Case study of Donjek debris flow, southwest Yukon

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ABSTRACT

A high-magnitude debris flow occurred in late summer 2000 from tightly folded sedimentary rocks in a steep 2.66 km^2 basin in the remote Donjek River valley of southwest Yukon. The debris flow deposited at least 206 344 m^3 of material, with a peak discharge on the order of 1000 m^3/s. No evidence of any previous events of this magnitude was found at the site. The headscarp is aligned with the strike of a west-plunging overturned syncline in heavily weathered Upper Paleozoic to Upper Triassic argillite, interbedded siltstone and argillite, and thinly bedded limestone. Tree-ring analysis on two white spruce killed by the debris flow indicate that the debris flow occurred in July to early-mid August 2000. The heaviest monthly total precipitation on record (1967-2003) for August occurred in 2000 and most likely played a role in slope failure. The volume and peak discharge estimated are the largest reported from a debris flow occurring in the last 100 years in the St. Elias Mountains.

RÉSUMÉ

Une importante coulée de débris s'est produite à la fin de l'été 2000. La coulée s'est produite dans des roches sédimentaires à plis serrés, dans un bassin abrupt de 2,66 km^2 situé dans la vallée de la rivière Donjek, au sud-ouest du Yukon. La coulée de débris a déposé au moins 206 344 m^3 de matériaux, avec un débit de pointe de l'ordre de 1000 m^3/s. Aucune trace d'évènements antérieurs de cette ampleur n'a été trouvée sur le site. L'escarpement est aligné avec l'orientation est-ouest d'un pli synclinal renversé composé d'argilite fortement altérée de siltite et d'argillite interstratifiées, et de calcaire finement stratifié du Paléozoïque supérieur ou du Trias supérieur. L'analyse dendrochronologique de deux épinettes blanches tuées par la coulée de débris révèle que cette dernière s'est produite en juillet ou vers le début ou le milieu d'août 2000. Des précipitations mensuelles record pour la saison (données de 1967 à 2003) en août 2000, et ont très probablement joué un rôle dans le glissement de terrain. Le volume et le débit maximal de ce glissement de terrain sont les plus importants jamais enregistrés pour une coulée de débris depuis au moins un siècle dans les monts St. Elias.

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INTRODUCTION

Mass wasting is extremely active in the St. Elias Mountains (e.g., Huscroft et al., 2004b). There are small frequent debris flows and rockfalls, as well as occasional large debris flows and rockfall avalanches (e.g., Broscoe and Thomson, 1969; Power, 1989; Harris and Gustafson, 1993; Everard, 1994; Harris and McDermid, 1998; Clague, 1981). To date, debris flows have caused millions of dollars in damage to the Alaska Highway (Evans and Clague, 1989). The aim of this paper is to report details of an unusually large debris flow in a remote part of the St. Elias Mountains. This debris flow, termed the Donjek debris flow, occurred recently and has not been reported in the literature. It is important to monitor and report landslides in the St. Elias Mountains because of concerns that have been raised (e.g., Kulkarni and Blais-Stevens, 2004; Huscroft et al., 2004a) with the potential impact of climate change on landslide frequency and the resulting threat to existing and planned infrastructure in the region.

SETTING

LOCATION

The Donjek debris flow is located in the southwest Yukon on the southwest slope of the Donjek River valley (Fig. 1). The debris flow was undocumented for a number of years, mainly because of the paucity of human activity and lack of debris-flow monitoring in this part of the St. Elias Mountains. The failure was observed from the air in either 2000 or 2001 and the Yukon Geological Survey was notified in summer 2004.

PHYSIOGRAPHY

The Donjek debris flow spans two physiographic elements of the St. Elias Mountains (Rampton, 1981): the Icefield Ranges and the Donjek River valley. The debris flow originated from the north-facing headwall of a v-shaped basin, here termed the Donjek basin, with a peak

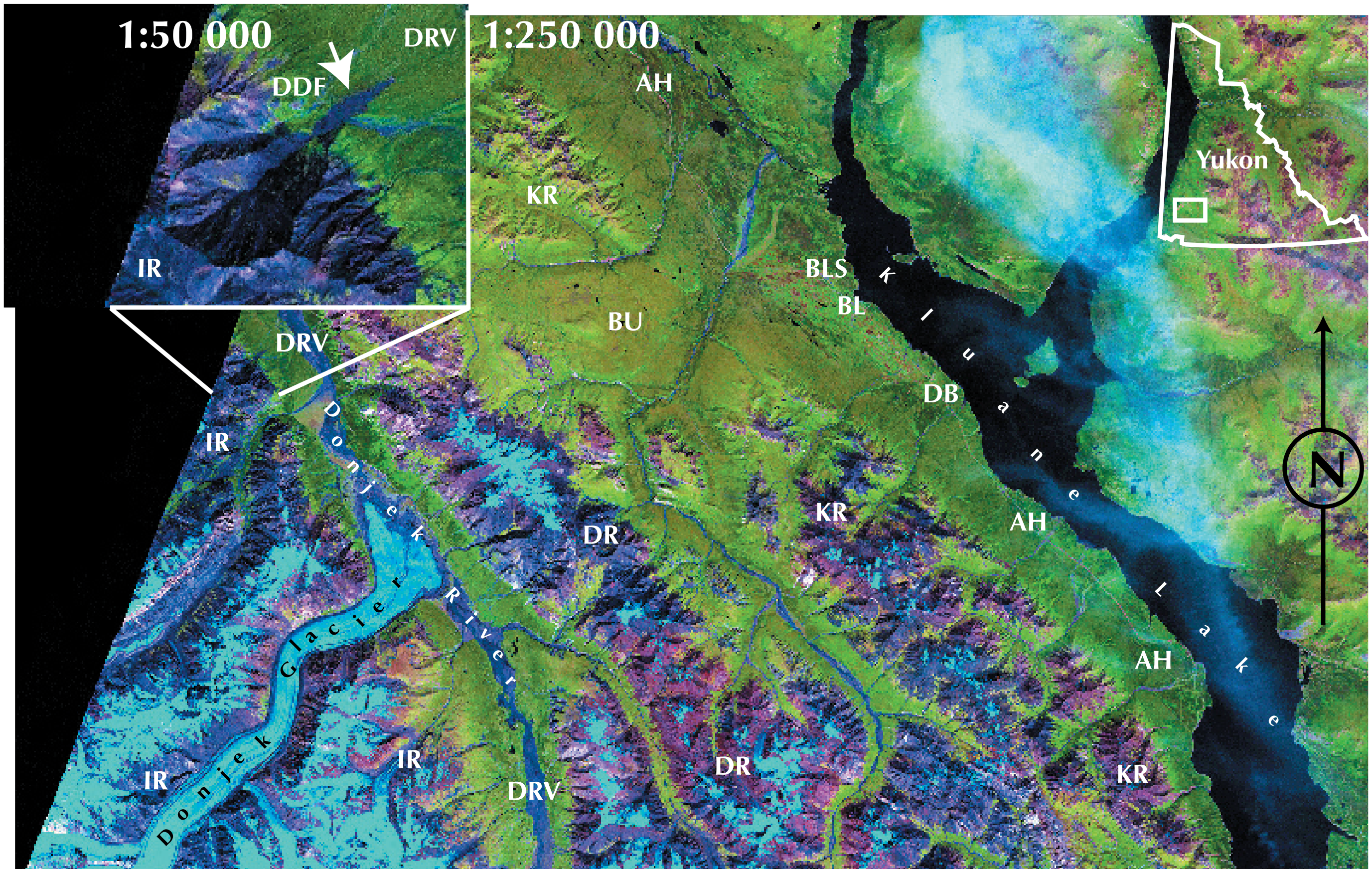

Figure 1. *Landsat 7 scene (July 19, 2000) of the St. Elias Mountains and Shakwak Valley, southwest Yukon. The Donjek debris flow is shown at 1:50 000 in the inset. BLS=Burwash Landing station; DRV=Donjek River valley; IR=Icefield Ranges; KR=Kluane Ranges; BU=Burwash Uplands; DB=Destruction Bay; DR=Donjek Range; BL=Burwash Landing; AH=Alaska Highway; DDF=Donjek debris flow. The inset map of Yukon shows the location of the 1:250 000 Landsat scene.*

elevation of 2363 m above sea level (a.s.l.). The area of this northeast-trending pear-shaped basin is estimated to be 2.66 km^2. The debris-flow material is deposited on a gentle forested slope a maximum of 1197 m below and 2745 m away from the source scarp.

Ice extends northeast from the interior of the Icefields Ranges to within 300 m of the Donjek debris-flow source basin. The Donjek River valley is one of several major trunk valleys in the St. Elias Mountains (Rampton, 1981). The Donjek River collects meltwater from the Kluane, Donjek, Spring and Steele glaciers.

GLACIAL HISTORY

There have been a number of glaciations in the St. Elias Mountains since the late Tertiary (Denton and Stuiver, 1967). The most recent glaciation occurred from 29 000 to 12 500 years ago (Rampton, 1981). During the last glaciation, ice reached a maximum elevation of 1520 m a.s.l. (Rampton, 1981) approximately 36 km down the Donjek River from the Donjek debris flow. Ice was therefore at least that deep in Donjek River valley at the location of the debris flow. This is important because valley glaciers over-steepen valley walls (e.g., Johnson, 1984), predisposing them to relaxation through mass wasting. However, no mass wasting deposits are observed on the valley slope in front of the Donjek basin (e.g., Rampton, 1981), and if paraglacial mass wasting occurred at this site, receding valley ice carried the resulting deposits away.

BEDROCK AND SOILS

The bedrock geology in the Donjek basin was mapped by Dodds and Campbell (1992) and is composed of Upper Paleozoic to Upper Triassic sedimentary rocks. They provided the following descriptions of the bedrock geology and structural features in the basin. A relatively small area at the top of the headscarp consists of light grey massive limestone and thin-bedded dark blue-grey limestone (uPc). Most of the basin, however, is composed of dark argillite, interbedded dark siltstone and argillite, and minor thin-bedded blue-grey limestone (uPpc). The former unit is tightly folded into the axis of a west-southwest-plunging overturned syncline that is oriented parallel to the strike of the headscarp.

Most soil in the basin is poorly consolidated, dark coloured and contains variable amounts of ice (Fig. 2). A veneer of light beige colluvium covers the southeast-facing slope. The soil on the northwest-facing slope is likely derived mainly from dark siltstones. The basin more closely resembles a transport-limited than a weathering-limited basin because of the abundance of unconsolidated soil (e.g., Bovis and Jakob, 1999). The v-bottom of the basin contains high-density ice, under which the watercourse flows. Frozen colluvium, derived from dark siltstone in the walls of the gorge, is also indicative of interstitial ice in the basin. The presence of ice is important because retrogressive thaw slumps and other related processes have been responsible for producing unconsolidated sediment that is susceptible to failure by debris-flow processes in other areas of the St. Elias Mountains (Harris and Gustafson, 1988). Therefore, ice in the basin suggests that rising temperatures could contribute material that would be susceptible to mass-wasting processes (e.g., Harris and Gustafson, 1993).

Figure 2. *Deeply weathered loose dark and icy soil in the basin amongst vertically bedded limestone units. View looks toward the Donjek River from the north slope of the basin.*

CLIMATE

Climate in this area has been historically dynamic. A warm interval occurred between 8700 and 2800 years ago (Rampton, 1981). One estimate shows that the warm interval was 2.5°C warmer than present temperatures in the foothills of the Canadian Rockies (Harris, 2002). Subsequent cooling took place during Neoglaciation, which involved glacier advances 2800 years ago, between 1250 and 1050 years ago and during the last 450 years (Rampton, 1981).

Meteorological data have been collected to the east of the Donjek debris flow (Fig. 1) at the Burwash Landing airport (806 m a.s.l.) by Environment Canada since 1967.

The following climate statistics for the period 1971-2000 were collected. The daily average temperature (and standard deviation) for January is -22.0°C (6.6), whereas for July it is 12.8°C (0.8). These two months represent the extremes in temperature magnitude and variability. Average precipitation for January and July are 9.6 mm and 66.2 mm respectively, with the month of July receiving the most rain on average. Typically, snow melts in May and returns by the end of September.

DONJEK DEBRIS FLOW

MAGNITUDE

Volume

Debris-flow volume is estimated by multiplying the plan area of the debris flow by an estimate of the average thickness. The plan area of the debris flow was calculated by field mapping and a geographic information system (GIS). First, a field map was created using 81 GPS points that were taken at major inflection points around the debris-flow perimeter. Second, the 81 data points were entered into a GIS and converted to a polygon shape file. The shape of the polygon was then improved by using oblique aerial photographs taken from a helicopter. This detailed map of the debris flow is shown in Figure 3. The area of the debris flow is 206 344 m^2. This area does not include the levees and the material underlying the fan and gorge.

As pointed out by Jakob and Bovis (1996), debris-flow volume can be difficult to determine because of subsequent fluvial reworking. An inactive channel, incised by a temporarily diverted watercourse, was traced for 1.12 km on the surface of the Donjek debris flow (Figs. 3 and 4). This watercourse deposited variably sorted fluvial material in an elongate series of 'pools' down the centre of the debris flow. The diversion of the watercourse onto the debris flow probably redistributed more material than was added or subtracted. The watercourse regained its original path, however, by eroding through and transporting away the dam-forming debris-flow material. Therefore, some unknown volume of debris-flow material was removed. Furthermore, material continues to be removed since the current streambed is composed of debris-flow material.

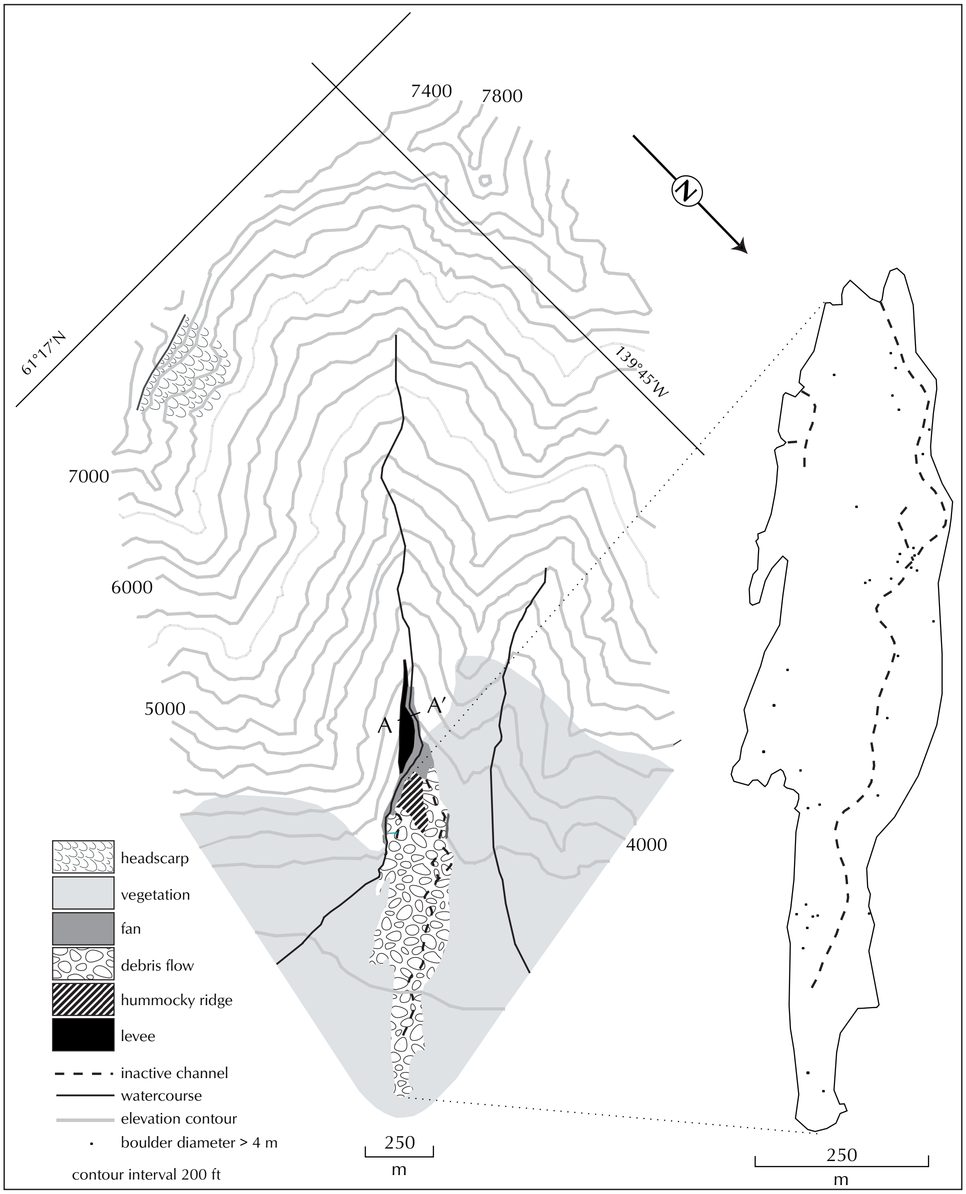

Figure 3. *Map of Donjek debris flow.*

The thickness of the Donjek debris flow is highly non-uniform. Organic regolith is present at the surface in an area where flow diverged into two streams (Fig. 4). Vegetated ground cover is found beneath nearly 1 m of debris near the toe of the debris flow. A pebbly alluvial fan surface is found beneath 2.33 m of debris where the watercourse leaves the debris flow. Trees rarely protrude from the debris-flow surface, which implies that the thickness is enough to bury the timber completely. The greatest thickness is at the head of the debris flow (Fig. 4). For instance, debris flow material rises as high as 5.02 m above the channel bed in the largest of the inactive channels created when the watercourse was diverted onto the debris flow. Furthermore, the channel bed in this location is composed of large boulders embedded into the channel bottom, which suggests that the debris flow thickness is more than 5 m at this location. Although there are places on the lower portion of the debris flow where thickness is close to zero, much of the lower area of the deposit is probably more than 1 m thick. The head of the debris flow has a thickness in excess of 5 m in many places, which suggests that an overall 1 m thickness of the debris flow is an underestimate. By multiplying the area by a conservatively estimated average thickness of 1 m, the volume obtained is 206 344 m^3. This estimate is much greater than any of the reported debris flows that have occurred in the last 100 years in the St. Elias Mountains.

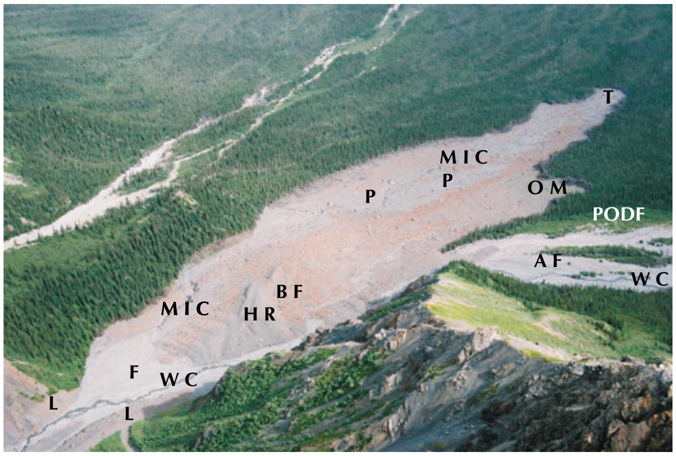

Figure 4. *Oblique aerial photo to the north-northeast of the Donjek debris flow. The hummocky ridge (HR) at the head of the debris flow represents the greatest thickness. MIC=main inactive channel; L=levee; BF=boulder front; OM=an area where organic material is exposed at the surface; AF=alluvial fan; WC=the water course; F=fan; PODF=possible older debris flow; T=the toe of the debris flow where original regolith is found below 1 m of debris flow material; P=the "pools" of sorted fluvial deposits.*

Peak discharge

Debris-flow peak discharge is estimated using cross-sectional area and velocity. It is important that the cross-sectional area is calculated at a location in the confined gorge where levees are formed on both walls (Fig. 5). Jakob et al. (2000) note two reasons why calculating peak

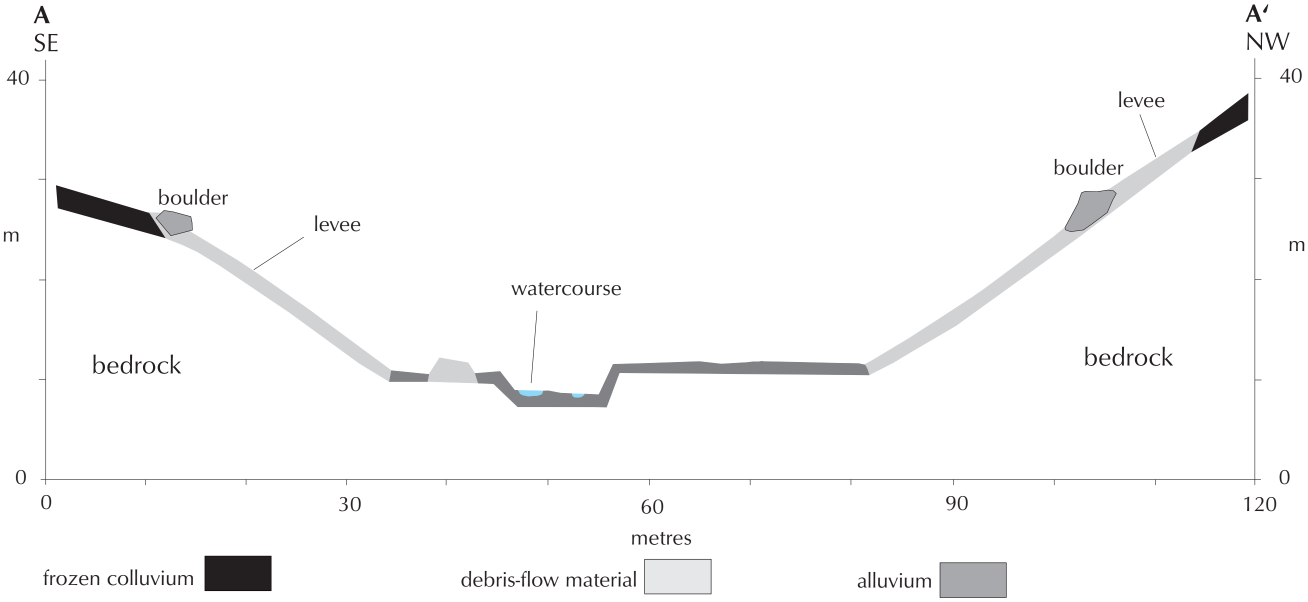

Figure 5. *Cross-section in the gorge where peak discharge was calculated. The location of this cross-section is shown on Figure 3.*

discharge from the product of cross-sectional area and velocity can be problematic. First, the cross-sectional area can be inaccurate because of scour or deposition after the debris flow. Second, cross-sectional area measured at channel bends may be greater than that measured where the channel is straight. In the case of the Donjek debris flow, there is material within the cross-section (Fig. 5) that could be from a subsequent debris flow or snow avalanche. Additionally, as discussed earlier, the watercourse has lowered the channel bed. An attempt was made to determine the original cross-sectional area at this location by estimating the amount of material removed by scour or added by deposition. A conservative estimate of the original cross-sectional area of the debris flow is 80 m^2. The fact that the location of the cross-section is in a part of the gorge that is straight for approximately 480 m increases the confidence of this area estimate.

The velocity used to estimate the peak discharge of the debris flow was subjectively inferred rather than calculated. The velocities of most debris flows range from 1 to 20 m/s (Hungr et al., 2001), and those classified as extremely rapid are >5 m/s (Cruden and Varnes, 1996). Extremely rapid velocity must have been attained by the Donjek debris flow, because 100-tonne boulders were moved 1.25 km from the mouth of the gorge down a 9° slope to the furthest reach of the debris flow. Therefore, a subjective estimate of the peak velocity of the Donjek debris flow is between 5 to 20 m/s. When this velocity range is applied to the area estimate of the channel cross-section, a peak discharge of 400 to 1600 m^3/s is obtained. This discharge is far greater than any of the reported peak discharges from debris flows in the St. Elias Mountains to date.

FREQUENCY

No evidence for an earlier large debris flow was found in the area. A 1979 air photo (#A25288-04) of the area of the Donjek debris flow shows tree density to be the same at the debris flow site as it is on the slopes surrounding the present-day debris flow. No major debris-flow levees were identified in the gorge from the air photo. The course of the pre-debris-flow stream is very similar to its course today. There is a partially forested arm that extends away from the debris flow where the watercourse bends sharply, which may be an old debris-flow fan or a fluvial fan (Fig. 4). The area of this surface, however, is much less than that of the Donjek debris flow. Without high-resolution imagery of the site after 1979 it is difficult to determine whether the Donjek debris flow was deposited on an older event.

MATERIALS AND MORPHOLOGY

The materials that comprise the Donjek debris flow are like those expected in debris flows (e.g., Hungr et al., 2001). The texture is highly variable and surficial deposits range from clast to matrix supported. For example, in front of a matrix-supported hummocky ridge at the head of the debris flow there is a clast supported boulder front (Fig. 4). Rough inverse grading is observed where clast-supported surficial material gives way to matrix-supported material below. Materials are unsorted, except where inactive channels on the debris-flow surface give way to sorted fluvial deposits (Fig. 4). Grain size of the debris-flow material ranges from clay to boulders several metres across. Clay content is low overall.

The hummocky and lobate shape of the deposit suggests flow-like movement. For example, the hummocky ridge and boulder front are features produced when longitudinal sorting is facilitated by large flow depth, which is only possible when flow occurs within a confined channel (Hungr et al., 2001). These deposits are located a short distance from the mouth of the gorge, where velocity must have decreased after leaving the confinement of the gorge. The levees are also features that are deposited when velocity decreases as a debris flow reaches the apex of its fan (Hungr et al., 2001). In total, 1.53 km of the 3.29 km Donjek debris-flow path are confined. Furthermore, most of the confined channel is a first order drainage channel where low-magnitude debris flows have probably been a recurrent process. These characteristics suggest that the mass movement should be classified as a debris flow.

HEADSCARP GEOLOGY

Boulders located on the debris flow provide clues to the pre-failure geology. In total, 36 boulders with diameters >4 m are exposed on the debris-flow surface (Fig. 3). Each of these boulders weighs over 100 tonnes. Invariably, they are composed of dark argillite and interbedded argillite and siltstone. Many smaller dark blue-grey limestone boulders with diameters of <4 m were also identified.

All the boulders are oxidized and weathered to some extent, and the debris flow has a remarkable rusty appearance. This suggests that chemical weathering played a role in predisposing the rock-slope material to failure. A soft, yellow weathered material that has a sulphurous odour is common on rock surfaces. Small, thinly bedded siltstone boulders are particularly susceptible to this type of weathering, which suggests that this lithology may have formed a weak inner layer in or at the base of the failure volume that succumbed to intense chemical, and probably, physical weathering.

Most of the large boulders are foliated and folded at a small scale. For instance, on one boulder there is a tight fold preserved on a 100-cm^2 surface in argillite. The foliation and tight folding suggests that the source rocks to the debris flow suffered a considerable degree of tectonic stress. Folding could have resulted in reorientation of bedding planes to positions that are unfavourable for slope stability.

A headscarp was identified during helicopter reconnaissance by well-defined scarp edges and the fresh dark appearance of unconsolidated material in a lower wedge-shaped depression (Fig. 6). Further investigation of the source scar revealed upright bedding and foliation that is oriented parallel to scarp slopes. The predominant headscarp structure dips 65° to the north-northwest (Fig. 7), which is oblique to the valley axis. The sediments in the wedge-shaped depression appear remarkably similar to those found on the debris flow. Furthermore, argillite and siltstone-argillites with minor dark blue-grey limestone bands outcrop in the wedge-shaped depression (Fig. 6). At the scarp, siltstones are the dominant lithology.

The observations at the headscarp further suggest that a siltstone unit may be the failure surface from which a volume of argillite and interbedded siltstone-argillite was ejected. The failure mode was probably a slide, because the dips are 65°, and at this low-angled orientation, the toppling or fall failure mechanisms are mechanically unlikely. Since the boulders were subangular to subrounded, not angular or very angular, it is inferred that the prefailure rock mass was broken into blocks. Geological mapping in the source basin (Dodds and Campbell, 1992) indicated the presence of an overturned syncline oriented parallel to the strike of the headscarp. Careful analysis of the 1979 air photo reveals that a

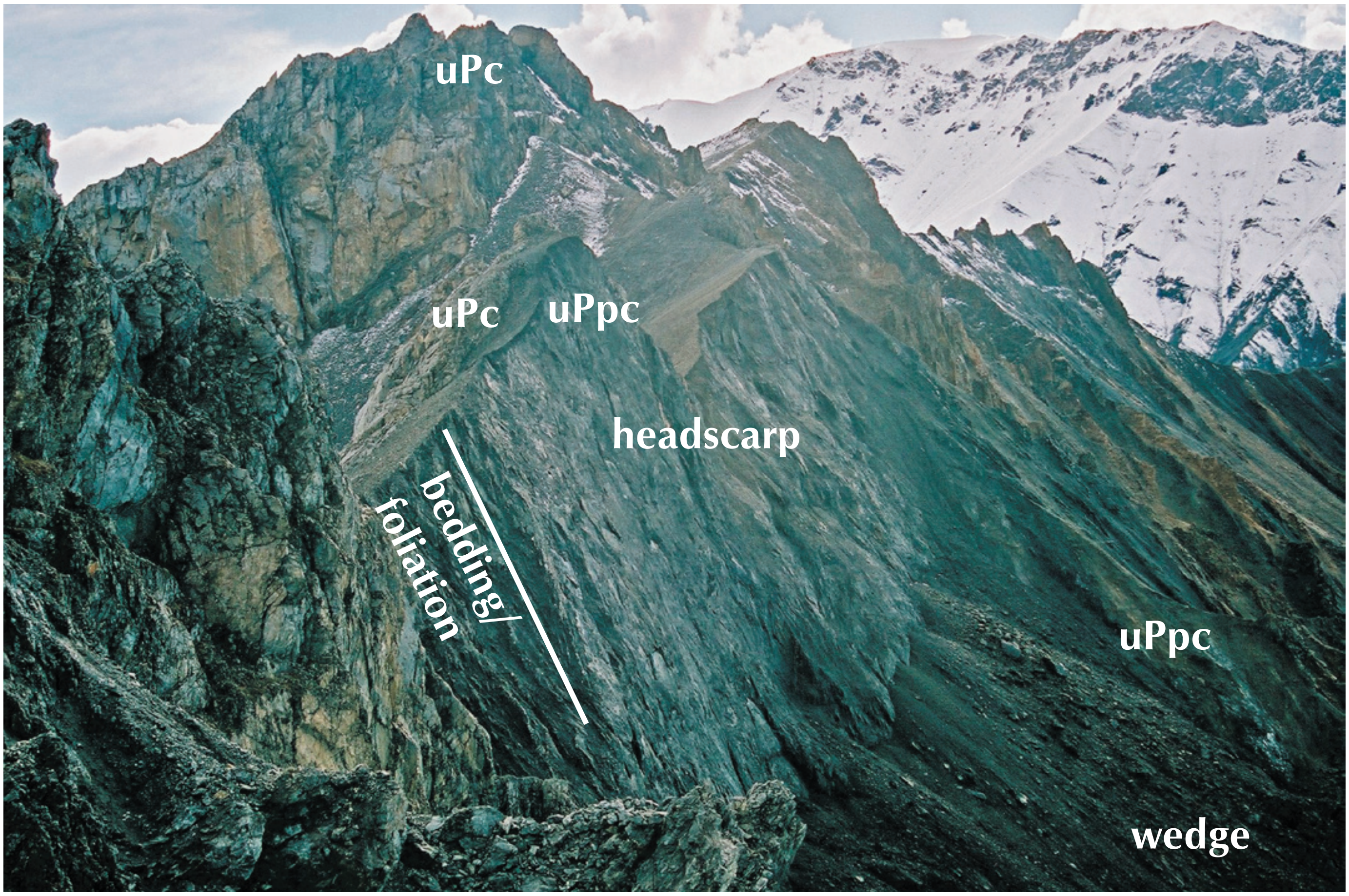

Figure 6. *Photo of the headscarp showing the fresh scarp edges and the dark sediments below. Units uPc and uPpc are massive limestone, and interbedded argillite and siltstone respectively; from Dodds and Campbell (1992).*

volume of material is missing from the location identified initially as the headscarp, which confirms the location of the principle source area. Finally, the description of unit uPpc (Dodds and Campbell, 1992) matches the lithologies described in this study on the deposit in the wedge-shaped depression below the headscarp, as well as those of the boulders.

DEBRIS-FLOW TIMING

Anecdotal information suggests that the Donjek debris flow occurred in summer 2000 or 2001. Tree-ring cross-dating suggests that the debris flow occurred in late summer 2000. Timber is violently uprooted and accumulated into piles around the landslide perimeter. The trees killed by the debris flow allow for tree-ring cross-dating analysis.

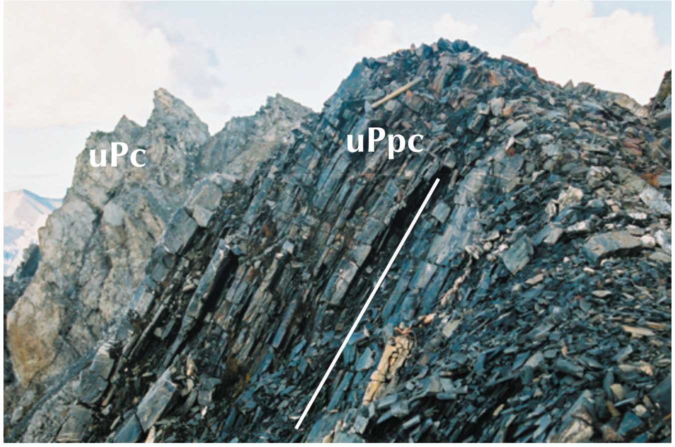

Figure 7. *Photo of bedding and foliation planes in siltstones and argillites at the headscarp. Rock hammer for scale.*

Table 1. *Results of tree-ring cross-dating between collected specimens and on-site chronology.*

Radii	Interval	Years	N. intervals	Flags	Correlation with master
209Da	1848–1999	152	6	2	0.51
209Db	1848–1999	152	6	1	0.49
212Da	1653–1999	347	13	3	0.55
212Db	1653–1999	347	13	0	0.55
203Da	1719–1804	86	4	0	0.50
203Db	1719–1804	86	4	0	0.55
207Aa	1950–2003	54	2	0	0.55
207Ab	1950–2003	54	2	1	0.30
213Aa	1798–2003	206	9	1	0.54
213Ab	1799–2003	205	9	0	0.57

Note: A "D" following the sample number indicates a tree killed by the debris flow; an "A" after the sample number indicates a tree that was living when cut for sampling. Two radius measurements (a and b) were taken for each sample.

Seven tree-discs were sampled, five from trees that were killed by the landslide and two from trees standing alive outside of the landslide impact zone. Tree-discs were processed at the University of Western Ontario tree-ring lab. Ring widths were measured under a microscope to ±0.001 mm on each of the seven specimens on two different radii to ensure dating and measurement consistency.

The ring widths from the living trees were cross-dated initially, then individual dead trees were cross-dated with the living tree chronology. As individual dead trees were successfully dated, the ring width patterns were added to the master chronology for the debris-flow site. These data were then cross-dated against a chronology based on measurements from 15 to 20 trees at the Donjek Bridge (35 km away) to validate the Donjek site cross-dating.

The tree-ring lab was able to establish weak but consistent cross-dates in three of the specimens killed by the landslide (Table 1). The number of flags in Table 1 indicates the number of 50-year ring-width intervals where individual series did not match with a series from the Donjek Bridge chronology or the correlation coefficient was not significant. Four radii (209a, b and 212a, b) showed 1999 as their last complete rings. Tree rings are composed of inner and outer parts. Earlywood is the inner component of a tree ring that is established in the spring. Latewood is the outer portion and is usually thinner than earlywood and is established towards the end of the summer. These specimens showed earlywood (B. Luckman, pers. comm., 2004) but no latewood, which suggests that the landslide occurred before latewood was established. Latewood is established in late August or September in southwest Yukon (B. Luckman, pers. comm, 2004). These results suggest that the landslide occurred sometime in July or early-to-mid August 2000. The third specimen (203a, b) showed 1804 as its final complete ring, which most likely indicates that the tree was already dead when partially buried by the landslide.

DEBRIS-FLOW INITIATION

EARTHQUAKES

Evidence outlined below suggests that earthquakes are unlikely to have initiated the Donjek debris flow. Keefer (1984) inventoried 300 earthquakes worldwide with and without associated reports of landslides. Out of 62 earthquakes with seismic-moment magnitude (M) less than 4.0, only one was associated with a landslide report. Therefore, the minimum intensity of earthquakes that are able to cause landslides is considered to be M=4.0 (Keefer, 1984). Also, a more recent study by Malamuda et al. (2004) has found M=4.3 to be the minimum magnitude of earthquake capable of generating slides. Furthermore, Keefer (1984) examined the relationship between earthquake magnitude and the maximum distance of reported slides or falls from earthquake epicentres. He found that for M=5.0, the maximum distance at which slides or falls were reported was 16 km from the epicentre. Table 2 is the list of recorded seismic events that occurred within 200 km of the Donjek debris flow between 1 July 2000 and 30 September 2000. In this list, all earthquakes are M < 5.0 and all are much further than 16 km from the Donjek debris flow. Therefore, it is unlikely that any of the recorded seismic events caused the initial slide that produced the Donjek debris flow.

METEOROLOGY

The evidence presented below suggests that the initiation of the Donjek debris flow may have been influenced by excess pore-water pressure associated with abnormally wet conditions in August, 2000. The cumulative monthly total precipitation, tallied from January to June, July and August, for each year in the period 1968-2000 is presented in Figure 8. These data represent the amount of precipitation received at Burwash Landing station from January to June, July and August. The data in Figure 8 do not represent soil moisture at the Donjek debris flow headscarp, since antecedent soil moisture conditions and factors such as snowmelt, evapotranspiration and runoff have not been considered. Thus, the data in Figure 8 may

Table 2. *Recorded seismic events within 200 km of Donjek debris flow between July 1, 2000 and September 30, 2000.*

Date (time) UT	Distance (km)	Magnitude (M)
00 07 01 (14:16:22)	127.6	2.9
00 07 03 (17:24:44)	123.8	4.1
00 07 03 (19:23:00)	137.2	4.1
00 07 03 (19:45:13)	102.9	2.5
00 07 04 (02:21:19)	115.3	3.1
00 07 04 (10:26:48)	99.1	2.5
00 07 13 (21:20:44)	170.3	2.8
00 08 01 (15:36:27)	196.5	3.4
00 08 03 (13:12:59)	187.6	4.5
00 08 03 (13:54:03)	190.7	2.9
00 08 10 (14:34:13)	95.2	2.5
00 08 27 (21:48:04)	193.7	2.8
00 09 03 (14:55:03)	103.0	3.1
00 09 27 (08:16:13)	61.5	2.5

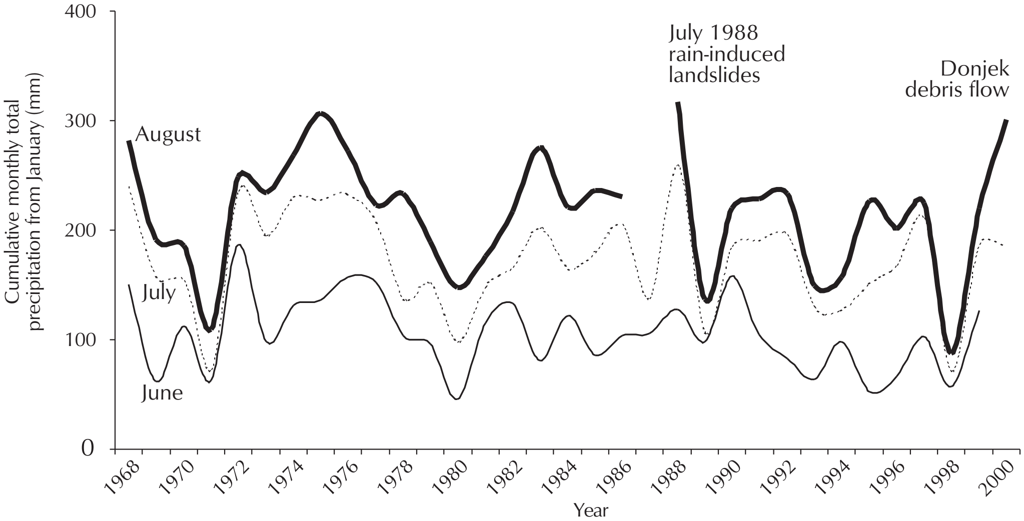

Figure 8. *Cumulative monthly total precipitation from January to June, July and August at Burwash Landing from 1968 to 2000.*

only provide a crude indication of possible soil moisture levels at any location in the area surrounding the Burwash Landing station. Slopes are more susceptible to failure in years with high soil moisture because pore-water pressure increases with increases in soil moisture, thus decreasing the shear strength of slope material. Cumulative monthly total precipitation from January to August, 2000 was abnormally high, primarily because the August, 2000 monthly total precipitation (115.7 mm) was the highest on the 1968-2003 August record. These data suggest that high pore-water pressures likely contributed to instability at the headscarp of the Donjek debris flow.

DISCUSSION

An unusually large debris flow occurred in the Donjek River valley in mid-to-late summer, 2000. The movement mechanism probably began as a slide and changed to flow shortly after initiation and collapse of the initial source volume. The initial slide movement is inferred from the predominant dip of 65° at the source scarp and the large number of boulders in the debris flow. It is often difficult, however, to distinguish between slide and flow mechanisms in most mass movements (Hungr et al., 2001). Flow movement shortly after initiation is inferred from the flow-like features of the Donjek debris flow. The structural features in the bedrock, associated with an overturned syncline (Dodds and Campbell, 1992), acted to predispose the slope to failure. The failure surface appears to be a bed of relatively highly weathered siltstones in an interbedded siltstone and argillite mass. This mass likely had a higher porosity allowing water to infiltrate more readily, thus setting up an unstable hydrogeologic condition for the initial failure volume. Intensely weathered and oxidized boulders within the debris flow suggest that chemical weathering was involved, and the abundance of residual soil clinging to steep slopes in the basin allowed the initial bedrock failure to entrain a larger volume of material.

Water that infiltrated the slope material is likely a major factor in predisposing the initial slope to failure, as well as facilitating the entrainment of residuum in the debris-flow path. This is inferred from the flow-like form of the debris flow and from the anomalous precipitation from January to the end of August, 2000. Ongoing research aims to date the event more precisely and thereby characterize the daily-scale meteorological conditions leading up to the event. Unfortunately, there are not enough detailed case studies of debris flows in southwest Yukon to fully understand the relationship between hydrological and mass-wasting processes. The monitoring of debris flows is certainly warranted if future development is intended for southwest Yukon, especially considering the possibility that global climate change could make meteorological extremes more common (e.g., Kulkarni and Blais-Stevens, 2004).

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