



STREAM SEDIMENT GEOCHEMISTRY IN TODAY'S EXPLORATION WORLD

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ABSTRACT

Worldwide use of stream sediment geochemistry for almost 50 years has shown it to be a robust method for identifying areas of high mineral potential. The basic premise is that a stream sediment is representative of the products of weathering and erosion upstream of the sample site. However, detailed studies show that this premise greatly oversimplifies the real situation. In particular, sediment supply to the stream and sorting of sediments by fluvial processes, strongly influence the composition and representativity of stream sediments. For example: (i) a flood plain may decouple the stream from its interfluves so that they contribute no material to the channel, or (ii) supply of new sediment to a stream may be from a few point sources the activity of which varies with time. Sediment supply may also be disturbed by logging or agricultural activities.

Once material enters the stream, processes that move sediment also change its texture and geochemical composition. For example, light mineral fractions < 100 μm tend to be swept away in suspension whenever sediment transport occurs. The geochemical consequences of sediment sorting are not so obvious for elements (e.g., base metals) that are rather uniformly distributed in different components of the sediments. However, sorting has important consequences for elements such as gold, that are present as constituents of rare heavy minerals. Theory and field studies show that enrichment of these elements on the stream bed is most consistent for the fine sand fractions. Concentrations in coarser size fractions become increasingly erratic, in both space and time, depending on local hydraulic conditions. The finer fractions thus better represent the geochemistry of the drainage basin and also reduce the nugget effect during sampling.

On this basis the design of stream sediment surveys must consider: (i) if the sediment represents its catchment basin, or are there gaps in the coverage where some other medium should be used; (ii) where (and sometimes when), depending on the objectives of the survey, sediment should be collected (bar head, pools, moss mats, etc.); (iii) what size fraction to analyze; and hence (iv) how large a field and analytical sample is required to ensure representativity for rare particles of heavy minerals such as gold.

INTRODUCTION

Geochemical surveys based on analysis of stream sediments are a well-established technique that, over five decades, has been used worldwide wherever stream drainage networks are well established. This usage is based on the cost-effective ability of such surveys to identify anomalous watersheds as targets for further exploration. Also, starting from about the early 1970s, stream sediment surveys have been used to monitor environmental quality. In both applications, the basic premise is that the sediment is a composite of the products of weathering and erosion derived from the catchment basin, and funneled into and along the stream channel.

Stream sediment surveys were reviewed at Exploration '87 (Plant *et al.*, 1989) and more recently in Volume 6 of the Handbook of Exploration Geochemistry (Hale and Plant, 1994). Why another review of

their application? First it must be emphasized that stream sediment geochemistry has proven a remarkably robust exploration method that can be successful, to a degree, even when poorly executed. This review is not therefore about making stream sediment surveys work, but rather getting them to work better on the basis of improvements in understanding of stream processes achieved during the last decade. The topic will be approached through consideration of what, ideally, a sediment sample should represent and what it may actually represent from the catchment basin scale down to the analytical sub-sample.

THE OBJECTIVES, THE IDEAL AND THE MODEL

Here we are concerned with stream sediment surveys for mineral exploration, rather than assessing the environmental status of a catchment.

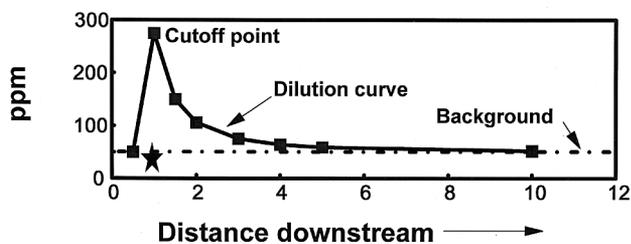


Figure 1: Hypothetical anomaly dilution curve based on Hawke's model. The star marks the location of the source anomaly, the background concentration is 50 ppm and the cutoff point is the maximum extent of the anomaly upstream.

The ideal sample would represent all parts of the catchment basin equally so that mineralization anywhere in the basin would have an equal chance of being detected. Hawkes (1976) formalized this ideal as a model that relates the source of the anomaly to the metal content of the anomalous sample and catchment basin size (Figure 1):

$$Me_m A_m = A_a (Me_a - Me_b) + A_m Me_b \quad [1]$$

where Me_m is metal content of the source anomaly of area A_m , A_a is catchment area above the anomalous sample site with metal content Me_a , and Me_b is the background metal content.

Assumptions of the model are uniform rates of erosion throughout the catchment, uniform background metal concentrations, and no transfer of metal between sediment fractions or between waters and sediment. The model then predicts that metal concentrations will decrease downstream from the "cutoff point", close to the source, following an asymptotic dilution curve. The product of anomalous metal concentrations and catchment basin size remain constant: the "productivity" (P) of the catchment.

$$[P = A_a (Me_a - Me_b)] \quad [2]$$

A corollary is that identical anomalous sources ($Me_m A_m$) will produce shorter anomalous dispersion trains, with steeper geochemical gradients, as the catchment basin area increases. Thus, as emphasized by Mackenzie (1977), the lengths of anomalous dispersion trains can be less significant in prioritizing anomalies than consideration of the size of the catchment basin area upstream of the sample site.

For mineral exploration the size fraction of the sediment and method of analysis are chosen (ideally via an orientation survey) to optimize anomalies with respect to anomaly strength (contrast) and/or length of the anomalous dispersion train. However, the more specific our geochemical methodology becomes, the greater the chance of excluding a potential target having a different geochemical signature. Consequently, for grassroots regional surveys, the methodology is often compromised—e.g., the near-generic use of the $-177 \mu\text{m}$ (-80 mesh ASTM) fraction, a strong acid decomposition, and multi-element ICP analysis—rather than optimized. Except in very deeply weathered terrains, a quick check on the overall effectiveness of such surveys is to compare geochemical patterns to geology, if the "geology" cannot be seen in the geochemistry the reliability of the survey (or the geology!) is suspect.

THE CATCHMENT BASIN SCALE

Hawke's model will fit best in small, first and second order, streams where the valley slopes and the stream channel are rather closely linked or coupled. For example, Sleath and Fletcher (1982) found that dispersion of lead in a small stream in British Columbia followed the model closely. Conversely, the model will become increasingly unreliable as catchment size increases, and the links between the valley slopes and supply of sediment to the stream become more complex. In this situation we can say that the stream is decoupled from its valley sides and the sediment no longer represents all parts of the catchment equally.

Decoupling arises in many ways: in the simplest case, as a stream gets larger an alluvial flood plain appears alongside the channel. At first, the flood plain is intermittent but with increasing size the stream flows entirely through its own alluvial deposits. Where the flood plain is present material eroded from the valley slopes is deposited and stored at the base of slope along the outer margins of the flood plain. The interfluvies are thus no longer represented in the composition of the sediments. Leggo (1977) gives an example from Fiji (Figure 2). Two copper prospects are associated with colluvial soils and give strongly anomalous copper values in streams draining them: a third prospect is covered by alluvium and gives no response in stream sediments.

Decoupling can also be complex. For example, in Harris Creek, British Columbia, new sediment is only supplied to the channel where an intermittent flood plain is absent and undercutting of the banks results in landslides (Figure 3) (Ryder and Fletcher, 1991). The location and timing of the landslides varies with time and only four out of fourteen landslides identified are currently active. Furthermore, insofar as the landslides are largely in glaciolacustrine sediments their input to Harris Creek does not represent the bedrock geology of the catchment.

In mature geomorphic terrains, with wide flood plains and broad interfluvies of low relief, decoupling may be so extreme that stream sediments are of limited use, and widely spaced soil samples become the best approach to reconnaissance sampling. Zeegers (1979), for example, recommended soil sampling on a 2000×500 m grid, with sediment samples being taken where lines crossed streams, for exploration of 6000 km^2 in French Guyana. Tooms (1987), however, did not find this approach as effective as use of stream sediments and pan concentrates in Suriname and Liberia.

ON THE STREAM BED

Here we must choose the medium to be sampled; the sample site and the sampling interval; and the quantity of sediment to collect. It may also be necessary to decide when to sample in regions of marked seasonal climates. Choice of sample media includes stream sediment, pan concentrates (Stendal and Theobald, 1994), and various forms of organic sediment (Bjorklund *et al.*, 1994). Other materials that are sometimes sampled include overbank (flood plain) sediments and moss-mat sediments.

For routine exploration surveys the material chosen is usually "active" silt and fine to medium sand that has recently been transported by the stream; care is taken to avoid collapsed bank material. In fast flowing streams suitable material can be found:

1. behind large boulders, logs etc.,
2. in low energy pools at the tail-end of bars or between riffles shuttes; or,
3. infilling voids below the surface of cobble-gravel bars.

A small sample (500 g) should provide at least several grams of fine material for analysis but may not be adequate for determination of heavy mineral associated elements (HMEs). Each of the above sites are distinct fluvial environments with their own depositional characteristics, as follows:

- Silt-sand in the lee of boulders: most likely to have been deposited in the final stages of bedload transport as a flood peak wanes.
- Pools: as discharge falls sediment transported over bar-tops are deposited at low energy sites—typically in pools between riffles or in eddy pools at the tails of point bars. Where pools have beaches, samples for HMEs should be taken well below the waterline to avoid very erratic enrichments of heavy minerals that form in wave swash zones on the beach face (Day and Fletcher, 1989, 1991; Fletcher, 1990).
- Cobble-gravel pavement: (re)forms on bar surfaces at high discharges as a flood peak falls. Coarse sands and heavy minerals are initially trapped in the voids between cobbles but later become buried by finer, heavy-mineral-poor sediments (Day and Fletcher, 1989, 1991).

The differences between these environments are not too important for base metals and other elements that are rather uniformly distributed through the components of the sediment. However, the differences are

critical for HMEs because very different results can be obtained at each depositional environment (Figure 4). The underlying theory and practical implications of the behaviour of the HMEs have been studied extensively (Saxby and Fletcher, 1986; Day and Fletcher, 1989, 1991; Fletcher and Day, 1989; Fletcher and Wolcott, 1991; Paopongsawan and Fletcher, 1993; Fletcher and Loh, 1996a,b; Fletcher *et al.*, 1987, 1992). Most important, selective elimination of light grains from the stream bed locally enriches the sediments in heavy minerals. For sediments finer than about 100 μm winnowing of light mineral grains probably occurs whenever there is bedload transport (Bagnold, 1973) and is thus widespread on the stream bed. Conversely, elimination of coarse lights and enrichment of coarse heavies is restricted to high energy environments (e.g., bar heads). Practical consequences are:

- At the catchment scale, the enrichment of heavy minerals in stream sediments compared to soils. This can be especially apparent in tropical streams where deeply weathered soils are clay-rich whereas (except in disturbed watersheds) sediments are typically clay-poor. The sediments thus undergo the equivalent of a panning-heavy mineral upgrading process whereby heavy mineral content of the fine sediments is greatly increased compared to the associated soils. For example, in a case study in Malaysia, Sirinawin *et al.* (1987) found that sandy sediments have a much higher Sn content than associated clay-rich lateritic soils (Figure 5).
- At the bar scale, there are large variations in HME concentrations on the stream bed. These differences are most pronounced for the coarser fractions and very high density heavy minerals, but decrease

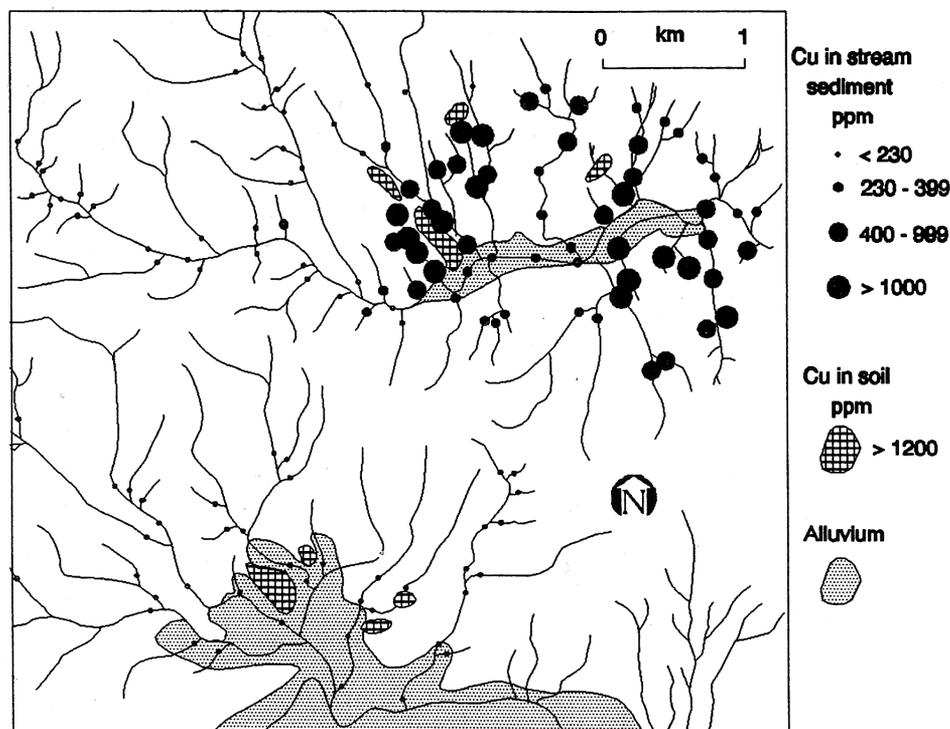


Figure 2: Dispersion of Cu from copper prospects in the Namosi district of Fiji. The southern prospect is not reflected in the stream sediment geochemistry because of the influence of the alluvium decoupling the stream from the bedrock. From Appleton and Ridgway (1994), based on results of Leggo (1977). Reproduced with permission from Elsevier.

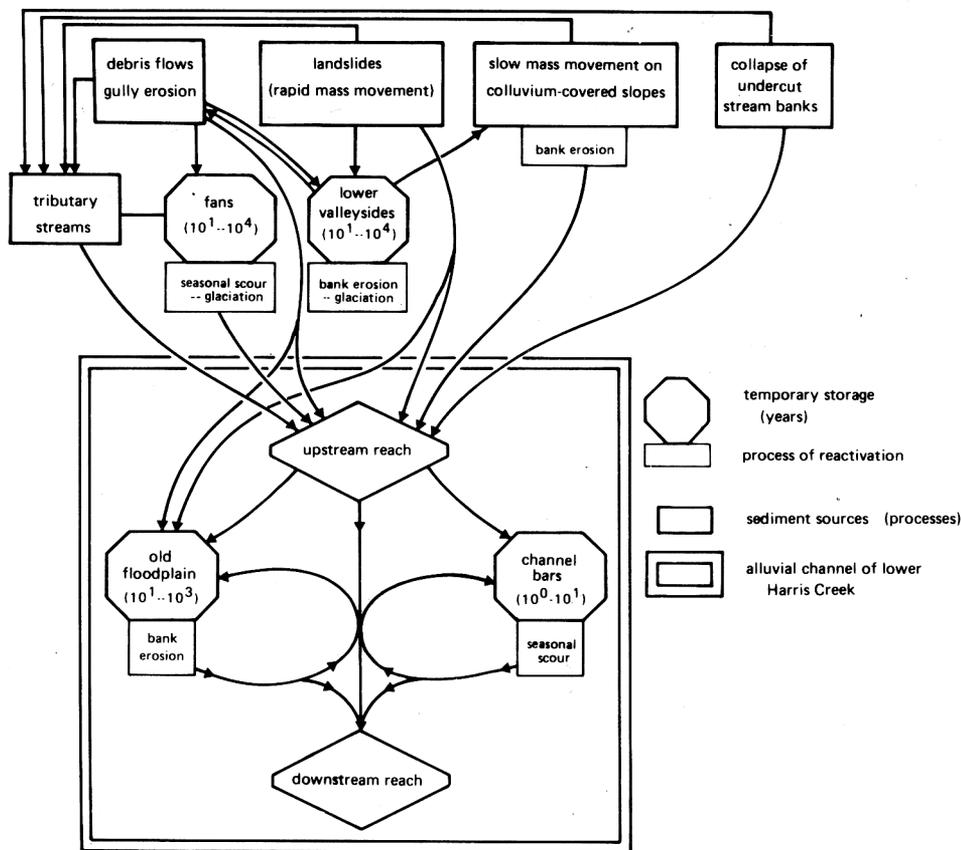


Figure 3: The sediment cascade for Harris Creek. Numbers in parentheses are the estimated storage time. From Ryder and Fletcher (1991).

with decreasing density and grain size so that they are (usually) minor for fractions finer than about $50\ \mu\text{m}$ (Figure 6). For example, Fletcher *et al.* (1987) found fine cassiterite was rather uniformly upgraded at both high and low energy sites in a small stream in Malaysia (Table 1). However, coarse cassiterite was only concentrated at the high energy sites. No such effects were observed for lead and arsenic because these elements are not present in the sediment as heavy minerals. Although concentrations of fine sand-sized HMEs are similar in both high and low energy environments (Figure 6), very fine HMEs may be swept from high energy sites and preferentially deposited at low energy sites. For example, in Harris Creek gold particles smaller than $50\ \mu\text{m}$ collect at low energy, bar-tail, sites (Hou and Fletcher, 1996).

- Size of the field sample, cobble-gravel sites at bar heads are deficient in fines so that large amounts of bed material may have to be field-screened to obtain sufficient material for analysis. For example, based on Day and Fletcher (1986) for streams in British Columbia, it may be necessary to field-process a few hundred kilograms of bar-head material to obtain 10 or more kilograms of sand to provide a representative sample for gold. Obviously this approach is only appropriate for reconnaissance surveys in which, as described below, advantage is taken of the long anomalous dispersion trains provided by upgrading of concentrations of HMEs on the stream bed. Sediment at low energy sites is usually sufficiently fine that field-screening is not required.

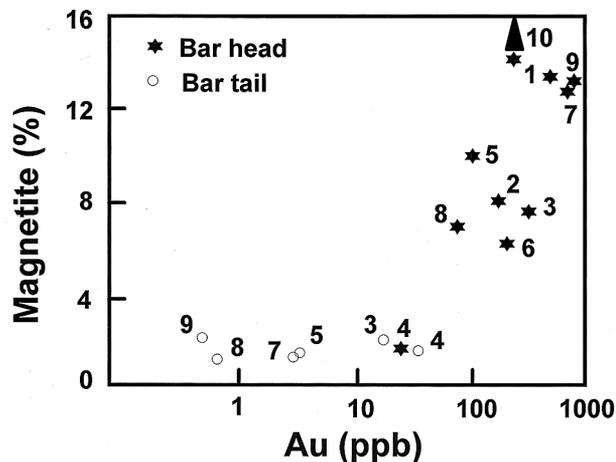


Figure 4: Concentrations of magnetite ($-212+150\ \mu\text{m}$) and gold ($-106+75\ \mu\text{m}$) in bar head and bar tail sediments from Harris Creek, British Columbia. Numbers indicate increasing distance downstream. Note the very different trends: gold and magnetite are both concentrated at bar head, heavy mineral trap sites but not in sandy bar tail pools. In the pools magnetite concentrations are approximately constant whereas gold values increase upstream (towards an unknown source). Based on Day and Fletcher (1991).

Table 1: Comparison of concentrations of Sn and associated elements in various size fraction of sediments from ten high and low energy environments in the S. Petal. All data in ppm. Data from Fletcher et al. (1984).

Element	Environment		Ratio ^[1]	t ^[2]
	High energy (n=10)	Low energy (n=10)		
Sn in a range of size fractions				
<53	252 (24) ^[3]	260 (38)	1.03	-0.24
53-75	513 (38)	320 (54)	1.60	2.22
75-106	695 (63)	245 (41)	2.84	3.02
106-150	543 (60)	144 (35)	3.77	3.69
150-212	323 (95)	65 (55)	4.97	2.85
212-300	308 (78)	41 (55)	7.51	3.48
300-425	229 (169)	30 (27)	7.63	1.62
425-600	212 (171)	27 (32)	7.85	1.63
Sn and associated elements in the < 177 μm fraction				
Sn	444 (70)	184 (78)	2.41	2.70
W	32 (52)	16 (41)	2.01	3.19
As	24 (25)	27 (21)	0.90	-1.14
Pb	18 (18)	19 (33)	0.92	-0.74

1. Ratio of concentration in high to low energy environment
2. t with 9 df $t_{.99} = 2.821$, $t_{.95} = 1.833$, $t_{.90} = 1.383$
3. Coefficient of variation (%)

Because HMEs finer than about 100 μm are less influenced by local hydraulic effects they best represent the catchment and give the most consistent anomalous dispersion trains (e.g., Figure 7). Samples can be collected from high or low energy sites, but are easier to obtain at the latter. Conversely, if fractions coarser than 100 μm are to be analyzed for HMEs, larger samples are needed, anomalous dispersion trains will be much more erratic, selection of suitable trap sites becomes more critical, and isolated anomalies at high energy sites can be displaced a considerable distance downstream from their source.

The unique behaviour of the HMEs is also relevant to the choice of sample interval. In this context, the upgrading of fine HMEs on the stream can offset downstream anomaly dilution. Conversely the loss of fine lights by winnowing tends to lower concentrations of elements associated with these fractions. Anomalous dispersion trains for mobile elements are thus likely to be shorter and closer to the bedrock source than anomalies for HMEs. An example is show in Figure 7: both tin and arsenic have strongly anomalous concentrations in soils at the source, but the anomalous dispersion train for tin in the -177 μm sediments is significantly longer than the associated arsenic anomaly. Similar results have been obtained for gold versus base metals at Mt. Bini in Papua New Guinea (Figure 8) (Dugmore et al., 1996). The longer dispersion trains provided by the HMEs, if properly sampled for, is especially useful for reconnaissance surveys.

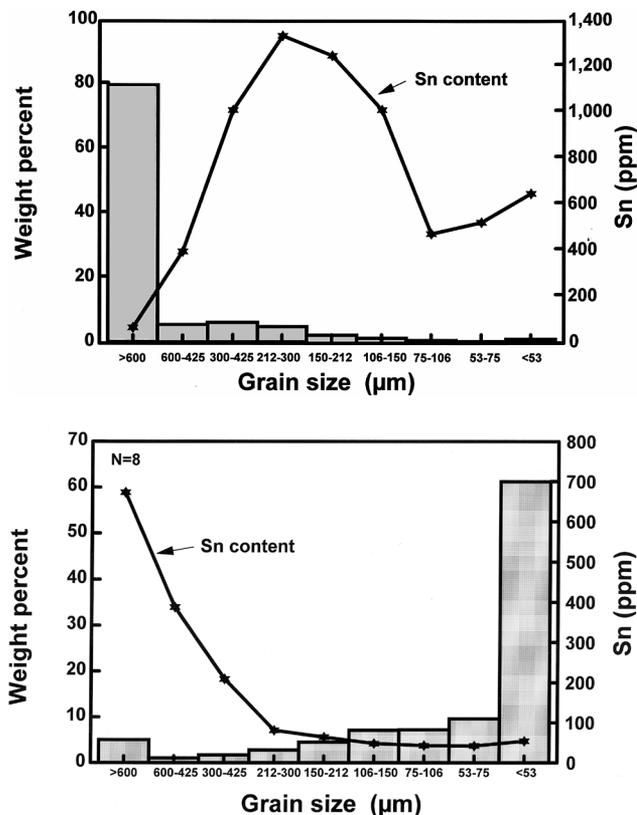


Figure 5: Grain size distribution and concentrations of Sn in sediments (a) and soils (b), Tanjong Tualang, Malaysia. Based on Sirinawin et al. (1987).

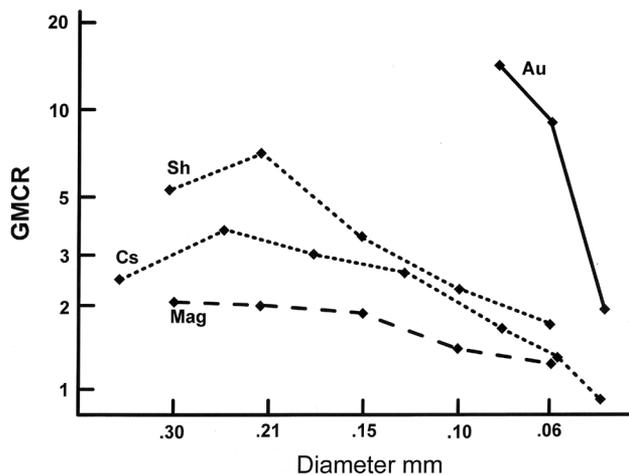


Figure 6: The Geometric Mean Concentration Ratio (GMCR) for gold (Au) in Harris Creek, British Columbia; scheelite (Sh) and magnetite (Mg) at the Clea deposit, Yukon Territory; and cassiterite (Cs) in a Malaysian stream. The GMCR is a measure of the log average difference in concentration between an element in high versus low energy environments on the stream bed. Note how the GMCR increases with mineral density but decreases with grain size. Modified from Fletcher and Day (1989).

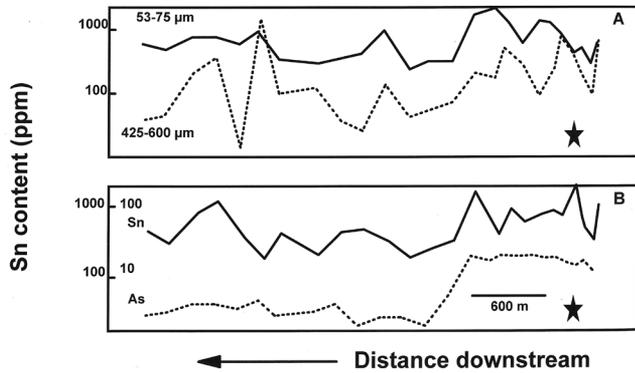


Figure 7: (a) concentrations of Sn in the $-75+53 \mu\text{m}$ and $-600+425 \mu\text{m}$ stream sediments from the S. Petal, Malaysia; and (b) concentrations of Sn and As in -80 mesh sediments from the S. Petal. Soil anomalies at the source contain 1300–1800 ppm Sn and 1930–2600 ppm As. The downstream dispersion pattern for W is similar to that for Sn whereas patterns for Cu, Pb, Zn, Li and F are similar to the As patterns. Location of the primary tin mineralization indicated by (*). Based on Fletcher et al. (1984, 1987).

Although an advantage in detecting anomalous conditions, the possibility that concentrations of HMEs may increase downstream away from their source can complicate interpretation. Several criteria can be used to identify such anomalies:

1. absence of anomalies of the more mobile elements (e.g., as in Figure 7);
2. reduced anomaly contrast if concentration of the HME is ratioed to (a) the abundance of a more ubiquitous heavy mineral such as magnetite (e.g., Figure 9b); or, more generally as described by Fletcher and Loh (1996a), by (b) reexpressing concentrations relative to the transport equivalent size fraction of the sediment (Figure 9a); and,
3. by recognizing sites on the stream bed where heavy minerals are likely to have been concentrated—helpful field notes include stream width, bed roughness (recorded with a photograph), and changes in stream gradient.

WHEN TO SAMPLE

Trapping of heavy minerals in the voids on the surfaces of bars gives the greatest concentrations of HMEs immediately after a flood peak passes. In the southern interior of British Columbia this occurs shortly after snowmelt in early summer. Later in the season the HME-rich layer is buried and gold concentrations on the bar surface fall so dramatically that gold anomalies found early in the field season may disappear entirely later in the year (Figure 10). Effects of high stream discharge on concentrations of HMEs have also been described in the tropics. For example, in the Solomon Islands concentrations of elements (Fe, Mn, V and Ti) associated with magnetite increased after the tail of a cyclone had passed through the region (Ridgway and Midobata, 1991).

Logistical constraints usually make it impossible to sample over a short time interval after a seasonal event. Sometimes, however, a similar

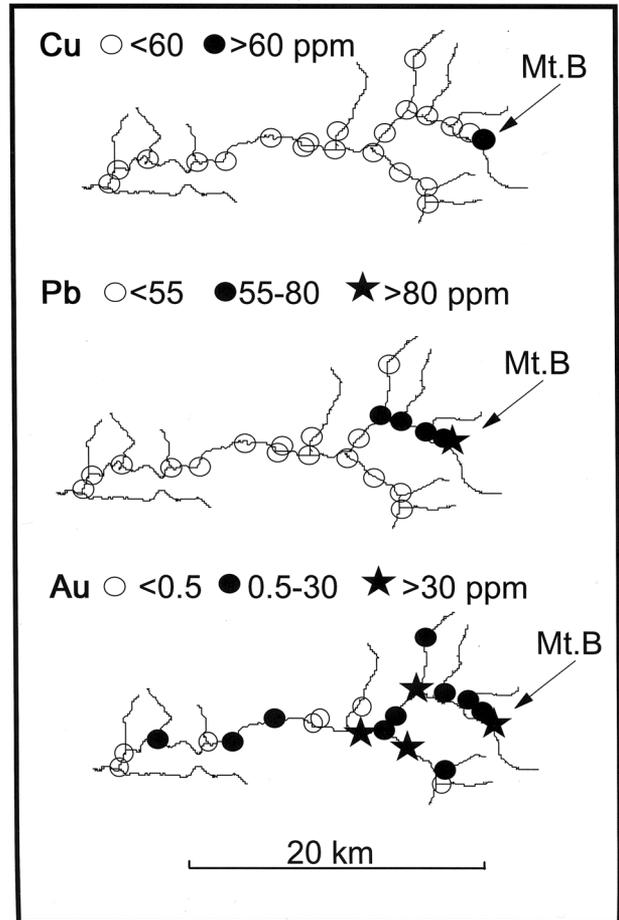


Figure 8: Results obtained in a reconnaissance stream sediment survey downstream from the Mt. Bini copper-gold-molybdenum deposit in Papua New Guinea: gold content in heavy mineral pan concentrates; copper and lead in ground <2 mm sediments. Bulk cyanide leach gold (not shown) did not display a distinct anomalous dispersion train at the reconnaissance level. Modified from Dugmore et al. (1996).

benefit can be obtained by sampling sediment in moss-matts that grow above the normal water level. The moss-matts trap sediment transported during floods when heavy minerals buried in the stream bed are released by scouring. This approach works extremely well in the high rainfall regions of western Canada and Alaska (Figure 11). Overbank sediments are also deposited on the flood plain during periods of high discharge; however, the author's experience is that they are too patchy and stratigraphically complex to be used for routine exploration surveys.

Seasonal effects also occur for elements not associated with heavy minerals. For example, Ridgway and Dunkley (1988) and others have reported strong temporal variations in concentrations of Cu, Pb, Zn, Fe, Rb and Sr in stream sediments from Zimbabwe. Such effects, which can be attributed to the influence of the climatic extremes of alternating droughts and wet seasons on retention of element by hydrous oxide phases and organic matter, are most likely to be severe when relatively weak extractions are used in sample analysis.

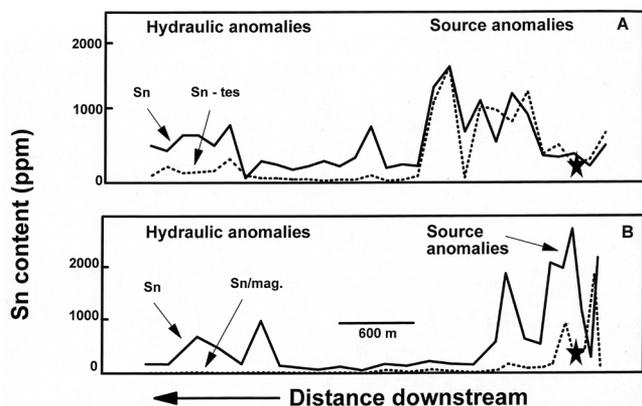


Figure 9: Identification and correction of hydraulically upgraded Sn anomalies in the S. Petal, Malaysia. (a): Sn content of the $-75+53 \mu\text{m}$ fraction has been ratioed to the abundance of the transport equivalent sediment $-212+150 \mu\text{m}$ fraction (modified from Fletcher and Loh, 1996b); (b): Sn content of the $-212+150 \mu\text{m}$ fraction has been ratioed against the abundance of magnetite (modified from Fletcher et al. (1987). Note that transport equivalent size fractions are up to 50% larger than would be estimated on the basis of grain settling velocities.

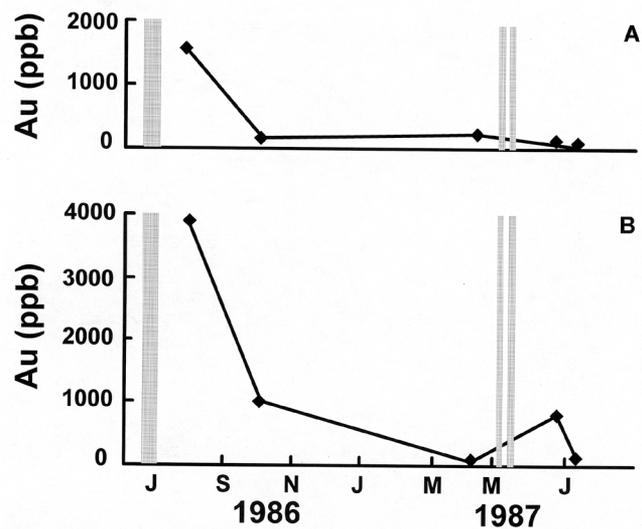


Figure 10: Seasonal variation of gold concentrations in the heavy mineral concentrates from Harris Creek, British Columbia, July 1986 to June 1987. (a) $-106-75 \mu\text{m}$ fraction and (b) $-75+53 \mu\text{m}$ fraction. Shaded areas indicate periods when the stream was in flood with discharges $>10 \text{ m}^3/\text{sec}$. Modified from Fletcher and Day (1989).

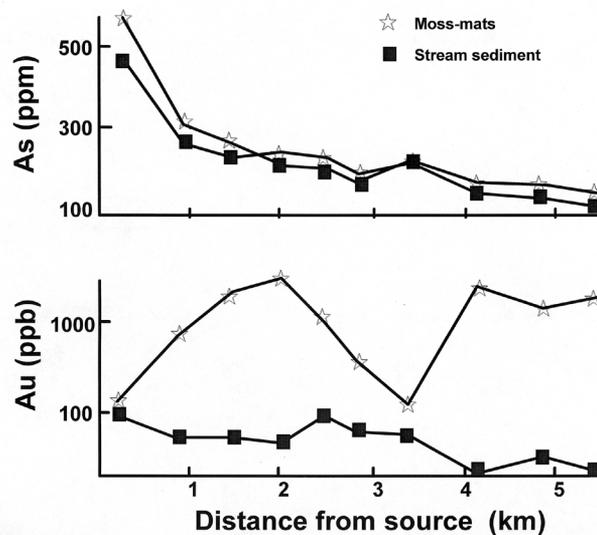


Figure 11: Gold and arsenic dispersion patterns in moss-mats and stream sediments in McKay Creek, Mount Washington, British Columbia. Note the accumulation of gold in the moss-mats relative to the sediments. Arsenic shows no such pattern because it is not stored in the stream bed as a heavy mineral. Modified from Matysek et al. (1989).

REPRESENTATIVITY OF THE SAMPLE AND SUB-SAMPLE

There are two interrelated considerations here: (i) use of a particular fraction or analytical procedures to optimize the anomalous response; and, (ii) particularly for HMEs, ensuring that the sample is adequately representative with respect to abundance of rare grains.

Size and/or density fraction

Assuming that the weathering and breakdown of material from the mineralization supplies metal to a range of size fractions, a choice must be made as to which fraction to use. No universal recommendation is possible but certainly the $-177 \mu\text{m}$ (-80 mesh) fraction is no panacea. For example, this fraction is obviously inappropriate when anomalous concentrations of an element are largely present in coarse lithogenic fragments—as is likely to occur in arid regions or in regions of high relief where mechanical disintegration of bedrock or gossans dominates weathering. Similarly, $-177 \mu\text{m}$ material would give less than optimum results if the anomalous signal is associated with clay minerals or hydrous oxides precipitates in the finer fractions of the sediment, as might be the case for hydromorphically transported elements.

Use of fractions $<100 \mu\text{m}$ can also be beneficial if gold or other HMEs are sought. In this case sedimentological theory, as described in the preceding sections, and exploration case histories (e.g., Carlile et al., 1990; Watters et al., 1989; van Leeuwen, 1994) suggest that fractions $<100 \mu\text{m}$ give the strongest and most consistent anomalies. For example,

in Sulawesi, Carlile *et al.* (1990) found that the Au content of $<90 \mu\text{m}$ sediments and $<177 \mu\text{m}$ pan concentrates gave similar gold concentrations and exploration targets (Figure 12). They concluded that "By sampling the fine sediment fractions with high sampling density, uncertainty associated with the nuggety nature of gold can be reduced to a level where individual results are both repeatable and their concentration values directly comparable throughout the survey areas." The similarity of Au concentrations in the pan concentrates and $\sim 90 \mu\text{m}$ sediments suggests that gold in the latter has been naturally upgraded by flushing of fine lights.

An exception to use of fine ($<100 \mu\text{m}$) sediments for HMEs can occur in disturbed watersheds if increased soil erosion overwhelms the stream's ability to flush fine material from its bed. For example, in the Huai Hin Laep, Thailand, strongly anomalous concentrations of gold in heavy mineral concentrations cannot be detected reliably in conventional stream sediments (Table 2) (Paopongsawan and Fletcher, 1993). Failure to detect the anomaly results from greatly increased soil erosion, caused by ploughing to grow maize, that dilutes the anomaly below the 5 ppb detection limit of fire assay methods of determining gold. The likelihood of detecting the anomaly is greatly increased by use of heavy mineral or field pan concentrates. Alternatively the gold content of the sediments can be determined by: (i) use of more sensitive analytical methods (Fletcher *et al.*, 1995), or possibly (ii) by analyzing the $\sim 106+53 \mu\text{m}$ fraction rather than the whole sediment, i.e., by eliminating the fine sediment contributed by soil erosion (Table 2). The latter approach could probably be further improved by analysis of 100 g samples (by cyanidation) rather than 30 g portions by fire assay procedures.

Sample size

Whenever gold or other elements associated with rare mineral grains are to be determined, sample representativity and the nugget effect become important. The severity of this problem for gold in stream sediments was described by Harris (1982) and dealt with in detail by Nichol *et al.* (1989) at Exploration '87. A simple, ballpark approach that is adequate for most purposes uses the Poisson distribution to estimate the probability of detecting (or missing) an anomaly on the basis of the average number of rare grains likely to be present in a sample (or sub-sample) of a specified size.

In Table 3, the probability of *missing* anomalies has been estimated for analysis of 30 g analytical sub-samples in which gold is assumed to be present in particles equivalent in size to $53 \mu\text{m}$ spheres. One such sphere has a mass of approximately $1 \mu\text{g}$ of gold and will contribute roughly 30 ppb gold to a sample of this size. With a single, 30 g sample containing fewer than three gold particles (i.e., $<100 \text{ ppb Au}$) there is a $>5\%$ chance of an anomaly being missed. The corresponding lower limit of anomaly detection is at 30 ppb with 100 g sub-samples and at 300 ppb with 10 g sub-samples. It is thus apparent why a 30 g fire assay is better than a 10 g fire assay, and why analysis of 100 g samples by cyanidation might be even better. The data in Figure 13, from a stream sediment survey in British Columbia, confirm that 30 g sub-samples are much more likely to detect anomalous conditions than 10 g sub-samples.

From Table 3 it should be noted that once an average of three or more particles of gold are present in a sub-sample of a given size there is a $>95\%$ chance of at least one gold particle being present in any analytical

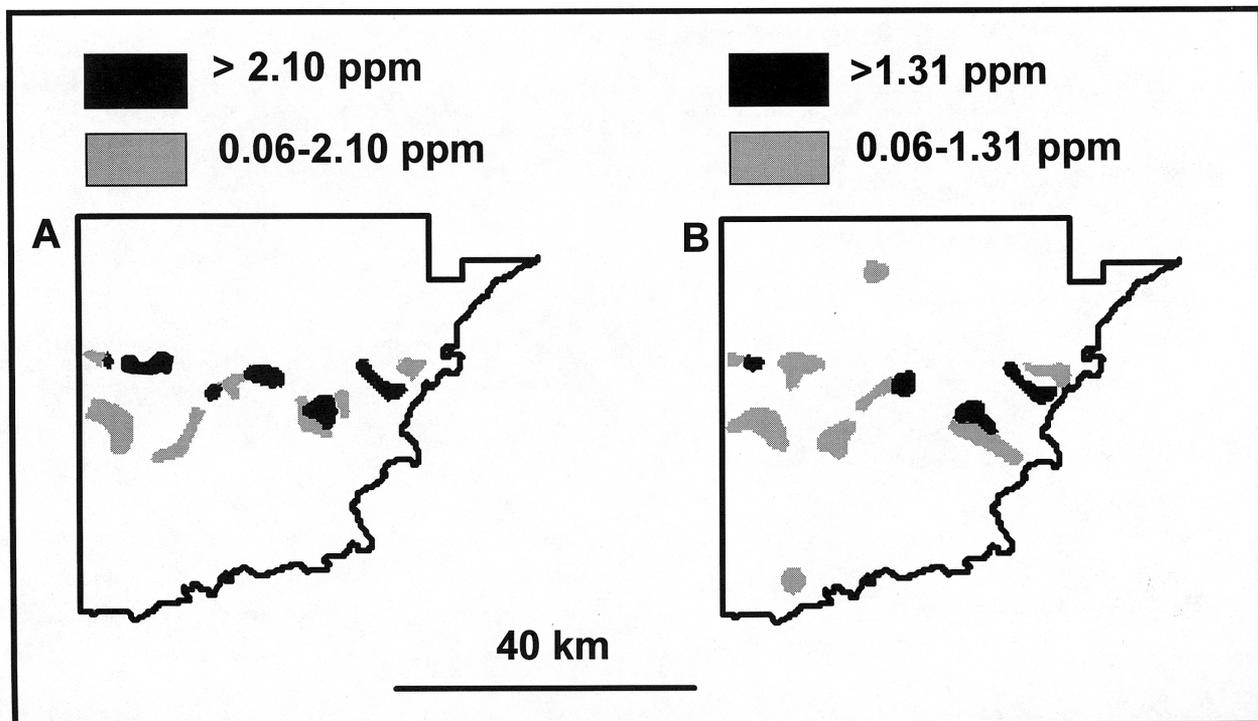


Figure 12: Gold in (a) $\sim 177 \mu\text{m}$ pan concentrates and (b) $\sim 90 \mu\text{m}$ stream sediments from a regional geochemical survey in northern Sulawesi, Indonesia. Modified from Carlile *et al.* (1990).

split of the specified size. There is a correspondingly high probability of the anomaly being detected provided that random errors (field sampling and laboratory errors) are small compared to the difference between the background concentration of gold and the concentration given by the *background + one gold particle*. For example, with a background concentration of 5 ppb, 30 g samples and 53 μm gold spheres, *background + one gold particle* would be approximately 40 ppb gold, background + 2 gold particles would be approximately 70 ppb, and so on. The criteria of Clifton *et al.* (1969) for a sample to contain a minimum of 20 particles of gold results in a sampling error of $\pm 45\%$. However, in surveys intended *only* to detect the presence of anomalies, Clifton's criteria is too severe insofar as there is a high probability of anomalies being detected with as few as three particles of gold. Based on the above, probabilities of missing the gold anomaly in the Huai Hin Laep were estimated for various fractions and fluvial environments (Table 2).

Table 2: Gold content of stream sediments and heavy mineral concentrates, estimated numbers of gold particles and probability to miss an anomaly based on a single sample, Huai Hin Laep, Thailand.

	Bar (n=11)		Pavement (n = 5)	
	-106+53 μm	-106 μm	-106+53 μm	-106 μm
Au in sediment (ppb)	60	<5	160	10
Sediment (%)	6.38	100	6.86	100
Gold particles in 30 g	0.37	0.02	1.13	0.07
P (%) to miss anomaly	69	98	32	93
Gold particles in 100g	1.23	0.07	3.77	0.23
P (%) to miss anomaly	29	93	2	79
HMC (%)	0.45		0.49	
Au (ppb) in HMC	12,000		32,000	
Gold particles in 30g	74		226	

A recommendation to use the $-100\mu\text{m}$ fractions for HMEs seems to contradict use of BLEG (Bulk Leach Extractable Gold) and BLC (Bulk Leach Cyanide) methods that use cyanidation to extract gold from bulk ($>1\text{ kg}$) samples of coarsely screened or unscreened material. However, bulk samples should contain sufficient of the fine, gold-bearing size fractions to be representative. For example, if 5 kg of sandy gravels taken for BLEG analysis contain only 100 g (i.e., 2%) of $-100\mu\text{m}$ material, this is still three times more than the 30 g used in fire assay. BLEG thus improves sample representativity and, as argued by Radford (1996), the probability of detecting very rare flakes of gold released by erosion and weathering of a gold deposit. He quotes a cost of US\$1,200 per site for a helicopter-supported BLEG programme in Southeast Asia.

A disadvantage of BLEG is that variation in the content of fine sediment in the bulk samples causes variable dilution of the gold content

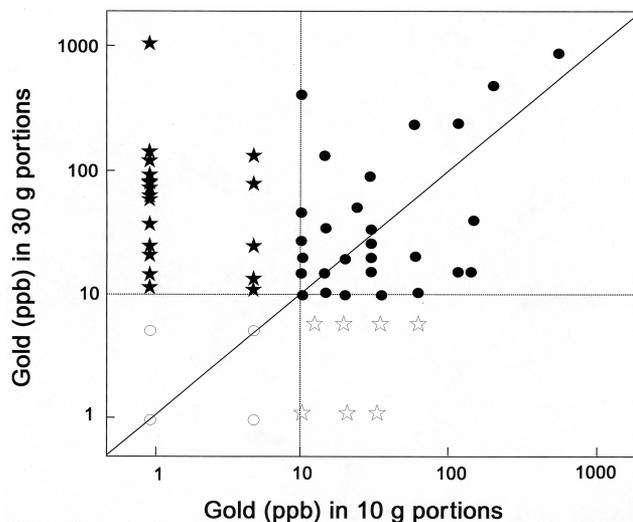


Figure 13: Determination of gold content of 10 and 30 g splits of stream sediment samples from British Columbia. Note that with a threshold of 10 ppb thirteen anomalous samples went undetected in the 10 g splits versus only three using 30 g splits. The considerable scatter in the data probably results from there being too few gold particles in samples of these sizes. Data courtesy of Westmin Resources Ltd.

(Mazzucchelli, 1992, 1994). More consistent results would be expected if the coarse (Au-barren) material was screened-off and the fines were then treated by either fire assay (if $< 30\text{ g}$) or cyanidation ($> 30\text{ g}$). Bearing in mind the cost of sampling quoted by Radford, the relatively modest additional cost of screening the sample to obtain the optimum size fraction, minimize variability, and maintain sample representativity would seem to be warranted.

ORIENTATION SURVEYS

Orientation surveys are an important first step to the exploration effort to establish optimum sampling densities, sampling media, size fractions and the analytical procedures to be used (Rose *et al.*, 1979). They can take several forms, ranging from detailed research, through prior experience in a region, to literature surveys. Here we emphasize the importance of addressing the following questions:

Will stream sediments adequately represent the survey area

It is important to recognize where streams are decoupled from the adjoining valley slopes and stream sediments do not, therefore, represent the catchment basin, i.e., any gaps in the coverage provided by stream sediments should be identified. This can come from field observation, air photos, terrain analysis etc. Depending on the terrain, remedial action may range from augmenting the sediments with base-of-slope colluvial soils to use of widely spaced soil sampling grids.

Table 3: Concentrations of gold, probability of missing an anomaly, and sampling precision at the 95% confidence level. Based on analysis of a single 30 g sample. All values “ballpark” based on gold sphere 53 μm diameter and probabilities from the Poisson distribution.

Gold (ppb)	5	10	25	33	50	100	250	500	666 ^[1]	1000
Av. num. of grains	0.15	0.30	0.75	1.00	1.50	3.00	7.50	15.0	20.0	30.00
P to miss (%)	85	75	50	37	22	5	<<1	<<1	<<1	<<1
Precision (\pm %)	>>>	>>>	>>>	>>>	>>>	>>>	73.0	51.6	44.7	36.5

1. The value of 20 grains corresponds to the criteria of Clifton *et al.* (1969).

>>> Precision worse than \pm 100%

Sample site

Where to sample

What fluvial environments are present in the stream channels (e.g., bar head, pools, riffles etc.), are they easy to recognize, and how are they going to influence geochemical responses? Which of the environments is most appropriate to sample? (This may differ for reconnaissance and detailed follow-up surveys, and will also depend on whether HMEs are to be determined.)

Sample density and spacing

This depends on the objectives and logistics of the survey. From Hawke's model the length of the dispersion train is controlled by relative size of the source anomaly and the drainage basin: however, a large deposit may have only a small surface expression exposed to weathering and erosion. For routine surveys conservative sampling intervals might be around 1 sample per 200 m along first, second and third order streams, and immediately upstream of confluences. Sampling densities might safely be lower (1 per 10 km²?) if advantage can be taken of the behaviour of heavy minerals. However, it is probably prudent to take more than one type of sample and at different densities. (It is not uncommon, for example, to get divergent results between gold in pan concentrates and stream sediments [Tooms, 1987].)

Sample size

This becomes especially important when HMEs are involved. Choices must be made between preparation of field pan concentrates (with possible loss of fine heavies and large differences in panning efficiency between individuals (Stendal and Theobald, 1994)) or transporting large samples for either separation of a representative size fraction or laboratory preparation of a heavy mineral concentrate (or analysis by BLEG for gold).

When to sample

Where there are seasonal or other large climatic variations, the possible effects of these on the survey must be considered. Use of alternative media (e.g., moss-mats) may have to be considered.

CONCLUSIONS

Stream sediment geochemical surveys provide a robust, cost-effective method of mineral exploration wherever stream drainage systems are well developed. The results of such surveys can be improved by careful attention to the representativity of the sediment sample at scales that range from the catchment basin, through location of the sample site on the stream bed, to the size of the field and analytical samples.

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