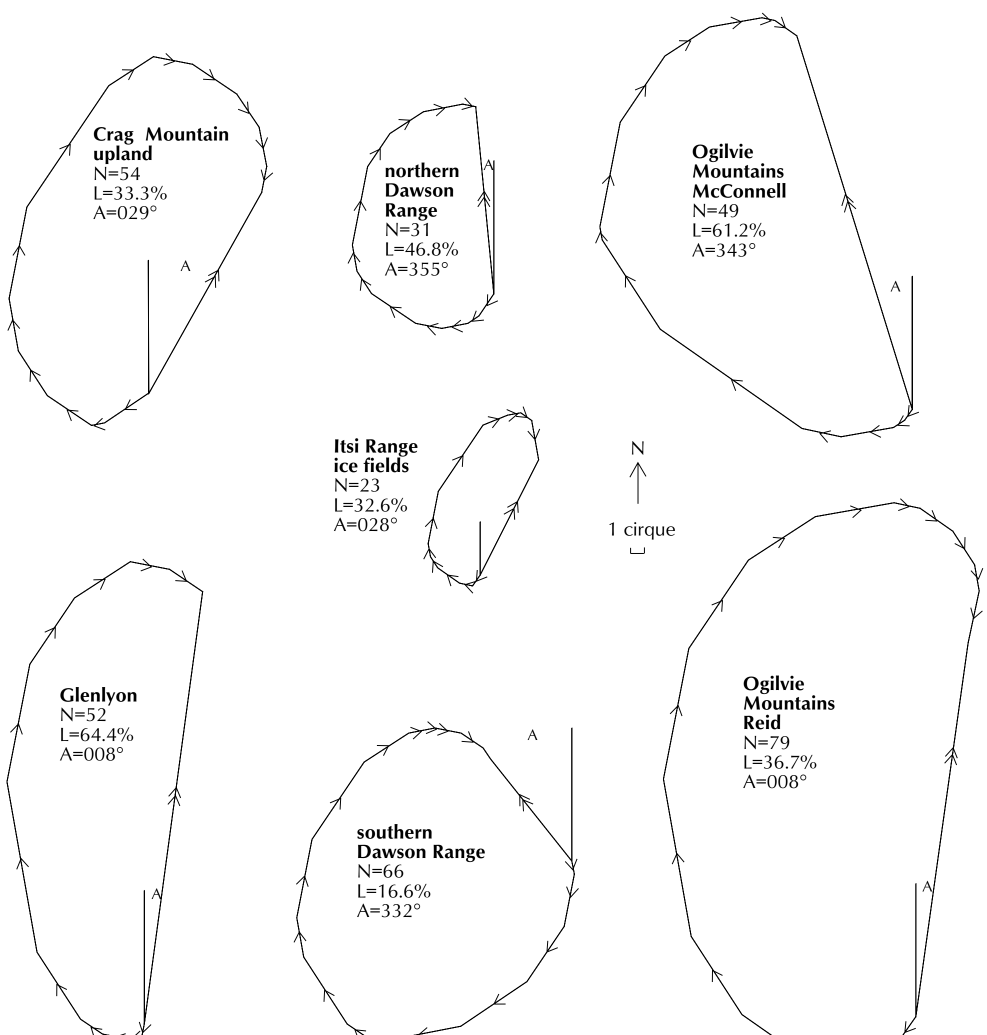


Figure 8. *Cumulative vector diagrams showing cirque aspects. Each leg is proportional to the number of cirques within one of 16 aspects. The resultant vector (double arrow) joins the first and last legs and represents the mean vector angle (A), or mean aspect, in degrees. Vector strength (L) is the length of the resultant vector expressed as a percentage of the total length of individual vectors. N= total number of cirques.*

grade 3 or 4 whereas only 18% of 'McConnell' distribution is grade 3 or 4. Assuming degradation of form over time, this difference may represent the longer period of degradation since the Reid Glaciation (300 to 200 ka B.P., Huscroft et al. 2001; Westgate et al. 2001) as opposed to time since McConnell Glaciation (<26 ka to *ca.* 12 ka B.P., Jackson and Harington, 1991; Ward, 1989). The lower limit of 'Reid' cirques likely reflects the altitude at which adjacent valley glaciers 'trimmed' or otherwise limited the extent of cirque formation and preservation.

Cirque aspect also provides evidence of a change in the character of alpine glacierization between the Reid and McConnell glaciations (Fig. 8). The 'Reid' aspect distribution is weakly asymmetric, with a greater number of southern hemisphere aspects (29%) than the strongly asymmetric 'McConnell' cirque forms (18%). This supports the view that the earlier glaciation was stronger than the later one, either because of lower mean summer temperatures or greater precipitation.

Glenlyon Range

Unlike the Ogilvie Mountains, one or more Cordilleran ice sheets overrode the Glenlyon Range (GR) during pre-Reid glaciations. During Reid and McConnell glaciations, GR was a nunatak within the Cordilleran Ice Sheet and cirques supplied little or no ice to the ice sheet (Ward and Jackson, 1992).

Cirque glaciation was marginal in GR during Reid and McConnell glaciations: distribution of cirque aspect is highly asymmetrical to the north (Fig. 8). Furthermore, cirque-floor elevations (mean 1667 ± 122 m) indicate that the ELA was about 276 m and 180 m higher than that present in Ogilvie Mountains (OM) during Reid and McConnell glaciations, respectively, and about 260 m lower than the contemporary ELA in the Itsi Range (Table 2). This is consistent with the view of Ward and Jackson (1992) that localized high aridity existed in GR at the climax of the McConnell Glaciation relative to divide areas of the Cordilleran Ice Sheet to the east in Pelly Mountains. The quality of cirque form is high: grade 1 and 2 cirques comprise 92% of the population. The apparent explanation for the lack of degraded (grade 3 and 4) cirques at lower elevation in GR is its history as a nunatak: trim-lines of the surrounding Reid and McConnell ice sheets defined the lower limit of cirque formation.

Dawson Range

The Dawson Range was beyond the limit of the last Cordilleran Ice Sheet. However, glaciers flowed through valleys of the eastern parts of Dawson Range during pre-Reid glaciations and pressed against the western and southern margins of the range during the Reid Glaciation (Jackson, 2000). Duk-Rodkin (1999) mapped cirques on scattered upland surfaces as being pre-Reid. These upland surfaces are surrounded by unglaciated terrain. Bostock (1936) noted that the valley heads resemble cirques formed by Early Pleistocene ice. High-grade cirques are found only on Apex Mountain, in the highest part of the Dawson Range, where one cirque contains a small lake held in by morainal debris and solid rock. Bostock (1936) believed this cirque developed during the last glaciation. Its 1585 m elevation falls within the elevation range of 'McConnell' cirques in OM, corroborating Bostock's age estimate. Two cirques on Apex Mountain were removed from the descriptive statistics (Table 2) due to their apparent youth.

Cirque-floor elevations in the northern Dawson Range (NDR) and southern Dawson Range (SDR) (mean 1433 ± 125 m and 1451 ± 117 m, respectively) indicate that the ELA was about 40-60 m higher than that present in Ogilvie Mountains (OM) during the Reid Glaciation, 40-55 m lower than that present in OM during the McConnell Glaciation and about 480-496 m lower than the contemporary interglacial ELA in the Itsi Range (Table 2). High-quality NDR cirque forms have a mean cirque-floor altitude of 1397 to 1544 m, while low-quality cirque forms have a mean altitude of 1371 to 1503 m (0.95 confidence interval) (Fig. 7).

NDR is markedly asymmetric with respect to aspect (marginal glaciation), with the average cirque facing 355°. The aspect distribution in the SDR is symmetric, indicating little preference for aspect (robust glaciation) (Fig. 8). The striking difference in vector strengths suggests that SDR experienced a lower snowline than NDR during pre-Reid glaciations.

Crag Mountain upland

Crag Mountain upland (CMU) is most distant from the limits of past ice sheets of all the upland areas investigated. The bimodality of the altitudinal frequency distribution suggests two separate populations of cirque forms (Fig. 6). The major mode includes the cirque forms noted by Lowey (2000) in the Fifty Mile Creek basin, as well as forms from the larger CMU region. Lowey (2000) correlates the high quality CMU forms with the Eagle glaciation of Alaska and the Reid glaciation in the Yukon. These cirque forms are at a mean elevation of 1346 ± 92 m and have a length:width ratio of 1.3. The minor, lower elevation mode (mean 1054 ± 96 m) represents the 'cirque problematica' of CMU. These cirque-like forms are similar to stream-head bowl-shaped depressions in areas covered by glaciers during the Charley River Glaciation in the Yukon-Tanana Upland (F. Weber, pers. comm., 2000). The minor, low-quality mode forms in CMU have an average length:width ratio of 1.0, being on average 631 m wide and 690 m long. The average quality is grade 3, with all but two being grade 3 or 4. If they are Early Pleistocene cirques, their mean elevation of 1054 ± 96 m indicates that the ELA was about 337 m lower than that present in Ogilvie Mountains during Reid Glaciation and about 875 m lower than the contemporary interglacial ELA in the Itsi Range (Table 2). Crag Mountain upland as a whole exhibits a northeastward resultant and weak asymmetry (Fig. 8), indicating that it has experienced alpine glaciation during the Early Pleistocene.

DISCUSSION

The overlap between 0.95 confidence intervals of high- and low-grade cirques indicates that the low-grade cirques are likely part of the same population, although perhaps older and degraded (Fig. 7). Exceptions to this are the poor-quality low-outliers of Crag Mountain upland, the 'cirque problematica,' which are at a significantly lower altitudinal level, although their distribution is not so drastically different as to preclude a glacial origin. They could be glacial cirques dating to the Early Pleistocene and highly degraded by nivation. Since younger glaciations were less extensive than older glaciations, cirques at lower altitudinal levels would have experienced more degradation from periglacial processes compared to higher cirques. According to Evans (1999), "drastic changes in the spatial pattern of climate would be needed if cirque glaciers were not to grow while ice cover expanded greatly elsewhere" (p. 33). Evans suggests a hypothesis of time-transgressive cirque glaciation whereby as higher mountains become covered by ice caps, previously unaffected lower mountains may undergo cirque glaciation. This would lead to more altitudinal variation and higher complexity of cirque aspects (Evans, 1999).

The 0.95 confidence intervals of mean cirque-floor elevation indicate that the ELAs throughout west-central Yukon Territory fell approximately the same amount during each glaciation, as all intervals tend to overlap. This likely indicates a similarity of summer temperatures throughout the region during glaciations. The fact that glaciers formed in the Ogilvie Mountains during the Reid and McConnell glaciations, but not at comparable altitudes in the Dawson Range and Crag Mountain upland, indicates that moisture availability was the controlling factor in the extent of alpine glaciation. Burn (1994) suggests that the greater extent of ice sheets in central Yukon during pre-Reid glaciations is attributable to the St. Elias Mountains being substantially lower during the Late Pliocene/Early Pleistocene, thus decreasing their rain-shadow effect. This explanation could presumably be applied to the extent of cirque glaciation as well.

However, recent work in the interior of North America since Burn (1994) leads us to propose another possible explanation for a progressive decrease in moisture reaching the Yukon interior. Pleistocene ice sheets influenced atmospheric circulation, either through associated high-pressure systems deflecting storm tracks and reducing precipitation, or by acting as precipitation traps (Porter, 1964). Barendregt and Irving (1998) presented evidence that continental ice sheets became progressively larger through the late Cenozoic in North America. This culminated with the Late Wisconsinan Laurentide Ice Sheet; it had the greatest extent of all ice sheets in Western North America (Duk-Rodkin et al., 1996; Jackson et al., 1999). The progressive decrease in the extent of Cordilleran ice sheets in Yukon and increase in the marginality of cirque glaciation in uplands west of these ice sheets through time from pre-Reid to McConnell glaciations may be linked to the progressive increase in the size of continental ice sheets east of the Cordillera. The high-pressure systems associated with successively larger continental ice sheets may have been progressively more effective in steering storm tracks away from west-central Yukon during glacial periods. This would account for the progressively limited ice sheet and cirque glaciation in west-central Yukon throughout the late Cenozoic.

IMPLICATIONS FOR PLACER GEOLOGY

Cycles of aggradation and degradation in stream systems can be caused by the growth and disappearance of alpine ice centres in upland areas (Vandenburghe, 1993). Lowey (2000) suggested that glaciation may have been a control in placer formation along streams draining Crag Mountain upland (CMU). With the exception of the upper Sixtymile River basin and Matson Creek, the streams draining CMU are unexplored or are just starting to be explored for placer gold (e.g., Fifty Mile Creek). The work reported in this paper suggests that other areas of the Stewart River map area (115 N and O) with extensive elevations in excess of 1200 m likely supported cirque glaciers or small ice caps during the Early Pleistocene. Consequently, deposition of placer gravels, and reworking and concentration of gold placers in those areas, may have had a glaciofluvial component. The South Klondike Placer District (e.g., Thistle, Kirkman and Barker creeks) has extensive upland areas exceeding 1200 m. This possibility of past cirque glaciation should be kept in mind during the exploitation and interpretation of placers gravels in these areas.

CONCLUSIONS

Cirque-like landforms in Dawson Range and Crag Mountain upland are glacial in origin, although some are highly degraded by periglacial processes. Alpine glaciation in west-central Yukon was time-transgressive, whereby some cirques were active during early glaciations but inactive during subsequent glacials. Glacial deposits associated with valley glaciers that originated in cirques of the Crag Mountain upland have soils developed on them, suggesting that the last ice advance occurred during the Early Pleistocene pre-Reid glaciations; the paleo-ELA of high-quality cirques is between 1217 and 1417 m (0.95 confidence interval). A relative decrease in moisture reaching west-central Yukon during the Reid and McConnell glaciations, as compared to pre-Reid glaciations, resulted in the cessation of cirque glaciation in Crag Mountain upland and most of the Dawson Range. The authors suggest that the progressive marginality of cirque glaciation and progressive decrease in the extent of ice sheets in west-central Yukon through the late Cenozoic may be related to the progressive enlargement of continental ice sheets east of the Cordillera during the same interval of geologic time. High-pressure systems associated with the continental ice sheet may have diverted storm tracks away from west-central Yukon.

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