Particle-size distribution of gold within the Sulphur and Dominion creek drainages, Klondike District, Yukon, and implications for gold winning and the formation of distal placers containing fine gold

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ABSTRACT

A reduced efficiency of gold recovery with decreasing particle size using a sluice box raises the possibility of a very fine gold resource within the Klondike. The grade of fine gold within gravel recovered from the southern Klondike was assessed using a combination of screening and bulk leaching by cyanidation. This approach eliminates the nugget effect and size ranges selected correspond to particle sizes exploitable by different metallurgical methods: <53 µm (cyanidation), 53-125 µm (‘enhanced g’ concentrators), 125-500 µm (sluice boxes). Colluvium, virgin gravel and tailings from various mining operations were collected from a relatively long drainage where accumulation of fine gold could feasibly occur. In all samples, gold <125 µm was negligible. Despite this negative result, this approach to resource evaluation is straightforward and could be applied advantageously in other areas where source mineralization contains fine gold. A distinction should be made between placer gold grains of fine but equant nature derived from proximal mineralization and gold rendered fine and flaky by fluvial transport.

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INTRODUCTION

Although the total gold production from the Klondike District will never be known with any certainty, it is clear that the region hosts one of the world's major placer resources. The vast majority of the gold recovered to date has been separated from the host gravel by basic sluicing techniques, as operated both by small-scale mining operations and larger scale dredging operations. The recovery of fine gold using sluices becomes less efficient with decreasing gold particle size. Consequently, there is potential for a resource of fine gold either remaining in tailings or within virgin gravel.

Recovery of gold particles greater than 250 µm (60 mesh) in size using a simple sluice is usually straightforward, and previous studies on the presence of fine gold within placers and implications for metallurgical efficiency (*e.g.*, Wenquian and Poling, 1983; Subasinghe, 1993; Clarkson, 1994) have focussed on the recovery of gold in the 150-250 µm (100-60 mesh) size fraction. Retention of gold of this size range in a sluice box is influenced by gravel pre-treatment, sluice design and operation. Empirical metallurgical data have shown that the recovery of gold in the 150-250 µm range varies substantially according to the sophistication of the processing circuit (Clarkson, 1989), a factor which has undoubtedly contributed to the successful reworking of some of the main placer areas in the Klondike goldfield. Analysis of the efficiency of gold recovery in Malaysian gold and tin dredges by Fricker (1984) indicates relatively low recoveries of fine gold, with 90% of the gold particles lost being less than 200 µm. Many of the main valleys in the Klondike goldfield were last exploited by dredging and consequently it is possible that a substantial amount of gold recoverable by traditional methods remains in the Klondike goldfield.

An extensive evaluation of metallurgical plant performance of placer operations in the Klondike was reported by Clarkson (1989, 1994). Samples of sluice tailings were collected and upgraded by shaking tables to characterize the efficiency of various processing circuits. On the basis of these tests it was concluded that fine (<140 µm, 100 mesh) gold formed only about 2% of the total gold head grade. However, this figure was based on recoveries in gravity concentration circuits and it could be that a resource of fine gold exists which is too small to be recovered in this way.

Metallurgical approaches to the recovery of fine gold have developed since the last major studies investigating the recovery performance of placer mines. The advent of the Knelson concentrator and related 'enhanced g' separators has effectively lowered the gold particle size exploitable by gravity concentration circuits (*e.g.,* Laplante *et al.*, 1996; Apling *et al.*, 1997) to a point where gold particles >53 µm in diameter are a valid target. However, recovery of placer gold is not only a function of particle size. Flaky gold grains, formed during fluvial transport, are particularly difficult to recover in conventional sluice circuits as a consequence of their modified settling velocities. Chapman and Houseley (1996) noted that the recovery of placer grains from a particular area may be very high because the gold grains have already been concentrated by hydraulic sorting. The implications of gold shape on recovery, and hence plant performance, have been quantified to some degree (Wenquian and Poling, 1983; Chapman and Houseley, 1996; Apling *et al.*, 1997). Wenquian and Poling (1983) recorded a strong correlation between gold shape and recovery for placer gold from the Fraser River in British Columbia. They noted that the gold lost from the combined jig/sluice processing was much flakier than that recovered, and that this effect was progressively more pronounced in the smaller size ranges. Although this effect can be alleviated to some extent using 'enhanced g' concentrators, their effective operation had more rigorous classification stages than are currently commonly employed within sluice circuits. Consequently it seems unlikely that simple substitution of Knelson concentrators for sluices within existing processing circuits would be of benefit unless a substantial resource of fine gold exists.

For very fine gold grain sizes, hydrometallurgical approaches are the only processing option, and there have been previous attempts to evaluate the suitability of cyanidation to treat White Channel Gravel (Macdonald, 1985). Cyanidation trials were hindered by the high clay content of the solid feed, although the more modern approach of Carbon in Pulp (CIP) or Carbon in Leach (CIL) process could alleviate this problem. Testwork carried out in a leaching column returned gold recoveries of 62%, which is a very low figure for the cyanidation of free gold and possibly reflects the presence of larger gold grains in the feed sample, which were only partially digested during the leaching period.

The potential benefits of applying 'enhanced g' concentrators or a hydrometallurgical approach to auriferous gravel in the Klondike may be assessed by characterization of the particle size of gold within the feed. The widespread belief that there is no fine-gold resource in the Klondike is largely based on the observations of sluice box performance and the assertions of Clarkson (1989, 1994) that this resource is insignificant. However, recent exploration and associated research has provided two independent lines of evidence which suggests that fine gold could be present in concentrations greater than previously believed.

Klondike Star Mineral Corporation operated a pilot plant facility between 2005 and 2007. Several bulk samples (a total of about 150 tonnes) of ore from various localities on Lone Star Ridge and Hunker Dome (Fig. 1) were treated. Analysis of the gold from these sources indicates compositional consistency with gold from the adjacent placers (Chapman *et al.*, submitted, a,b). Metallurgical testwork in the pilot plant mill indicates an average recovery of 57% for samples from Lone Star Ridge and 44% for samples from Hunker Dome, *i.e.*, around half the gold from the *in situ* source was too small to collect in a simple gravity circuit under carefully controlled conditions. To some extent this low recovery could be ascribed to the generation of fine flaky gold within the mill, which is very difficult to recover by traditional gravity methods (Chapman and Houseley, 1996). However, it could be argued that the milling action of the ball mill is replicated during fluvial transport, so placer gold generated from fine *in situ* gold would also be difficult to recover by conventional gravity separation. If the *in situ* mineralization identified by Klondike Star is representative of the original eroded orebodies, which yielded the Klondike placers, then about half of the original gold remains unrecovered. Also, a recent study of a 5 g nugget from Last Chance Creek revealed a matrix surrounding the nugget impregnated with fine (1-3 μm) gold particles. Where primary gold has been available to study in the Klondike, there is some evidence for the presence of gold particles too small to recover by conventional sluicing.

The present study was designed to generate information concerning the variation in abundance of fine gold within the placer environment. In addition, it aimed to characterize any resource according to the metallurgical technique appropriate for that size range of gold. The data from this investigation could then directly inform subsequent metallurgical evaluations of the resource.

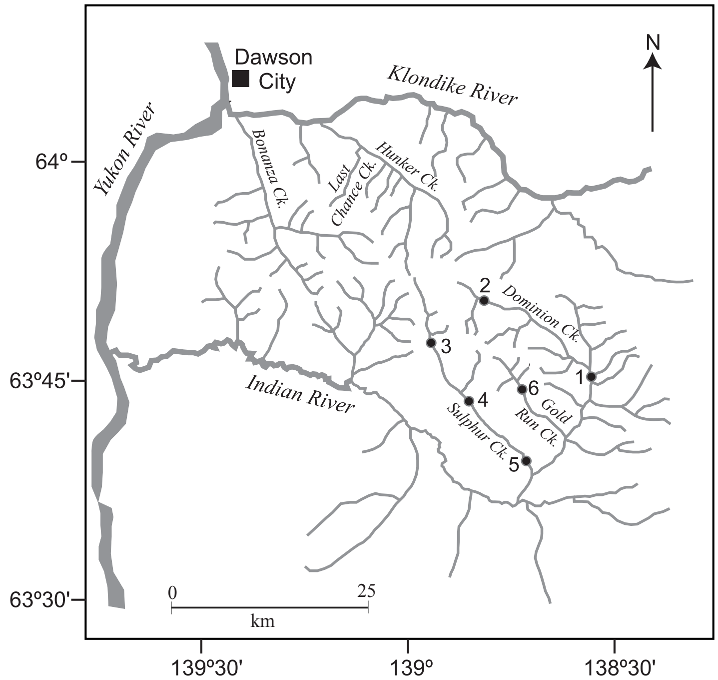

Figure 1. *Map of Klondike District showing location of southern Klondike sampling sites. Sites 1 – 6 refer to numbers used in Tables 1 and 2.*
1 = lower Dominion Creek, 2 = upper Dominion Creek, 3 = upper Sulphur Creek, 4 = mid Sulphur Creek, 5 = lower Sulphur Creek, 6 = Gold Run Creek.

TESTWORK PROGRAM

CHOICE OF STUDY AREA

The rationale for the study is centred on evidence for the presence of fine gold in the north of the Klondike goldfield, although there were practical barriers to effective sampling in that area. Bonanza and Hunker creeks have both been dredged extensively and only a limited amount of placer mining currently exploits virgin gravel. Collection of samples is greatly facilitated by access to active placer mines, and in their absence, sampling would be largely confined to dredge tailings. Furthermore, the study of Chapman *et al.* (submitted, b) showed the presence of several zones of mineralization in the Lone Star Ridge area. These represent different mineralizing events between which the gold particle size could vary. Sequential influx of gold with different size ranges complicates the process of tracking dispersion of fine gold. In addition, Bonanza Creek is relatively short, whereas other drainages in the Klondike goldfield provide the opportunity for the concentration of fine gold in placers distal to the source. The placer gold in Dominion Creek and most of the placer gold in Sulphur Creek (Fig. 1) is derived from sources near Hunker Dome (Chapman *et al.*, submitted, a). This part of the Klondike afforded sampling of a variety of materials ranging from virgin gravel to recent and historically produced tailings. Gold Run Creek (Fig. 1) was included in the sample targets because the composition of the placer gold differed from that recorded in Sulphur and Dominion creeks (Chapman *et al.*, submitted, a), which suggests that the gold was derived from a separate source. Thus, a study of the placer gold within the three main southern drainages would permit evaluation of the transport of fine placer gold from different sources constrained by the individual valleys.

SAMPLE COLLECTION

Various types of material were available for sampling, and these have been categorized according to their processing history (Table 1). Colluvium was sampled at the head of Sulphur Creek. Virgin gravel at the bedrock interface was sampled at various locations. Virgin gravel, 2 m above the bedrock contact, was sampled in an active cut in upper Sulphur Creek. Various tailings samples were collected both from modern and historical operations (Fig. 1). Duplicate samples were collected at various sites. Summary data are provided in Table 1. Material was dry sieved at a 2.7 cm size fraction on site, and the undersized fraction was air-dried prior to dry sieving to generate fractions of 1 to 2.7 cm, 1 mm to 1 cm, 0.5 to 1 mm, and <0.5 mm. Sample masses were recorded for each fraction. All fractions, except those <0.5 mm, were panned to recover gold particles. Although the mass of these gold particles was recorded, these data were not used to generate gold grades because of the relatively small sample size and large gold particle size.

RATIONALE FOR SAMPLE TREATMENT

The testwork was designed to establish the distribution of gold by size fractions suited to different methods of gold recovery. The finest size (<53 µm) may contain some gold recoverable by 'enhanced g' separators but also finer gold amenable to cyanidation. Gold particles in the 53-125 µm size range are often difficult to recover in sluicing

Table 1. *Description of sample locations.*

Sample	Creek	Description	Easting	Northing
1A-i	Lower Dominion	Virgin gravel on bedrock, active cut	621919	7073389
1A-ii		Virgin gravel on bedrock, active cut	621919	7073389
1A-iii		Sluice discharge at 1 m from exit	621919	7073389
1A-iv		Sluice discharge at 10 m from exit	621919	7073389
1B-i		Virgin gravel on bedrock, active cut	620310	7074162
1B-ii		Virgin gravel on bedrock, active cut	620310	7074162
1C-i		Tailings	620503	7073970
1C-ii		Tailings	620477	7073954
2i	Upper Dominion	Colluvium	604358	7082656
2ii		Colluvium	604358	7082656
3A	Upper Sulphur	Virgin gravel on bedrock, active cut	601723	7078831
3B		Virgin gravel, 2 m above bedrock, active cut	601691	7078719
4	Mid Sulphur	Virgin gravel on bedrock	601714	7078820
5	Lower Sulphur	Dredge tailings	613044	7063080
6A	Gold Run	Tailings at sluice box	613294	7071077
6B		Tailings pond (fine fraction)	613318	7071054
6C		Virgin gravel about 30 cm above bedrock, active cut	612722	7071504
6D		Virgin gravel on bedrock, active cut	612722	7071504
6E		Tailings from 1960s operation	613502	7070922

operations, whereas higher recoveries are assured using 'enhanced g' separators. Finally, gold in the size range of 125-500 μm is recoverable using sluices, where the gold is not flaky, and the feed has been adequately classified.

The <500 μm (<0.5 mm) material was submitted to ALS Laboratories, Vancouver, for further analysis. Each sample was wet sieved at 125 μm and 53 μm to yield 3 sub samples: <53 μm, 53-125 μm and 125-500 μm, each of which was subsequently dried and weighed. Representative 1 kg samples of each of these size fractions was subjected to bulk leach extractable gold (BLEG) analysis to generate a gold grade. The gold distribution to the various size fractions was calculated from particle-size distributions and gold grade data. In this way, erroneous values from the nugget effect were avoided.

RESULTS

The gold grades of the <500 μm fractions determined by the BLEG analysis are presented in Table 2, together with the gold distribution of the finest two fractions. The <53 μm and 53-125 μm fraction have been combined because of their general very low values in virgin gravel. The high values of distribution of gold to the finest sizes occur only in tailings samples and particularly in those tailings selected specifically for their fine particle size. These values only coincide with very low overall gold grades in the <500 μm material, and most probably reflect the increasing importance of the ultra-fine gold following removal of coarser particles.

VIRGIN GRAVEL

The <53 μm fraction of this gravel comprised less than 10% of the mass for samples from lower Dominion and upper Sulphur creeks. A slightly higher value was recorded for the sample from mid Sulphur Creek, which may reflect the lower energy of the mid reaches of the river system, or a different depositional environment within the ancient meandering river system. The samples from Gold Run Creek consist of around 25% of <53 μm material. In every case, the gold grade of the two finest size ranges was extremely low, which coupled with the small mass fractions of those sizes resulted in a negligible gold distribution to the fine material.

OTHER SAMPLES

The gold content of the colluvium sample was negligible, and this sample is not considered further. The various samples of tailings exhibited a range of size distributions, overall gold grades and gold distributions to the finest sizes. Table 2 shows that the gold grades in the finest two fractions were all extremely low. Tailings samples collected adjacent to the sluice discharge contained more gold than in samples collected a few metres away in the tailings dam.

Table 2. *Gold distribution according to size fraction. Quantitative data applies to the <500 μm material. As the full particle size distribution of the sample is not available, these data cannot be used to generate an overall grade.*

Sample	Creek	Gold grade in <500 μm fraction (g/t)	% gold in the <125 μm fraction	
			individual	mean
1A-i	Lower Dominion	5.92	0.4	0.35
1A- ii		2.46	0.3	
1A		0.16	48	
1A		3.38	2.5	
1B-i		1.67	1.1	1.15
1B-ii		1.76	1.2	
1C-i		0.04	17	32
1C-ii		0.07	47	
2i	Upper Dominion	0.03	9	13
2ii		0.03	17	
3A	Upper Sulphur	0.58	3.1	
3B		0.04	17.8	
4	Mid Sulphur	4.04	2.3	
5	Lower Sulphur	0.25	2.9	
6A	Gold Run	0.04	24	
6B		0.02	85	
6C		0.49	0.9	
6D		0.65	16	
6E		0.04	9.1	

DISCUSSION

RELIABILITY OF DATA

In general, the testwork program has generated reproducible data, although it is acknowledged that this may be a consequence of the general absence of gold in the fine fractions studied. However, the technique yielded very consistent results for the 125-500 μm fraction, with the only discrepancies appearing in samples with a very low overall gold content.

SAMPLES FROM VIRGIN GRAVEL

In all samples derived from virgin gravel taken from the bedrock interface on Sulphur and Dominion creeks, only 1% of gold present in the >500 μm material was present in the two finest size fractions. The amount is slightly higher for the samples from Gold Run Creek, which may be a consequence of the gold particle size in a different gold source, or reflect the destinations of small equant gold grains derived from very local mineralization, present before transport affected their morphology. The sample of virgin gravel collected 1.5 m above bedrock on upper Sulphur Creek also contained gold predominantly in the 125-500 μm range which suggests that the grade change with depth in gravel is simply a consequence of abundance of gold grains of the same size rather than an indication of increasing gold particle size with depth.

Gold grades in <500 μm fractions of tailings samples were also low and samples collected at the point of sluice discharge returned grades of between 0.6 g/t and 3 g/t, whereas those of samples taken elsewhere in tailings lagoons were negligible. This suggests that fine tuning of sluice boxes could improve overall recovery. A single sample of dredge tailings from lower Sulphur Creek recorded a value of 0.25 g/t (in the <500 μm fraction). This value may be of interest if representative of the huge volume of tailings present in the area.

Even though this study is of a pilot–project scale, it seems evident that there is no resource of fine gold within the southern Klondike. There are two possible explanations for this observation. Firstly, the compositions of the placers remained consistent with the source mineralization, *i.e.*, no fine-gold particles existed originally. Secondly, all fine gold has been completely winnowed from the system. The consistent absence of fine gold in all the different types of material studied from all sample localities suggests the former scenario is more likely.

In light of this result, it is unfortunate that samples were not collected from the Bonanza Creek drainage. At present, it is unclear whether the metallurgical data from Klondike Star indicate a potential resource or an inefficient processing circuit. Wenquian and Poling (1983) allude to the hydrophobicity of gold within milled material. Flaky hydrophobic gold may ‘float’ and consequently concentrate in the tailings. Although the shaking table was closely monitored during these bulk tests it is not known whether any surfactants were employed to counter the loss of hydrophobic gold.

IMPLICATIONS FOR APPROACHES TO GOLD RECOVERY

This study has shown that it is extremely unlikely that a resource of fine and ultra-fine gold exists in the southern Klondike. Consequently there is no advantage in applying ‘enhanced g’ separators or cyanidation to either virgin gravel or tailings. However, the higher gold grades recorded in the 125-500 μm size range may translate to a valuable resource, which may currently be incompletely recovered by standard gravity concentration circuits. Previous work has established that gold recovery increases with the degree of pre-screening (Clarkson, 1994). However, although fine equant gold from near the source may be relatively easy to recover (Wenquian and Poling, 1983), this gold grain population becomes more difficult to recover with progressive fluvial transport as the grains become thinner. The progressive flattening of gold will also influence the apparent size of gold as determined by screening. Thus, the recorded values of gold in the 125-500 μm range present in tailings at a sluice discharge from mid-Gold Run Creek (0.6 g/t), may be lower than those for an equivalent sample from lower Dominion Creek (3.38 g/t) because these grains are proximal to source and less flaky.

DEVELOPMENT OF DISTAL PLACERS

During this study changes in the morphology of gold grains were observed between different sites. Placer gold in lower Dominion Creek was particularly flaky and difficult to recover as described above. Much of the fine flat gold could not be separated from the black sand using a gold wheel, and while careful operation of a ‘Le Trap’ sluice affected a significant concentration of gold within this material at very high recoveries, it was impossible to generate a clean concentrate. The size of this gold was relatively coarse (up to 3 mm) and it could be reasonably expected that progressive transport downstream would further exacerbate the problems generally acknowledged with efficient recovery of flakier gold, which becomes thinner before ultimately splitting into smaller particles.

When considering the development of placers containing well-travelled gold grains, it is appropriate to consider the controls on sedimentation resulting from particle shapes. In his seminal paper, Dietrich (1982) used a large experimental data set to demonstrate that the settling velocity of natural particles increases exponentially with particle size, and that very small particles have very slow settling velocities. In addition, Dietrich (1982) showed that the shape of particles additionally influences their settling velocity. Particle shapes are frequently characterized using mathematical expressions involving the three dimensions of the particle. The Corey Shape Factor (CSF; Corey, 1949) is commonly employed and is defined as $T/(BxL)^{1/2}$, where T, B and L are the thickness, breadth and length of the grain. Perfectly spherical grains have a CSF = 1, whereas flatter grains will record a smaller CSF (CSF = 0 for totally flattened particles). Flatter particles, with a low CSF, experience increased drag from the fluid, which further hinders their settling. For all particles, both reduction in size and increased flatness are a hindrance to particle settling (Dietrich, 1982). Dietrich's data were collected in stationary water, and do not account for the high specific gravity of gold, and thus do not replicate settling conditions within Klondike placers. Additionally, although it may be assumed that the effect of reduced settling velocity of smaller, non-spherical particles would be exacerbated in a fast-flowing river (because the effects of turbulence would further hinder settling), preferential collection of fine-gold particles may be favoured by vortices created behind obstacles on the river bed. Clarkson (1994) reported the CSF for fine gold (+100 mesh) from various sites in the Klondike to be between 0.3 – 1.0. However, gold grains recovered in this study, from site 1A (Fig. 1; Table 1), have an average CSF = 0.1, which is interpreted to reflect shape modification during fluvial transport. Wenquian and Poling (1983) concluded that gold particles with a shape factor of less than 0.15 were difficult to recover in gravity circuits. Further transport in the Dominion Creek/Indian River drainage would presumably reduce the CSF further, progressively reducing the likelihood of fluvial concentration of all the gold present in the sediment load into pay streaks.

Studies of the nature of gold within placers are generally considered problematic because of the overall low abundance of gold particles, which necessitates very large sample sizes, (e.g., Clarkson 1994). Various Russian studies have included reference to gold grain shape as a control on placer formation (W. LeBarge, pers. comm.), but these employ qualitative shape descriptors rather than shape factors and hence the data are difficult to compare with those discussed here. The most useful information available to the present study, in the context of placer development, is derived from metallurgical studies which have sought to characterize gold recovery in terms of particle shape. In general, material accumulating in the sluice tailings represents material less likely to be concentrated by fluvial action to form a placer. Clarkson (1994) noted that the action of a sluice was similar to a centrifugal concentration device due to the formation of vortices downstream of the riffles. Consequently, application of free-settling velocities of particles to the hindered settling/centrifugal-influenced deposition within a sluice box, may be simplistic, but such conditions also exist in the fluvial environment.

Chapman and Houseley (1996) evaluated various methods of shape classification in relation to the destinations of gold grains within a gravity concentration circuit. They showed that indices which include a measurement of gold grain thickness are the most efficient at predicting behaviour in the concentrating circuit, whereas an index utilizing only the length and breadth of the gold particle is far less useful. The implication, for studies of placer development, is that use of sieve aperture as the sole criteria for gold grain characterization is not appropriate, whereas measurement of the third dimension enables prediction on whether the grains could be concentrated by fluvial action. Collection of data, for large populations of gold grains, which describe three-dimensional shape has traditionally been time consuming and labour intensive. However, Crawford (2007) developed image analysis software capable of this task and applied it to relate morphological modification of gold grains to transport distance. This approach could be adapted to predict 'future' morphological change to establish the point downstream beyond which concentration of gold particles by fluvial action is no longer likely.

The consideration of the effect of gold grain shape on placer formation indicates that a distinction should be made between gold made fine (and flat) by fluvial transport and that which consists of equant grains of equivalent sieve aperture. The absence of fine gold in the southern Klondike probably indicates that the original grain size was relatively coarse, and this may be typical for placers derived from orogenic gold. Thus, it may be possible to speculate on the potential for fine placer gold on the basis of the style of source mineralization, with epithermal, porphyry and intrusion-related offering the best prospects for contributing to economically important placers of fine gold.

CONCLUSIONS

This study has established that there is unlikely to be a viable resource of fine gold in the southern Klondike and that this probably reflects the original size distribution of the hypogene gold particles. Similar studies are required elsewhere in the Klondike goldfield, where placer gold was derived from different source mineralization, to establish whether fine gold is absent throughout the entire area. The methodology developed here avoids spurious results caused by the nugget effect and can establish the resource of gold, within specific size ranges, extractable using different processing options. Field observations of major changes in the shape of gold grains have been correlated with qualitative reports of ease of gold recovery by simple gravity circuits. Metallurgical data describing gold behaviour in gravity concentration circuits can be used as a proxy for predicting placer development. Consequently, the shape indices of gold grains used as a predictive tool in metallurgical research could find application in speculating whether there is potential for fine-gold accumulation. It seems likely that economic concentrations of fine gold could result from those styles of mineralization where the particle size of gold is small within the hypogene source. Thus, equant small particles are more likely to form a placer than fine and thin gold particles generated through prolonged fluvial transport. We propose that screen aperture alone is unsuitable for prediction of fine placer gold accumulation. Recently developed image analysis techniques may permit statistical evaluation of populations of gold grains, and mapping these data onto predicted shape change could prove beneficial for identifying possible targets for further exploration.

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