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ALLUVIAL GOLD CHARACTERISATION IN EXPLORATION PLANNING: PROJECT SUMMARY REPORT

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British Geological Survey

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M T Styles

A Report prepared for the Overseas Development Administration under the ODA/BGS Technology Development and Research Programme, Project 92/1

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Alluvial gold grains from Zimbabwe

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EXECUTIVE SUMMARY

This report summarises the work carried out under the BGS-ODA Technology Development and Research (TDR) Programme (Project 92/1 R5549), ‘Alluvial gold characterisation in exploration planning’, during the period April 1992 to March 1995.

The aim of the project was to establish whether alluvial gold inherited features from its bedrock source and if this was the case, which features are the most useful to indicate the type of bedrock source. This was investigated by detailed mineralogical characterisation of bedrock and where possible, closely associated alluvial gold. The characterisation involved the measurement of physical and particularly chemical features of the gold grains. Samples were collected in Malaysia, Zimbabwe, Ecuador and Fiji.

The methods developed and used during the project are described and a summary of the results obtained is given.

Measurements of the size and shape of gold grains impart little information about the source of alluvial gold. Very angular and irregular shapes, easily observed with a binocular microscope, show that alluvial gold is very close to its source but abrasion and rounding of grains occurs within a few kilometres transport in streams and rivers.

Chemical analysis of gold grains, by electron microprobe, show that silver is the only other element detected in all gold and that copper and mercury may be present, in some areas, in concentrations up to a few wt%. The silver content of alluvial gold can give a broad indication of the type of source, higher silver contents (greater than 15% Ag) tend to indicate lower temperature 'epithermal' type deposits, while lower silver contents tend to indicate higher temperature mesothermal deposits. Secondary gold, formed by near surface processes, has a very low silver content, less than 1wt%.

The variation in silver content of alluvial gold can be used to show if there are single or multiple compositional populations present. This might be related, either to variation in a single source or multiple sources. In many places the composition of alluvial gold has been demonstrated to be very similar to its bedrock source.

Many alluvial gold grains contain microscopic inclusions of other minerals. These inclusion bear a close relationship to minerals found with gold in the bedrock source. The inclusions can be used to indicate single or multiple populations of gold and possible types of bedrock source.

Alluvial gold clearly inherits most of its features from its bedrock source. Secondary alteration is a minor process in all the areas studied, which cover a wide range of climatic regimes, ranging from semi-arid in southern Africa to tropical rainforest in south east Asia.

A combination of gold composition and the assemblage of included minerals can be used to build up a 'fingerprint' of different types of gold deposit. This information can be used to recognise multiple sources of gold and predict possible bedrock sources of alluvial gold. Such indications can be used to guide gold exploration programmes at
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1. INTRODUCTION

This report summarises the work carried out under the BGS-ODA Technology Development and Research (TDR) Programme (Project 92/1 R 5549, Alluvial gold characterisation in exploration planning), during the period April 1992 to March 1995. The TDR Programme is part of the British Government provision of technical assistance to developing countries. The report presents the objectives, methods used, principal results, developmental implications and conclusions of the research carried out. It covers the overall aspects of the project in general terms, while the more technical aspects and results, for the interested specialist, are described in a series of technical reports which are listed in Appendix 1.

2. BACKGROUND

Gold is a resource of great value in many developing countries and an important source of foreign currency. Methods that increase the efficiency of gold exploration will decrease the cost of exploration and increase the likelihood of gold resources being discovered and exploited.

Gold is found in two different types of environments; in the rocks in the ground, here referred to as bedrock deposits and in stream and rivers, as a result of weathering of gold from bedrock deposits, referred to as alluvial deposits. In many developing countries small alluvial deposits and minor occurrences of gold are widespread but bedrock deposits are few. While gold can be produced from alluvial deposits there are many disadvantages in this being the main source of gold production.

Alluvial mining:

- Often small scale, involving a few people, with little, often inadequate or inappropriate, equipment and hence tends to be very inefficient. In particular fine-grained gold, which is often a significant proportion of the gold present, is not recovered.

- It is often illegal and uncontrolled, carried out for short periods of time in remote locations. As it is illegal it provides little or no revenue to the government.

- Because it is uncontrolled it is often environmentally unfriendly with the destruction and contamination of watercourses, that may well be the water supplies for the local population. Of particular importance is the widespread use of mercury as one of the few methods used to extract fine gold. This often pollutes the rivers and contributes a major health hazard.

- As alluvial gold is the gold weathered out from the surface of a deposit it is likely that most of the gold reserve still remains in the ground.
In contrast bedrock gold mining has many advantages over alluvial mining:

- Larger scale, carried out with proper equipment with more efficient recovery of gold present. In many developing countries, though, there is often considerable room for improvement.

- Mining is carried out at permanent sites with licences etc. from the authorities and hence is monitored and controlled and should therefore be carried out in a much more environmentally friendly manner.

- The gold mines generally sell their production to the government, which levies taxes and subsequently provides much needed national income and foreign currency.

- A much greater proportion of the gold reserves are recovered by bedrock mining.

Currently practiced exploration methods use the presence of alluvial gold as an indicator that gold is present in an area but do not use any features of the alluvial gold itself to predict its source. If methods could be found to locate the sources of alluvial gold from properties of the gold this could make significant improvements in the efficiency of gold exploration.

A limited amount of previous work in the UK had shown that alluvial gold can show complex internal variation. These examples were often from areas where there was little alluvial gold present and the bedrock sources were not known and it could not be established whether these were primary features inherited from the bedrock source or were secondary features formed during weathering and transport.

3. AIMS

A project was formulated to check whether alluvial gold inherits features from its bedrock source and if this is the case, which features are the most useful indications of the type of bedrock source. The latter information can be used to guide and target gold exploration programmes and increase their efficiency. The proposed way of achieving this was by a programme of gold characterisation, studying a range of characteristics of gold, particularly from bedrock sources and closely associated alluvial deposits.

The characteristics to be studied covered:

- a wide range of physical characteristics such as the size and shape of gold grains

- the chemical characteristics such as the composition of the gold, the internal variation and the minerals included in the gold.

It is well known that gold occurs in bedrock deposits in various types of rocks and different geological settings. Study areas were selected to cover a range of these
types. It is obviously important to be able to recognise different types of gold mineralisation if origins of alluvial gold are to be predicted.

The effects of weathering and erosion on gold deposits vary in different climatic regimes and hence might affect the features found in alluvial gold and this was also considered in the selection of study areas.

4. SELECTION OF FIELD STUDY AREAS

The selection of study areas had to take into account many factors, primarily those mentioned above but also various logistical matters. In particular, a good local knowledge of geology and mineral deposits would be of great importance in the detailed selection of sample sites. Collaboration with geologists with that knowledge would greatly increase the project’s chances of success. It was fortuitous that during the early part of the project there were ODA-BGS Technical Co-operation (TC) projects on gold in Malaysia, Zimbabwe and Ecuador and these countries fulfilled a range of the requisite scientific criteria. A further, mutual benefit working in countries with existing gold projects was that work on this project would add to the work of the TC projects and make information gained, readily available to the geological surveys in those countries. In addition to the countries with TC projects work was also carried out in Fiji.

4.1. Malaysia

All work in Malaysia was carried out with full collaboration and extensive assistance from the Geological Survey of Malaysia (GSM), and two field sampling visits were made by project staff. Malaysia has widespread minor alluvial gold workings and occurrences but few bedrock gold mines. This was one of the reasons for the ODA funded, GSM-BGS, Gold Sub-programme that was in progress at the time of the project. The Gold Sub programme investigated many of the known gold deposits in Malaysia and was able to direct us to three areas in peninsular Malaysia where we would be able to collect closely related bedrock and alluvial gold samples. These samples were crucial to investigate one of the main objectives of the project; that alluvial gold inherits features from its bedrock source.

In simple terms the geology of the Malay peninsula consists of Eastern and Western Granite belts, where the tin deposits are found, and a central 'gold belt' (Figure 1). These belts were formed during major periods of earth movement about 300 million years ago. Two areas, quite close together, in the central 'gold belt' and one on the north east coast were studied in detail. Those in Pahang state, in the central belt, were the long established mine at Raub and a new prospect at Penjom, some 30 km away. Though close together and from similar geological setting, in shear-zone type deposits, they had detailed differences in the mineralogy of the gold-bearing veins. This would provide a good test of the ability of the technique being developed to discriminate between relatively similar deposits.
Figure 1. Map of peninsular Malaysia showing the locations of primary gold occurrences and the areas studied.
The Lubuk Mandi area in Terengganu state, in north east Malaysia, was on the eastern side of the Eastern granite belt. At this location a new mine was being developed very close to previous alluvial workings. This provided an ideal opportunity to study bedrock gold and alluvial gold, only a km or so away from its source, where there could be no doubt about the source of the alluvial gold.

Plate 1. View of the Lubuk Mandi site showing the mine ore zone on the hill in the background and the alluvial workings in the foreground. (Photograph by A G Gunn)

In contrast to the areas already described, the Mersing area in Johore state in south east Malaysia had minor alluvial gold workings but with the exact bedrock origin of the gold unclear. An area in Negri Sembilan state, in south west Malaysia, also had alluvial gold but again the bedrock source had not been identified. These areas would test whether any useful information about the origin of the gold could be gained from studies of the alluvial gold.

Work was also carried out in Sarawak in East Malaysia, centred mostly on the Bau mining district near Kuching. Gold has been mined at Bau for a long period and the type of mineralisation is different from that in peninsular Malaysia, being associated with granitic intrusions and associated with different types of minerals. This would show whether gold from different types of deposits developed and preserved different characteristics.

4.2. Ecuador

Work in Ecuador was carried out in collaboration with the Cordillera Real TC project. The TC project was finishing soon after this TDR project started and they
offered to provide samples for study, as gold exploration had been an important part of that project. Ecuador has extensive alluvial mining but very little bedrock mining and in addition would provide an interesting contrast with the geological setting and climate type encountered in Malaysia. Alluvial gold was provided by the Cordillera Real team but unfortunately little bedrock gold was available.

4.3. Zimbabwe

The work in Zimbabwe was carried out in collaboration with the Zimbabwe Geological Survey (ZGS) and the ODA-ZGS-BGS ‘Midlands goldfields’ TC project. The reasons for the work in Zimbabwe were rather different than those in the other areas, as Zimbabwe already has a well developed gold mining industry and is a major world producer of gold. Zimbabwe is a good example of the ‘greenstone-belt’ setting of gold deposits a major type of deposit that is important, not only in Africa but also Australia and Canada. These are old volcanic and sedimentary sequences, intruded by granites, that were formed 2,500-3,000 million years ago, much older than any of the other deposits studied.

There would be no problem obtaining bedrock gold samples, as had been the case in Ecuador, as there were numerous working mines and the data from Zimbabwe would provide a good database of the ‘greenstone belt’ deposit. Secondly the semi-arid climate of southern Africa would provide a good contrast to the tropical rain forest of Malaysia and the high mountains of Ecuador, to test the effects of climate on weathering and alteration of gold. Unfortunately, at the time of the field visit there was a very serious drought and some difficulties were found collecting alluvial samples as most of the rivers had dried up.

4.4. Fiji

There was no TC project in Fiji but BGS has a good relationship with the Department of Mineral Resources and the work was carried out with DMR collaboration and assistance. Gold is an important export commodity in Fiji and there was considerable interest in collaborating in research that might provide useful information about their deposits. One field visit was made by a project staff member. The gold deposits in Fiji are connected with relatively recent volcanic episodes and intrusions. The ocean island setting contrasts with the other areas studied.

5. METHODS USED AND DEVELOPED

A brief description of the methods used and developed will be given as this was a project exploring new avenues of research and technique development was a significant part.

5.1. Field sampling

The aim of the field sampling was to obtain paired samples of bedrock and alluvial gold, with both coming from the same source. This is not a particularly straightforward exercise as typical gold ores only contain 5-10 grams of gold per ton and
often do not contain free (visible) gold grains, as the gold may be in solid solution in other minerals. Most of the bedrock samples from Ecuador, studied in the early part of the project, were supposed to be 'high grade' ores but we were unable to find any gold grains and hence there were no candidates for possible sources for the alluvial gold. In the later stages of the project we made particular endeavours to obtain samples with visible gold. Most of these samples were generously donated by mine owners, managers or geologists, both from rock samples and drill cores. At several mines, where there was supposed to be very little free gold, but small amounts of the high-grade concentrate from the mineral processing plants were collected and these yielded many small gold grains. In some areas, particularly Sarawak, the bedrock gold is very fine-grained and unlikely to be seen. Rather than taking huge numbers of rock samples and hoping for gold, it was decided to pan the fine material from crushed ore, spoil heaps etc. to increase the chance of gold. This collects the heavy minerals from a large volume of ore and was generally successful.

Plate 2. Panning for alluvial gold in Sarawak, East Malaysia.

The alluvial samples were collected by standard panning techniques, though the emphasis was of course, on finding gold rather than obtaining representative samples, as is the aim of geochemical surveys. At all sites the target was to obtain a minimum of 20 grains, though this was not always achieved, even when five or six pans of alluvium were processed. In general the standard BGS method of sieving to less than two mm prior to panning was used to improve the efficiency of panning and retention of fine gold. (It was noticeable that the very expert panners in the GSM field teams in Malaysia were impressed by the improved results obtained from sieved material, as their normal practice is to pan unseived material).
In a few cases alluvial gold samples were obtained from alluvial miners. There were however considerable variations in the size of gold grains in these samples, which probably reflects different panning methods etc. In general there was less very fine gold, which effected the results of size and shape measurements.

5.2. Sample preparation

Sample preparation was an important part of the project as all the subsequent analytical procedures rely on good sample preparation.

5.2.1. Gold grain separation

The aim of laboratory preparation of bedrock gold was to produce polished thin sections for microscopic study of the gold grains and associated minerals and make microchemical analyses of individual grains of interest. Where gold grains were visible on the surface, the sample could be sliced in the appropriate place but in other cases gold grains were plucked from the surface and mounted in epoxy resin for further study.

The purpose of preparation of the alluvial samples was to extract gold grains from the heavy mineral concentrates that had been collected in the rivers and streams. Even these heavy concentrates often contain less than 1% of gold grains. This separation was mainly carried out using a 'Superpanner', a laboratory panning machine, that can be very closely controlled to yield a concentrate, much enriched in gold. This can then be hand picked under a binocular microscope. The grain size of gold recovered ranged from 3 - 0.1mm.

5.2.2. Gold Grain Mounting

The gold grains separated from alluvial samples were to be subjected to a range of characterisation measurement and had to be mounted in an appropriate manner. Unfortunately one mounting method is not appropriate for all the types of examination as physical measurements of size and shape are made on the outer surface, while chemical analyses are made on the inside, on a cross section of the grain.

At the start of the project the separated grains were placed in an ordered fashion on double sided adhesive tape stuck on to a glass slide. Each grain was given a unique identification number, so that all the properties of an individual grain could be correlated when required. Size and shape measurements were made on all grains and details of the surface of a selection of grains were studied using a scanning electron microscope (SEM). Following this, the small grains were transferred to glass slides coated in epoxy resin, and the larger ones placed in special moulds to be encased in blocks of epoxy resin. As a part of this process, the grains also had to be size graded, so that when they were ground down prior to polishing, the plane of grinding was as near as possible to the equator of the grain. This mounting, moving and remounting was an extremely delicate and time consuming operation as many grains were very small, less than 0.5mm and great care had to be taken to ensure the grains were not mixed up.
The time taken for this was significant as several thousand grains were being studied during the project and a range of tests and experiments were made in an attempt to find a method that avoided moving the grains from one mount to another. Several methods were tried including mounting on black, electrically-conducting tabs used for SEM work, Plate 3. None of them proved to be entirely successful in the long run and resulted in some gold grains being lost during the grinding and polishing process. Finally it was concluded that whenever there were sufficient grains to split a sample, a separate fraction should be mounted for each type of examination. If there were few grains they should be mounted directly into epoxy resin and whatever surface measurements were still possible should be done. The most important tests are the chemical analyses (see conclusions in subsequent section) and the risk of losing gold grains during preparation must be minimised.

Plate 3. Alluvial gold grains mounted prior to size and shape measurements. Field of view 8mm.

5.2.3. Grinding and polishing

The grinding of gold grains to reveal a cross section is a delicate operation that must be done with the utmost care. With small gold grains the difference in the amount of grinding between first exposing the gold grains and totally removing them from the slide is minimal.

Polishing of the surface of the exposed grains was done using standard polishing techniques. It is emphasised that a very high quality polish is required to reveal the details of internal variation, particularly the presence of microscopic mineral inclusions in gold.
6. GOLD GRAIN CHARACTERISATION

The characterisation of bedrock and alluvial gold samples involved the measurement of various physical and chemical parameters.

6.1. Size and shape of alluvial gold grains

Previous studies of size and shape of alluvial gold grains had shown that in general gold gets more rounded the further it moves from its point of origin. This could be used as a very crude exploration tool. From the outset it had been intended that the main thrust of this project would be on chemical rather than physical characterisation. It was considered, however, that some size and shape data was an important adjunct to chemical analysis, provided it could be gathered quickly and easily.

To this end a system of gold grain measurement using an image analysis system was developed. After initial consideration it was decided to use two dimensional projections, or silhouettes of grains as a suitable approximation to the complex three dimensional shape. This would record the main features of the grains, the 'size' of the grain, the overall shape, whether it was equant or elongate and whether the perimeter was rough or smooth. The silhouettes of the gold grains were recorded using a video camera attached to a petrological microscope and measurements made using software developed during the course of this project. The method developed enabled measurements to be made quickly and easily and was carried out on all the grains studied.

In addition to these measurements the surface features of alluvial gold grains were studied using an SEM. The SEM has many advantages over optical microscopes, having a much greater range of magnification and a much greater depth of field. This is very important when studying rough surfaces.

6.2. Optical petrographic examination

After the gold grains have been polished to reveal cross sections they were then examined in detail using a petrological microscope. In the case of alluvial grains it was to check for obvious variation in the colour of gold, which indicates differences in composition and the presence of other minerals included in the gold. In the case of bedrock samples a proper petrographic examination was carried out to differentiate the various phases of mineral growth that had taken place and particularly which minerals had formed during the same mineralisation events as the gold. This was an important part of the check as to whether alluvial gold could be related to a particular source.

6.3. Electron microprobe studies

The main characterisation of the internal variation within gold grains was carried out using an electron microprobe. This is an instrument, similar to a scanning electron microscope that uses a very fine beam of electrons to generate X-rays and hence make chemical analyses of an area of a grain around 1µm in diameter.
For the bedrock samples, the gold grains were analysed along with any other minerals that occurred inside or in close proximity to the gold grains. For the alluvial samples, points in the centre of the grain and also close to the margin were analysed to check for variation. Many gold grains contain microscopic inclusions of other minerals (on average comprising around 20% of gold grains). These were also analysed and identified.

7. SUMMARY OF RESULTS OF LABORATORY STUDIES

The results of the work carried out during this project have been documented as a series of technical reports covering the various geographic areas studied (see Appendix 1). These contain a large amount of data and are suitable for readers with some technical knowledge of the subject. Here, a simplified summary of the main findings of the results will be given, with reference to examples in the technical reports.

7.1. Size and shape studies

Size and shape measurements have been made of several thousand alluvial gold grains. All samples studied showed several size populations, but in no instance could these size populations be related to any chemical features in samples where several chemical types were also identified. Examples of this type of study are given in all the technical reports.

The size and shape measurements essentially quantify what can be seen by studying the grains under a binocular microscope, i.e. the distribution of sizes and whether the grains are rounded or irregular. Indeed, visual examination may reveal more as the shape measurements are rather crude due to the limitations of only using a two dimensional shape projection.

SEM studies of the surfaces of alluvial gold grains provide valuable information about the deformation and abrasion during transport and also the processes operating at the site of deposition, such as overgrowths of other minerals. This is however, probably of limited use in mineral exploration.

It is concluded that only if accurate size information is required, perhaps for mineral processing planning, is it worthwhile making these kind of measurements on a regular basis. Most of the important information can be obtained from visual inspection. Our studies have shown that gold from soil and alluvium close to the source, is very irregular (Plate 4) but transport of only a few km rounds and flattens the grains to the typical alluvial grain shape (Front cover).
Plate 5a. Bedrock gold from Penjom, Malaysia, intergrown with silver, lead and bismuth tellurides (grey and brown colours). Field of view 0.5mm

Plate 5b. Bedrock gold from Raub, Malaysia, intergrown with and including pyrite. Field of view 1.5mm.
Plate 4a. Gold from soil from Sarawak showing very irregular shapes. Field of view 5mm.

Plate 4b. Alluvial gold collected close to its bedrock source, from Lubuk Mandi, Malaysia, showing preservation of irregular outlines. Fov. 10mm.
7.2. Electron microprobe studies

7.2.1. Bedrock Gold

Polished thin sections were made of all the samples known to or suspected to contain gold grains. Detailed petrographic studies were made of these thin sections to locate the gold grains and to establish the order of crystallisation of the different minerals in the gold bearing veins. Many of the veins have several phases of mineralisation and it is important to ascertain during which phase the gold was formed. In many cases gold was formed late in the sequence of mineralisation.

Following petrographic examination, electron microprobe analyses were made of the gold grains and related minerals, particularly the sulphide minerals that may have formed at the same time as the gold. Examples of these minerals are illustrated in Plate 5.

The gold grains were analysed for 16 elements that are reported in the literature to be constituents of gold. It was hoped that the minor element contents of gold might be a useful fingerprint. The detection limits of the method used are around 0.05 wt % element but the only element detected consistently (every grain) was silver, while mercury and copper were found at low levels in a number of grains. Other elements were found inconsistently at levels very close to the theoretical limit of detection and little reliance is placed on them being reliable values. The values of mercury and copper show regional scale variations, for example certain areas of Zimbabwe and Malaysia have high mercury, and this is an aid to other diagnostic properties.

The main chemical variation is in silver content which ranges from 0.1 to 50 wt %. In many cases a single thin section of bedrock gold gives a narrow range of silver contents. In a few examples a wider range, and in some places a bimodal distribution, was found, probably indicating two phases of gold mineralisation. Figure 2, a composite of gold compositions from various mines in Zimbabwe, clearly shows the narrow ranges recorded in many single samples (a line of points with a gentle slope) but the differences in silver content between the different mines. The data from Commoner and Indarama mines, in contrast, show a bimodal distribution with both low silver and higher silver gold.

The data from Zimbabwe, shown on Figure 2, are based on only one or two thin sections per mine, as it was difficult to obtain a larger number of gold-bearing samples in the short period of time available. It became apparent during the course of the study that small numbers of samples were often not adequate to characterise fully a bedrock gold source and gave a false impression of the range of gold contents present.
Figure 2. Composite plot of silver content of gold from bedrock samples and table concentrates from Zimbabwe.

In some of the areas in Malaysia where a greater number of samples were obtained a wider range of silver contents were found. A good example of this is provided by the samples from the Penjom prospect (Figure 3). This shows a comparison between a single sample with very abundant gold, over 150 grains, and the composite of all the bedrock samples from the area. The single sample has compositions in the range 10-17% Ag, strongly dominated by compositions close to 15% Ag, while the composite shows a range up to 25% Ag. The composite clearly shows a silver-rich population that was not found in the single sample, even though it contained very many gold grains.
Comparing hand samples with table concentrates provides a further test on the extent to which a few hand samples with visible gold are representative of a whole mine. (Table concentrates are the gold that has been recovered from ore after the ore has been crushed and subjected to a range of mineral processing techniques). A small sample of table concentrate will provide gold that is representative of many tons of ore. A comparison of the silver contents of hand specimens and concentrates from two mines in Zimbabwe can be seen in Figure 2, clearly shows that the concentrates from C Mine and Oceola Mine have a much greater range of compositions than were found in hand specimens.

From this it is concluded that concentrates are a far superior type of sample for gold deposit characterisation but if these are not available several hand samples should be studied if possible.

7.2.2. Alluvial gold

Electron microprobe analyses were made of the alluvial gold grains in a similar manner to the bedrock gold. Again only silver was found in all grains with low and variable amounts of copper and mercury occurring sporadically in the samples studied. The silver contents were plotted as modified S curves. These show a wide variety of silver contents and the number of populations present.

Alluvial gold from many places in Malaysia shows relatively simple patterns with narrow ranges of compositions. Fig 4 shows an example from Lubuk Mandi with a single population and a narrow range composition, between 8-13 \% Ag. This reflects both the fact that this alluvial gold is very close to its source and hence is probably a
single source and that the bedrock mineralisation is relatively simple. Most of the samples from Zimbabwe, such as the samples from the Mazowe area, in contrast, show large ranges in composition and complex shapes of the S curve Fig 5. The curve shows compositions ranging from 1-25% Ag and several populations, shown by the numerous breaks in the slope of the curve.

Figure 4. Silver content of alluvial gold from Lubuk Mandi, Malaysia

Figure 5. Silver content of alluvial gold from the Mazowe area, Zimbabwe.
7.2.3. Micro-inclusions in gold

Our studies of the internal variation in alluvial gold grains has revealed the presence of microscopic inclusions of other minerals (Plate 6). A detailed discussion of this is given in a report specifically covering the interpretation of gold compositions and inclusions (Leake et al. 1995). The proportion of grains that contain inclusions varies from one country to another and even between different sites within an area. The average proportion of grains containing inclusions is around 15% but ranges from 0% in one site in Zimbabwe to over 50% from one very fruitful site in Malaysia.

Around 100 different types of minerals have been identified as inclusions in gold, during the course of this project and other BGS work. A summary of the main types of minerals found is given in Table 1. below. Many of these minerals are rare in general terms but occur quite commonly as inclusions in gold.

Table 1. Main types of inclusions found in gold

| Sulphides: | Base metals, Mo, Ni, Bi, Ag |
| Sulpharsenides: | Fe, Ni, Co |
| Sulphantimonides: | Cu, Pb, Ni |
| Sulphotellurides: | Bi |
| Tellurides: | Ag, Bi, Cu, Hg, Pb, Ni, Pd |
| Selenides: | Ag, Pb, Hg, Pd, Bi, Cu, |
| Gold ‘alloys’: | Cu, Bi, Sb |
| Silicates: | many |
| Carbonates: | Ca, Mg, Fe, Mn |
| Oxides | Fe, Ti |

Fewer inclusions have been found in gold grains in thin sections of bedrock gold veins. However when grain mounts of table concentrates from the same mine were studied, a much higher proportion was found (a similar proportion to alluvial gold). It appears that the method of sample preparation has a significant effect on the likelihood of finding inclusions. Alluvial gold and table concentrates are both prepared in the same way, as grain mounts, where the grains are size graded so that they can be ground to reveal cross sections. The aim is to prepare grains with a large proportion exposed roughly through their equator, which is likely to give a maximum chance of finding inclusions. A thin section cut from a rock, will be a random section through the gold grains, with few close to the centres of grains, possibly giving a lower chance of exposing inclusions.

The types of inclusions found in alluvial gold tends to be limited within a sample or closely associated group of samples, but shows wide variation between different types of gold deposits. This is an important characteristic for classifying and differentiating various types of gold. The inclusion assemblages from most gold deposits contain base metal sulphides, pyrite, arsenopyrite and galena, as a major component but it is the other minerals that make the assemblages diagnostic. Figure 6. shows the assemblages from the areas studied in peninsular Malaysia. Each area either has unique minerals or distinctive ratios of minerals present.
Plate 6a. Alluvial gold from Lubuk Mandi, Malaysia, showing inclusions of galena (purple-grey). Field of view 0.8mm

Plate 6b. Alluvial gold from Raub, Malaysia, showing inclusions of pyrite (pale yellow-brown). Field of view 0.8mm.
Figure 7. Inclusion assemblages in alluvial gold from Zimbabwe
Figure 6. Inclusion assemblages in alluvial gold from Malaysia.
The inclusion assemblages from the areas studied in Zimbabwe are shown in Figure 7 and again they have either unique minerals or distinct ratios. The Zimbabwe assemblages are not only different from each other but also different from those from Malaysia, demonstrating how effective this data is in characterising individual gold deposits in different geological settings.

7.3. Laser ablation microprobe ICPMS analysis

Very few minor and trace elements were detected in gold during electron microprobe analysis, which has detection limits around 500ppm for the conditions used. A pilot study of trace element analysis using the laser ablation microprobe-inductively coupled plasma-mass spectrometer was used. This instrument analyses a volume in a thin section between 10-50μm in diameter with detection limits around 1ppm. This microbeam technique can avoid inclusions visible on the surface of the sample and analyse the gold free from interference. This study showed that trace elements, even at the 1ppm level, are rare and it was concluded that most trace elements reported in bulk analyses of gold are due to the presence of micro-inclusions. Further analyses for trace elements in gold were not made as this showed little prospect as a diagnostic tool.

7.4. Secondary alteration of gold

Secondary alteration of gold, either during weathering or alluvial transport and burial, could destroy features inherited from the bedrock source and create a whole new set of characteristics, related to alteration, not its source environment. Extensive secondary alteration would make characterisation of the bedrock source difficult if not impossible. Throughout these studies particular attention was paid to checking for the effects of secondary alteration of gold as there are many reports in the literature that this is extensive. The most widespread form of alteration reported is the alteration of silver-bearing gold to very pure gold by near surface processes.

Our investigations, which are based on the study of cross sections through gold, show that the formation of pure secondary gold is widespread, though in many cases it is a very thin surface layer, only a few microns thick. This layer can often be easily seen during optical microscope examination due to the different colour of the gold and an extensively altered example is illustrated in Plate 7 to demonstrate this feature. In a few areas, such as Fiji and Sarawak, the formation of secondary gold is more extensive and is possibly a feature of these types of deposits.

A further feature that might be considered to be secondary alteration is the formation of silver-rich 'tracks or films' within gold grains. These are thin layers, rich in silver, that appear to have formed along subgrain boundaries within the gold. They have been seen in many alluvial grains and a few bedrock samples. The exact mode of formation is not known, though various possibilities are discussed in the technical reports (Henney et al 1994, Styles et al 1995, Leake et al 1995), but the fact that they are found in bedrock samples shows they are not a surface environment phenomena.
Plate 7a. Alluvial gold grain from the Mazowe area Zimbabwe, showing alteration of primary, silver-rich gold (yellow-white) to secondary, pure gold (orange-yellow). Field of view 0.2mm.

Plate 7b. Alluvial gold grain from Lubuk Mandi, Malaysia, showing alteration by mercury around the margin and along fractures. Mercury-rich gold is grey-white colour. Field of view 0.2mm.
A second type of secondary alteration that has been seen in several areas is alteration by mercury. Alluvial gold miners use mercury for the extraction of fine gold from panned concentrates but accidental releases of mercury often occur. This is generally thought to be the source of the mercury that causes gold alteration. The effects of mercury attack on gold grains is very distinctive and easily recognised as is shown in Plate 7. The outer parts of the gold form gold-mercury intermetallic compounds which are very unstable. The mercury-rich parts are very soluble and are often dissolved away to leave a very irregular ‘honeycomb’ surface. The remaining mercury-rich gold is very white and distinct from the normal gold.

Our technique of studying gold grains in cross section, though adding to the difficulties in sample preparation, reveals the inner, generally unaltered parts of the gold grains. This has many benefits over analysis of the surface of grains which will often only be analysing secondary gold.

7.3. Comparison of bedrock and alluvial gold

The preceding sections have shown that both the composition of bedrock and alluvial gold and the inclusions they contain show a wide variation from area to area. A crucial feature of the project was to establish if this variation in alluvial gold is inherited from its bedrock source and hence can be used as an exploration tool. Three examples will be given to demonstrate this; two from Malaysia, where we had good control with a large number of bedrock samples and alluvial gold collected close to the source, and one from Zimbabwe where there were fewer samples and alluvial gold was farther from its source.

7.3.1. Lubuk Mandi, Malaysia

The gold deposit at Lubuk Mandi was the simplest we studied in terms of the range of gold compositions encountered and the mineralogy of bedrock gold veins and inclusions in alluvial gold (Henney et al 1994). The alluvial gold was collected within two kilometres of the bedrock source (Plate 1). S curves for the silver content of all the bedrock and all the alluvial samples are shown on Figure 8. This shows that both the bedrock and alluvial gold have a very dominant population containing around 10% Ag, strongly indicating that alluvial gold has the same composition as the bedrock gold. The alluvial gold also has minor subgroups with higher and lower silver that were not found in bedrock samples, possibly indicating that the bedrock samples did not cover the entire range of gold compositions.

The inclusions in alluvial gold (Figure 6) were pyrite, arsenopyrite and galena, minerals that occur as constituents of the gold-bearing veins in the bedrock samples. The close match of gold compositions and inclusions clearly shows that there is little or no change in gold during weathering and short transport in this setting.

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7.3.2. Raub, Malaysia.

The studies around the Raub gold mine also provide a clear example with a good range of bedrock samples from the mine and alluvial samples collected up to five kilometres from the mine (Henney et al 1995). The S curves of bedrock and alluvial gold are shown on Figure 7, which shows a more complex pattern than Lubuk Mandi. The bedrock gold shows several compositional populations, with large groups between 7-9% Ag and 4-6% Ag and small groups between 3-4 Ag % and less than 2% Ag. These compositional groups can be matched by groups in the alluvial gold that are indicated by the breaks in slope of the curve. The alluvial gold shows a large groups with 10-5.5% and 5.5-3.5% Ag, very similar to the main populations in the bedrock samples. The grouping of the lower silver grains is more complex but a group with 1-3% Ag, similar to the low-silver bedrock gold is present, with an additional group of grains with very low silver that may result from near surface alteration. The two high-silver analyses are from silver-rich tracks in grains.

The inclusion assemblage found in alluvial gold, (Figure 6), is dominated by pyrite, with lesser amounts of the copper and lead antimony-rich minerals, tetrahedrite and boulangerite and the nickel arsenic sulphide gersdorffite. Pyrite is common in the bedrock samples and the antimony minerals were also found here, (but nowhere else in peninsular Malaysia). Again, a good match was found between bedrock and alluvial gold, even the complex variation in gold compositions.
Figure 9. Comparison of bedrock and alluvial gold from Raub, Malaysia.

7.3.3. ‘C’ mine, Zvishavane, Zimbabwe

An interesting suite of samples were collected in the vicinity of ‘C’ mine near Zvishavane in southern Zimbabwe. The mine manager donated a hand sample of quartz-vein with visible gold, up to 1mm in size, though this was not typical of the main mine production, which was very fine-grained. A sample of table concentrate composed of typical fine gold was also collected, as well as a sample of soil from above the main vein. A sample of alluvium was collected from a river a few km away, that had ‘C’ mine and several other small mines in its catchment area.

’S’ curves showing the silver content of all these sample types are shown in Figure 10. They show that the gold in the bedrock hand sample had a very narrow range of silver content around 10% Ag, while the table concentrate had a much greater range from 11-21% Ag. The soil gold had a greater range still, from 3-30% Ag, with some similar to that from the mine but much of it richer in silver, possibly indicating a source of silver-rich gold that has been weathered away from the upper levels of the deposit. The alluvial gold contains examples of all the compositions found at the mine, a dominant group between 10-20% Ag similar to the main ore type, with a few low and high-silver types that were found in the soil. Very few inclusions were found in the alluvial gold but these were galena and pyrite (Figure 7), minerals known from the gold veins. Again there is a good match between the alluvial gold and that observed from studies of bedrock samples.
Figure 10. Ag content of different samples from 'C' mine

ROCK

'S' Curve for Silver

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ALLUVIAL

'S' Curve for Silver

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7.3.4. Comparison studies in other areas

These three examples, described in detail, are drawn from many examples, some of which will be mentioned briefly here. Work in the Penjom area in Malaysia showed good correlation between bedrock and alluvial gold. Although only 30km from Raub and in a similar geological setting, both the composition of gold and the inclusion assemblages are different. Studies at Mersing and Negri Sembilan in Malaysia were of alluvial gold occurrences where sources were unknown. In both cases source rock types could be suggested and at Mersing multiple sources were indicated. The work in Sarawak examined a lower temperature, 'epithermal'-type deposit, different to those studied in peninsular Malaysia. Bedrock and alluvial samples clearly showed this difference, with dominantly silver-rich gold and silver and copper minerals as inclusions. Differences between subareas show a complexity of mineralisation.

The work in Zimbabwe was not as detailed as in Malaysia, but again showed close similarities between bedrock gold and alluvial gold collected close to the source. Most of the alluvial gold was from sites with many gold mines in the catchment area. This was reflected in a much greater variation and complexity in gold compositions with multiple populations in all samples. There were regional variations in mercury content of gold. Micro-inclusion assemblages were dominated by base metal sulphides, with bismuth and tellurium minerals also quite abundant in many areas. These features give the 'greenstone-granite' type of deposit found in Zimbabwe a distinctive signature.

The work in Fiji revealed three types of bedrock epithermal mineralisation, each with a distinct gold composition and association of minerals, with silver, tellurium and antimony minerals prominent. Alluvial gold was studied from an area where the source was not known and results showed there were two distinct sources. One was a porphyry-copper intrusion that was known within the catchment area but the other must be a source yet to be discovered.

The work on samples from the Cordillera Real in Ecuador, was done early in the project and the sample set supplied had many shortcomings, particularly the lack of bedrock gold. The alluvial gold showed differences between areas based on the assemblages of inclusions but these could not be related to sources. Further investigation in the area would be merited now that the requirements and appropriate techniques are firmly established.

These studies clearly show that alluvial gold inherits most of its characteristics from its bedrock source. This is the case both in the tropical rainforest of Malaysia, the semi-arid savannah of Zimbabwe and from other work, in the temperate climate of western Europe. Secondary alteration of gold is minor and generally easily recognised and is not a significant hindrance to characterisation studies in these areas.
8. APPLICATIONS TAKE-UP AND IMPLEMENTATION

It has been demonstrated that alluvial gold inherits most of its features from its bedrock source. This means that characterisation of alluvial gold can provide important information to those planning and carrying out gold exploration programmes. The important types of information include:

- Discrimination of gold of primary or secondary origin
- Indication of type of source mineralisation
- Identification of single or multiple sources
- Comparison with known possible sources
- Definition of appropriate pathfinder elements for geochemical exploration
- Identification of zonation within ore deposits
- Advance warning of impurities which may cause ore processing problems

The areas with the most potential for beneficial application of alluvial gold characterisation studies are those where exploration or mineral potential schemes cover large areas where the geology is relatively poorly known. This applies particularly where exposure is poor and access difficult, such as densely forested areas. The streams and rivers, which are often the most accessible parts of such areas, are the medium which brings the samples from the inaccessible hinterland.

From the countries visited, Malaysia and Ecuador are ideally suited to such studies and south east Asia and South America in general are probably well suited. Gold characterisation studies could easily be incorporated into regional geochemical or mapping programmes in areas thought to have gold potential. Gold sample collection is more time consuming than standard geochemical sampling but a wider sample density could be used. The information from gold characterisation would help to build up a clearer idea of the gold potential of an area at a very early stage and provide vital information for more detailed exploration programmes.

Mineralogical studies as a part of mineral exploration are often underused by the mining industry and many geological surveys, particularly in developing countries. Gold characterisation is a new technique and there has been considerable interest expressed by both mining companies and geological surveys in the countries visited, once the techniques were explained. Various lectures have been presented by project members and this has also developed further interest.
As a result of the project work and related work in the UK, several large international mining companies are in discussion with BGS regarding possible development or contract work, in one case following a successful pilot study in South America. BGS has carried out one commercial study, in Europe, for a company and following promising results further work has been requested.

The technique is now sufficiently developed for scientists in developing countries to be trained for local implementation of the methods. The main pre-requisite, in terms of equipment required, is access to electron beam microanalysis equipment to analyse small gold grains and inclusions. Countries such as Zimbabwe and Malaysia are known to have electron microprobes, but an electron microprobe as sophisticated as that at BGS is not essential, and a scanning electron microscope with energy-dispersive analysis is adequate to do this work. This type of equipment is available in many developing countries, though possibly in Universities rather than Geological Surveys. However training will be essential as many of the techniques of sample preparation and laboratory study have been specifically developed for gold characterisation.

Future TC projects that include mineral exploration among their activities should include gold characterisation, both as a demonstration of the technique and a vehicle for on-the-job training of counterpart staff in the developing countries. Given the interest that is already being shown by the industry, further dissemination and training at relevant institutions in developing countries is warranted. Further work will also extend the knowledge base of the relevant type of mineralogical information and improve the source prediction aspect of alluvial gold studies.

9. CONCLUSIONS

1. A range of techniques for field sampling, sample preparation and laboratory analysis has been developed and successfully implemented for gold characterisation studies.

2. Studies of the size and shape of alluvial gold grains provide a large amount of data that can be rapidly and cheaply acquired. The data is complex and difficult to interpret and cannot be related to chemical features that are thought to be related to the genesis of the gold. It does not therefore appear to carry much useful information about the source of the gold and its use on a regular basis is not recommended. A simple examination of alluvial gold with a hand lens will reveal the general shape of grains. If the grains are angular and highly irregular they are very close to the source, probably within 2-3km, but if they are rounded and abraded they are further from the source.

3. Studies of the composition of alluvial gold showed that the only widespread variation was in silver content, which ranges from 0.1 to 50%. Studies of silver content, particularly when plotted as 'S' curves indicate different compositional populations. These populations may be due to multiple generations of gold within a single deposit or multiple sources. Our studies of bedrock gold show that multiple populations and wide ranges of composition are not common. It was,
however, recognised that obtaining sufficient bedrock samples to fully cover the whole range of compositions may be difficult. A very good sample type to achieve this is table concentrates from mines, which are very useful for characterising known sources within an area of interest. The silver content of gold can give a broad indication of the type of deposit that is the source of the gold. Predominantly high silver contents, 15% or greater, are generally associated with lower temperature, epithermal type deposits. Lower silver contents are more typical of mesothermal deposits. Gold formed by secondary, near surface, processes has a very low silver content, less than 1%.

4. Mercury and copper were detected in a number of samples and give indications of regional variation superimposed on the broad categories described above. Investigation of the trace element content of gold by laser ablation microprobe ICPMS showed that gold contained little if any trace elements when measured by microbeam techniques. Trace element contents reported by analysis using bulk techniques is probably due to the presence of micro-inclusions of other minerals.

5. Microscopic inclusions of other minerals, mostly between 1-100 microns in size, were found in alluvial gold from most localities studied. The inclusions found in alluvial gold bear a close relationship to the minerals formed with gold in the bedrock source. The assemblage of inclusions found can be a good indicator of multiple populations of gold. Sulphides of iron arsenic and lead are widespread but a great variety of other minerals were found and these can give indications of the type of rock from which the gold originated. Nickel and cobalt sulphides and sulpharsenides are a good indication of an origin from mafic and ultramafic igneous rocks. Bismuth minerals, particularly tellurides and sulphotellurides indicate an association with granitic rocks.

6. Alluvial gold inherits characteristics from its bedrock source. This was clearly demonstrated in several examples from Malaysia. There, the range of gold compositions was small, the gold mineralisation was relatively simple and these features were closely matched in alluvial gold collected very close to the source. It is also apparent from samples from Zimbabwe, where although there are mixed sources, many features can be matched between bedrock and alluvial gold.

7. Gold characterisation studies can form an important part of gold exploration programmes, particularly at an early stage where exploration covers large areas of poorly known ground.

8. Implementation of this technique in developing countries is possible. Further dissemination through workshops, seminars and on-the-job training of local geologists/mineralogists in the specialised techniques is required to maximise the benefits of this research.

10. ACKNOWLEDGEMENTS

We would like to thank the Geological Survey of Malaysia, the Geological Survey of Zimbabwe and the Department of Mineral Resources in Fiji for considerable assistance and advice during the planning and execution of the fieldwork associated
with this project. The local knowledge and expertise of field teams greatly enhanced the field sampling programme. Many mines and individuals, too many to mention, donated samples which greatly benefited the work on the project. Valuable support and assistance was provided by resident BGS-ODA TC officers, Mr A G Gunn in Malaysia and Mr P Pitfield in Zimbabwe.
APPENDIX 1. PROJECT TECHNICAL REPORTS


APPENDIX 2. OTHER PUBLICATIONS AND PRESENTATIONS


Lectures/seminars were given to collaborating organisations as part of all the overseas field visits, to the Geological Survey of Malaysia in Ipoh and Kuching, Geological Survey of Zimbabwe and the University of Zimbabwe in Harare and the Department of Mines in Fiji.

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