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The relations between false gold anomalies, sedimentological processes and landslides in Harris Creek, British Columbia, Canada

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Abstract

Harris Creek is a Au-rich, cobble-gravel bed stream in southern British Columbia, Canada. A preliminary study, based on analysis of < 0.053 mm sediments and heavy mineral concentrates (SG > 3.2) from bulk sediment samples, identified accumulations of Au at breaks-in-slope of the stream gradient. This is consistent with theoretical models of heavy mineral transport by streams (Day and Fletcher, 1991). However, the breaks-in-slope also coincide with active landslides that might, because of the form of the Au anomalies, be interpreted as the source of the Au. To investigate this we have: (1) monitored erosion of the landslides and determined their Au content; and (2) used multi-element geochemistry (with Al, Mg, Na, Ba, Ti, P and Sr) to fingerprint the influence of one of the landslides on the composition of the < 0.053 mm fraction of the stream sediments.

Material eroded from the toe of the Landslide #1 forms soft clay-rich balls that are initially deposited in high-energy, bar-head environments. Observations and geochemical fingerprinting indicate that over a distance of 0.5 to 1.0 km downstream from the landslide these balls break down and release fine-grained sediment that is transferred from high- to low-energy (bar-tail) environments. Gold concentrations in the landslides are low (average 0.6 ppb) and the input of this material into Harris Creek dilutes Au values downstream from the landslide.

The combined effect of accumulation of Au at breaks-in-slope in stream gradient and gradual dilution by landslide material, is to create peak Au values and false anomaly cut-off points downstream from a landslide. It is not clear if the association of active landslides with changes in stream gradient is coincidental or linked to local or catchment basin-scale geomorphic processes. Nevertheless, for Au and other elements transported in stream sediments as heavy minerals, the presence of anomalies and anomaly cut-offs near landslides and breaks-in-slope in stream gradient should be interpreted with caution.

Keywords: geochemical exploration; stream; landslide; gold

1. Introduction

Harris Creek is a Au-rich, cobble-gravel bed stream in the southern interior of British Columbia, Canada (Fig. 1). For nearly a decade it has been the research–observation catchment for ongoing studies into transport of gold and other heavy minerals by streams. As part of these studies, Ryder (1991) and Ryder and Fletcher (1991) showed that intermittent landslides are the principal source of new material to

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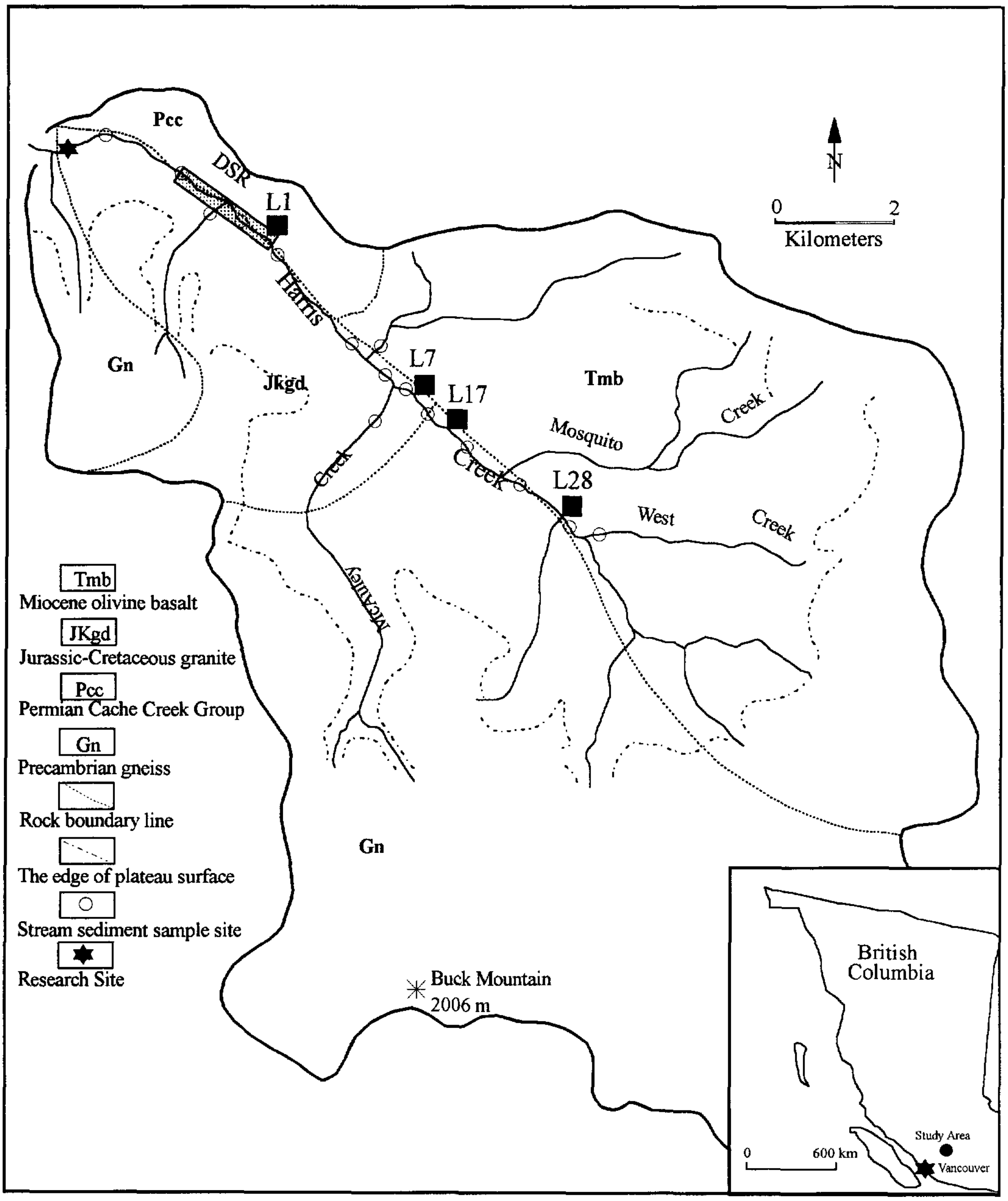

Fig. 1. Location of the study catchment, simplified geology, and locations of active landslides and stream sediment sampling sites. (DSR = detailed study reach; L1, L7, L17, and L28 are landslides). Geology modified from Jones (1959).

Harris Creek (Fig. 2). This situation differs markedly from relatively simple drainage basin models that relate dilution of geochemical anomalies to catchment area by assuming a uniform rate of sediment supply throughout the catchment (Polikarpochkin, 1971; Hawkes, 1976). We have therefore investi-

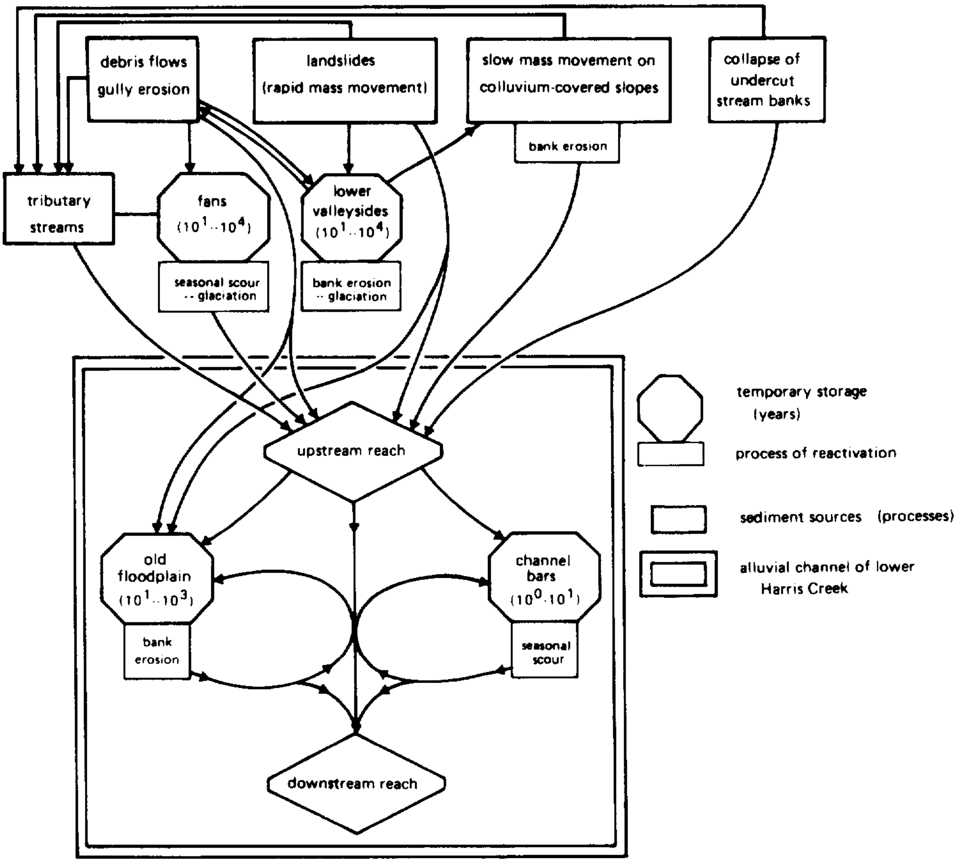

Fig. 2. The sediment cascade for Harris Creek (from Ryder and Fletcher, 1991). Numbers in parentheses represent the estimated storage time.

gated the influence of landslide activity on the sediment budget and the distribution of Au in Harris Creek.

2. Description of the field area

The pear-shaped Harris Creek catchment basin has an area of 225 km^2, of which about 60 percent lies at an elevation between 1300 and 2000 metres above sea level on the dissected plateau of the Okanagan Highland (Fig. 1). At lower elevations the river, which has a series of braided and meandering reaches intermittently flanked by floodplain deposits, flows in a valley deeply incised into a three-dimensional complex of till, glaciolacustrine and glaciofluvial sediments deposited during the Fraser Glaciation (Ryder, 1991; Ryder et al., 1993).

Transport and deposition of sediment in Harris Creek is closely tied to annual snow-melt floods that disrupt the framework of the bed and mobilize the cobble-gravels. Two distinct fluvial environments are recognized: high-energy environments at bar-head sites are characterized by high flow velocity, high bed roughness, and bimodal sediments consisting of a cobble-gravel framework with a sand matrix (Fig. 3). Conversely, low-energy environments at bar tails are characterized by lower flow velocities, lower bed roughness, and unimodal sands. Day and Fletcher

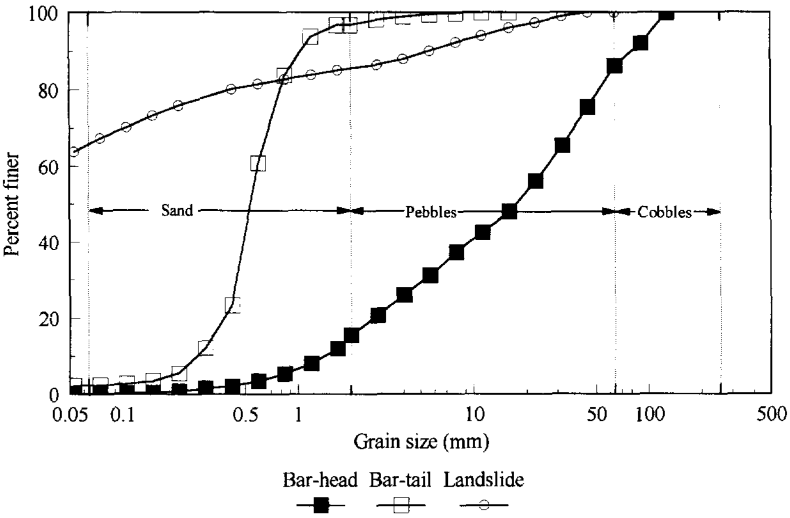

Fig. 3. Size distribution of stream sediments and material from the toe of Landslide #1.

(1989, Day and Fletcher, 1991) and Fletcher and Wolcott (1991) showed that mobilization and transport of sand-sized gold and magnetite was closely related to disruption of the bed by the annual flood event. During the flood, gold and magnetite are swept over the heads of the bars and deposit in the lower energy environment at the bar-tail. As the flood peak passes the reformed bar-head cobbles form a very effective trap site for sand-sized heavy minerals.

Terrain mapping in the Harris Creek basin (Ryder, 1991; Ryder and Fletcher, 1991) has shown that the supply of new sediment to Harris Creek is dominated by landslides and other mass wasting events that are spatially and temporally discontinuous. These point sources of sediment are all located in the area below the plateau edge (Fig. 1). At present only four of fourteen landslides are active. Landslide #1, the focus of these studies, is located on the north bank of Harris Creek 4.3 km upstream from the Research Site. It consists of about 90% glaciolacustrine sediments and 10% till by volume. The glaciolacustrine sediments are cohesive silts and clays. From field surveys it is estimated that the sliding block amounts to 9×10^4 t which are being gradually supplied to Harris Creek by undercutting and collapse of the active toe. Measurements of the toe of the landslide indicate that it supplied roughly 1.8 t sediment from July 1991 to May 1992, 1.0 t from July 1992 to April 1993, and 71 t from April to May 1993 during a major flood event. On average, about 60% of the toe sediment is finer than 0.053 mm (Fig. 3).

3. Study methods

3.1. Sediment sampling and analysis in 1991

Sediment samples were collected along lower Harris Creek and its major tributaries at the locations shown in Fig. 1. At each location a 50 kg of < 2 mm sample was collected from the bar-head and bar-tail environments. Collection of the bar-head sample involved field sieving up to 300 kg of material through a < 2 mm screen into a plastic pail. Care was taken to catch any overflow water and suspended sediments in an outer tank. Bar-tail samples were collected directly, without sieving, because most of the sediment in these low-energy environments is finer than 2 mm.

In the laboratory the bulk sediment samples were wet sieved into seven size fractions between 2 mm and < 0.053 mm using a recirculating water system to prevent loss of fines. Each size fraction was dried and weighed. Heavy mineral concentrates (HMCs) were separated from the < 0.149, > 0.105 mm, < 0.105, > 0.075 mm and < 0.075, > 0.053 mm fractions using methylene iodide (SG. 3.3). A hand magnet was then used to separate the HMCs into magnetic and non-magnetic fractions. The latter were re-combined to obtain a composite < 0.149, > 0.053 mm non-magnetic HMC for determination of Au by routine fire assay–atomic absorption spectrometry (detection limit 5 ppb). The lower detection limit required to determine Au content of the < 0.053 mm fraction was obtained using an *aqua regia*–ion exchange column–inductively coupled plasma method with a detection limit of 0.1 ppb Au (Fletcher et al., 1995).

3.2. Sampling and analysis in 1993

Sampling the toes of all four active landslides and collection of high- and low-energy stream sediments in the detailed study reach from 100 m upstream to 2500 m downstream of Landslide #1 (Fig. 1) was undertaken in 1993. To sample the landslides, 5 to 10 cm of material was scraped off the surface of the active toe before collecting 15 kg samples of fresh material. In addition, 1.5 kg stream sediment samples were collected from six bar-head and seven bar-tail sites along the detailed study reach.

Bulk landslide samples were wet sieved using the same method employed for bulk sediments in 1991. Stream sediment samples were wet sieved into four size fractions between > 0.425 mm and < 0.053 mm. After drying and weighing, the < 0.053 mm fractions of the landslide and sediment samples were disaggregated. Splits were then decomposed by evaporation to dryness with mixed hydrofluoric–nitric–perchloric acids, followed by resolubilization of the residue in hydrochloric acid and analysis by inductively coupled plasma spectrometry. Gold content of the < 0.053 mm fractions was determined by the *aqua regia*–ion exchange column method.

4. Results

4.1. Recognition of the problem in the 1991 data

Distribution of Au in the < 0.053 mm sediments from lower Harris Creek is shown in Fig. 4. Gold concentrations at high-energy sites range from 0.8 to 6.8 ppb and are much lower than concentrations at the associated low-energy site. The latter have abnormally high peak values of 27.4 ppb and 25.0 ppb immediately downstream from Landslides #7 and #1, respectively. Further downstream from both landslides concentrations of Au decline to less than 4 ppb over a distance of several hundred metres. Although concentrations of Au are much higher (up to 6.1 ppm) in the HMCs, the distribution of Au in HMCs along lower Harris Creek is similar to the distribution of Au in the < 0.053 mm fraction except that peak Au values are found at the high- rather than the low-energy sites (Fig. 5). Measurement of stream gradient, from 1 : 50,000 maps and air photographs, shows that the two sites (i.e., near Land-

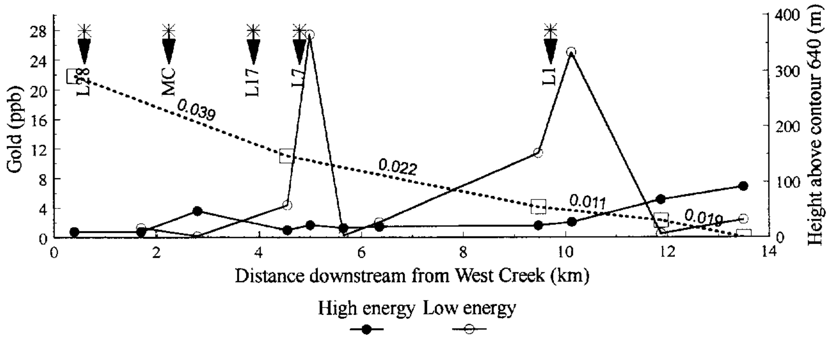

Fig. 4. Stream gradient and distribution of Au in the < 0.053 mm fraction of stream sediments from bar-tail and bar-head sites along lower Harris Creek. L1, L7, L17, L28 and MC are Landslides #1, #7, #17, #28 and Mosquito Creek, respectively. The number on the dashed line is the stream gradient.

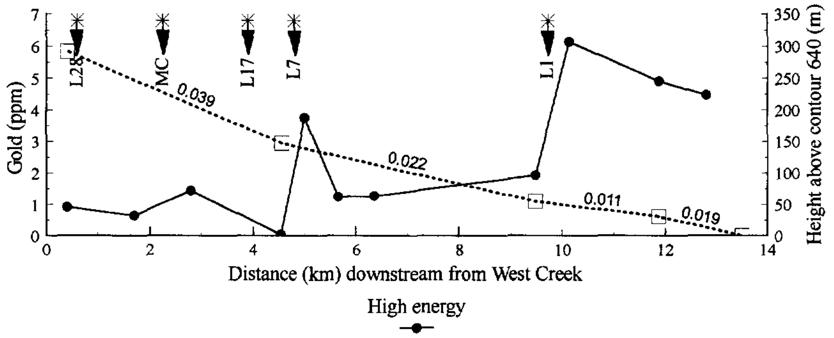

Fig. 5. Stream gradient and distribution of Au in the < 0.149, > 0.053 mm non-magnetic fractions of HMCs from bar-head sites. L1, L7, L17, L28 and MC are Landslides #1, #7, #17, #28, and Mosquito Creek, respectively. The number on the dashed line is the stream gradient.

slides #1 and #7) giving peak Au values coincide with breaks-in-slope of the gradient of Harris Creek.

The 1991 results suggested a possible spatial relation between peak Au values, in both the silt–clay and HMC fractions, and Landslides #1 and #7. Because both landslides are active and because cutoffs for the Au anomalies appear to be present just downstream from the landslides, it might be supposed that the landslides are the source of the Au. Alternative explanations are that the landslides are not the source of the Au and that either: (i) the apparent association of two Au anomalies with the landslides is coincidental, or (ii) the association of the landslides with the Au anomalies is related to geomorphic processes in the Harris Creek catchment. To test these possibilities we have undertaken more detailed studies of what, if any, effect the introduction of landslide material has on the composition of sediments in Harris Creek.

4.2. Results from the detailed study reach — 1993

The 1993 results confirm the 1991 data: that is, Au content of the < 0.053 mm fraction of sediments

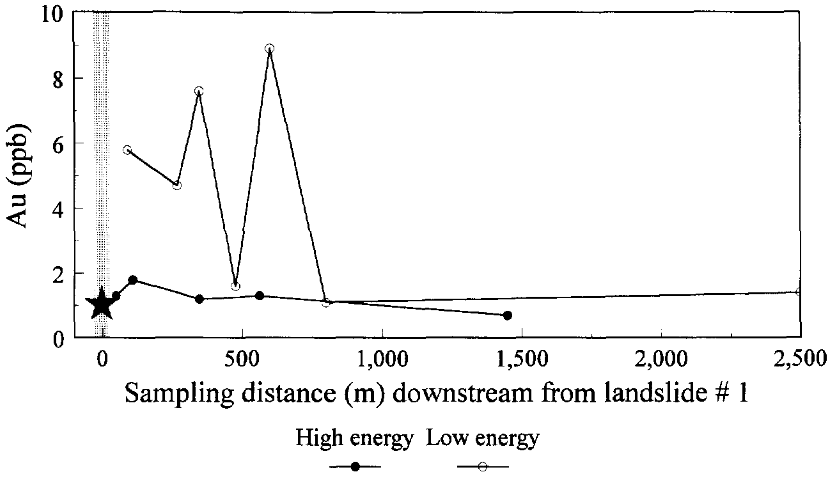

Fig. 6. Distribution of Au in the < 0.053 mm fraction of stream sediment downstream from Landslide #1 in the detailed study reach (DSR in Fig. 1). The shaded area is the location of Landslide #1 and the star shows the average Au content of the toe of the landslide.

from high-energy sites is less than in the associated low-energy sediments and the peak concentration (8.9 ppb) in the latter is found roughly 600 m downstream of Landslide #1 (Fig. 6). Beyond this point Au values at low-energy sites fall to less than 2 ppb and are comparable to concentrations of Au at high-energy sites. Gold content of the < 0.053 mm fraction of the landslides ranges from < 0.2 to 3.6 ppb with an average of 0.6 ppb (Table 1). These results suggest that Landslides #1 and #7 are not the source of the high Au values found in lower Harris Creek. What, then, is the link between the landslides and distribution of Au in Harris Creek?

During collection of sediment samples from the detailed study reach, clay balls, similar to the glaciolacustrine sediments, were found at high-energy sites. Although it was difficult to remove the balls intact from the stream bed, observations indicated that the number, size and angularity of the clay balls decreases over a distance of about 500 m downstream from the landslide. They were never observed at low-energy sites downstream, or at the high- or low-energy sites upstream from the landslide. Thus, from the composition and distribution of the clay balls, it is obvious that their most likely source is glaciolacustrine sediments from the toe of Landslide #1. The changes in the size, shape and abundance of the balls suggest that they are gradually disaggregated, over a distance of about 0.5 km, during their transport downstream.

The multi-element geochemical data have been used to fingerprint the effect of this input of material from Landslide #1 on the geochemical composition of the < 0.053 mm sediments. Seven elements (Al, Mg, Ba, Na, P, Sr and Ti) of the twenty four determined were chosen on the basis that they best differentiate the composition of the landslide from that of the sediments (Table 2). Of the seven elements chosen, Al and Mg have significantly (95% confidence level) higher average concentrations and Ba, Na, P, Sr, and Ti significantly lower average concentrations in the landslide than in sediments upstream from the landslide.

Table 1
Gold content of the < 0.053 mm size fraction of the four landslides in the Harris Greek basin. See Fig. 1 for locations

Landslide	Gold concentration (ppb)	
	Mean	Range
1 (7) [a]	1.8	1.0–3.6
7 (3)	0.4	< 0.2–0.8
17 (2)	0.2	< 0.1–0.5
28 (3)	< 0.2	< 0.2

[a] ( ) number of samples.

Table 2
Concentrations of elements in the < 0.053 mm fraction of material from the active toe of Landslide #1 and from Harris Creek upstream of the landslide. See Fig. 1 for locations

Element	Stream sediment [a] $n = 1$	Landslide [b] $n = 3$
Al (%)	7.5	8.5 ± 0.37 [c]
Mg (%)	1.3	1.8 ± 0.07
Ba (ppm)	975	860 ± 0.0
Na (%)	1.8	1.5 ± 0.14
P (ppm)	1900	843 ± 36.1
Sr (ppm)	470	324 ± 7.2
Ti (%)	0.74	0.43 ± 0.02

[a] Sample 100 m upstream of the landslide.
[b] Samples from the active toe of the landslide.
[c] 95% confidence limits.

Distribution patterns of the seven elements are shown in Fig. 7. Geochemical patterns downstream from the landslide are of two distinct types that depend on whether elemental concentrations in the active toe are higher or lower than in sediments of Harris Creek. For the former (i.e., Al and Mg) concentrations at high-energy sites first increase immediately below the landslide but then decrease further downstream. Conversely, concentrations of these elements are initially unchanged at the associated low-energy sites but then show a concomitant increase as concentrations at the high-energy sites decline. Elements with relatively low concentrations in the landslide material (i.e., Ba, Na, P, Sr, and Ti) show the exact opposite trends.

To further estimate the relative contributions of landslide material to the sediments, a simple mixing model modified from Peart and Walling (1986) has been used:

$$C_s = 100 \times \frac{(P_d - P_u)}{(P_l - P_u)} \qquad \text{when } P_l > P_u$$

$$C_s = 100 \times \frac{1 - (P_d - P_l)}{(P_u - P_l)} \qquad \text{when } P_u > P_l$$

where C_s = contribution (%); P_d = value of selected

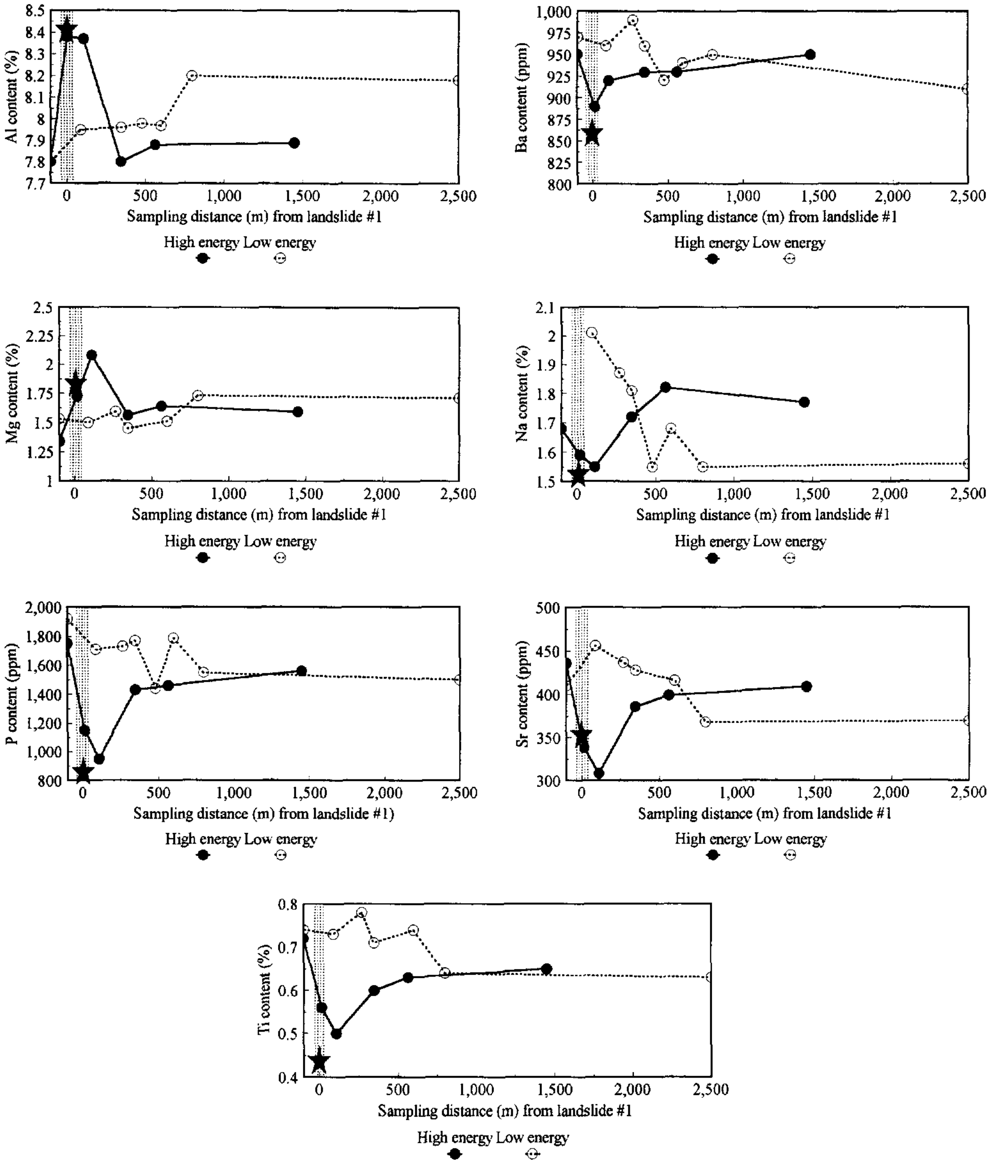

Fig. 7. Distribution patterns of Al, Ba, Mg, Na, P, Sr and Ti in the < 0.053 mm fraction of stream sediment downstream from Landslide #1 in the detailed study reach (DSR in Fig. 1). The shaded area is the location of Landslide #1 and the star shows the average concentrations of the element in the toe of the landslide.

property for stream sediment downstream from Landslide #1; P_l = value of selected property for the landslide; and P_u = value of selected property for stream sediment upstream of the landslide.

Results of applying this model to Ti, Ba, P and Sr are shown in Fig. 8. Although there are some differences between the estimates, the general trend is for the contribution of landslide material to the < 0.053 mm fraction at high-energy sites to decline from about 60 to 80% near the landslide to 20% or less over a distance of 1 to 1.5 km. Over the same distance the contribution of landslide material to the low-energy sediments increases from less than 10% to about 40%. It should be pointed out that the mixing model is based on several simplifying assumptions (e.g., no sediment–water interaction, and

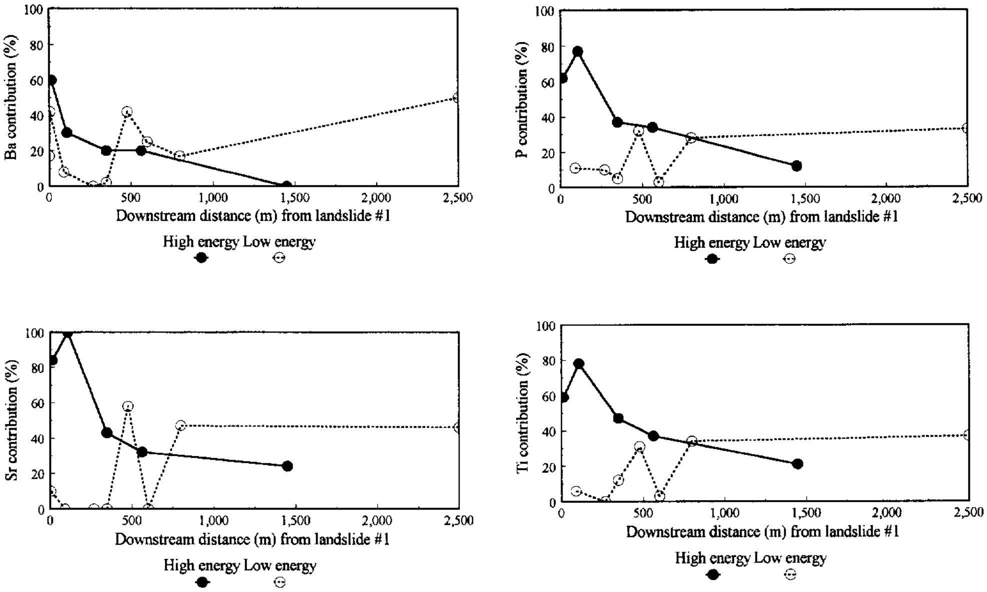

Fig. 8. Relative contribution (%), estimated from the mixing model and concentrations of Ba, P, Sr, and Ti, of material from Landslide #1 to the < 0.053 mm fraction of stream sediments in the detailed study reach.

equal rates of transport for different mineralogical components of the sediments) that may not be entirely valid. Departure from these assumptions probably accounts for the minor differences between the predictions based on different elements.

5. Discussion

Early studies over a relatively short 5 km study reach of lower Harris Creek showed that Au concentrations increase where stream gradient decreases (Day and Fletcher, 1989). Subsequently this was shown to be consistent with theoretical models of transport and deposition of gold and other heavy minerals by streams (Day and Fletcher, 1991). Results reported here confirm that preferential accumulation of Au occurs at breaks in stream gradient throughout lower Harris Creek (Figs. 4 and 5). It is now also apparent that two of the four active landslides, Landslides #1 and #7, coincide with major breaks in stream gradient where landslide activity is triggered by lateral instability of the stream channel causing the stream to undercut its banks. This association of channel instability and landslides with change in stream gradient may be coincidental. Alternatively, all three phenomena may be linked by geomorphic processes on either a local or catchment-wide scale by, for example, either (i) the knick-point, created by changes in stream gradient, retreating upstream; or (ii) the excess energy of the stream, associated with the decrease in gradient at the knick-point, being partially dissipated by lateral migration of the channel and erosion of the banks. Considering the long time-scales of the geomorphic processes involved in the evolution of a drainage basin, there is no possibility of proving or disproving such links in the short term. Nevertheless the association of two of four active landslides with breaks-of-slope in stream gradient suggests that the association may be more than a coincidence.

Whatever the relation between the changes in stream gradient and the landslides, the low Au content of the landslides (Table 1) and geochemical fingerprinting of material eroded from the Landslide #1 (Figs. 7 and 8) clearly shows that the landslides are not the source of the Au and that landslide material will dilute Au concentrations in the < 0.053 mm fraction of the stream sediments. However, because of the cohesive nature of the clay balls, this dilution only becomes apparent some distance downstream from a landslide. Thus the combined effect of accumulation of Au at breaks-in-slope, in response to the change in hydraulic conditions (Day and Fletcher, 1991), and dilution by material derived from the landslide, is to create peak Au values and an apparent cut-off for the Au anomaly a short distance downstream from the landslides.

Based on these results it seems likely that, contrary to relatively simple dilution models of geochemical anomalies in stream sediments, the interactions of sedimentological process, mass wasting, and perhaps large scale geomorphic processes can produce complex downstream distribution patterns for Au in stream sediments. Insofar as these interactions can create the appearance of Au anomalies and anomaly cut-offs, the possible effects of landslides and changes in stream gradient should be taken into account when interpreting exploration geochemical data. Because both the sedimentological and mass wasting processes involved are widespread and of a general nature, particularly in regions of high relief and high rainfall, it is reasonable to expect that their influence on stream sediment geochemistry may also be a correspondingly common occurrence.

6. Conclusions

Along lower Harris Creek decreases in stream gradient are associated with accumulation of Au and landslide activity. Material eroded from the toe of landslides dilutes the Au content of the sediments and thereby creates an apparent cut-off to the Au anomaly some distance downstream from a landslide. Anomaly cut-off points that might be related to landslide activity and changes in stream gradient should be interpreted with caution for elements, such as Au, that are transported as the principal constituents of heavy minerals.

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