THE INTERPRETATION OF ALLUVIAL GOLD CHARACTERISTICS AS AN EXPLORATION TECHNIQUE

R C Leake, M T Styles, D J Bland, P J Henney, P D Wetton and J Naden
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Table 1 Maximum concentrations of elements within cores of alluvial gold grains (wt %).  

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EXECUTIVE SUMMARY

The potential of gold grain characterisation as an exploration technique is discussed in
the light of a synthesis of the results of a wider ODA-funded investigation of bedrock
mineralisation and alluvial gold carried out under ODA/BGS Technology Development
and Research (TDR) project “Alluvial gold characterisation in exploration planning”,
(Project 92/1, R5549). The TDR Programme is a contribution to the British
Government programme of technical assistance to developing countries. Results from
Ecuador, Malaysia and Zimbabwe are discussed with some reference to equivalent
information from Western Europe.

The silver content of individual gold grains in most, but not all, hand specimen samples
of mineralisation from mines or drill core shows a very small range in comparison to
typical alluvial samples of gold. Where gold grains from several samples from different
points in the same mineralised structure have been studied, as in the Lubuk Mandi and
Penjom areas of Peninsular Malaysia, a greater range in silver content is apparent. The
silver content of gold grains extracted from table concentrates from two Zimbabwe
mines has a much greater range in silver content than single specimens from the same
mines, and is comparable to the range in silver content of samples of alluvial gold.
These data indicate that single hand specimen samples are inadequate to give an
indication of the range of composition of gold within one mineralised structure.

Differences in silver content between different mineralised areas, e.g. Penjom and Raub
in Peninsular Malaysia, are as apparent from the alluvial samples as from the spread of
bedrock gold samples. The range in silver content of gold from five soil samples
collected near to mines in Malaysia and Zimbabwe is similar to that of corresponding
alluvial samples and there are very few grains of pure gold that could have crystallised
within the soil matrix.

Microscopic inclusions of opaque minerals of at least 75 different types, occur widely
in alluvial gold grains from all areas investigated. The proportion of grain sections
containing inclusions is no smaller in the gold from the tropical countries studied than
in alluvial gold from temperate western Europe. Allowing for inadequate samples of
bedrock mineralisation or incomplete mineralogical studies in the published literature,
there is generally good agreement between inclusions in alluvial gold and minerals
associated with gold in primary mineralisation upstream. This is even observed in
Zimbabwe where the drought necessitated collection several kilometres away from
bedrock sources. Inclusion assemblages from different areas can be classified into
different groups which reflect different types of mineralisation.

Alluvial gold inherits many features from its bedrock source. Gold grain chemistry and
its inclusion assemblage can be used as a powerful new exploration technique,
particularly in the reconnaissance stage in areas where the geology and mineral
potential are not well known.
1. INTRODUCTION

This report discusses the potential of gold grain characterisation as an exploration technique in the light of a synthesis of the results of the ODA-funded investigations of material from Ecuador, Malaysia and Zimbabwe carried out on the ODA/BGS Technology, Development and Research (TDR) Project 92/1/R5549, entitled “Alluvial gold characterisation in exploration planning”. Details of methods of analysis used and the results of studies of gold from the individual areas are given in separate reports (Styles et al 1993, 1994, 1995, Henney et al 1994, 1995a, 1995b, Naden et al 1994). Some reference is also made in this report to equivalent BGS information on gold from localities in western Europe.

Three types of internal compositional variation can be seen in gold grains, particularly those from alluvium. These characteristics can be used to construct a classification of different types of gold and to establish a signature which can be related to different types of source mineralisation. The three types of compositional variation comprise: a) the overall composition of gold grains, b) the nature of the internal compositional heterogeneity within gold grains and c) the nature and abundance of inclusions of other minerals within the gold. The variation of each of these compositional features is described in turn and its potential use in gold exploration is discussed.

One of the most important aspects of the ODA-funded work has been to investigate the relationship between gold present in mineral deposits and the gold grains which are present in alluvium downstream which are potentially derived from the surface expression of such mineralisation. An effective comparison between the two types of gold is not easy because in relatively few cases is there only one occurrence of outcropping gold-bearing mineralisation undergoing active erosion by a river and hence only one possible source of gold in the alluvium. Furthermore, there is often a considerable mismatch in the size of the drainage samples from which gold grains have been extracted and a typical outcrop or drill-core sample of mineralisation containing gold which are being compared. Thus it is often necessary to compare gold in a sample of mineralised rock the size of a thin section with gold grains extracted from several kilograms of alluvial sediment which is itself derived from the breakdown of a much greater volume of rock. This difference in sample size has to be taken into account when alluvial gold is being compared with bedrock gold.

2. COMPOSITION OF GOLD GRAINS

There is a large range in the silver content of gold grains from different areas which is related to the type of source mineralisation and its geological setting. Other elements can also be detected within gold grains by electron microprobe analysis but usually at lower levels and much less frequently. In approximate order of frequency of detection these elements are mercury, copper, palladium, antimony and platinum. Mercury can be both of natural and artificial origin. The maximum concentrations of various
elements occurring in solid solution within gold from several locations are shown in table 1

Table 1 Maximum concentrations of elements within cores of alluvial gold grains (wt %)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Grains</th>
<th>Ag min</th>
<th>Ag max</th>
<th>Cu</th>
<th>Pd</th>
<th>Pt</th>
<th>Hg</th>
<th>Sb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>1813</td>
<td>&lt;0.3</td>
<td>50.6</td>
<td>2.7</td>
<td>11.9</td>
<td>15.9</td>
<td>7.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Ecuador</td>
<td>233</td>
<td>0.6</td>
<td>37.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>204</td>
<td>&lt;0.1</td>
<td>42.6</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>Penjom Malaysia</td>
<td>126</td>
<td>0.8</td>
<td>25.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Raub Malaysia</td>
<td>101</td>
<td>&lt;0.1</td>
<td>33.5</td>
<td>0.2</td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Mersing Malaysia</td>
<td>47</td>
<td>0.7</td>
<td>19.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lubuk Mandi</td>
<td>116</td>
<td>2.5</td>
<td>14.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sarawak</td>
<td>105</td>
<td>&lt;0.1</td>
<td>33.5</td>
<td>1.3</td>
<td></td>
<td></td>
<td>4.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Grain with 9.3% Cu is from a site where sediment is derived from tailings

Silver is almost always present in solid solution within gold and the median level and spread of the concentrations of this element is particularly useful in recognising multiple sources of gold in an alluvial sample. Differences in silver contents within and between areas can be displayed by plotting the compositions of the cores of grains from different samples cumulatively on the same graph. This allows the shape of the plots of silver content and the median levels of silver in gold from several samples to be compared easily and similarities and differences noted. This is discussed below for each sample area in turn.

Mercury has long been used in the extraction of gold. This is because it wets gold and forms an amalgam causing fine gold grains to coagulate into larger masses which can then be easily extracted from a heavy mineral concentrate. The gold can then be recovered by heating the amalgam which decomposes and vapourises the mercury leaving the gold. Gold which has reacted with metallic mercury is easily identifiable because of characteristic porous textures extending from the outside of the grain inwards. Gold containing mercury of natural origin in solid solution shows none of these textures and is not related in its distribution to the outside of the grain. Mercury concentrations appear higher in the gold from Sarawak compared with other areas (table 1) though the element reaches higher levels at a few localities in Europe (Leake et al 1993).

Copper shows only limited solubility in gold at the lower end of the range of temperatures associated with hydrothermal mineralisation and coexists with an intermetallic compound with the formula (Au₃Cu). Grains with a composition of this intermetallic compound can be present in alluvial samples along with native gold and
several have been found from various sites in Europe (Leake et al 1993) though none have been found in the material studied as part of the ODA-funded work. Other grains consist of an intergrowth of gold and the same intermetallic compound. Relatively high levels of copper in solid solution in gold is a clear indication of a high temperature of origin.

The presence of palladium in solid solution in gold, in some cases with platinum also present, is indicative of a distinctive type of gold source, probably associated with alkaline mafic igneous rocks and red-bed sequences. In this type of mineralisation, crystallisation has been from oxidising solutions carrying the precious metals as chloride complexes rather than as bisulphide complexes which are thought to be responsible for most of the transport of gold in hydrothermal solution. No examples of palladian gold have been found in the gold examined during this study but several examples of this type of gold are known from Britain (Leake et al 1991). Antimony has been detected within gold from Sarawak to a maximum concentration of 2.4%, but not in other areas.

2.1. Composition of gold grains from bedrock samples

The composition of the gold within a thin section from a hand specimen of gold-bearing mineralisation is relatively easy to obtain with the electron microprobe and this has been achieved in many samples of rock from mines in Zimbabwe and from mines and prospects in Malaysia. Only the silver content of the gold is sufficiently often above the detection limit of the method of analysis to be widely useful in comparative studies of gold from different mines and of differences in composition between gold from rock, overburden and alluvium. The silver contents of a range of samples of gold from rock taken from mineralisation in Zimbabwe mines or from outcrop or drill core are compared in a cumulative percentage form in figure 1. The plot demonstrates that there are major differences in the median silver content of the gold between different mines even working the same style of mineralisation within the same general geological environment. These differences may be sufficient to trace gold from individual mineralised structures in alluvium if the rock samples are in fact fully representative of the mineralisation that is worked in the mine.

The shape of the cumulative percentage plots of the silver content of gold provide evidence for the presence or absence of multiple populations of gold. The very small range in silver from most samples is manifest from the very flat plots on the cumulative percentage plots in figure 1. However, there is evidence of small populations of grains with very low silver contents in samples from Athens and Indarama mines in Zimbabwe. The sample from the Dalny mine shows a completely different type of distribution, with a much greater range in silver content, which results in a much steeper gradient in the plot. Mineralisation which results from one well defined pulse of activity in a relatively stable environment may be expected to produce gold with relatively constant composition. In contrast mineralisation which is multiphase, or gold
which crystallised in an environment where there was rapid change in physical or chemical conditions, may be expected to be compositionally more complex.

The silver content of gold grains in rock and core samples from the Lubuk Mandi and Penjom areas in Peninsular Malaysia are shown in figures 2 and 3 respectively. In most cases the plots are flat, signifying a small range of compositional variation, similar to the mine samples from Zimbabwe, but there are some samples with a much greater range of composition e.g. samples Pcore5 and Pcore28 from Penjom (Figure 3). In both these plots there is a sharp increase in gradient at around the 60 percentile level which suggests the presence of separate populations of relatively silver-rich grains. The same characteristic can be seen to a lesser extent in the plots of the silver levels in samples Pcore30 and Pcore31. The reason for the presence of subordinate numbers of grains with elevated silver contents in these samples but not others is not known but presumably reflects differences in the history of mineralisation between different sites. Although the individual plots of most of the samples from both the Lubuk Mandi and Penjom samples are generally flat there is a considerable spread of median silver levels, particularly for Penjom. This indicates that the composition of the gold from different parts of the same mineralised system at both Lubuk Mandi and Penjom varies.

It has been possible to compare the composition of gold in hand samples of mineralisation with that of a corresponding table concentrate from the same mine in two cases from Zimbabwe. Figure 4 shows cumulative percentage plots of silver in gold from hand specimens and table concentrates from the Oceolla and C mines in Zimbabwe. It is immediately evident from this plot that there are significant differences in median silver contents and in the shape and gradient of the plots of the two sample types from the same mine. Moreover, in both cases the silver contents of the two sample types do not actually overlap. These data indicate that a single sample of gold-bearing mineralisation is inadequate to provide a measure of the full range of gold composition from at least these two mines. The reason for this is probably that the table concentrate is derived from a much greater volume of rock than the hand specimen and, showing a wider range in composition, is more representative of the composition of the gold from the mine as a whole. The samples with coarse visible gold which were chosen for study may represent a minor part of the mineralisation that is mined. Furthermore, the lack of overlap in composition between the two sample types indicates that the variation in the composition of the gold from a single mine is greater still and that even the table concentrate composition is likely to vary with time as different parts of the same mineralised structure are mined. Thus single hand specimens of mineralisation are unlikely to provide an adequate range of gold compositions to compare with gold from alluvium. Nevertheless the relative difference in silver content between the gold from the Oceolla and C mines (higher at C mine) is evident from both the table concentrates the hand specimens.

Gold from table concentrates from two other mines in Zimbabwe is also shown in figure 4 but it was not possible to obtain corresponding gold from outcrop samples.
The gold from the Puzzle mine (PuzzTC, figure 4) shows a small high silver population but with the majority of grains similar in composition to the table concentrate from the Oceolla mine. The gold from the table concentrate from the Goldleaf mine (GoldlTC, figure 4) shows a large range in silver content and plots as a high-gradient line.

There is thus considerable evidence that the composition of gold within one mineralised structure shows greater variation than is evident from small hand specimens. This presumably results from slight differences at different points within a structure in the physical and chemical characteristics of the mineralising solutions and also the host rocks which are being invaded. It is therefore potentially misleading to compare directly the composition of alluvial gold which is derived from the weathering of much greater volumes of rock with gold from single samples of mineralised material. However if the composition of gold from several related samples of mineralisation is used for comparison then the exercise will be more meaningful.

2.2. Composition of alluvial gold and comparison with the composition of bedrock gold.

The compositions of gold in the alluvial samples from Ecuador are compared with the composition of gold in bedrock mineralisation from Campanilla in figure 5. The Campanilla samples are the only ones from Ecuador where there is any degree of association between the two sample types. The plot of rock sample gold composition overlaps with only the lower half of the alluvial gold compositions. Whether the more silver-rich gold in the alluvial sample is derived from a different variety of the same type of mineralisation or from an entirely different type of mineralisation is not clear. The gradient of the plot of the silver content of the sample from Shumiral is lower than the corresponding plots of the other alluvial samples. This probably reflects a difference in the type of mineralisation source.

Comparison between the compositions of gold in rock and alluvial samples from the Lubuk Mandi area (Figure 6) shows a greater range of silver contents in the alluvial samples but a close correspondence between median silver levels of the drainage samples and two of the rock samples. The majority of the alluvial samples fit within the spread of the silver content of rock and core samples except for a few grains with slightly higher silver contents. Only one of the drainage samples contains a significant population of gold grains with distinctly lower silver contents than the bedrock samples.

The composition of the alluvial gold samples from Mersing are also shown on figure 6 but there are no corresponding rock samples from this area and the source of the gold is not known. The composition of the alluvial gold from Mersing is only slightly different in range and median silver content from that of the Lubuk Mandi samples. In contrast, the sample from Mersing beach is distinctly different from the other samples in both range and median silver level, probably indicating a different type of source.
The alluvial gold from Penjom shows a greater spread of silver values than the gold from Lubuk Mandi and a smaller degree of overlap with the composition of the bedrock gold samples (Figure 7), though the median silver contents are, with one exception, within the spread of the bedrock samples. This greater spread of silver contents within the alluvial gold could reflect a greater complexity of mineralisation in the Penjom area compared with Lubuk Mandi. Similarly the alluvial gold from the Raub area shows a greater range in silver than the samples of bedrock gold (Figure 8), the main difference being the presence of a few grains in the alluvial samples with a significantly higher silver content. One sample of alluvial gold (Raub 90, Figure 8) is very low in silver and only partly overlaps with the range of silver in gold from bedrock samples. The sample from Sungai Kemehang, 10 kms to the north of Raub, contains a relatively high silver component not seen in the Raub samples. Comparison of the data for both Raub and Penjom shows that the lower silver content of the gold from bedrock mineralisation in the Raub area is also clearly apparent from the alluvial samples.

Visible gold is known to be rare in Sarawak and few hand specimens containing gold were collected. However, several gold grains were extracted from mine tailings and crushed ore, demonstrating that it does occur as fine-grained discrete grains of the native metal. The plots of the silver content of the gold from crushed ore (slurry) at Tai Parit shows a range of silver contents similar to that found in bedrock samples (10-30% Ag). The gold from three tailings samples (Figure 9) show higher gradients than typical of gold in hand specimen samples, but gradients similar to the table concentrates from Zimbabwe mines (Figure 4). The plots of silver in alluvial gold from Sarawak show a wider range of shapes and median silver levels than the tailings samples. This suggests that several sources of different types are present in the area, though with groupings with around 6% and 13% median silver levels respectively. From the sharp breaks in slope of some of the plots several of the alluvial samples would seem to be derived from multiple sources.

Plots of silver in alluvial gold from Zimbabwe (Figure 10) show steeper slopes than the corresponding hand specimen samples but are similar to the table concentrates. Median levels of silver in alluvial gold fit within the range of median silver in the hand specimens from all the mines. The main difference between the alluvial samples and the mine samples is the small number of silver-rich grains usually present in the former. However similar silver-rich grains are present in two of the table concentrate samples (Figure 4) and also in soil samples.

2.3. Composition of gold from soil samples

Gold has been extracted from two soil samples in the vicinity of a mine in the Penjom area of Malaysia and at three sites close to mines in Zimbabwe. In the Penjom area, the plots of silver in gold from soil are very similar in shape and median concentration to those for gold in alluvial samples from the area (Figure 7). The plots of silver in gold
for both samples from the Kadoma area of Zimbabwe are similar (Figure 10), except for a few more argentiferous grains in the alluvial sample. In contrast, there are considerable differences between the corresponding plots for the Mazowe and Zvishavane areas. In the Mazowe area the soil sample was collected near the Oceola mine and the composition of gold in the soil is more similar to the gold in the hand specimen from this mine than to the corresponding table concentrate. In the Zvishavane area the soil sample was collected close to the C mine but the composition of the soil gold is more variable and more argentiferous than the table concentrate from the mine and the alluvial sample from the area.

It is widely thought that in tropical areas, where chemical weathering is important, gold is frequently redistributed in the near surface environment. This conclusion is based on differences in gold abundance in different parts of soil profiles, differences in grain size distributions and differences in surface texture and composition of gold grains between overburden and bedrock samples. There are no comparative studies prior to this work of the compositions of the interior of gold grains from these different environments. Gold grains originating from the primary bedrock mineralisation source are thought to be leached in the near surface environment and the gold is then redistributed and recrystallised as new grains of essentially pure gold. There is no doubt that this process does occur but information on its frequency and controls is lacking.

The comparison of the compositions of soil gold, alluvial gold and bedrock gold which have been carried out in this study indicate that the process of leaching and recrystallisation is much less common than previously thought. Very little pure gold has been detected in either soil or alluvial samples in all areas in Ecuador, Malaysia and Zimbabwe that have been sampled. On the contrary the soil and alluvial gold is very similar to the bedrock gold, which implies that it is not greatly affected by the weathering processes typical in these countries. Alluvial gold contains features in the grain interior formed at the time of original crystallisation in bedrock which are preserved unaltered. This is a very important conclusion with significant implications for mineral exploration. The study of the chemistry of the interior of alluvial gold grains can thus be used as an exploration technique. The same conclusion is also apparent from the study of alluvial gold from many sites in Europe (Leake et al. 1993).

3. INTERNAL CHEMICAL HETEROGENEITY WITHIN GOLD GRAINS

Some chemical heterogeneity within gold grains can be detected during optical examination of polished blocks or sections by differences in colour. However such chemical variation generally only becomes apparent as a result of microchemical mapping of the grains using an automated electron microprobe. Internal chemical heterogeneities comprise regular and irregular growth zonation, intergrowths of gold of different composition, penetrating films either more argentiferous than the body of the grain or of pure gold, overgrowths or rims of different composition and the residue of selective leaching of different parts of a gold grain. These features have been
observed in European gold much more frequently than in gold from Ecuador, Malaysia and Zimbabwe but this is probably a reflection of different types of source mineralisation. In some European examples (BGS data) the history of a complex sequence of stages of grain growth is revealed by the microchemical mapping but nothing like this has been seen in the gold studied in this project.

Most of the grains of gold within bedrock samples that have been mapped show a uniform composition. Examples of microchemical maps of gold in bedrock from Ecuador showing a uniform composition are given in Styles et al. 1993. Penetrating films of either pure gold or of more argentiferous gold or a combination of the two do occur in some alluvial grains but not as commonly as in European gold. An example of microchemical maps showing the tracks of gold-rich films in an alluvial grain from the Sebakwe river in the Kwekwe area of Zimbabwe is given in Styles et al. 1995. In addition, maps showing the distribution of a combination of gold-rich and silver-rich tracks in a grain of alluvial gold from Lubuk Mandi is shown in Henney et al. 1994. European examples (BGS data) demonstrate that a combination of the two types of tracks in one grain is much less common than tracks of just one type. Though penetrating films have frequently been found in alluvial gold grains, they are generally absent in the more limited number of bedrock samples of gold that have been studied. This suggests that such films might be formed in the near-surface environment. However the discovery of gold grains containing films of more argentiferous gold in a Zimbabwe mine table concentrate demonstrates that the process leading to their formation is active in the deep rock environment.

In most cases the boundaries of the penetrating films are very sharp but some examples have been found in European alluvial gold where the boundaries are diffuse, suggesting diffusion of silver away from the track centre into the surrounding less argentiferous matrix. This feature is an indication of a period of relatively elevated temperature subsequent to the formation of the film. This diffusion could have taken place where the mineralisation environment remained at relatively high temperature for a significant period of time after crystallisation or where the mineralisation containing the gold grains was subsequently metamorphosed.

The significance of some of the types of internal chemical heterogeneity in alluvial gold grains is not yet clear and further work is required to establish to what extent some of these features are useful in deducing the environment and history of gold crystallisation in the source mineralisation.

4. INCLUSIONS OF OPAQUE MINERALS IN GOLD

Probably the most significant finding that has come out of the systematic study of the interiors of alluvial gold grains is the frequency and variability of microscopic mineral inclusions present.
4.1 Incidence of inclusions

The proportion of grains sections containing inclusions is highly variable from site to site with a range from 3.5% to 64.7%, though most fall within the range of 12% to 28%. The proportion of gold grains containing inclusions from tropical and sub-tropical South America, Zimbabwe and Malaysia is similar to that in gold from temperate Europe. This observation was not expected at the start of this ODA-funded work as chemical weathering is a much more important process in tropical areas than temperate ones. It was thought that chemical weathering in the tropics would promote dissolution of primary gold and its subsequent recrystallisation with a different composition and this process would tend to destroy any inclusions originating in the primary mineralisation. If this happened alluvial gold containing inclusions of sulphide and similar minerals would be expected to be much less abundant than in temperate Europe. The present work shows that this is not the case in the areas studied, which are climatically typical of a large part of the world, and is strong evidence that the amount of dissolution of gold within many, if not most, tropical environments is limited.

It is quite probable that some environments e.g. deserts with aggressive saline groundwaters, could promote extensive dissolution of primary gold but this study indicates that such environments would be of restricted distribution in world terms and recognisable. Some grains have been found which seem to be extensively leached but even in these sectors of the grain remain pristine. This is an important conclusion for mineral exploration as it suggests that in most tropical environments the interiors of alluvial gold grains are preserved largely unaltered during all the stages in the weathering process and thus reflect features of the primary mineralisation.

4.2. The nature and size of opaque inclusions

A vast range of opaque mineral inclusions have been identified in alluvial gold grains world-wide, comprising at least 75 different mineral species and these are given in the appendix. The majority can be recognised as well established minerals on the basis of quantitative microprobe analyses but others have been found with well defined compositions that have not previously been described. In addition there are some inclusions with complex compositions which are of uncertain nature, being either new minerals or mixtures of two or more simpler minerals which are intergrown at a scale finer than the resolving power of the electron microprobe (< 1μm).

Most of the opaque inclusions within gold are <10μm and frequently <3μm in size. In some cases the inclusions are <1μm in size and only detectable with difficulty, even using a sophisticated electron microprobe such as the CAMECA SX50 at BGS. Some inclusions are composite but resolvable with microchemical mapping and assemblages of up to 5 separate minerals in close spatial association have been found.
4.3. The origin of inclusions

Four or possibly five modes of origin are indicated for inclusions in alluvial gold grains. Some inclusions, particularly the larger examples of pyrite and arsenopyrite with euhedral shapes, predate the gold and represent the surface upon which the gold grain crystallised. Continuation of gold deposition encompassed the sulphide, which was then left as an inclusion within gold. The majority of inclusions have rounded forms and are probably of the emulsion type, minerals which crystallised at the same time as the gold. Some inclusions of intermetallic compounds and alloys could represent the results of exsolution of an element, originally in solid solution within the gold, during cooling after the formation of the mineralisation. In a few cases inclusions are clearly the result of reaction between existing gold and solutions depositing gold of a different composition. It is also possible that a mineral could become mechanically embedded in the surface of a gold grain during transport in a river and physically incorporated into the grain as it is deformed on further transport. Minerals have been found adhering to the surface of some gold grains but none of these are completely surrounded by gold and therefore inclusions.

4.4. Relationship between inclusions in alluvial gold and minerals coexisting with gold in bedrock mineralisation.

A comparison of the incidence of inclusions in alluvial gold and the mineralogy of gold-bearing mineralisation upstream of alluvial sites in Ecuador, Malaysia and Zimbabwe is made in table 2. Data on the mineralogy of the bedrock mineralisation is derived from pre-existing information augmented by mineralogical work carried out as part of this study. Mineralogical studies of mineralisation based on reflected light microscopy rather than electron probe analysis are likely to be incomplete and some minerals are likely to go unnoticed. The quality of the mineralogical information about the bedrock mineralisation which can be obtained from the professional literature is variable and likely to be incomplete in many cases because electron microprobe study was not carried out or covered insufficient material. These factors have to be borne in mind when a comparison between bedrock mineralisation and alluvial gold is made.
Table 2 Comparison of inclusion assemblage in alluvial gold with minerals associated with known gold mineralisation upstream

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# mineral in both sample types, * mineral in only one sample type.
pyr = pyrite, pyrr = pyrrhotite, ars = arsenopyrite, gal = galena, sph = sphalerite.

The degree of agreement between inclusions in alluvial gold and minerals associated with bedrock gold mineralisation varies from site to site. At Campanilla in Ecuador the agreement between the two is relatively poor and several minerals have been found as inclusions which have not been observed in the mineralisation. This is probably largely due to the limited number of bedrock samples of mineralisation from the area that were examined (Styles et al 1993). However, relatively uncommon Bi-rich telluride minerals were detected in both samples. For Lubuk Mandi the relatively simple mineralogy of the ore is clearly evident from the nature of inclusions in the alluvial gold. At Penjom there is generally good agreement between the incidence of the commoner opaque minerals but there is less correspondence between the nature of the rarer minerals associated with each sample types though bismuth telluride was found in both. The degree of agreement between the mineralogy of the two types of samples from Raub is higher than that for Penjom. Apart from the common sulphide minerals tetrahedrite is recorded in both sample types. For most of the material from Zimbabwe the agreement between the inclusions in alluvial gold and the known mine mineralogy is less good, especially for the rarer minerals. The reason for this must partly be the fact that because of the drought it was generally not possible to sample alluvial sediment close to individual mines. Only large rivers which drain a catchment containing several different mines were sampled. Furthermore, the bedrock samples studied comprise only a small proportion of the potential sources. Thus the variety of inclusions in alluvial gold from the Sebakwe river is much wider than the mineralogy of the Kwekwe mines.
studied, probably reflecting several other sources of mineralisation in the alluvial material. In contrast the agreement between the mineralogy of the C mine and the alluvial gold from Zvishavane is good and this could reflect the fact that the alluvial sample was taken close to this mine (Styles et al 1995).

4.5. Inclusion assemblages in alluvial gold from different sites

Though individual inclusions may provide information as to the type of source mineralisation, the inclusion assemblage within a population of several gold grains from the same site is more useful. The accumulated BGS data on the incidence of inclusions suggests that in most cases examination of more than 40 grains does not add significantly to the establishment of an inclusion assemblage. In many cases it has been necessary to try and establish the inclusion signature from lower numbers of grains. In some cases this is valid down to as low as 15 grains but this is not universal and such low numbers of grains will mean than in some cases the inclusion assemblage is inadequately defined. The inclusion assemblages from each area are portrayed in histogram form and discussed in turn. For clarity it is usually necessary to split the inclusion assemblage into two. The first group comprises minerals classified in terms of their non-metallic or semi-metallic element content (S, As, Sb, Te and Se) as these elements are usually, but not always, combined with the metallic elements. Antimony behaves as a metallic element in the minerals stibnite (Sb$_2$S$_3$). The iron sulphides pyrite and pyrrhotite are also included in the first group. The second group comprises minerals classified according to their metallic element content (Cu, Pb, Zn, Ag, Bi, Ni, Co and Hg). A complex mineral appears as its simple components and will appear in more than one bar on the histogram. A constant colour coding is used for each of 16 different categories of mineral so that plots from different areas can be compared.

4.5.1. Ecuador

Histogram plots of the relative abundance of different inclusion types in the alluvial gold samples from Ecuador are shown in figures 11 and 12. Only in the case of the gold from Campanilla is the source, skarn-type mineralisation, clearly known. However some conclusions can be made about the source of the alluvial gold from the other areas on the basis of the inclusion assemblage. The inclusion assemblage in the gold from Los Linenos is quite similar to that from Campanilla. The presence of selenides in association with dominant sulphides is particularly distinctive. The presence of Cu, Pb and Bi as the three main metallic elements in inclusions in the gold from both sites also suggests a close similarity in source. Slight differences between the two sites are suggested by the higher abundance of pyrrhotite at Los Linenos, which may indicate a higher temperature source mineralisation than that at Campanilla. The gold from the other three sites contain significantly different inclusion assemblages both to Campanilla and Los Linenos and to each other. All three contain As-rich inclusions which are absent in the gold from the other two sites but in other respects they differ from each sufficiently to suggest different types of source mineralisation. The assemblage within gold from Chigunda is marked by inclusions of copper and silver.
minerals but not of other base metals. This suggests a copper-rich type of source mineralisation, possibly a copper-gold type. The assemblage from Shumiral resembles some gold from Europe which is thought to be derived from greywacke-hosted mesothermal shear-zone mineralisation (BGS data). The sample from the Rio Santa Barbara near Peggy mine could be derived from mineralisation of the sort worked there but the inclusion assemblage of galena, arsenopyrite, plagioclase and tetrahedrite has not much in common with the pyrite - chalcopyrite - arsenopyrite ore sample studied from the Peggy mine (Styles et al 1993).

4.5.2. Peninsular Malaysia

Histogram plots of the relative abundance of different types of inclusion in gold from the Mersing and Lubuk Mandi areas are shown in figures 13 and 14. The inclusion assemblages in the samples from Mersing and Mersing beach are sufficiently different as to suggest different source components, though each sample may be derived from multiple sources. The selenide inclusions in one of the grains from Mersing suggest derivation from red-bed unconformity type mineralisation as outlined in Styles et al 1994. The presence of pentlandite inclusions and the absence of galena inclusions in the alluvial gold from Mersing beach suggests a source with some connection to mafic or ultramafic rocks, which is unlike any of the other mesothermal shear-zone mineralisation sampled elsewhere in the region (Styles et al 1994). The inclusions in the gold from the four samples from the Lubuk Mandi area are very similar (Figures 13 and 14) with galena the dominant inclusion in all. Apart from the mercury selenide inclusions the assemblage within the gold grains in the Mersing sample is similar to those in the alluvial gold samples from Lubuk Mandi.

The relative abundance of different inclusion types in alluvial gold from the Penjom and Raub areas are shown in histogram form in figures 15 and 16. There is more variation in the inclusions within the Penjom samples compared with those from Lubuk Mandi with Bi, Te and Se-rich inclusions present in some samples but not others. Though the predominant inclusion type is galena, as in the Lubuk Mandi samples, the presence of these additional inclusions in some grains suggests that the mineralisation at Penjom is more complex. The inclusions in the alluvial gold from the Raub area differ from those within gold from other areas in peninsular Malaysia in the lower abundance of galena and in the presence of a small amount of pyrrhotite. The relative scarcity of galena is also evident in the bedrock mineralisation in the area. The presence of pyrrhotite may indicate a slightly higher temperature of mineralisation at Raub compared with the other areas. The presence of gersdorffite inclusions (NiAsS) in gold from one sample in the Raub area may indicate some association of the mineralisation with basic magmatic rocks, possibly connected with mafic and ultramafic rocks within the Raub-Bentong suture.

4.5.3. Sarawak, Malaysia

Histograms showing the relative abundance of inclusions in the four largest samples of alluvial gold from Sarawak are shown in figure 17. The relative abundance of
inclusions in alluvial gold from this area seems relatively low compared with most areas. The inclusions are in some cases entirely different from those found in alluvial gold from Peninsular Malaysia. Antimony-rich inclusions, comprising the alloys aurostibite (AuSb₂), a silver-antimony alloy and stibnite (Sb₂S₃) are dominant in three of the samples. The samples containing alloy inclusions rather than sulphides may indicate crystallisation under relatively oxidising conditions. The presence of one sample with pyrite and copper sulphide inclusions rather than minerals rich in antimony suggests that different types of mineralisation source exist in the area. It is evident that differences in the inclusion assemblages in gold from location to location provide particularly useful information in an area like Sarawak, where detailed mineralogical work does not seem to have been carried out on mineral deposits.

4.5.4 Zimbabwe

The relative abundance of different types of inclusion in alluvial gold from different areas in Zimbabwe are shown in histogram form in figures 18 and 19. There is considerable variation in the inclusions from area to area. At Zvishavane and Kadoma the inclusions comprise simple sulphides while at the other four sites the assemblages are more complex. Silver-rich minerals and tellurium-rich minerals are present in all four of these more complex assemblages and Bi-rich minerals in three of the four. The sample from the Sebakwe River contains the most complex assemblage that has been found so far. A total of 17 different minerals have been found in gold grains from this site and this is reflected in the large number of categories in the histogram plots (Figure 18 and 19). The degree of complexity almost certainly reflects multiple sources since the sample was taken from a large river downstream of several mines.

5. POTENTIAL USE OF ALLUVIAL GOLD GRAIN CHARACTERISATION IN MINERAL EXPLORATION.

Most previous work on alluvial gold grains has concentrated on the nature of the surface of the grain. The present work has demonstrated that the surface of the grain is quite often not representative of the grain as a whole and could provide misleading information as to the source of the grain if studied in isolation. The surface of a gold grain may frequently have been influenced by chemical processes in the secondary environment but the effects of this penetrate only a few microns into the grain. Since gold is such an inert material under most conditions, minerals originating at the same time as the gold mineralisation, including those which are usually unstable at the earth’s surface, are preserved within the interior of grains.

The widespread occurrence of opaque and sometimes diagnostic non-opaque mineral inclusions in alluvial gold grains throughout the world indicates that their nature can be used, together with variations in the chemistry of the gold grains themselves, as a signature which reflects different modes of origin. Where it has been possible to make adequate comparisons between inclusions in alluvial gold and the mineralogy of the nearest bedrock mineralisation, a high degree of positive correlation is apparent. Where
several closely spaced samples of alluvial gold which are largely, if not entirely, derived from the same source mineralisation have been studied there is a close correspondence between them in both inclusions assemblage and grain chemistry.

The study of the nature of the interior of alluvial gold grains is particularly valuable during the reconnaissance stage of exploration. This is particularly so where the geology of the area surveyed is imperfectly known and where the knowledge of the mineralisation and environments potentially favourable to mineralisation incomplete. Different types of gold can be distinguished and related to potential types of source mineralisation. This study has contributed significantly to the comprehensive database and classification of different types of particulate gold which is being assembled by BGS. Because of the complexity of inclusion assemblages it is necessary to measure similarity mathematically in multicomponent space or, more subjectively, using bar plots of the type included in this report. Nevertheless some plots of the abundance of two components can demonstrate meaningful relationships. A plot of the relative proportions of pyrite and pyrrhotite inclusions in alluvial gold grains examined as part of this study together with similar data in alluvial gold from sites in western Europe is shown in figure 20. As pyrrhotite is generally more abundant as a component of mineralisation at relatively high temperatures this plot indicates alluvial gold grain populations most likely to be derived from higher temperature mineralisation. The Ecuador samples are distinguishable on this plot from most of the samples from other areas, though there are several European samples which plot similarly. As more characterisation studies are carried out it should be increasingly possible to deduce a considerable amount about the source of any gold and its potential economic significance at an early stage in exploration. This would facilitate the choice of targets for more detailed exploration thus saving considerable time and resources. If a type of gold is already known to have economic potential, it should be relatively easy to recognise this same type of gold in other areas, after the signature of this gold has been established.

Pathfinder elements are often used in gold exploration because they may be easier and cheaper to determine analytically than gold or because they show a wider distribution in the mineralised environment which it is easier to detect geochemically. The nature of the inclusions within gold can indicate the nature of the elements most closely associated with gold in the source mineralisation. Though elements like arsenic are often associated with gold mineralisation and used as a pathfinder, this association is far from universal and several types of gold mineralisation do not have any significant amounts of arsenic associated with them. In areas of complex and multiphase mineralisation it is important to recognise the elements most closely associated with gold which may be associated with only one phase of activity.
6. REFERENCES


APPENDIX. LIST OF ALL OPAQUE INCLUSIONS FOUND WITHIN ALLUVIAL GOLD GRAINS WORLD-WIDE

Sulphides

Pyrite
Pyrrhotite
Chalcopyrite
Bornite (Cu$_2$FeS$_4$)
Chalcocite (Cu$_2$S)
Covellite (CuS)
Galena
Sphalerite
Molybdenite
Millerite (NiS)
Pentlandite (Ni,Fe)$_2$S$_3$
Argentite/acanthite (Ag$_2$S)
Stibnite (Sb$_2$S$_3$)
Cinnabar (HgS)
Matildite(AgBiS$_2$)
Stromeyerite (CuAgS)
Galenobismutite (PbBi$_2$S$_4$)
Wittichenite (Cu$_3$Bi$_3$S$_9$)
Lilianite (Pb$_3$Bi$_2$S$_6$)
Stannite (Cu$_2$FeSnS$_4$)
Aikinite (CuPbBiS$_3$)
Friedrichite? (Cu$_3$Pb$_5$Bi$_7$S$_{18}$)
Stannoidite (Cu$_9$(Fe,Zn)$_3$Sn$_2$S$_{12}$)

Sulpharsenides

Arsenopyrite
Gersdorffite (NiAsS)
Cobaltite (CoAsS)
Lautite? (CuAsS)
Unknown Cu+Fe type
Enargite (Cu$_3$AsS$_4$)

Arsenides

Safflorite (CoAs$_2$)
Nickelinite (NiAs)

Sulphantimonides

Ullmanite (NiSbS)
Chalcostibite (CuSbS$_2$)
Antimonides
Breithauptite (NiSb)
Aurostibite (AuSb₂)

Sulphosalts
Boulangerite (Pb₃Sb₄S₁₁)
Plagionite (Pb₂Sb₈S₁₇)
Tetrahedrite (Cu₃Fe₁₂Sb₄S₁₃)
Jamesonite (Pb₄FeSb₆S₁₄)
unknown Cu sulphosalts
unknown CuPbFe sulphosalts

Bi sulphosalts
Bi fahlore

Sulphotellurides
Tetradytymite (Bi₁₄Te₁₃S₈)
unknown PbBiAg sulphotelluride

Tellurides
Hessite (Ag₂Te)
Stützite? ((Ag₃Te₁₃)
Petzite (Ag₃AuTe₂)
Calaverite (AuTe₂)
Tellurobismutite (Bi₂Te₃)
Tsumoite (BiTe)
Pilsenite? (Bi₄Te₃)
Coloradoite (HgTe)
Altaite (PbTe)
Melonite (NiTe₂)
Rucklidgeite (Bi₃Pb₃Te₄)
Merenskyite (PtTe₂)
Volynskite (AgBiTe₂)

Selenides
Naumannite (Ag₂Se)
Guanajuatite (Bi₂Se₃)
Tiemannite (HgSe)
Clausthalite (PbSe)
Berzelianite (Cu₂₋₋₂Se)
Fischesserite (Ag₃AuSe₂)
Pd selenide (PdSe₂)
Platinum selenide
Unnamed selenide (CuPdSe)
Selenotellurides

Bi selenotelluride
Pd selenotelluride

Intermetallic compounds
Gold copper (Au$_3$Cu)
Gold-copper (AuCu)
Isoferroplatinum (Pt$_3$Fe)
Tulameenite (Pt$_2$FeCu)
Copper-platinum
Maldonite (Au$_2$Bi)

Metals

Palladium
Bismuth
Silver content of gold in hand specimens from Zimbabwe mines

Figure 1. Cumulative percentage plots of silver content of gold grains in hand specimens of ore from mines in Zimbabwe. Storris G = Storris Golden Shaft mine, Comm = Commoner mine, Hazlem = Hazlemere Mine, Indaram = Indarama mine.
Figure 2. Cumulative percentage plots of silver content of gold grains in hand specimens of mineralisation in outcrop and core from the Lubuk Mandi area of Peninsular Malaysia.
Figure 3. Cumulative percentage plots of silver content of gold grains in specimens of drill core from the Penjom area of Peninsular Malaysia.
Figure 4. Cumulative percentage plots of silver content of gold grains extracted from table concentrates produced at Zimbabwe mines. The corresponding plots of silver content in gold from hand specimens of mineralisation from the same mine, where available, is also shown. TC = table concentrate, Oceol = Oceola mine, Puzz = Puzzle 2 mine, goldl = Goldleaf mine.
Figure 5. Cumulative percentage plots of silver content of alluvial gold grains from Ecuador. Also included is plot of silver content of gold in a hand specimen of mineralisation from the Campanilla area (Camp rc ). Camp= Campanilla, Linen = Los Linenos alluvial mine, Shum = Shumiral alluvial mine, Chig = Rio Blanco near Chigunda, Peggy = Rio Santa Barbara near Peggy mine.
Figure 6 Cumulative percentage plots of silver content of alluvial gold grains from Mersing and Lubuk Mandi areas of Peninsular Malaysia. Also shown are plots of silver content of gold in rock and core samples from Lubuk Mandi. Mers = Mersing, Mers B = Mersing Beach, LM = Lubuk Mandi.
Figure 7. Cumulative percentage plots of silver content of alluvial gold grains from Penjom area of Peninsular Malaysia. Also shown are plots of silver content of gold in core samples from area and in two soil samples from area (Penj 103s and Penj 104s).
Figure 8. Cumulative percentage plots of silver content of alluvial gold grains from the Raub area of Peninsular Malaysia. Also shown are plots of silver content of gold in hand specimens of mineralisation and in drill core from the Raub area. S Kem = Sungai Kemehang.
Silver content of gold from Sarawak

Figure 9. Cumulative percentage plots of silver content of gold grains from Sarawak, Malaysia. Slur = ball mill slurry of jasperoid ore, Tai Parit open pit, tail = tailings from Batu Bekajang (58,59) and from Arong Bakit (61), all = alluvial samples from Arong Bakit (60), E Paku quarry (62), Sungai Sipitas (68), Fairy Cave Bidi (74) Sungai Matung (78) and Sungai Pelandok (81), allt=alluvial samples derived from tailings at Lim Chong Bee Mine, soil77 = from trench at Ladang Dafa.
Figure 10. Cumulative percentage plots of silver content of gold in alluvial and soil samples from Zimbabwe. Maz = stream near Oceola mine, Maz soil = trenches near Storis Golden Shaft mine, Chegutu = Mupfuwe river, Chegutu, Kadoma = Umswezi River, Kadoma, Kad soil = soil around Heroine mine, Sebak R = Sebakwe River at Sebakwe Poort, Munyat R = Munyati River at Unmiati, Seb+Mun= below confluence Sebakwe and Munyati rivers, Silobela = Gweru River, Zvishav = Mtshingwe river, Zvish soil = above C mine.
Figure 11. Proportions of inclusions of different categories (non-metallic elements and iron sulphides) in alluvial gold from Ecuador. Locations as per figure 5.
Figure 12. Proportions of inclusions of different categories (metallic elements) in alluvial gold from Ecuador.
Figure 13. Proportions of inclusions of different categories (non-metallic elements and iron sulphides) in alluvial gold from Mersing and Lubuk Mandi areas of Peninsular Malaysia. Samples Lubuk Mandi 1, 2, 3, and 4 = 13, 14, 16 and 17 respectively.
Inclusions in alluvial gold from Malaysia (2)

Figure 14. Proportions of inclusions of different categories (metallic elements) in alluvial gold from Mersing and Lubuk Mandi areas of Peninsular Malaysia.
Figure 15. Proportions of inclusions of different categories (non-metallic elements and iron sulphides) in alluvial gold from Penjom and Raub areas of Peninsular Malaysia. Penjom 2 = sample 105, Penjom 3 = sample 109, Penjom 4 = sample 110, Raub 2 = sample 86.
Figure 16. Proportions of inclusions of different categories (metallic elements) in alluvial gold from Penjom and Raub areas of Peninsular Malaysia.
Figure 17 Proportions of inclusions of different categories in alluvial gold from Sarawak. Sample 1 = 67 draining tailings of Lim Chong Bee mine, sample 2 = 68 Sungai Sipitas, sample 3 = 74 Fairy Cave Bidi and sample 4 = 78 Sungai Matung.
Figure 18. Proportions of inclusions of different categories (non-metallic elements and iron sulphides) in alluvial gold from Zimbabwe. Locations as per figure 10.
Inclusions in alluvial gold from Zimbabwe (2)

Figure 19. Proportions of inclusions of different categories (metallic elements) in alluvial gold from Zimbabwe.
Figure 20. Incidence of pyrite and pyrrhotite inclusions in alluvial gold