Developing a new method to identify previously unrecognized geochemical and morphological complexity in placer gold deposits in western Yukon

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ABSTRACT

Placer gold has been, and is, a notable resource in the western Yukon; however, identification of the lode sources feeding these placer deposits has been difficult. Previous studies have used electron microprobe (EMP) and manual morphological analyses of gold grains with some success to define source-mineralization-style areas, but have not been able to accurately predict lode locations. This study utilizes EMP in conjunction with a new method for morphological analysis based on semi-automated digital image analysis to re-examine this problem. Examination of a sample suite collected over the entire Klondike goldfields area demonstrates that there is significant complexity in Yukon placer gold deposits that has not previously been recognized. Confronting this complexity using a statistical approach based on this new shape analysis method, EMP and a planned future laser ablation mass spectroscopy study will hopefully produce a method for locating lode gold sources.

RÉSUMÉ

L'or placérien a été et reste encore une ressource appréciable au Yukon occidental; cependant l'identification des sources filoniennes alimentant ces dépôts placériens s'est avérée difficile. Dans des études antérieures on a utilisé avec un certain succès des analyses à la microsonde électronique (MÉ) et des analyses morphologiques manuelles pour définir des styles de régions minéralisées d'origine, mais ces études n'ont pas permis de prévoir avec exactitude les emplacements des gîtes filoniens. Dans le cadre de la présente étude, la MÉ est utilisée avec une nouvelle méthode d'analyse morphologique basée sur une analyse semi-automatisée d'images numériques comme nouvelle approche pour la solution de ce problème. L'examen d'un ensemble d'échantillons recueillis sur toute la région des champs aurifères du Klondike démontre une grande complexité jusqu'à maintenant insoupçonnée des gisements d'or placérien au Yukon. On espère que le fait d'aborder cette complexité par une approche statistique fondée sur cette nouvelle méthode d'analyse morphologique utilisée avec la MÉ dans le cadre d'une étude projetée des échantillons traités par ablation au laser et spectrométrie de masse fournira une méthode de localisation des sources d'or filonien.

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INTRODUCTION

The composition of placer gold grains has been analysed in many studies to establish geochemical 'fingerprints' of gold from specific lode sources worldwide (e.g., Mortensen *et al.*, 2004; Grigorova *et al.*, 1998; Watling *et al.*, 1994). Placer gold grains have also been noted to change systematically with the distance travelled from the lode source, and several studies (e.g., Townley *et al.*, 2003; Knight *et al.*, 1999a; Youngson and Craw, 1999; Loen, 1995; Knight *et al.*, 1994) have attempted to develop variation curves between grain shape and the distance specific grains have travelled. Such a relationship could provide important constraints for identifying the most likely source location for gold from specific placer deposits.

Previous morphological studies of placer gold have followed the general procedure of identifying and measuring a morphological parameter of selected gold grains, estimating the distance those grains had travelled, and then trying to develop a model for the evolution of grain shape (proxied by the parameter) over distance. These methods are oversimplified in that they do not take into account the possibility of polymodality in the parameter. If a sample is polymodal, the use of an average parameter value for a sample to generate a model can have serious ramifications. For example, in a sample with two populations of equal proportions, the average value of the parameter for that sample may be a value which none of the grains individually record. Another limiting factor of previous morphological studies is that they have not attempted to correlate morphological parameters with other available data such as composition. While it has not yet been determined if composition plays a role in shape development (e.g., grains of differing alloy composition will vary in hardness and therefore deform differently during transport), assuming it does not may lead to erroneous conclusions.

Another problem faced when interpreting these data sets is visualizing the data. There is no standard parameter used to characterize gold grain shape evolution, nor any standard method of presenting the data. Although useful for comparing a few samples, many of the methods used in the literature become incomprehensible when applied to the increasingly large data sets that can now be easily generated using new computerized image analysis methods such as are discussed in this contribution.

Kernel density analysis provides a solution to many of the problems previously mentioned. It reduces all of the measurements on a sample to a single curve which accurately retains and easily presents the information available from those measurements. The shape of these curves allows for plots of multiple data sets to remain legible. Extending the analysis into two dimensions produces a 3D surface plot that allows for easy identification of the relationships between paired data, the contributing populations present, as well as the shape, location and relative contributions of those populations.

This contribution reports the preliminary results obtained from the application of a new semi-automated method for the objective measurement of morphological information on placer gold samples from a number of drainages within the Klondike District of western Yukon. It also presents the novel results that can be extracted from the data using one and two dimensional kernel density analysis with a case example. This method is currently being expanded to a much larger sample suite, and will hopefully yield new insights on the behaviour of gold in the alluvial environment.

PREVIOUS WORK

There have been many previous studies that investigated the evolution of gold grain shape with alluvial transport (Márquez-Zavalía *et al.*, 2004; Wierchowiec, 2002, and previously mentioned works). A number of these studies have utilized semi-quantitative or qualitative parameters, which, although easy to measure, are overly susceptible to operator bias, and their use will not be discussed further. Fully quantitative studies have generally been limited in scope, due to the amount of labour previously required to measure each grain manually. They are also limited in that only a few basic measurements (minor, intermediate and major axis lengths) can be reliably made in this fashion. Parameters that have been used which incorporate measurements of all three axes include the Cailleux flatness index (Cailleux, 1945) and the Corey (Corey, 1949) and Zingg (Zingg, 1935) parameters. Other previously used morphological parameters include roundness, flatness, rim thickness, and percentage of rimmed grains. Analysis of these measurements has generally been limited to plotting parameter values against distance, or using x,y plots to try to correlate between parameters (e.g., Knight *et al.*, 1999a; Youngson and Craw, 1999).

Extensive gold compositional studies have also been carried out (Mackenzie and Craw, 2005; Chapman *et al.*, 2000; Knight *et al.*, 1999b; Leake *et al.*, 1998; Loen, 1994);

however, no attempt has been made previously to link the compositions of individual grains to the shape parameters measured for those grains. The almost universally utilized method is electron microprobe analysis (EMP), which is generally restricted to the quantification of major and some minor elements (Au, Ag, Cu and Hg) that are present in sufficient concentrations to be measured reliably. Analysis of the compositional data obtained has typically been constrained to determining average concentrations for a sample, or plotting one concentration value against another.

COMPUTERIZED IMAGE ANALYSIS

Until now, quantitative shape measurements of placer gold grains has required manual measurement using a light or electron microscope. This method is slow, labour intensive and subject to operator bias. It is also restrictive in that it is difficult to record any measurements excluding the three major axis lengths.

The use of digital image analysis in this study has dramatically improved the speed and objectivity of grain analysis. ImageJ (a java implementation of NIHImage) is a freeware image analysis program that can be customized by the addition of user-generated macros. A new macro was developed specifically for morphological characterization of placer gold using this program. The new macro combines built-in features of ImageJ with several other open source macros, and has some novel capabilities. This macro allows for the simple and quick quantitative morphological characterization of large sample suites.

Although it would be ideal to record and digitize the entire 3D physical shape of every grain, then extract the desired parameters from the digital model, developing a method of that type was beyond the scope of this project. Instead, two perpendicularly oriented 2D images of every grain down the long or intermediate and short axes were collected, allowing for three-dimensional information on the grains to be determined. The macro developed for this purpose measured the feret and breadth, area, perimeter, convex area, convex perimeter, largest inscribed circle radius and smallest circumscribing circle radius on each bisecting image. Then it performed a fourier analysis on the outline shape. At present, only the feret and breadth measurements are used to obtain short, intermediate and long axis lengths for each grain.

The method is mentioned briefly here because it has allowed the generation of large morphological data sets. These data sets, along with other data recorded on placer gold grains, provide interesting insight on the study of placer gold. More than 7500 grains from 53 locations have been analysed using this program thus far, as compared to the most extensive previous quantitative morphological study in the literature which measured only the three axis lengths on 1502 grains from 60 locations (Townley *et al.*, 2003). This study uses the Hofmann (Hofmann, 1994) shape parameter (or Hofmann shape entropy) as the primary descriptor of shape. Unpublished ongoing studies by the authors indicate that this parameter will be the most useful for quantifying the evolution of shape with transport. The form of the parameter is given by equation 1.

KERNEL DENSITY ANALYSIS

Kernel density analysis (KDA, also known as kernel density estimation or the Parzen window method; Parzen, 1962) is a way to calculate a probability density function for a variable in a population from a number of measurements made on the variable. The equation for a kernel density analysis using a normal distribution kernel is given by equation 2.

For this study, Silverman's rule of thumb (Silverman, 1986) for bandwidths provides an objective method for selecting bandwidths. The calculation for the bandwidth is the minimum of the standard deviation and the interquartile range divided by 1.34, multiplied by 0.9, and

$$H = \frac{-1}{1.0986}\left(\frac{l \times \ln(\frac{l}{l+i+s})}{l+i+s} + \frac{i \times \ln(\frac{i}{l+i+s})}{l+i+s} + \frac{s \times \ln(\frac{s}{l+i+s})}{l+i+s}\right)$$

Equation 1. *The Hofmann shape parameter. l, i and s are the lengths of the long, intermediate and short axes, respectively.*

$$p_x = \sum_{0}^{n} N(o_n, w, x)$$

Equation 2. *The 1D kernel density estimation: p_x is the probability of a randomly sampled member of the population having the value x, N is a normal distribution function with a mean o_n (the observed values for the parameter) and standard deviation or bandwidth w evaluated at value x, summed over all observations n.*

divided by the number of observations to the one fifth power. Since the choice of bandwidth can have a significant impact on the results of the analysis, it is necessary to have specific criteria for selecting bandwidth values instead of just subjectively choosing values.

The KDA method can be also extended to multiple dimensions to examine relationships between variables, and generate probability distribution functions for those relationships.

CASE STUDY

A sample of placer gold grains (n=54; sample number EC-06) was recovered by hand panning from a location near Fox Gulch in the Klondike placer district in western Yukon (63°57'N, 139°21'W). After drying and hand picking, the grains were mounted on packing tape and imaged for analysis using the previously mentioned computerized image analysis method. The grains were then transferred to a conductive tape mount and examined by scanning electron microscopy (SEM) – backscattered (BS) and secondary electron (SE). Subsequently, the grains were mounted in epoxy, ground down and polished to expose a section roughly bisecting the grain along the major axis. After carbon coating the mounts, images of the cross-sections were recorded using SEM (BS only), and the major element composition (Au, Ag, Hg and Cu) of the core of the grains was determined by EMPA. Individual grains were tracked with unique identification numbers through all steps to allow for correlation of results.

ONE DIMENSIONAL KDA

The kernel density estimation method was applied to the data for sample EC-06; the results of those analyses are shown in Figures 1 and 2. In stark comparison to the methods used in previously published studies, these plots clearly show that the data is at least bimodal in both cases, and likely even more complex. The smooth curve and the ease of locating relative maxima makes plots of multiple samples much more readable when compared to plots of multiple samples using the cumulative percentage method.

After the KDA has been performed, the next step is to identify all of the component populations in a sample. To accomplish this, a number of normal distributions are generated and summed. The parameters (mean, standard deviation and relative weighting) of the individual distributions are then modified to minimize the difference between the summed curve and the curve calculated from the data. Assuming a good fit to the data is achieved, the parameters of those fitted distributions then provide information on the parameter values for the component populations in the sample. This method is far superior to previous methods of data analysis because it allows quantitative objective information on the parameters of interest to be recovered. It is also a vast improvement over using simple arithmetic means. The arithmetic means for sample EC-06 are 76.0 ± 7.6 for wt% Au and 0.897 ± 0.051 for the Hofmann shape parameter; the KDA shows that in neither case does the arithmetic mean correctly identify a component population (Figs. 1 and 2).

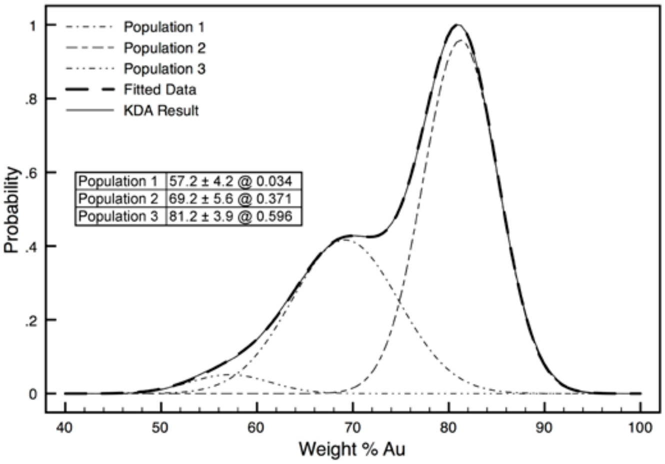

Figure 1. *One-dimensional KDA output, and fitted component populations for wt% Au data on sample EC-06. Included table contains the following parameters: mean, standard deviation and relative weighting for each identified peak.*

A visual examination of the KDA results (Figs. 1 and 2) clearly indicates that for both cases (wt% Au and the Hofmann shape parameter), the sample contains at least two component populations. Fitting the data to identify those populations reveals that in both cases there are three populations; it also returns the parameter values for those populations.

This analysis has been applied to a number of samples from the Klondike District, and has revealed significant complexity not previously recognized in samples. Furthermore, qualitative examination confirms consistent trends in the Hofmann shape parameter during alluvial transport (Fig. 3), suggesting that the development of a predictive model for the evolution of gold grain shape will be possible.

A preliminary shape evolution curve has been created using the fitted peak locations from the 1D analysis, using data from samples known distances apart or for which the distance to the lode source is known with a high level of confidence (Fig. 4).

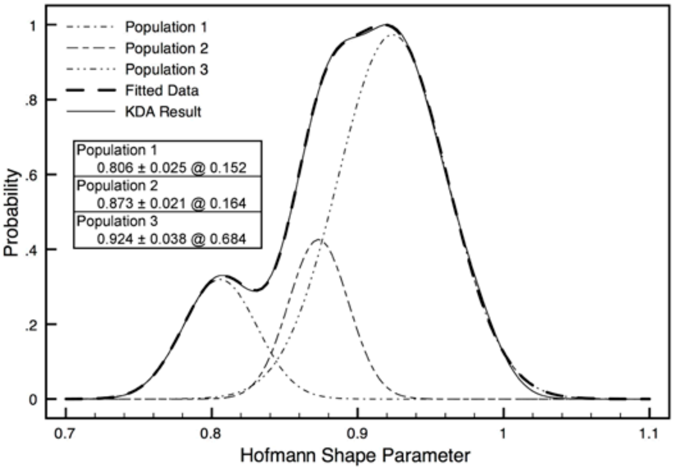

Figure 2. *One-dimensional KDA output, and fitted component populations for Hofmann shape parameter data on EC-06. Included table contains the following parameters: mean, standard deviation and relative weighting for each identified peak.*

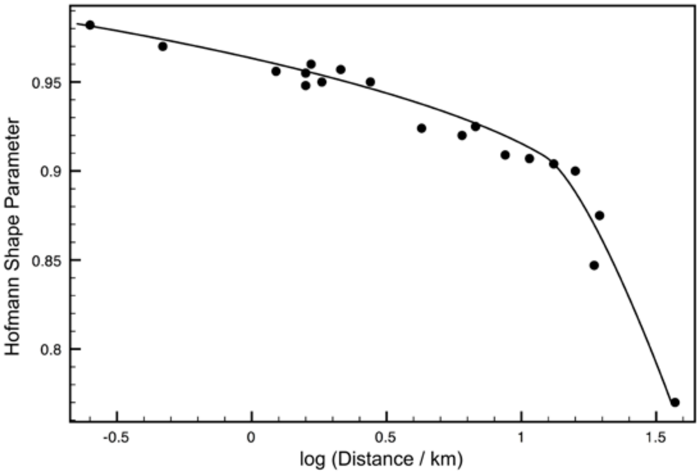

Figure 4. *A preliminary shape evolution curve for placer gold from the Klondike placer district.*

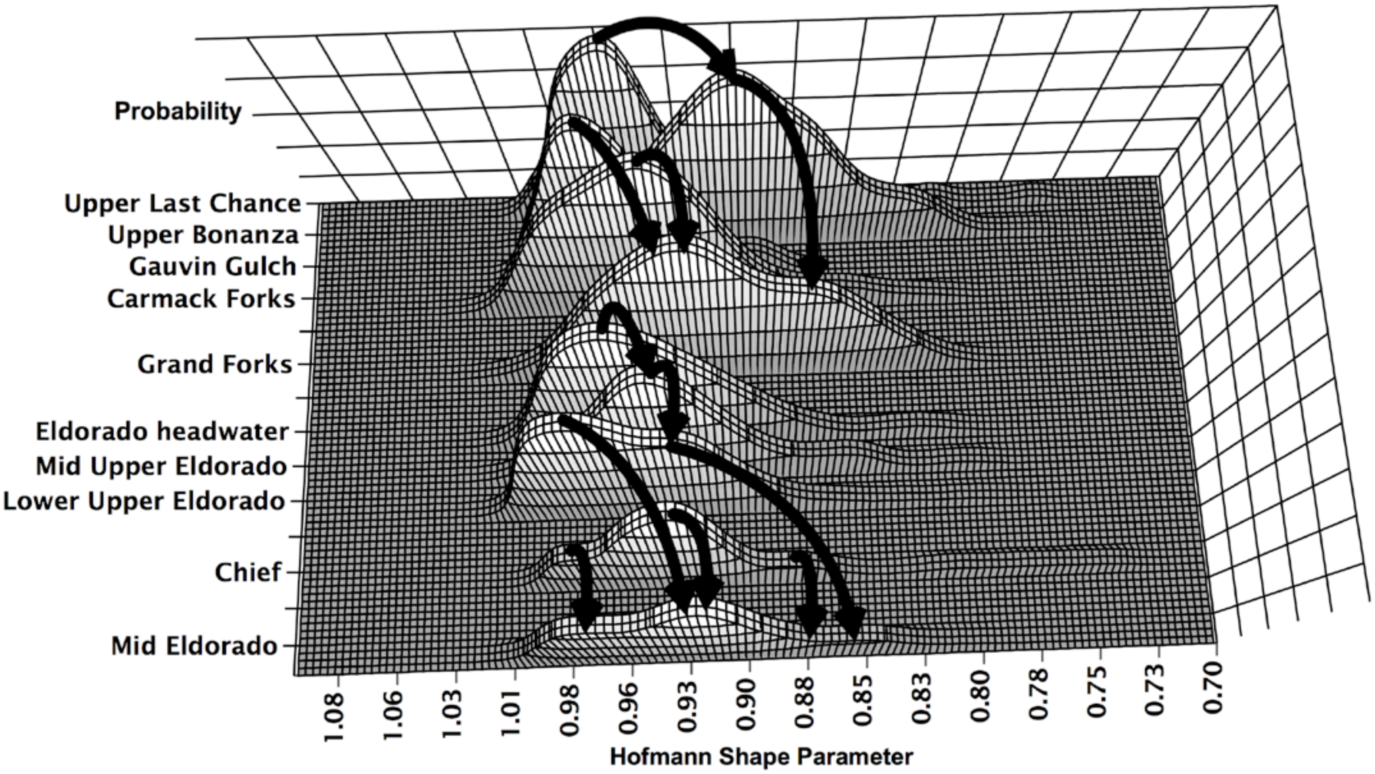

Figure 3. *Probability density plots of the Hofmann shape parameter for samples progressing down two drainage systems in the Klondike District. Five samples each from the two drainages are shown, with arrows indicating quantitatively identified evolution paths for grain populations with downstream transport.*

This shape evolution curve allows for prediction of distance to source; however, there is still significant scatter in the data, and the accuracy of the curve is uncertain. Several source types for Klondike placer gold are known, and it is likely that each source will have a different initial shape. Further complicating the issue is that each source has a different major element alloy composition, potentially resulting in different malleability, and hence a different rate of shape evolution during alluvial transport.

If the average composition of each grain-shape population were known, it would be possible to model many of these complications and eliminate much of the scatter. If identical numbers of populations were found from both the Hofmann and composition 1D analyses, and the relative weights of those populations were identical, then those populations would likely be identical. In this example, however, it is clear that this is not the case, so there is still confusion and an inability to determine both the Hofmann shape parameter and wt% Au values for individual populations. Fortunately, it is possible to extend the KDA into two dimensions and recover this information.

TWO DIMENSIONAL KDA

The traditional method for identifying correlation between variables is to plot results on an x,y plot and look for continuous relationships or groupings of data. This method works well when there are few or very distinct populations, but tends to be of decreased utility with more broadly distributed observations or when objective quantitative information is desired. There is no standardized method for visualizing paired data from placer gold (i.e., isochron diagrams in geochronology, or the many plots used to define geochemical composition fields, e.g., TAS plots). Since placer gold data tends to be broadly distributed, and quantitative information is desired from this analysis, two-dimensional KDA provides an excellent method for examining the available data in this case.

The method for performing a two-dimensional kernel density analysis is directly analogous to the one dimensional case. The formula for a 2D KDA is given by equation 3.

As with the 1D results, it is possible to fit a series of normal distributions to the KDA result obtained, and thus identify the populations present in a sample.

$$p_{x,y} = \sum_{0}^{n} N(o_{n_x}, w_x, x) \times N(o_{n_y}, w_y, y)$$

Equation 3. *The 2D kernel density estimation:* $p_{x,y}$ *is the probability of a randomly sampled member of the populations having the values x,y. n is the number of paired x,y data, N is the normal distribution function, evaluated using means of* o_{n_x} *and* o_{n_y} *which are the x and y observations for each pair and using standard deviations* w_x *and* w_y *which are the bandwidths for those variables.*

This method does suffer in that the output generated is a probability surface, and must therefore be viewed in 3D, making it difficult to display data from several samples in a single plot. However, the benefit of identifying the locations and distribution parameters of the component populations in a sample greatly outweighs this downside.

With the 2D KDA method, it would be possible to obtain an exact fit to the KDA results if one fitted the same number of populations as data points used to perform the KDA. It is vital that the number of populations chosen should have some kind of geological reasoning. For example, a sample collected near the top of a drainage should be expected to contain only a few contributing sources, whereas a major tributary draining a large area is much more likely to have more contributors.

Figure 5 shows a traditional x,y plot of the EC-06 data for comparison, and Figure 6 shows the two-dimensional KDA result. Six peaks were fitted to the KDA results; the summed results are presented in Figure 7, and the individual fitted component peaks are shown in Figure 8. All plots also show the projection of the 3D surface onto

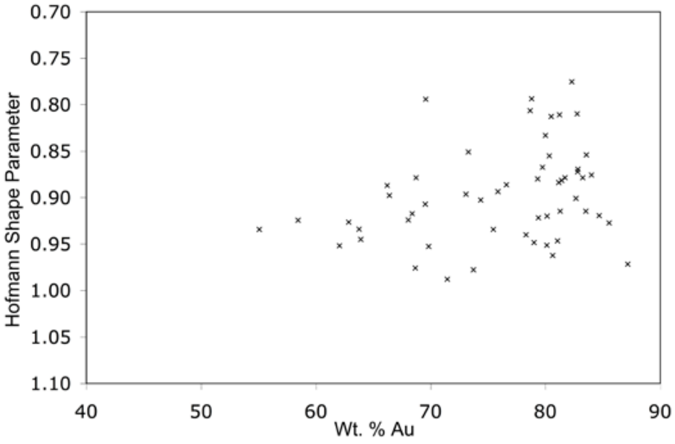

Figure 5. *An x,y plot of the data for EC-06.*

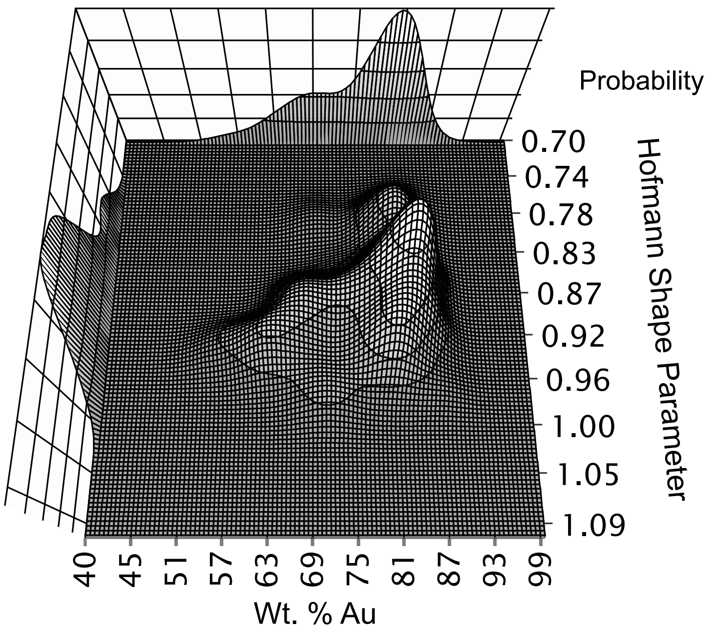

Figure 6. *Two-dimensional KDA results for sample EC-06.*

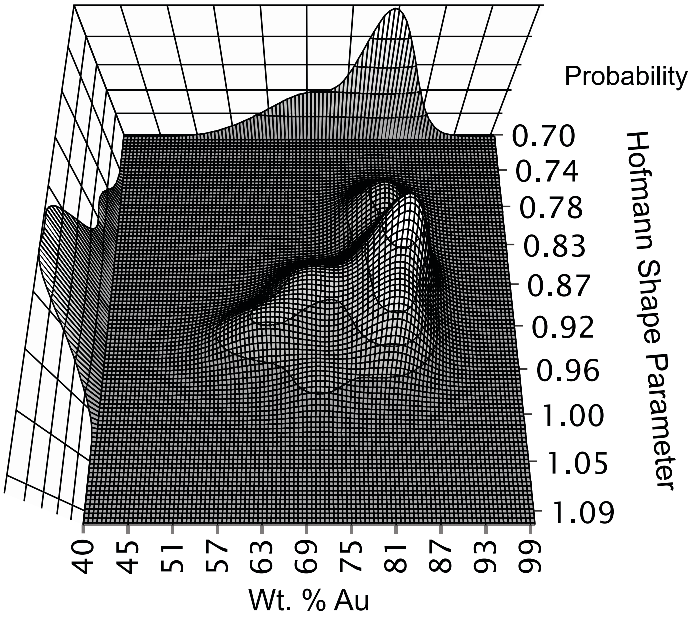

Figure 7. *The summed results of seven normally distributed peaks fitted to the KDA output for EC-06.*

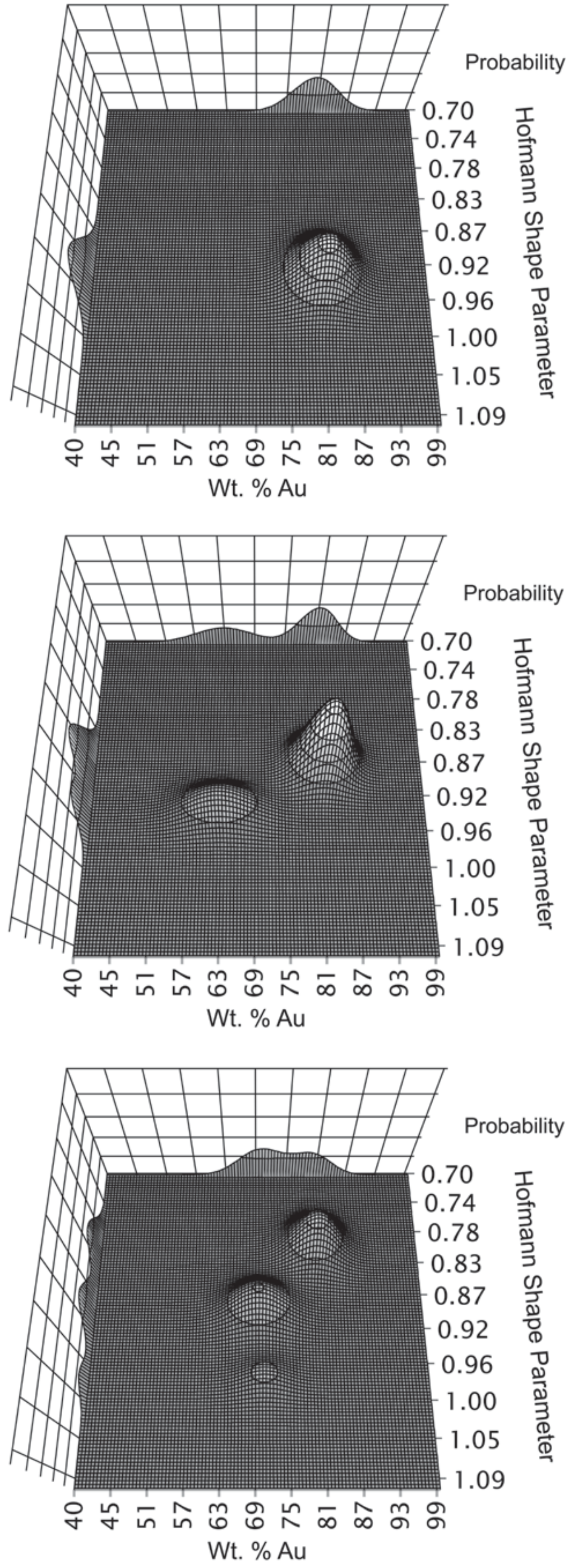

Figure 8. *(right column) The six component populations identified from the 2D KDA of sample EC-06.*

each individual axis for visual comparison to the 1D KDA results.

The EC-06 example illustrates the scrutiny required in choosing the number of peaks to be used in the fit. Although there is a definite peak at ~ 70, 0.8 (Fig. 6), when fitted, this peak represented a single observation. In a sample of n=54, this is likely to represent the sampling of a tail of one population rather than a unique population.

Two-dimensional KDA is far superior to previously used methods (e.g., the x,y plot) in demonstrating the presence and location of multiple contributing populations in the sample. It is also preferred over performing two 1D analyses because it returns correlated information for the two variables. It is interesting to compare the results of the 2D and 1D analyses. Table 1 shows that the 2D peak locations can be roughly grouped to correspond to the populations identified by the 1D analysis. The weights are given because although the mathematical analysis of the data provides interesting results, it is important to ensure that the results are not an artifact of the analysis, and do pertain to some true feature of the samples.

Although the following comparisons are qualitative, they provide another level of support for the method of analysis. In this case, grains were selected randomly from those grains that unambiguously belonged to each of the six identified populations. The whole grain BS and SE SEM images, as well as the BS SEM cross-section images (Fig. 9) were then visually compared. The compositional

Table 1. *Comparison of 1D and 2D KDA (shaded) results. S.D. = standard deviation.*

		1D Shape Results - Hofmann Parameter Values			
		Mean S.D. Weight Group	**Mean S.D. Weight Group**	**Mean S.D. Weight Group**	
	Mean S.D. Weight Group	0.806 ± 0.025 0.152 **C**	0.873 ± 0.021 0.164 **B**	0.924 ± 0.038 0.684 **A**	
1D Composition Results	57.2 ± 4.2 0.034 **1**			63.6 ± 5.6 0.935 ± 0.022 0.153 8	Mean S.D. Weight # of grains
	69.2 ± 5.6 0.371 **2**		69.9 ± 4.6 0.894 ± 0.024 0.148 8	70.9 ± 3.8 0.980 ± 0.019 0.055 3	Mean S.D. Weight # of grains
	81.2 ± 3.9 0.596 **3**	80.5 ± 3.9 0.808 ± 0.026 0.147 8	81.6 ± 3.7 0.875 ± 0.022 0.228 12	80.7 ± 4.4 0.932 ± 0.029 0.268 15	Mean S.D. Weight # of grains

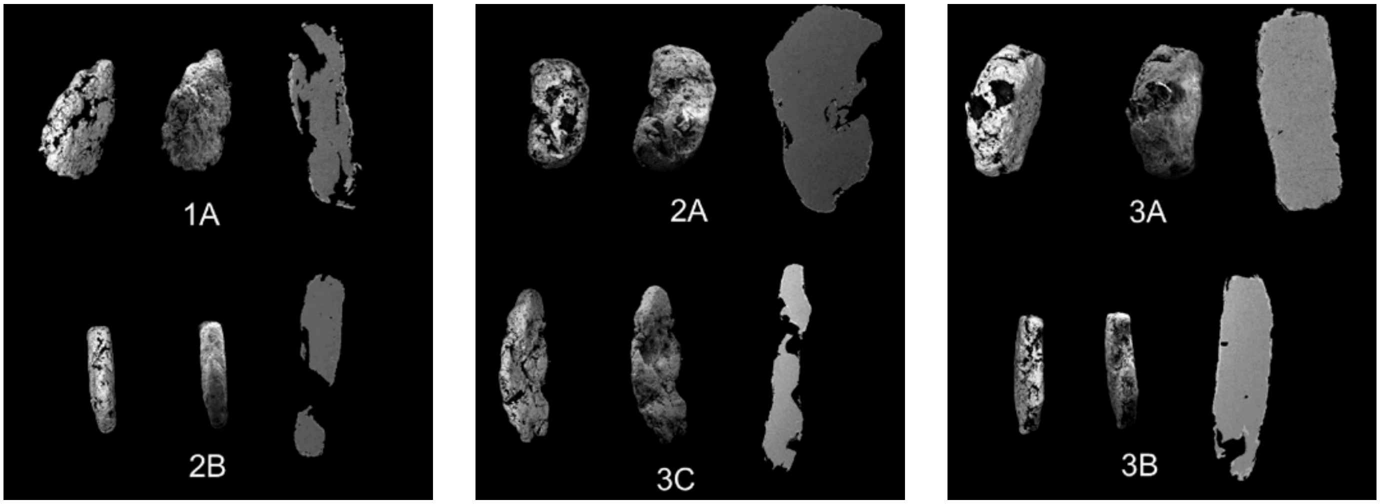

Figure 9. *Qualitative comparison of the six identified component populations in sample EC-06. Labels indicate compositional (letter) and morphological (number) groupings as per Table 1.*

populations are difficult to visually compare: the shade of the BS images generally relates to average atomic number, so the group 3 grains should be lighter than group 2, which should be lighter than group 1; however, this relationship can be complicated by the settings used to record the images. This comparison, if made, must be made on the sectioned grains since it is the core composition that is being examined due to the presence of gold-rich rims on many grains.

It is also interesting to note the differences in rimming between the populations: populations 3A, 3B and 1A show well developed rims, while those in the remaining groups are sparse and much thinner where present. A qualitative shape comparison is slightly easier. Group A contains the most boxy and irregular grains, whereas group B grains are mostly tabular, and the group C grain is flakier still. Overall, the correspondence between determined parameters and physical observations appears to be good, and provides some evidence that the method is revealing true information and not statistical artifacts.

CONCLUSIONS AND FUTURE WORK

Automating the measurement of morphological parameters on gold grains makes the collection of large, quantitative and unbiased sets of data relatively quick and easy. Although this provides a large amount of potentially useful information, a new problem arises in finding a way to visualize the data in a clear and concise manner that allows useful information to be extracted.

The use of kernel density analysis provides an easy way to process data into clearly interpretable diagrams. It also provides an excellent way to identify and extract quantitative information on individual populations within a sample. The 1D analysis has been shown to be an improvement over previous methods; however, it is still not sufficient to fully explain placer deposit complexity. The 2D method is a significant improvement; however, only once the predictive model is generated and tested will it be possible to determine if it adequately describes alluvial placer gold-shape evolution. Work currently underway to obtain correlated compositional data will allow the development of this model.

It is anticipated that laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) will be applied to further characterize the composition of Klondike placer gold. If compositional populations identified by electron microprobe and LA-ICP-MS are shown to be identical, then prior identification of those component populations using the KDA methods presented here will reduce the number of samples that need be examined by LA-ICP-MS.

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