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Some advances in understanding and application of stream sediment geochemistry to mineral exploration in SE Asia

W.K. FLETCHER

Geological Sciences, Dept. of Earth and Ocean Sciences
University of British Columbia
Vancouver, Canada

Abstract: Stream sediment geochemical surveys are a widely used method of mineral exploration in tropical rainforests worldwide. The basic premise of such surveys is that a stream sediment is representative of the products of weathering and erosion upstream of the sample site and can thus detect anomalous concentrations of metals released from a mineral deposit within the drainage basin. Ideally, representative samples must be collected from streams throughout the survey area at a sample density sufficient to detect anomalies related to mineral deposits. Representativity of the sample must then be maintained through all stages of sample processing and analysis. There are many situations in which these ideals cannot be achieved. For example, a flood plain may isolate the stream from the valley sides or supply of new sediment to a stream may be from a few point sources (e.g., landslides), the location and activity of which varies with time. Also, fluvial processes modify the composition of the sediment as it moves along the channel with important consequences for elements, such as gold and cassiterite, associated with heavy minerals.

Detailed sedimentological studies in the S. Petai, Malaysia have shown that sediments (SG~2.7) finer than about 100 µm tend to be rapidly swept downstream in suspension whenever sediment transport occurs. This causes both the greatest and most consistent enrichment of cassiterite to occur in the finer fractions of the sediments. Heavy mineral content of coarser size fractions becomes increasingly erratic because their accumulation is strongly dependent on local hydraulic conditions on the streambed. Based on the S. Petai studies, the relatively uniform enrichment of heavy minerals in the finer fractions (< 100 µm) of the sediments best represents the geochemistry of the drainage basin as a whole. Use of fine fractions also reduces the nugget effect during sampling, so that these fractions typically give the most consistent anomalous dispersion trains.

Anthropogenic disturbance, by logging or agricultural activities, can also influence sources of sediment and rates of supply. For example, in Thailand increased soil erosion, caused by deforestation and planting of maize, has resulted in a gold anomaly being diluted to the extent that it is not detected reliably by conventional stream sediments. However, effects of disturbance are not always so severe and results from a mature rubber estate in Peninsular Malaysia suggest that conditions return to near-normal once a groundcover of vegetation has been reestablished.

INTRODUCTION

Geochemical exploration methods are used widely for mineral exploration in the Southeast Asian region (for example, Watters *et al.*, 1989; Carlile *et al.*, 1990, 1998; Andrews *et al.*, 1991; van Leeuwen, 1994; Dugmore *et al.*, 1996). Appleton and Ridgeway (1994) review application of drainage surveys in tropical rain forest terrains and various aspects of stream sediment geochemistry in SE Asia have previously been discussed by Fletcher (1996a, b; 1997a, b). Sillitoe (1995) summarizes the important role that geochemical methods have played in discovery of base and precious metal deposits in the circum-Pacific, including SE Asia, during the last 25 years. Here we: (i) examine the validity of the premises underlying stream sediment geochemistry; and (ii) make recommendations to improve design and interpretation of stream sediment surveys in the Southeast Asian region.

Hawkes (1976) expressed the basic premise of stream sediment sampling as a simple dilution model that relates the source of an anomaly to the metal content of the anomalous sample and catchment basin size (Fig. 1):

$$Me_mA_m = A_a(Me_a - Me_b) + A_mMe_b$$

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.

Important assumptions 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. It follows that, as the catchment basin area increases, identical anomalous targets (Me_mA_m) will produce shorter anomalous dispersion trains, with steeper geochemical gradients. Thus, the length and/or strength of a stream sediment anomaly can be less significant than the size of the catchment basin upstream of the sample site (Mackenzie, 1977).

THE CATCHMENT BASIN SCALE

Hawke's model will best fit small streams where the valley slopes and the stream channel are rather closely linked or coupled. 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 interfluves are thus no longer represented in the composition of the sediments. Leggo (1977) gives an example from Fiji (Fig. 2). Two copper prospects associated with colluvial soils give strongly anomalous copper values in streams draining them: a third prospect is covered by alluvium and gives no response in stream sediments.

In mature geomorphic terrains, with wide flood plains and broad interfluves 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 2,000 x 500 m grid, with sediment samples being taken where lines crossed streams, for exploration of 6,000 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

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. Typically the –177 µm (–80 mesh ASTM) fraction is analyzed after a strong acid decomposition. Suitable material can be found: (i) behind obstacles such as large boulders; (ii) in pools at the tail-ends of bars or between riffles; or, (iii) infilling voids below the surface of cobble-gravel bars. Each of the above sites are distinct fluvial environments with their own characteristics. However, the differences between these environments are probably not too important except for heavy mineral associated elements (HMEs) which can give very different results depending on the fluvial environment. For example: (i) in the S. Petai, Malaysia, Sn concentrates in high energy environments (Table 1) (Fletcher *et al.*, 1984, 1987);

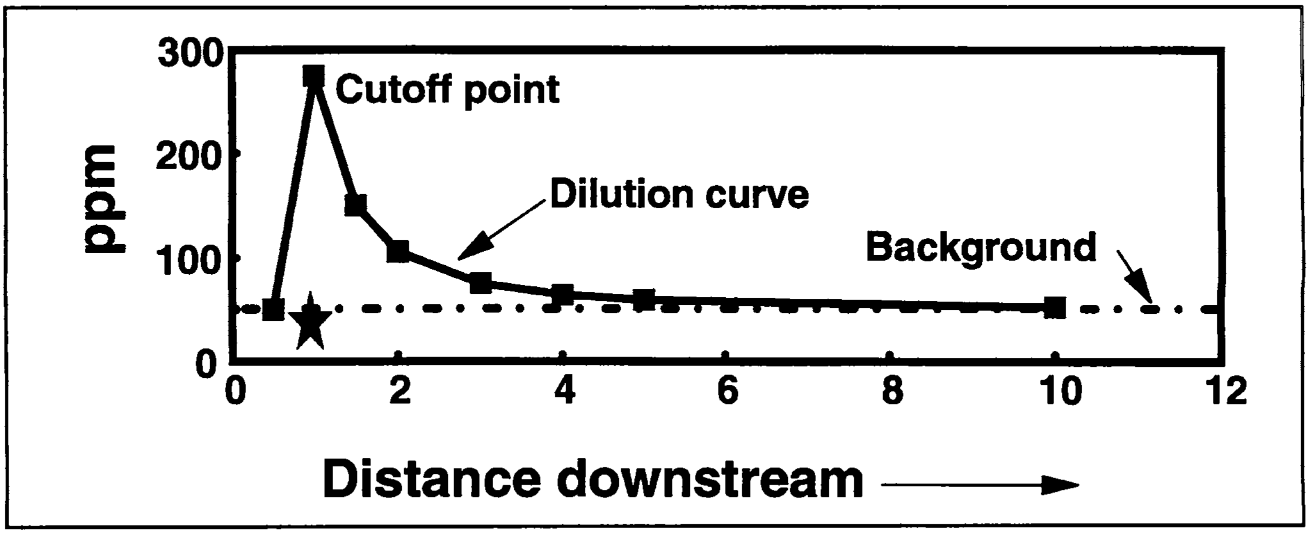

Figure 1. Hypothetical anomaly dilution curve based on Hawke's model. The star marks the location of the source anomaly, the background concentration is 50 ppm and the cutoff point is the maximum extent of the anomaly upstream.

and (ii) Paopongsawan and Fletcher (1993) found that gold accumulated at pavement versus bar heads sites in a small stream in Thailand (Table 2).

Fletcher and Loh (1996a, b; 1997) used pit traps in the S. Petai, Malaysia, to make detailed studies of the transport and deposition of cassiterite by a small stream. Most importantly, selective elimination of light mineral grains (SG~2.7) from the streambed was found to enrich the streambed in heavy minerals. For sediments finer than about 100 µm this process of winnowing probably occurs whenever there is bedload transport (Fig. 3) (Bagnold, 1973) and is thus widespread on the stream bed. Conversely, elimination of lights mineral grains larger than 100 µm 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 is especially apparent in the perhumid tropics where clay-size particles from the deeply weathered regolith are rapidly flushed from the streambed by frequent high discharge conditions (Fig. 4) (Fletcher and Loh, 1997; Pickup *et al.*, 1981). The sediments thus undergo the natural 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 small Malaysian stream, Sirinawin *et al.* (1987) found that sandy sediments have a much higher Sn content than associated clay-rich soils (Fig. 5).

At the bar scale, there are large variations in HME concentrations on the streambed. These differences are most pronounced for the coarser fractions and very high density heavy minerals, but decrease with decreasing density and grain size so that they are (usually) minor for fractions finer than about 50 µm. For example, Fletcher *et al.* (1987) found fine cassiterite was rather uniformly upgraded at both high and low energy sites in the S. Petai (Table 1). Conversely, coarse cassiterite is 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.

The field sample, 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., Fig. 6a). Samples can be collected from high or low

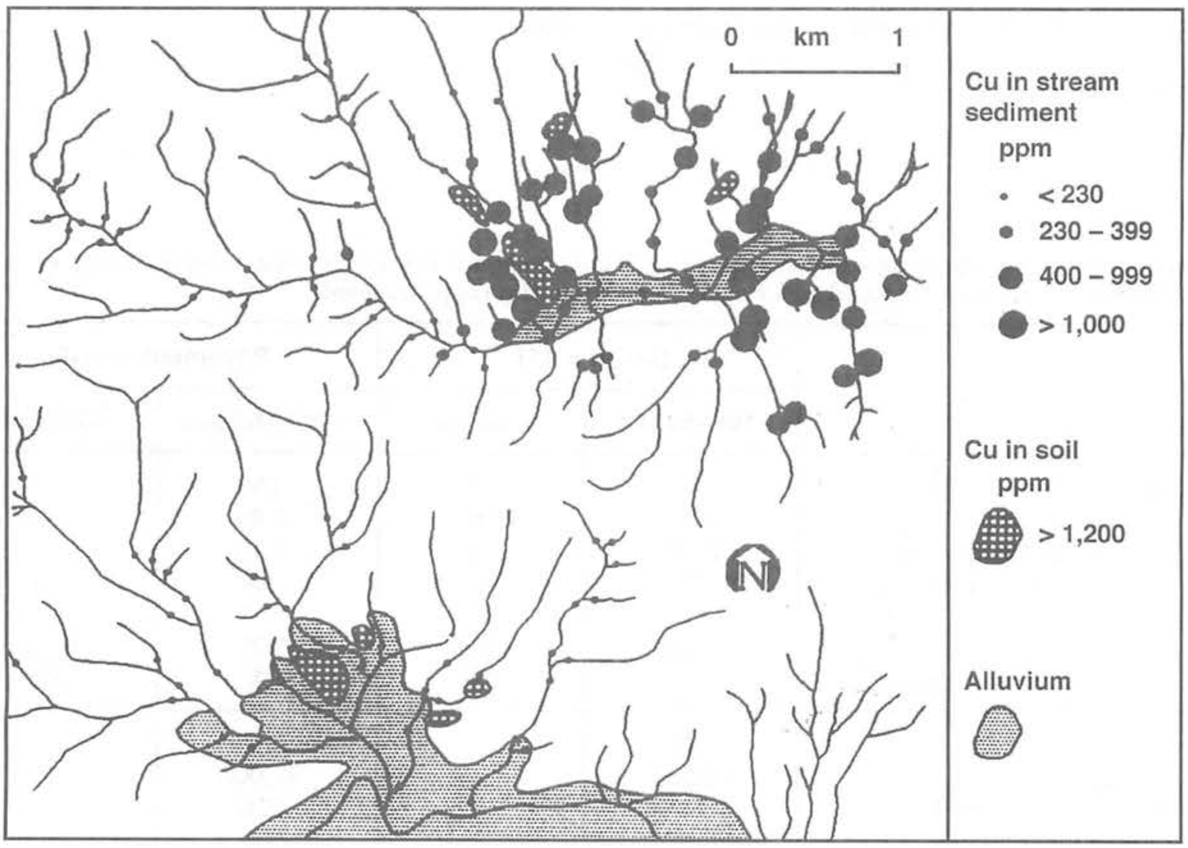

Figure 2. Dispersion of Cu from copper prospects in the Namosi district of Fiji. The southern prospect is not reflected in the stream sediment geochemistry because of the influence of the alluvium decoupling the stream from the bedrock. From Appleton and Ridgway (1994), based on results of Leggo (1977).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

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

SIZE (μm)	ENVIRONMENT		Ratio[1]	t^2
Element	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 (%)

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	

energy sites, but are easier to obtain at the latter. Conversely, if fractions coarser than 100 µm are used larger samples are required, dispersion trains become more erratic, and isolated anomalies at high-energy sites can be displaced a considerable distance downstream from their source.

Behaviour of the HMEs also influences the choice of sample interval by counteracting the effects of anomaly dilution downstream. Conversely, 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 Fig. 6b: both tin and arsenic have similar, 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

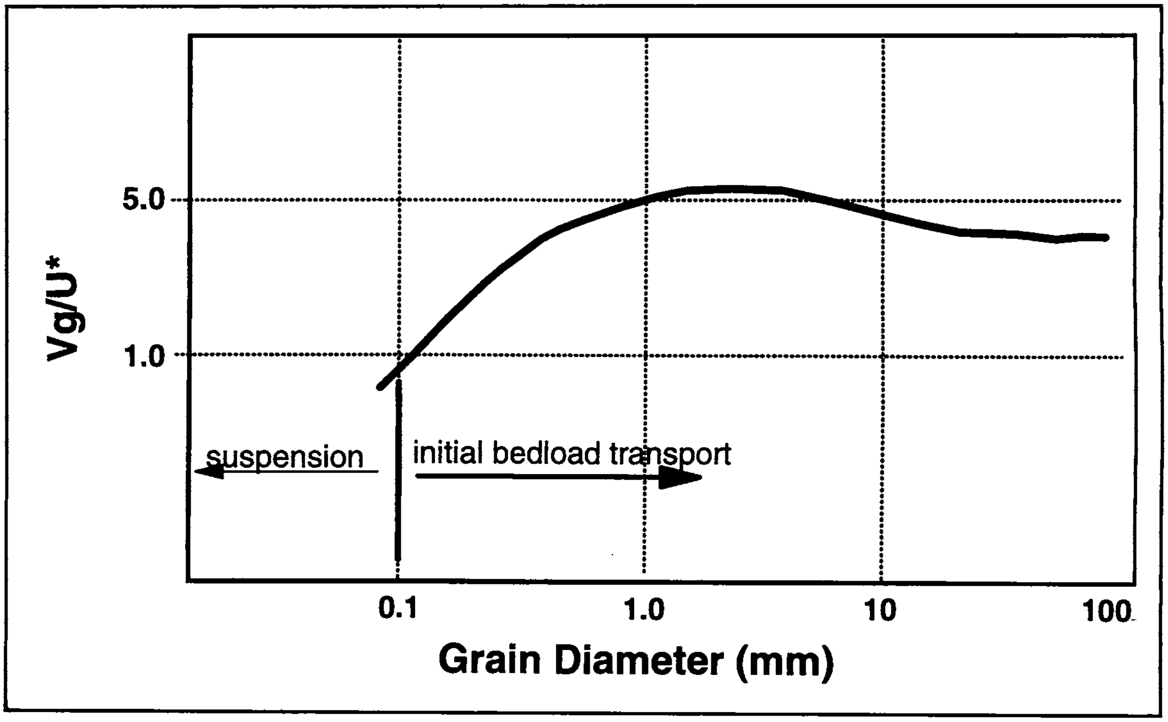

Figure 3. Ratio of grain settling velocity (Vg) to shear velocity (U*) versus grain size (Based on Bagnold, 1973).

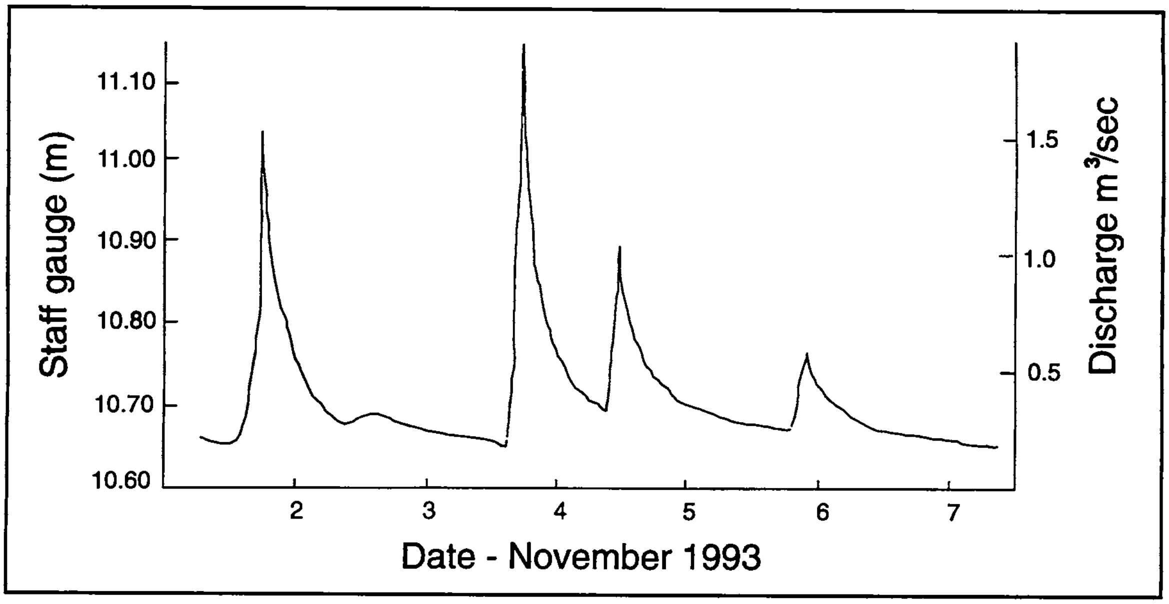

Figure 4. Hydrograph of the S. Petai, Malaysia, during the monsoon season (From Fletcher and Loh, 1997).

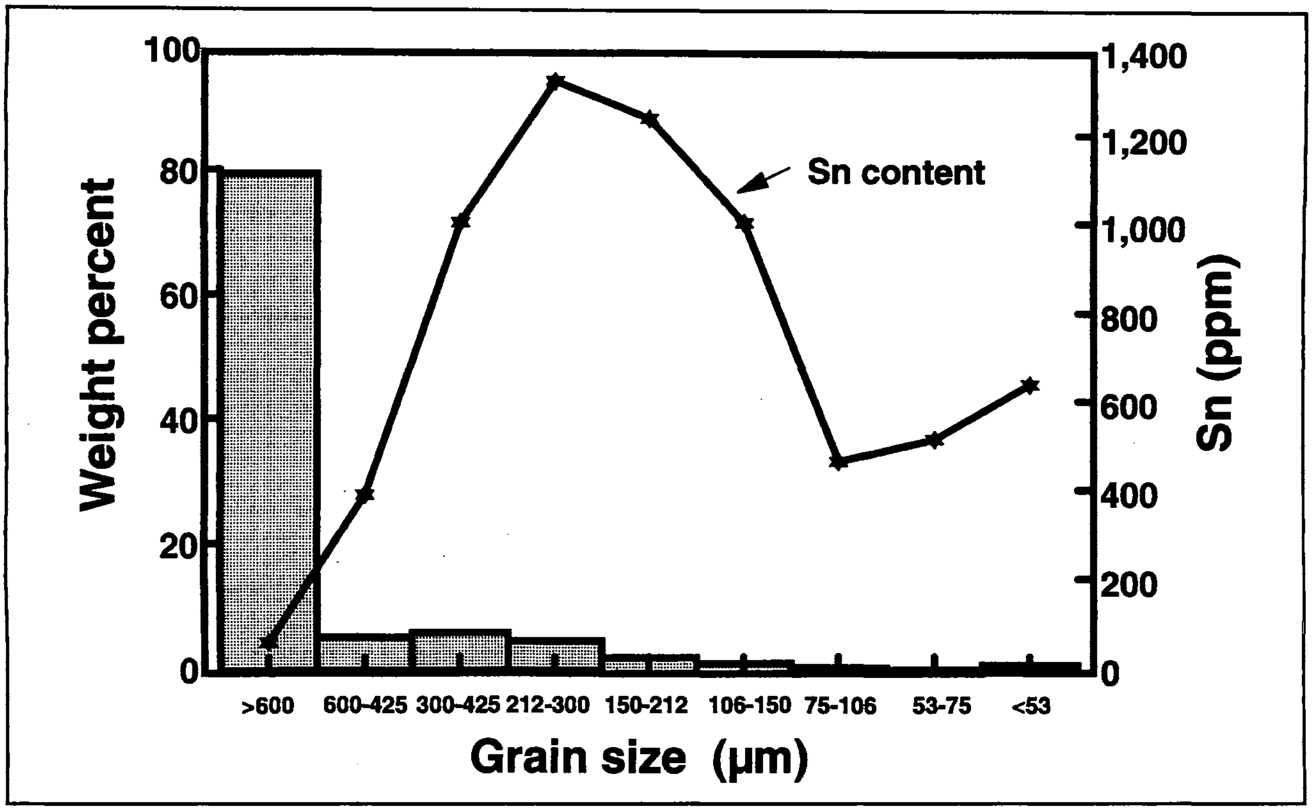

Figure 5a. Grain size distribution and concentrations of Sn in sediments, Tanjong Tualang, Malaysia. Based on Sirinawin *et al.* (1987).

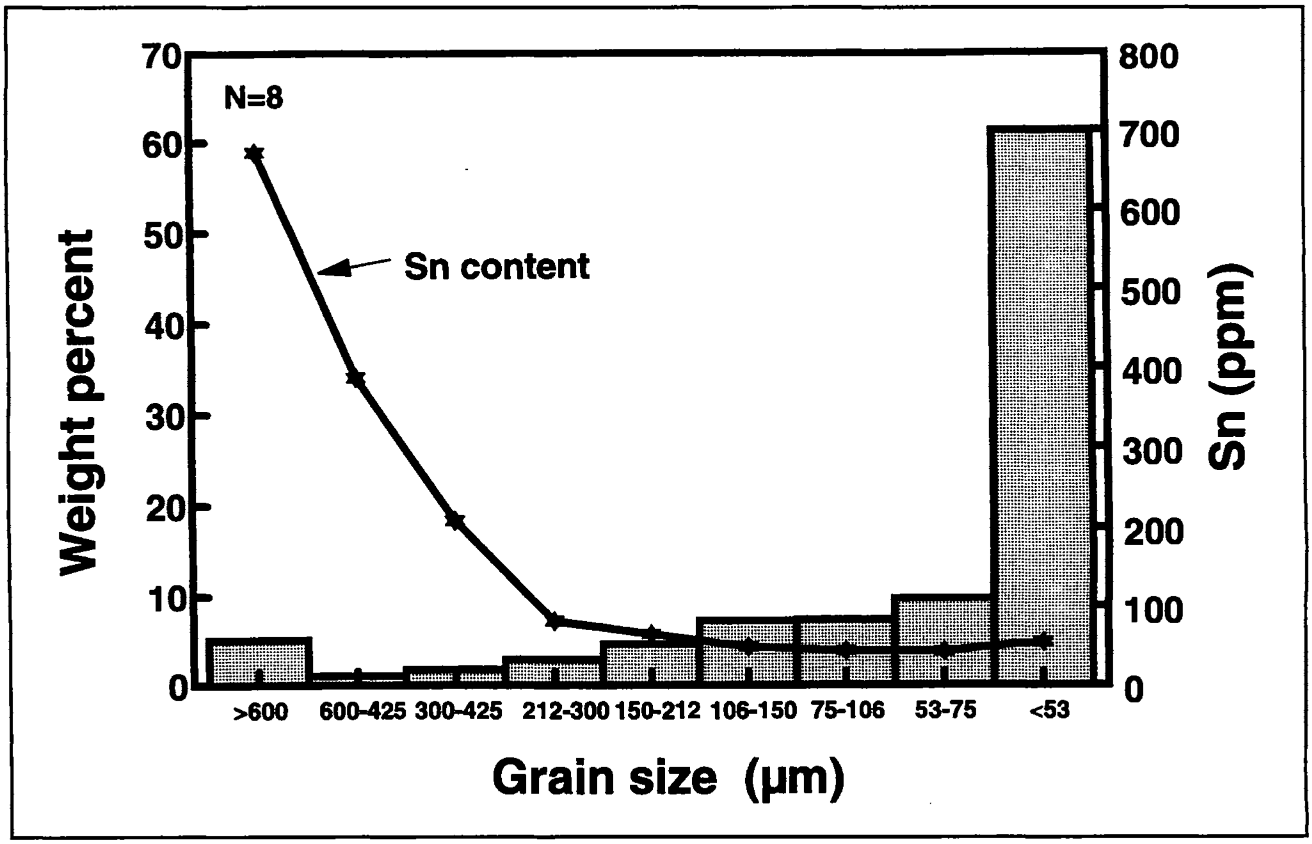

Figure 5b. Grain size distribution and concentrations of Sn in soils, Tanjong Tualang, Malaysia. Based on Sirinawin *et al.* (1987).

gold versus base metals at Mt. Bini in Papua New Guinea (Fig. 7) (Dugmore *et al.*, 1996) and perhaps at Batu Hijau (Fig. 8). Also, Carlile *et al.* (1998) reported that reconnaissance gold anomalies were displaced to a break-in-stream slope 6.5 km downstream from their source at the Gosowong epithermal deposit, Halmahera, Indonesia. The longer dispersion trains provided by the HMEs, if properly sampled for, are especially useful for reconnaissance surveys.

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: (a) absence of anomalies of the more mobile elements (e.g., arsenic in Fig. 6b, and Cu in Fig. 7); (b) reduced anomaly contrast if concentration of the HME is ratioed to (i) the abundance of a more ubiquitous heavy mineral such as magnetite (e.g., Fig. 9b); or, more generally, as described by Fletcher and Loh (1996a), by (ii) re-expressing concentrations relative to the transport equivalent size fraction of the sediment (Fig. 9a). With respect to the latter method, the transport equivalent sizes of cassiterite and gold are light mineral grains roughly three and five times larger, respectively. Field observations on stream width and changes in bed are also helpful (Paopongsawan and Fletcher, 1992).

SIZE FRACTION AND SAMPLE REPRESENTATIVITY

Assuming that weathering and erosion of primary 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 µm (–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 µm 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.

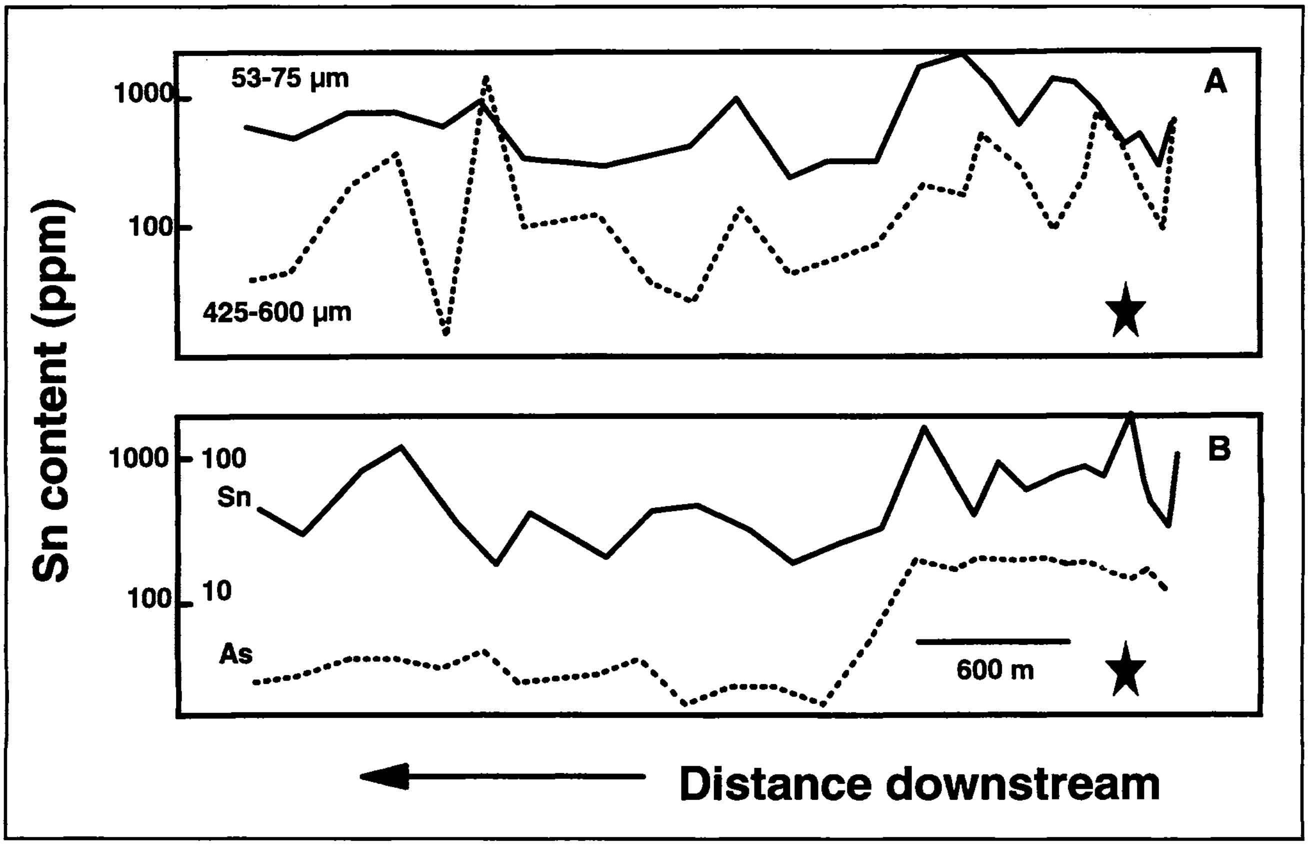

Figure 6. (a): concentrations of Sn in the –75+53 µm and –600+425 µm stream sediments from the S. Petai, Malaysia; and (b): concentrations of Sn and As in –80 mesh sediments from the S. Petai. Soil anomalies at the source contain 1,300–1,800 ppm Sn and 1,930–2,600 ppm As. The downstream dispersion pattern for W is similar to that for Sn whereas patterns for Cu, Pb, Zn, Li and F are similar to the As patterns. The * indicates the location of the primary tin mineralization. Based on Fletcher *et al.* (1984, 1987).

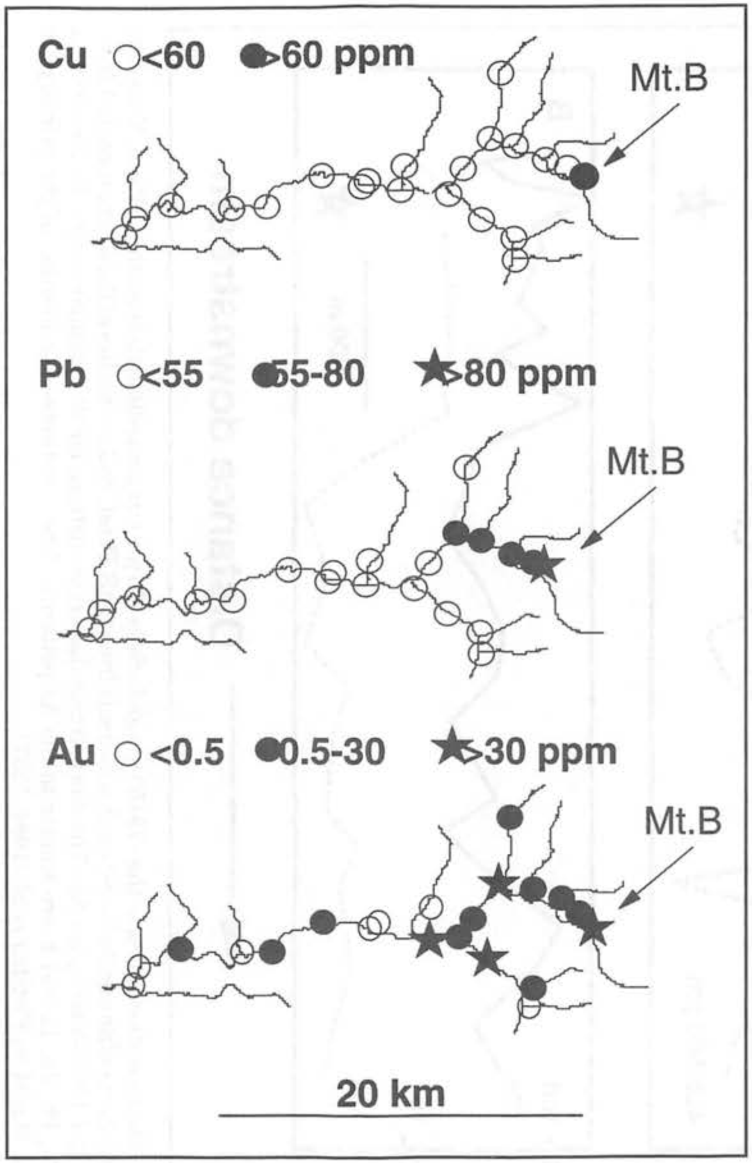

Figure 7. Results obtained in a reconnaissance stream sediment survey downstream from the Mt. Bini copper-gold-molybdenum deposit in Papua New Guinea: gold content in heavy mineral pan concentrates; copper and lead in ground < 2 mm sediments. Bulk cyanide leach gold (not shown) did not display a distinct anomalous dispersion train at the reconnaissance level. Modified from Dugmore *et al.* (1996).

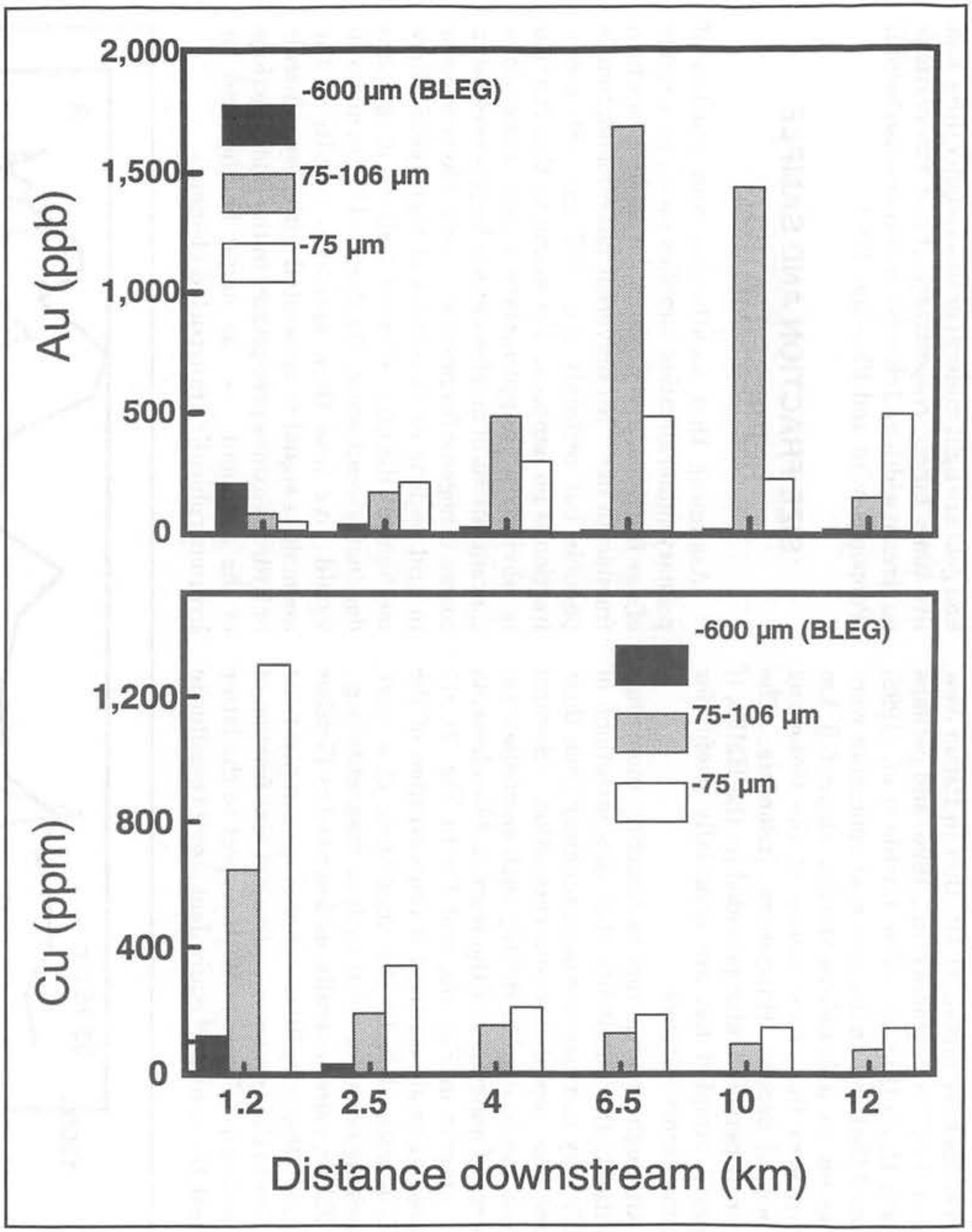

Figure 8. Dispersion of gold and copper in stream sediments at Batu Hijau (Data courtesy of Newmont Exploration Ltd.)

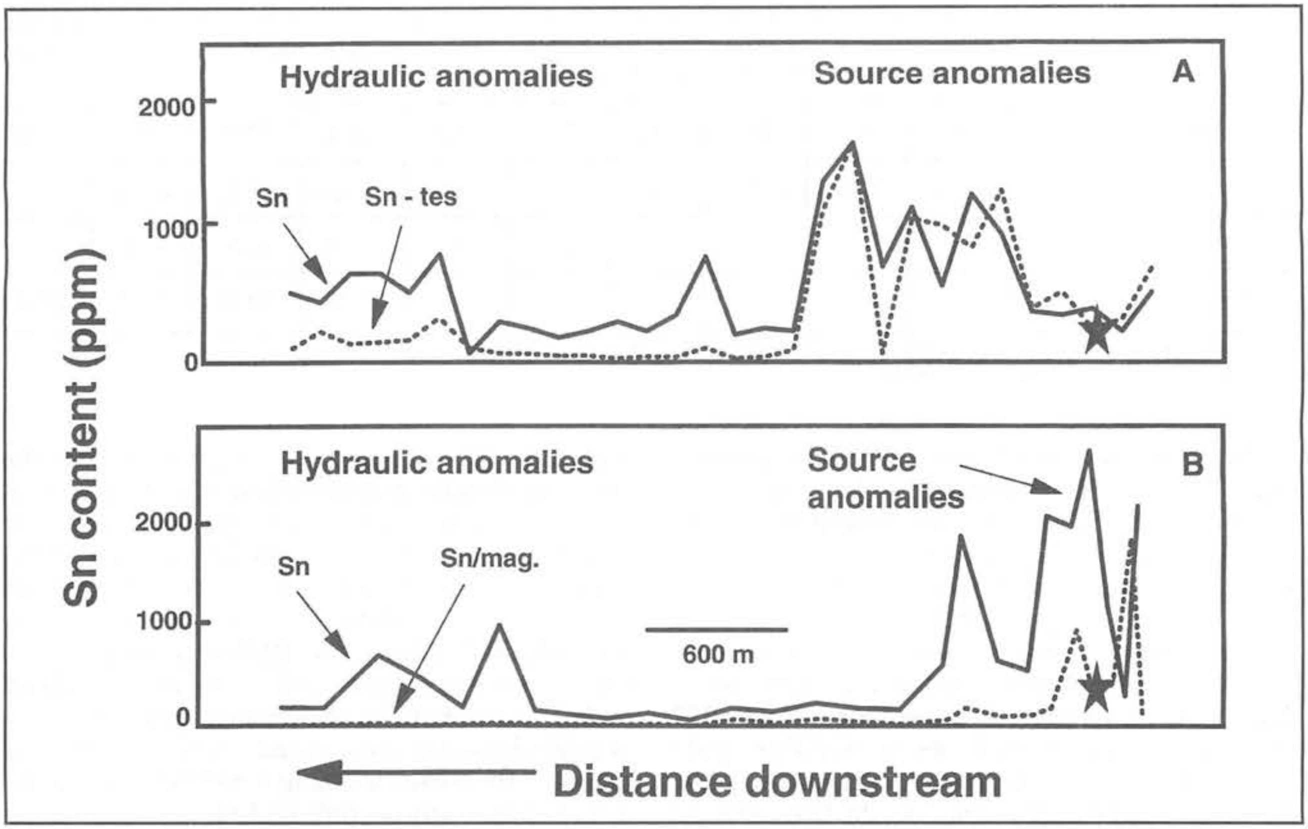

Figure 9. Identification and correction of hydraulically upgraded Sn anomalies in the S. Petai, Malaysia. (a): Sn content of the –75+53 µm fraction has been ratioed to the abundance of the transport equivalent sediment –212+150 µm fraction(modified from Fletcher and Loh, 1996b); (b): Sn content of the –212+150 µm 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.

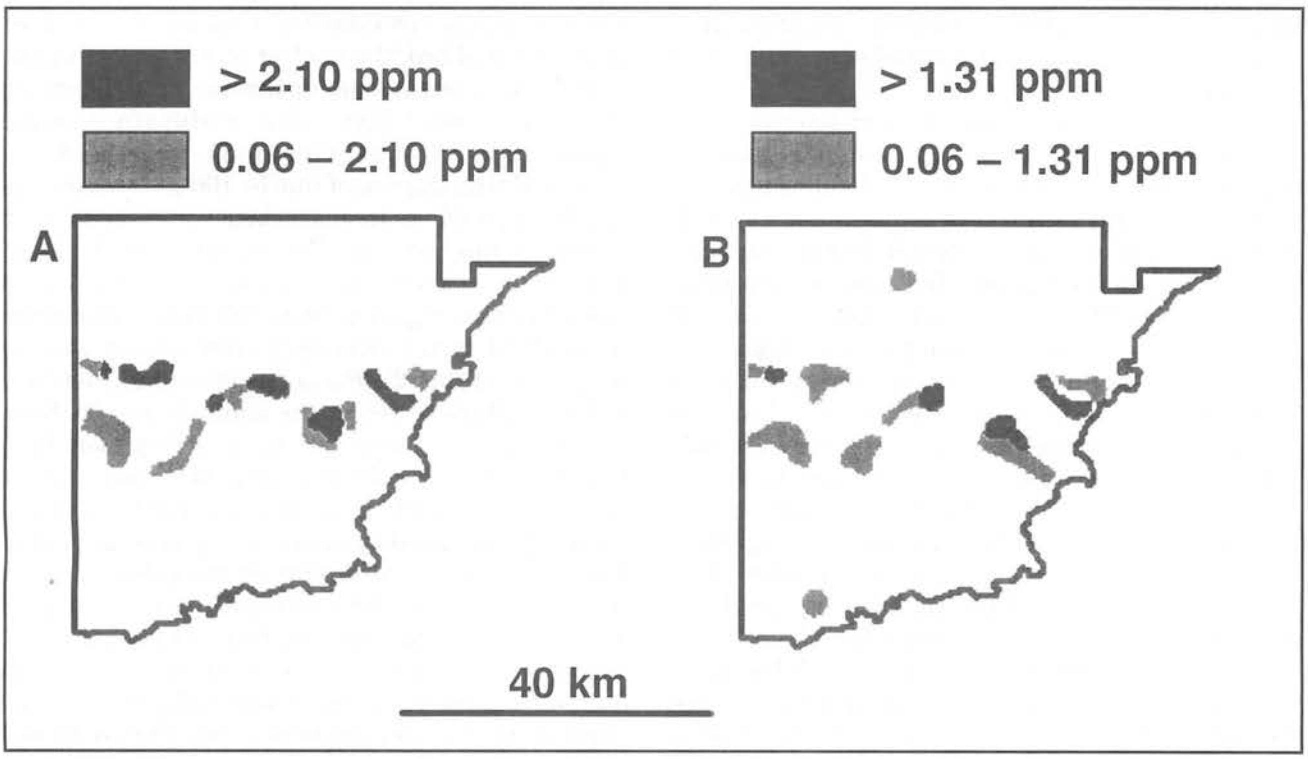

Figure 10. Gold in (a) –177 µm pan concentrates and (b) –90 µm stream sediments from a regional geochemical survey in northern Sulawesi, Indonesia. Modified from Carlile *et al.* (1990).

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 (From Fletcher, 1997a).

Gold (ppb)	**5**	**10**	**25**	**33**	**50**	**100**	**250**	**500**	**666***	**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 (+/–%)	>>>	>>>	>>>	>>>	>>>	>>>	73.0	51.6	44.7	36.5

* The value of 20 grains corresponds to the criteria of Clifton *et al.* (1969).
>>> Precision worse than +/– 100%.

Use of fractions < 100 µm is 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 µm give the strongest and most consistent anomalies. For example, in Sulawesi, Carlile *et al.* (1990) found that the Au content of < 90 µm sediments and < 177 µm pan concentrates gave similar gold concentrations and exploration targets (Fig. 10). 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 –90 µm sediments suggests that gold in the latter has been upgraded by flushing of fine lights.

Whatever size fraction is used for determination of gold it is important to ensure sample representativity. Clifton *et al.* (1969) suggested that for a reliable estimate of gold content a sample should be large enough to contain twenty particles of gold. From the Poisson Distribution sampling error $R(\%) = 100/\sqrt{z}$ where z is the average number of rare (gold) grains in a sample of a given size. Clifton's criterion is therefore equivalent to a sampling error of approximately ±22%. From an exploration viewpoint this usually requires a sample size that is much too large to be practical. If, however, the criteria for determining sample size is reduced to achieving a 95% chance of recognizing the presence of anomalous gold concentrations then only an average of three particles of gold are required in a sample of a given size (Table 3).

Use of the –100 µm fractions for HMEs seems to run counter to application of BLEG (Bulk Leach Extractable Gold) methods that use cyanidation to extract gold from bulk (> 1 kg) samples of coarse material. The expectation, however, is that the bulk sample will contain sufficient of the fine, gold bearing, size fractions to be representative. For example, if 2 kg of sandy gravels taken for BLEG analysis contain only 100 g (i.e., 5%) of –100 µm material, this is still three times more than the 30 g sample used in fire assay. BLEG can thus improve 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 fines in the bulk samples causes variable dilution of the gold content (Mazzucchelli, 1992, 1994). More consistent results would be expected if the coarse (Au-barren) material was removed before cyanidation. Considering the cost quoted by Radford, the modest cost of screening the sample to obtain the optimum size fraction, minimize variability, and maintain sample representativity would seem to be warranted.

For HMEs the use of fine (< 100 µm) sediments can be a problem in disturbed watersheds with increased soil erosion. For example, in the Huai Hin Laep, Thailand, strongly anomalous concentrations of gold in heavy mineral concentrates 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 gold anomaly below the 5 ppb. The probability 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 –106+53 µm fraction rather than the whole sediment, i.e., by eliminating the fine sediment contributed by soil erosion (Table 2).

Although Douglas *et al.* (1992) have shown that selective logging of tropical rain forests in Sabah increases soil erosion at least temporarily, it is not yet clear to what extent this can modify geochemical patterns in stream sediments. Results from streams in mature rubber estates suggest that once disturbance ceases and a groundcover of vegetation has been reestablished behaviour of heavy minerals on the streambed returns to near-natural conditions (Sirinawin *et al.*, 1987).

ORIENTATION SURVEYS

Orientation surveys are an important first step in designing an exploration geochemical. Here we emphasize the importance of addressing the following questions:

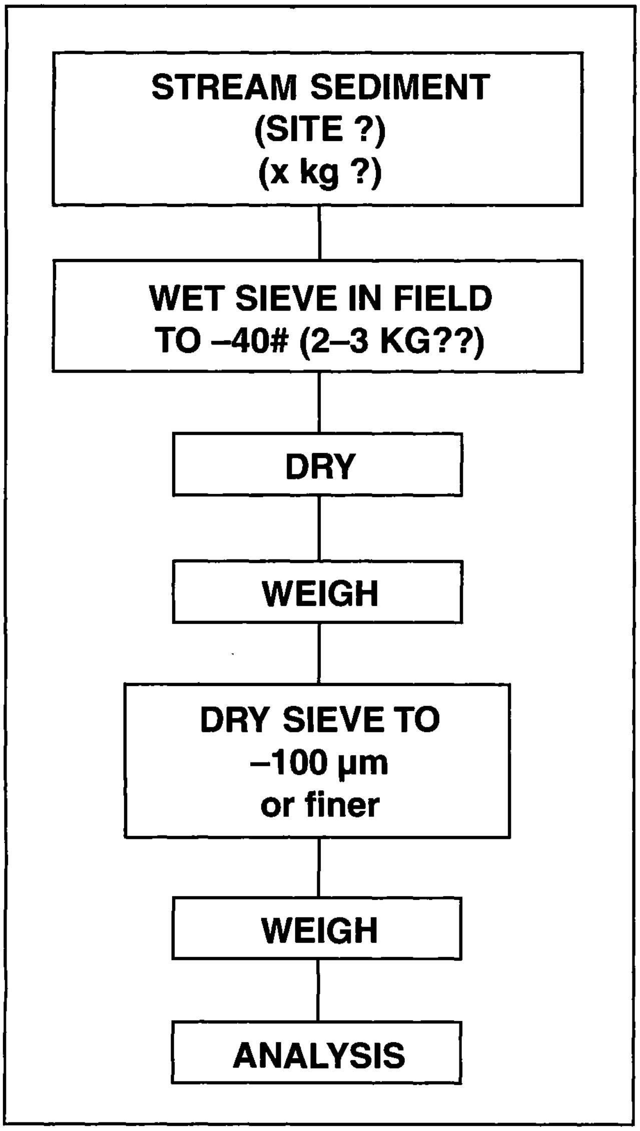

Figure 11. Flow sheet for sample collection, preparation and analysis when gold is to be determined (modified from Andrews *et al.*, 1991).

Will stream sediments adequately represent the survey area?

Are the streams decoupled from the adjoining valley slopes so that the sediments do not represent the watershed? This can be answered from field observation, air photos, and terrain analysis etcetera. Remedial action may range from augmenting the sediments with base-of-slope colluvial soils to use of widely spaced soil sampling grids.

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 if 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 very 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 km^2?) 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 different geochemical responses among pan concentrates and various size fractions of stream sediments (Andrews *et al.*, 1991; Tooms, 1987).

Sample size

Depending on logistics, this becomes especially important when HMEs are involved. Choices include preparation of field pan concentrates [with possible loss of fine heavies and large differences in panning efficiency between individuals (Stendal and Theobald, 1994)]; field sieving, with possible loss of some fines, to obtain several kilograms of –30 or –40 mesh sediment (Fig. 11); or transport of very large samples for subsequent laboratory separation of a representative size fraction or heavy mineral concentrate.

CONCLUSIONS

Stream sediment geochemical surveys provide a robust, cost-effective method of mineral exploration in SE Asia. Surveys can be improved by attention to representativity of the sediment sample at scales that range from the catchment basin, through location of the sample site on the streambed, to the size of the field and analytical subsamples.

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