Microchemical Characterization of Alluvial Gold Grains as an Exploration Tool

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There is considerable variation in the composition of native gold and the nature of minerals co-existing with it, and this reflects differences in the geological environment and chemistry of ore-forming processes. In areas where gold-bearing mineralization is subject to active fluvial erosion, especially in temperate climatic regimes, any discrete grains of native gold pass into alluvial sediment with little modification. The chemical characteristics of alluvial grains and the nature of preserved mineral inclusions provide a signature which points back to the type of source mineralization. This signature may be established using electron probe microanalysis and scanning electron microscopy and can be interpreted to provide information about the original bedrock mineralization. Identification of the type of source mineralization using the technique at an early stage in regional exploration can help focus attention on targets with the most potential economic importance.

In nature, gold occurs predominantly as the native metal, although it is commonly alloyed with highly variable amounts of other metals; primarily silver, but also mercury, copper and palladium. It may also occur within common sulphur-rich minerals such as pyrite and arsenopyrite either as sub-microscopic inclusions of native gold or as a minor component within the lattice of these minerals (1). In a few occurrences gold may be present primarily in combination with tellurium in such minerals as calaverite ($(Au,Ag)Te_2$) rather than as the native metal. There are a wide variety of types of gold mineralization, influenced by differences in their geological setting, the chemistry of the ore fluids, and the nature of their reactions with rocks into which they penetrate. Characterization and classification of ore deposits has long been based on assessment of the geological environment of formation as inferred from structures, and mineralogical and chemical features observable in the field, augmented by chemical data. More recently, genetic models of major deposit types have been formulated as a result of combining descriptive information with increased understanding of the physics and chemistry of mineralization processes obtained from experimental and theoretical work. The classification of gold deposits has developed progressively by the application of genetic models and as new types have been discovered as a result of exploration, such as the Olympic Dam Cu-Au-U deposit of South Australia (2). Comprehensive reviews of gold deposit classification follow after periods of extensive exploration and mineral deposit research, such as that of Foster (3) in response to the proliferation of exploration activity in the previous decade. Variation in chemical parameters, both in environments of ore fluid generation and ore precipitation, result in a considerable variety in the mineralogy of gold-bearing ores. This manifests itself both in the composition of the native gold alloy and the associated minerals. This variation may also be seen in comparisons of gold deposits of the same type, for example Hedenquist *et al* (4) indicates the range of minerals associated with some economically important epithermal gold deposits.

Commonly, minerals which co-exist with native gold in the source mineralization also occur as microscopic inclusions within the gold (Plates 1, 2). Grains of native gold are chemically stable within most, but not all, environments on the Earth's surface, and thus gold grains liberated from the hypogene ore are normally unchanged on passing from bedrock into superficial sediments as a result of weathering and erosion. Evidence for the ability of gold to form an effective barrier between inclusions and the atmosphere is provided by the case of an alluvial grain from Ecuador which contained large (200μm) complex multiple telluride inclusions. The inclusions were observed to have suffered marked oxidation and hydration in less than 3 weeks

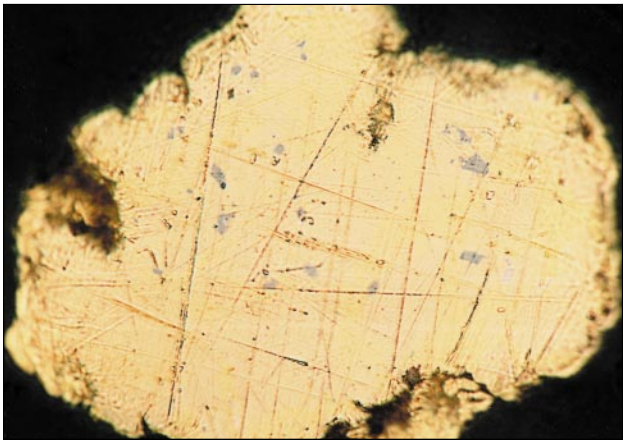

Plate 1
Alluvial gold grain from the Crediton Trough, Devon containing many microscopic inclusions of selenide minerals

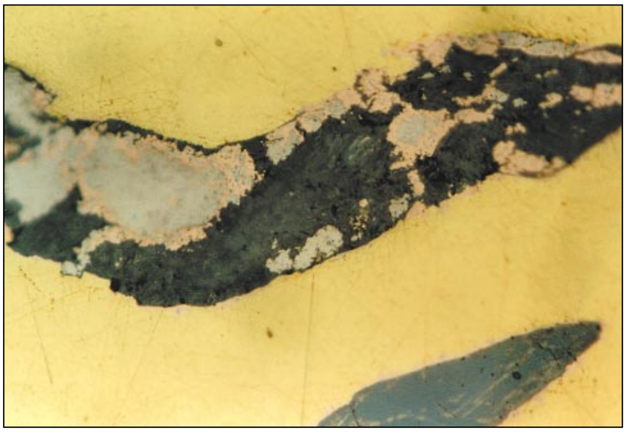

Plate 2
Alluvial gold grain from Ximena area of Ecuador containing relatively large complex inclusion of CuAg sulphotelluride (dark grey), Bi metal (pale grey) and a Bi+Cu+Au alloy (pink)

following preparation of the polished block and exposure to the atmosphere in the laboratory.

Some grains, especially those rich in silver, may show compositional modification of the outer part but even then a relict grain core that retains its original composition and inclusions is commonly recognizable (5 – 9). However, in areas which have suffered long and intensive periods of lateritic weathering, native gold may have completely recrystallized, so as to reflect this environment rather than that of the original source mineralization (10).

The search for bedrock gold deposits has historically involved systematic searches for alluvial gold in river gravels and the sampling of drainage sediment remains an important activity within the suite of modern exploration techniques. Gold concentrations can be determined directly by chemical assay of various size fractions or other components, including a heavy mineral fraction obtained by panning. Panning allows the visual detection of grains of native gold directly in the field which in many cases leads to the location of bedrock mineralization. However, there have also been fruitless searches for the source of alluvial concentrations of native gold. This paper describes how the microchemical characterization of a number of alluvial gold grains from a given site can provide information at an early stage in the exploration process that permits informed speculation about the type or types or mineralization from which the alluvial gold is derived.

Many workers have investigated the link between the composition of alluvial native gold grains and potential sources, examples being studies of Witwatersrand gold (11, 12), and gold from the Yukon (7). Desborough (13) first suggested the potential of mineral inclusions within the gold as an aid to distinguishing between alluvial gold from different sources. However, the work of the present authors, which is summarised here (and augmented by previously unpublished data for localities in North America and Australia), represents the first studies to systematically record the mineral inclusion assemblages and to generate classifications of gold grain chemistry which combine this information with that of the gold alloy composition. The resulting ‘microchemical signature’ provides a more powerful technique for interpreting the origin of alluvial gold than gold alloy composition alone, because the composition of native gold grains can vary from point to point within the same mineralized structure (9). This work has been undertaken for a period of over 15 years during which over 20,000 gold grains from 314 localities in Great Britain and Ireland, together with other sites in North America, South America, southern Africa, Australia, south east Asia, and Fiji, have been studied. A wide range of compositional variation in alluvial gold grains has been observed reflecting differences in the

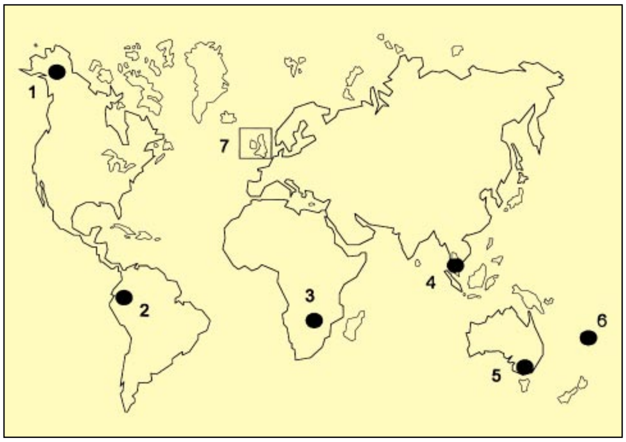

Figure 1
Worldwide locations of sites discussed in the text. 1: Klondyke District, Yukon Territory, Canada, 2: Ximena Province, Ecuador, 3: Mberengwa District, Zimbabwe, 4: Lubuk Mandi, Malaysia, 5: Victoria goldfield, Australia, 6: Wainmanu River, Fiji, 7: Localities in Great Britain and Ireland detailed in Figure 2

Table 1 *Location and References for Sites Described in the Text*

Country/Region	Detail of Locality	Geological Setting of Gold Mineralization	Geomorphological/Climatic Description of Locality	Reference
Great Britain and Ireland				
Southern Scotland	Leadhills area	Metasediments, Southern Uplands Terrain	Upland area, cool temperate climate	31
Southern Scotland	Tweed headwaters	Metasediments, Southern Uplands Terrain	Upland area, cool temperate climate	14
Southern Scotland	Glengaber Burn	Metasediments, Southern Uplands Terrain	Upland area, cool temperate climate	16
Central Scotland	Borland Glen, Ochil Hills	Acid-intermdiate volcanic sequence	Upland area, cool temperate climate	37
Northern Scotland	Sutherland area, Cononish R., Glengarry, West Water, Calliacher Burn, Glen Lednock	Metasediments Grampian Terrain	Upland area, cool temperate climate	8, 14
Northern Ireland	R. Bann, Mourne Mountains	Metasediments, Southern Uplands Terrain	Upland area, cool temperate climate	8
Ireland	Co Mayo	Metasediments, Southern Uplands Terrain	Upland area, cool temperate climate	8
Ireland	Balwoges, Co Donegal	Brecciated pipe and volcanic boss	Upland area, cool temperate climate	8
England, Devon	South Hams District	Red bed associated	Lowland area, cool temperate climate	15, 35
England, Devon	Crediton Trough	Red bed and alkali basalt associated	Lowland area, cool temperate climate	36
Wales, Dolgellau Gold Belt	Gwynfynnydd Mine	Metasediments	Upland area, cool temperate climate	9, 38
Zimbabwe				
Mberengwa District	'C' Mine	Greenstone Belt	Deep tropical weathering, slow erosion, semi-arid climate	24
	Sebakwe River	Greenstone Belt	Deep tropical weathering, slow erosion, semi-arid climate	24
North America				
Klondyke District, Yukon Territory	Bonanza Creek Bear Creek Hunker Creek	Metasediments	Upland area, sub arctic climate	7, 26
Australia				
Ballarat Goldfield, Victoria	Dolly Creek, Violet Town	Metasediments	Temperate rain forest	39
Walhalla Goldfield, Victoria	Jordan River, Woods Point	Metasediments	Temperate rain forest	39
Malaysia				
Lubuk Mandi		Metasediments	Steep relief, rapid erosion, tropical rainforest with waterlogged soils	25
Fiji				
	Emperor Mine	Alkali-epithermal	Tropical rain forest	23
	Wainmanu River	Porpyry+ alkali epithermal	Tropical rain forest	23
Equador				
Catopaxi province	Valetanga Perros Bravos		High altitude rain forest, no tropical weathering	30

style and geological environment of the host mineralization. Sufficient native gold obtained from bedrock and alluvial sources in Great Britain and Ireland has been studied to provide country-wide perspectives of the different types of gold mineralization present. Where possible, alluvial gold has been studied from several other parts of the world where the gold mineralization is of greater economic significance and which differ from the British Isles both geologically and

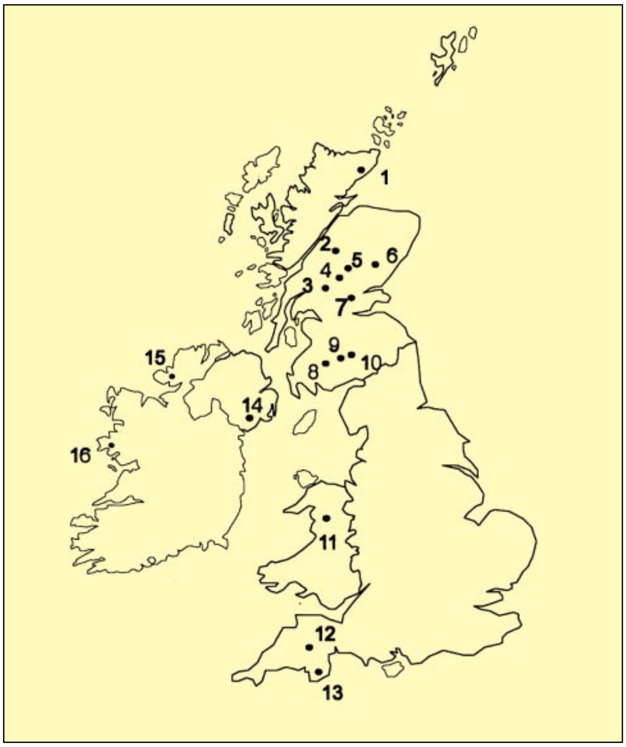

Figure 2
Locations of gold deposits in Britain and Ireland mentioned in the text. Scotland, N. Highland and Grampian Terriane: 1: Sutherland, 2: Glen Garry, 3: Cononish River, 4: Glen Lednock, 5: Calliacher Burn, 6: West Water, 7: Borland Glen, 8: Leadhills Region, 9: Tweed Headwaters, 10: Glengaber Burn, 11: Gwynfynydd Mine, Dolgellau Gold Belt, 12: Crediton Trough, Devon, 13: South Hams District, Devon, 14: River Bann, Mourne Mountains, 15: Balwoges, Donegal, 16: Co Mayo

climatically, but much more work is required to cover the whole range of mineralization types.

The geographical distribution of the gold localities referred to in the text are provided in Figures 1 and 2, and descriptions of the host environments of the gold mineralization are provided in Table 1.

Determination of the Microchemical Signature of Alluvial Gold Grains

The size of the population of grains studied from each locality is dependent upon the abundance of opaque inclusions within the grain. The proportion of sectioned gold grains containing identifiable opaque inclusions varies widely but in Britain and Ireland, they are typically found in about 20% of the grains (8), so a population of 30 grains is usually sufficient to generate useful information. Where the incidence of inclusions is lower and where multiple sources of alluvial gold contribute to the alluvial population, a correspondingly greater number of grains is required. This is rarely a problem in mining areas, but the collection of even 30 alluvial gold grains from some areas where mineralization is sparse or remote from drainage may be difficult and specialized field techniques have been developed for this purpose (14).

Prior to the mounting of gold grains in epoxy resin for grinding down and polishing, observations can be made on their size and shape. In a few cases grains with intricate shapes or surface textures may be present in alluvial sediment. At a few sites in South Devon (SW England), dendritic grains (Plate 3) were recorded in the alluvial sediment (15), very similar in form and composition to gold occurring in carbonate veins exposed on the coast at Hopes Nose near Torquay (Devon, SW England). Dendritic grains cannot survive more than a trivial amount of transport before dendrite spikes are folded around the core of the grain. Thus, their presence in alluvial sediment indicates very close proximity to a bedrock source.

After polishing, grains are examined by scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) to determine the concentrations of alloying elements (Ag, Cu, Hg, Pd, Sn) within the gold and the nature of the inclusion suite. Details of the experimental procedures are given in reference 8.

Mineral inclusions are of two types: opaque minerals, such as sulphides and sulpharsenides and translucent minerals, most commonly quartz and carbonates. In general, the opaque mineral assemblage is more useful in characterizing the type of source mineralization, although in some cases translucent minerals suggest the presence of specific types of mineralization, *eg* calcium-rich garnets and wollastonite may be indicative of skarn mineralization. The opaque mineral inclusion suite is reported in terms of the various mineral classes, *ie* sulphides, sulpharsenides and arsenides, sulphosalts and antimonides, tellurides and selenides which reflect ore composition in terms of Groups Vb and VIb elements. The classification of the inclusion assemblage is

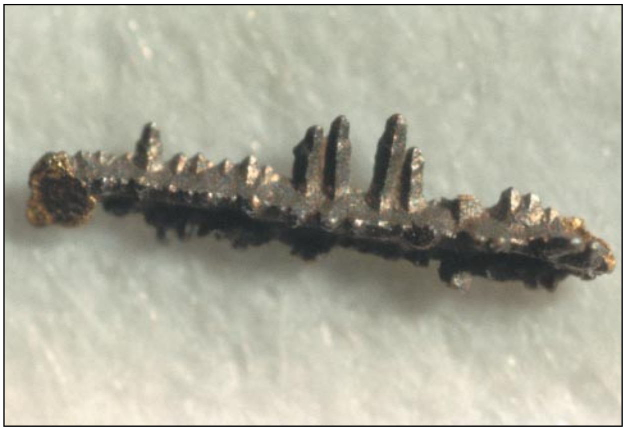

Plate 3
Dendritic gold grain from alluvium in South Devon. A thin rim made of Pt-rich alloys coats the gold grain

made in terms of the rough proportions of individual inclusions corresponding to the mineral classes. In a few cases the presence of specific or unusual inclusions may contribute significantly to the microchemical signature. For example, gold from Balwoges, a locality in Northern Ireland, contained a high proportion of copper sulphide inclusions, which are generally very rare (8). In other cases a distinctive inclusion suite may be restricted to populations of alluvial gold grains from specific sites within an auriferous region, and this may be indicative of a particular mineralizing event. For example, a study of the Glengaber Burn area in Southern Scotland showed that gold from the richest alluvial locality contained inclusions of tetrahedrite and sphalerite which were absent in alluvial gold from nearby rivers (16), despite the gold alloy compositions being broadly similar throughout the study area. A study of alluvial gold from three adjacent auriferous rivers draining the Dolgellau Gold Belt in North Wales also showed different inclusion assemblages in each case. One assemblage comprised sulphides and sulpharsenides whilst 40% of the inclusions from another were tellurium-bearing minerals. The third population was distinguished both by the presence of molybdenite inclusions and by a mean silver content in the gold alloy 15% higher than recorded for gold from the adjacent rivers (9).

The composition of a population of gold grains in terms of their silver content (and where appropriate other metals) is represented using a plot of the type presented in Figure 3. Each gold grain is represented as a percentile and plotted against increasing silver content. In this way, populations of differing numbers of grains may be compared directly. Figure 3 compares silver contents of gold grains extracted from mineralization intersected in drill core with grains extracted from nearby alluvial sediment in the Lubuk Mandi area of the Malaysia peninsular. The significance of the shapes of the plots is discussed further below.

The microchemical signature of a population of gold grains is derived from combining the chemical description of the inclusion assemblage with the quantitative data describing alloy composition. Broad differences between gold formed in different geological environments are readily apparent (8). Examples are presented in Table 2 which summarizes the chemical characteristics of composite populations of gold grains from Scotland and Ireland. Gold from the Tweed headwaters and Glengaber Burn area in Scotland is generally similar to that from Co Mayo in Ireland both in terms of silver content and inclusion assemblage, although approximately 200km apart, both lie within the same geological terrain. However, gold from the Leadhills region, also in the Scottish Southern Uplands terrain exhibits a different signature, with a far higher proportion of arsenic-bearing minerals in the inclusion assemblage. Gold from the Grampian terrain in Scotland and Northern Ireland is

Table 2 *Comparison of Inclusion Assemblages from Gold Localities*

Locality/ Sample Sets	Localities Contributing to Composite Samples	No Grains	Median Ag %	Inclusion Assemblage Characterized by Mineral Class				Diagnostic Minerals Within the Inclusion Assemblage
				% Sulphides	% Sulpharsenides	% Sulphosalts	% Tellurides	
Gold hosted by meta sediments								
Mayo, Ireland	Cregganbaun Shear Zone, Croagh Patrick	233	8.9	90	6	4	2	Sphalerite, tetrahedrite
Southern Scotland	Glengaber area Tweed headwaters	335	7.0-7.8	71	17	6	0	Sphalerite, tetrahedrite
Southern Scotland	Leadhills	500	10.6	51	49	0	0	
Northern Scotland	Sutherland area, Cononish R., Glengarry, West Water, Calliacher Burn, Glen Lednock	465	9.7-28	81	19	0	4	
Malaysian gold	Lubuk Mandi,	182	9-10.7	75	23	1	1	
Yukon gold	Bear, Hunker and Bonanza Creeks	83	15-33	59	41	0	3	
Australian gold	Dolly Creek, Jordan River	70	3.2 -8.2	68	20	12	0	
Gold associated with volcanics								
Fijian gold	Waimanu River	46	5-18%	63	0	0	37	Bismuth tellurides
Central Scotland	Borland Glen	50	6.4	60	0	0	40	Bismuth tellurides

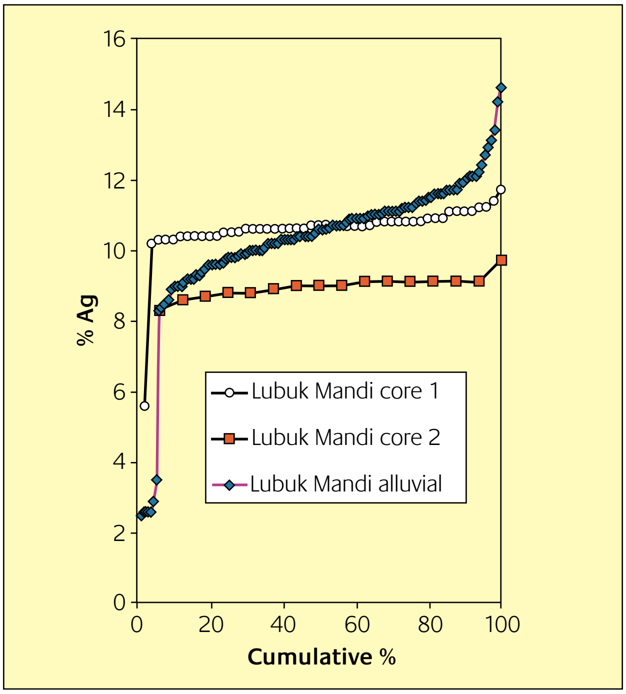

Figure 3
Comparison of silver contents of gold grains from drill core and nearby alluvial sediment Lubuk Mandi, Malaysia

generally of higher silver content than gold from the Southern Uplands and exhibits a tellurium signature in the inclusion assemblage absent in gold found to the south.

The technique is highly reproducible in terms of both sampling and analysis (9). The microchemical signature of gold from an area in the Leadhills district of Southern Scotland is independent of the field sampler, the date of collection and the exact location of the sampling site. In addition, the same microchemical signature was obtained using very similar analytical facilities but different analytical procedures in two separate laboratories.

Factors Modifying the Microchemical Signature of Alluvial Gold

The success of the microchemical characterization technique as an exploration tool depends on a close relationship between the microchemical signature of alluvial gold and the characteristics of the source mineralization. There are two ways in which the microchemical signature of a population of gold grains can be altered by post-liberation processes in the secondary environment: either by modification within the fluvial environment or by the addition of authigenic gold, and both are considered below.

The opaque mineral inclusion assemblage may become more difficult to identify with increased transport in the fluvial environment as most of the opaque mineral inclusions are unstable in an oxygenated fluvial environment and thus would decompose if deformation of the gold allows contact with air and water (17). However, for transport distances typical of alluvial gold from Britain and Ireland the host grains provide effective barriers to decomposition of inclusions as witnessed by the wide range of mineral species which are unstable in oxygenated surficial environments (*eg* galena, pyrrhotite, and chalcopyrite).

The formation of mineral inclusions by mechanical embedding into the grain surface is another mechanism by which the signature of alluvial gold could be altered. However, the typical size of inclusions (2-20μm) is much smaller than grains of the same minerals in the host mineralization and such grains would be particularly unstable in oxygenated fluvial environments. If mechanical incorporation of mineral grains into gold in the alluvial environment was prevalent, the most common mineral in alluvial sediment, generally quartz, would be expected to be most abundant and yet in most of the 20,000+ alluvial gold grains studied it is absent.

A population of gold grains can be augmented or even replaced by the addition of authigenic gold, that is gold precipitating from solution in the surficial environment. This can result in the formation of additional discrete gold grains or coatings on the original grains. The degree to which authigenic gold contributes to a population of gold grains is governed by the prevailing climate and geomorphology of the location (18). Authigenic gold may be important in some tropical environments where chemically aggressive groundwaters can alter the profile of gold distribution over long periods of time. This process is important in Australia (19), Ghana (20, 21) and various other tropical localities referred to by Nichol *et al* (18). Complete re-mobilization of gold will obliterate the textures and chemical signature of the original hypogene gold, however textures characteristic of authigenic gold such as crystalline form or extensive modification around the grain core are identifiable by SEM methods (40). Consequently an evaluation of the degree of modification to the population of alluvial gold is possible as part of the analytical procedure.

Studies of gold from Britain and Ireland (8, 9), North America (5 – 7), and New Zealand (41) failed to identify any evidence for augmentation of the alluvial population by authigenic processes, and the internal characteristics of the gold grains were considered consistent with those from the hypogene source. These results give a strong indication that for alluvial gold in temperate climates the contribution of authigenic gold is negligible, although many grains exhibit gold rich rims typically to a thickness of about 10 μm, which have been attributed to a process of silver depletion (22).

In studies of gold from Fiji (23), Zimbabwe (24), Malaysia (25), and the Victoria goldfield in Australia, the full range of inclusions found in alluvial gold from Britain have been observed, showing that preservation of the original features of gold grains as they pass into the fluvial environment is also possible in other climatic regions. However in some cases there is evidence for some post-depositional alteration of gold grains. Plate 4 shows a gold grain from the Mazowe area of Zimbabwe which shows the alteration of primary silver-rich gold to pure gold. Gold from Hunker Creek in the Klondike district of North America differs from grains from other Klondike localities studied by the authors in that they exhibit relatively large (up to 200 μm) rims typically containing up to 5% silver (Plate 5) with single or multiple cores containing 15-25% silver. Knight *et al* (26) also observed similar features in gold from this locality and interpreted the texture as indicative of silver depletion rather than the deposition of new authigenic gold.

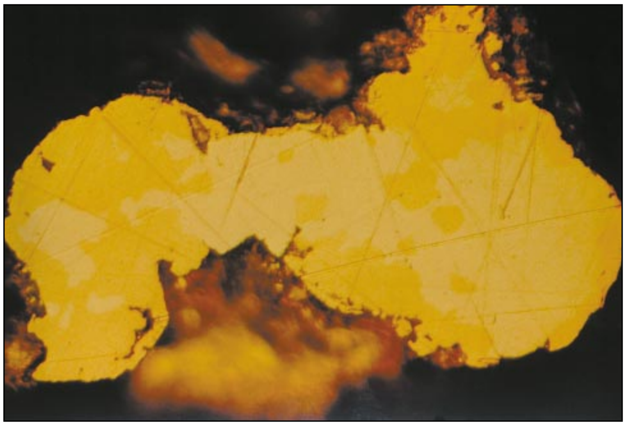

Plate 4
Alluvial gold grain from Mazowe area of Zimbabwe showing alteration of primary silver-rich gold (pale yellow) to secondary pure gold (deep yellow)

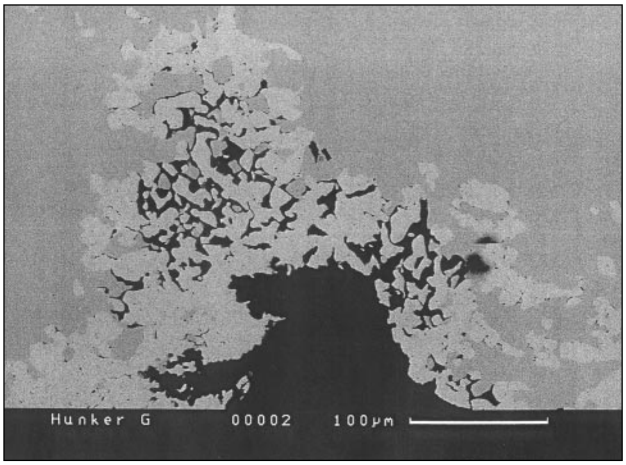

Plate 5
Back-scattered electron image of alluvial gold grain from Hunker Creek, Yukon showing irregular rim and patches (pale) of gold-rich gold around electrum

Relationship between Microchemical Signature of Alluvial Gold and Source Bedrock Gold

The close correspondence between minerals coexisting with hypogene gold in bedrock and the nature of inclusions within alluvial gold from nearby rivers was reported for all nine Irish and Scottish sites studied by Chapman *et al* (8) and for gold from Malaysia (27). In each case there is good agreement between the inclusions in alluvial gold, inclusions in gold extracted from bedrock (5 examples) and the nature of minerals coexisting with hypogene gold in the bedrock mineralization revealed by mineralogical study. Minor differences probably reflect the presence of additional sources of mineralization in the drainage catchment.

Populations of gold grains from both drill core of the bedrock source and alluvial sediment some 1-2 kms downhill in the Lubuk Mandi area of Malaysia are compared in Figure 3 (data from Henney *et al*, reference 25). The gold extracted from the core exhibits two main silver contents (8.5% and 10.5%) both of which are well within the range of silver contents of the alluvial gold. Such a simple relationship between bedrock gold and adjacent alluvial gold indicates that the mineralization is probably relatively uniform in composition with the alluvial site close to the source.

There are commonly differences between the composition of gold grains extracted from hand specimens

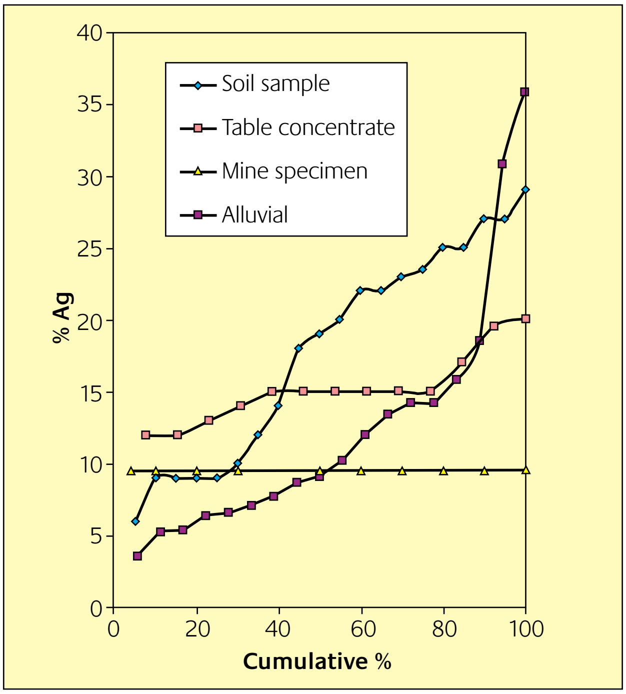

Figure 4
Comparison of silver contents of gold grains extracted from a hand specimen of ore from the 'C' mine in Zimbabwe, a mine table concentrate, a soil sample and nearby alluvial sediment

of ore and from mine shaking tables. At the 'C' mine Mberengwa district near Zvishvane in Zimbabwe, gold occurs in shear zone hosted quartz veins. Coarse, easily visible gold is rare and analysis of grains extracted from a sample provided by the mine manager (24, 28) shows little variation in composition about a 10% Ag level (Figure 4). Most of the gold in the producing veins is much finer grained and a sample of the production from the shaking table showed a much greater range of silver contents (10-20% Ag, Figure 4). Similarly, Chapman *et al* (9) who showed that gold from hand specimens of ore from the Gwynfynydd Gold Mine in North Wales are not necessarily representative of the gold from throughout the mineralization.

Gold grains were also extracted from a soil sample collected from the area above the main vein system at the 'C' mine and from alluvial sediment in a small river approximately 2 km from the mine, though this had some other small mines also within its catchment. The soil gold shows two populations (Figure 4), a small one with silver around 10% and thus similar to the hand specimen, and a larger population with between 20 and 30% silver, outside the range in the shaking table sample of deep mine ore. The alluvial sample shows multiple populations that reflect all the samples collected at the mine, a dominant group which corresponds to the mine shaking table gold, and a minor population with higher silver which is similar to that shown by the soil sample. The alluvial sample thus provides a representative sample of gold grains in environments where there is a considerable range in composition of the native gold in the mineralization.

In some areas where alluvial gold is of significant economic interest the precise relationship between placer gold and the source mineralization may be more difficult to establish. Knight *et al* (7, 26) undertook an extensive study of the chemical composition of both alluvial and lode gold from the Klondike district in an attempt to clarify the discrepancy between the amount of alluvial gold won from the region with the potential of known lode gold occurrences. They determined the chemical composition of the cores of 2,700 gold grains in terms of silver, mercury and copper content and were able to characterize the populations of alluvial gold in the various valleys according to the characteristics of different types of known lode gold. In addition they predicted that some types of gold in the alluvial populations were derived from unknown bedrock sources. In the present study, a more modest number of alluvial gold grains from this region have been analysed, but inclusion assemblages have been identified in addition to concentrations of the minor alloying elements. Figure 5 shows silver plots for alluvial gold obtained from Bonanza Creek, Hunker Creek and Bear Creek together with information on the composition of local lode gold from Knight *et al* (26). Further comparative information is presented in Table 3 which shows close agreement between the two data sets.

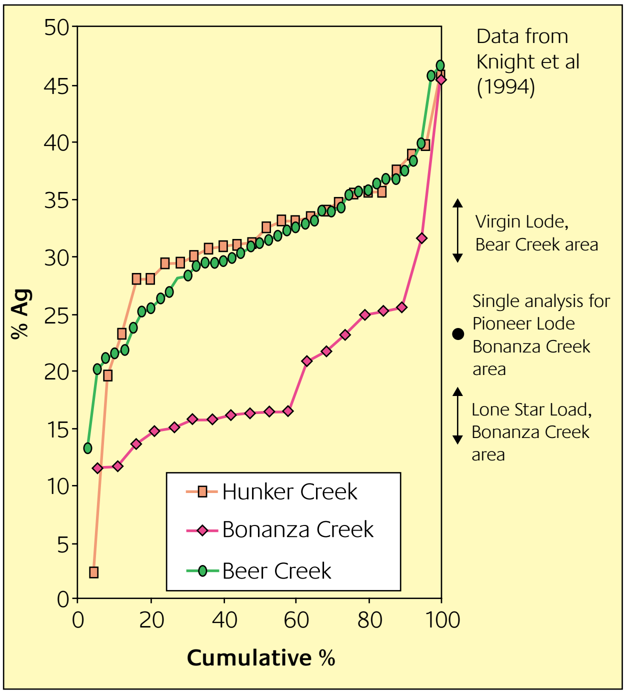

Figure 5

Comparison of silver contents of alluvial gold grains from different localities in the Klondike, Yukon

Gold grains from Hunker and Bear Creeks exhibit similar ranges of silver contents (Figure 5) with small numbers of low silver grains possibly representing separate populations, whereas the Bonanza Creek sample shows a completely different type of plot with a break in slope suggesting two contributing populations. The composition of Bonanza Creek gold is consistent with its derivation from two known lode-gold sources upstream (Lone Star and Pioneer), while that from Hunker and Bear Creeks is far closer to the composition of gold from the Virgin Lode in the Bear Creek area. This geographical correlation implies that gold in the Klondyke valleys is generally close to source. Knight *et al* (7) reported that the vein mineralogy of lodes throughout the region is dominated by base metal sulphides and arsenopyrite and during this study inclusions of galena, pyrite, chalcopyrite and arsenopyrite were observed in alluvial gold with silver contents of over 20% which suggests that this type of gold is derived from a number of related sources of mineralization. An inclusion of hessite ($(Ag,Au)_2Te$) was recorded in the population of low-silver (15% Ag) gold from Bonanza Creek which raises the possibility of an additional unrecorded bedrock source to that from the Lone Star lode. These data suggest that a more detailed knowledge of the inclusion signature of the alluvial gold in the region in addition to the gold alloy composition would greatly help in establishing the relationship between bedrock and alluvial gold.

The potential to correlate the inclusion assemblage of alluvial gold grains with their range of silver and other metal contents

Table 3 *Comparison of Gold Samples from The Klondike district, Yukon Territory*

Locality		%Ag Range	%Hg	Inclusion Assemblage*		
				%Sulphides	%Sulpharsenides	%Tellurides
Bonanza Creek						
Alluvial *		1. 12-16 2. 20-46	1. 0 2. 0	1. 80 2. 67	1. 0 2. 33	1. 20 2. 0
Alluvial+		14-24	0.3			
Lodes+	Lone Star	1. 14-17 2. 14-19	0.008 0.016			
	Pioneer	23.4	0			
Bear Creek						
Alluvial *		20-36	0.37	100	0	0
Alluvial+		Upper: 30-42 Lower 28-36	0.39 0.49			
Lodes+	Virgin	28-34	0.54			
Hunker Creek						
Alluvial * Alluvial+		28-38 18-28	0.2 0.03	38	62	0

* Data from present study

\+ Data from Knight *et al* (reference 26)

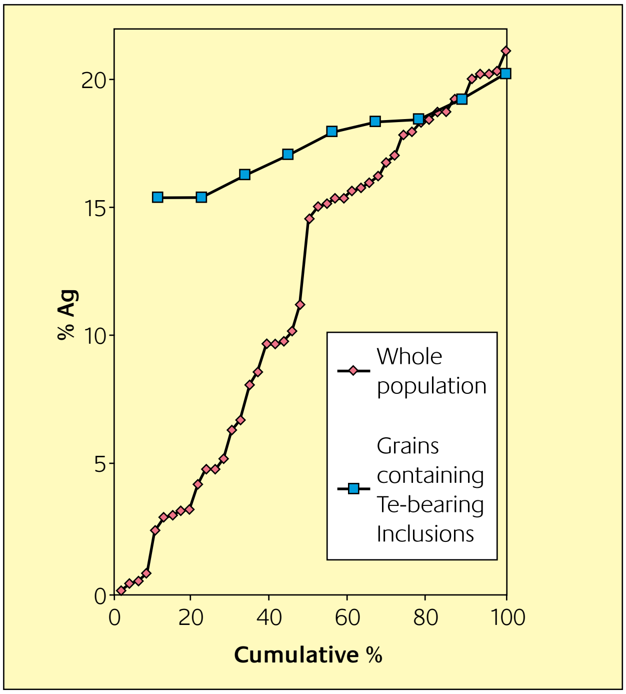

Figure 6

Two populations of alluvial gold grains from the Waimanu River, Fiji revealed by silver content and associated inclusions

is important in the identification of multiple sources. Whilst there may be overlap in silver contents between two contributing types, in most cases the inclusion assemblages are distinct. In alluvial gold from Shortcleugh Water, Leadhills, Scotland and from the River Bann in the Mourne Mountains of Northern Ireland, distinct silver-rich populations can be recognized on cumulative silver content plots (8, 14). In each case an inclusion suite in the silver-rich population is completely different from inclusions in the lower silver populations.

A similar scenario with potentially important economic significance is provided by alluvial gold grains from the Waimanu River in Fiji. Two distinct populations can be recognized on the basis of silver content (Figure 6) which also differ in their inclusion suites (23). The lower silver population (< 13% Ag) is probably derived from a porphyry-type source which is known within the catchment. The higher silver population contains a range of telluride inclusions which are absent in the lower silver gold but are similar to those in gold from a mine table concentrate from the Emperor gold mine. As the range in silver content is also similar it is possible that this type of alluvial gold in the Waimanu River is derived from undiscovered alkali-epithermal style mineralization similar to that worked at the Emperor gold mine.

Applications of the Technique to Exploration for Gold Mineralization

The Search for a Specific Style of Gold Mineralization

Alluvial gold is widespread in Northern Ireland and in one part the local geology suggested the presence of skarn mineralization (9). However, interpretation of the microchemical signatures of alluvial gold samples from the area shows that all the gold grains correspond to the two major types of mineralization further south, neither of which is of the skarn type. In addition, the microchemical signatures suggest that the alluvial gold was derived from a series of small sources of mineralization of these types, and not from glacially dispersed material derived from a large source further south. This result emphasizes that even a negative result is of potential value in an exploration context, as microchemical signatures of the alluvial gold allow informed evaluation of the prospect relatively cheaply and quickly at an early stage in the exploration.

Identification of Multiple Sources of Different Types of Gold within a Region

The Estero Hondo alluvial gold mine is situated in western Ecuador, at the foot of the Andes in Catopaxi province (30). The mine was operated by Odin Mining in the 1990's who also carried out exploration for bedrock gold deposits in the area. Odin Mining geologists had noticed that the alluvial gold on one side of the valley (Valetanga) tended to be bright and angular, whilst that on the other side (Perros Bravos) tended to be more rounded, darker and duller. Odin Mining wanted to know if this indicated two possible sources of bedrock gold or if it was due to processes acting in the secondary environment.

Styles *et al* (30) carried out a gold characterization study of samples from the Estero Hondo catchment area. This study showed first that the differences in the appearance of the alluvial gold were not due to variable amounts of secondary alteration as for both populations this was restricted to thin rims around the grains generally only a few micrometres thick. Second, microanalysis of the cores of the grains showed that there were large differences in silver content of gold between the two areas (Figure 7).

The gold from Veletanga is largely high-silver gold while that from Perros Bravos has much less silver. A division at 11% Ag separates roughly 90% of the gold from the sites, indicating that there are two different populations of gold. There are also differences in the spread of values within each site; Veletanga has a relatively narrow range with most in the range 12-17% Ag, while Perros Bravos shows a much more even spread of compositions.

There are also differences between the suites of micro-inclusions in the gold from the two areas. This can be demonstrated by comparing the composition of the host gold for the main varieties of inclusion on cumulative frequency curves (Figure 8). This demonstrates that most of the inclusion types, such as pyrite, galena and pyrrhotite occur in both types of gold but bismuth-rich tellurides and copper minerals are confined to the Perros Bravos type of gold.

The two different types of gold in the Estero Hondo alluvial gold mine are associated with different parts of the catchment area. A drilling programme showed that there was a significant skarn deposit in the Veletanga area but a bedrock source was not located in the Perros Bravos area. It was concluded that this source had probably largely been eroded away, which would also account for its greatest abundance in the lowermost gravels of the mine.

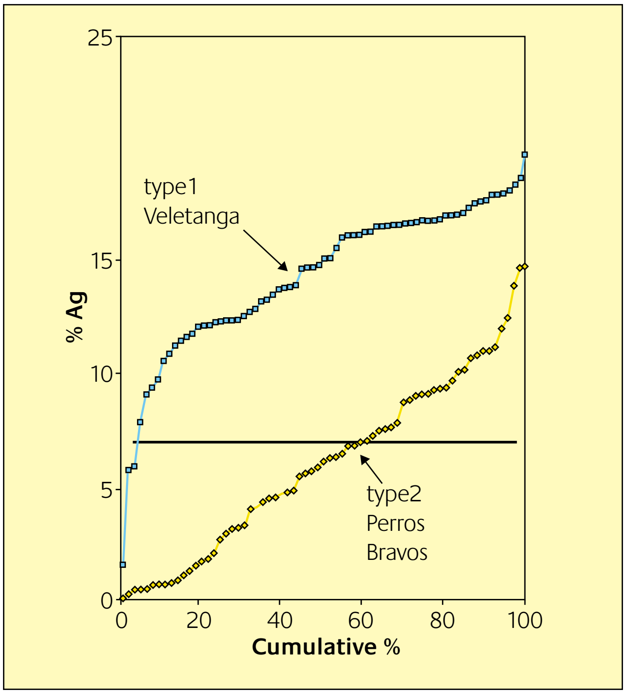

Figure 7

Comparison of silver contents of alluvial gold from two areas in the Ximena area of Ecuador

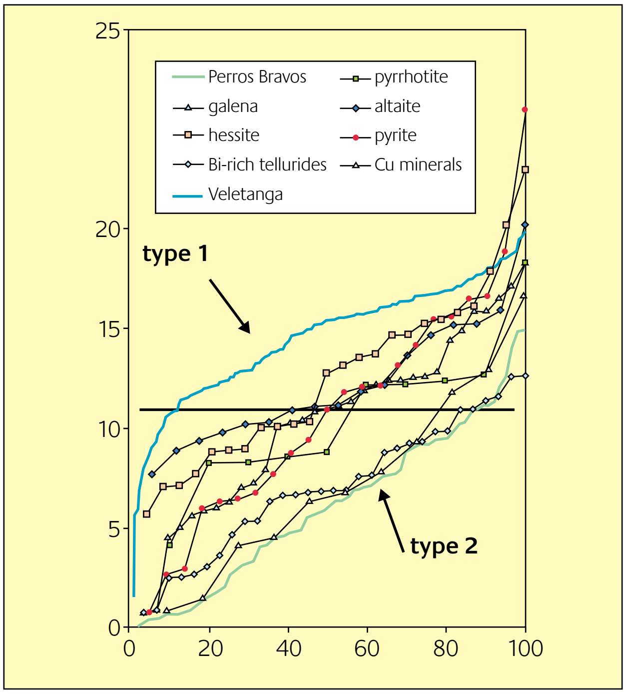

Figure 8

Comparison of silver contents of alluvial gold grains from the Ximena area of Ecuador containing different types of inclusions

Identification of Alluvial Gold that has been Dispersed Comparatively Far from its Source

Most of Britain and Ireland has been glaciated. This has had the effect of enhancing erosion in upland areas and causing deposition of glacial sediments in more lowland areas, particularly in valleys at the margins of uplands masses which housed large glaciers carrying ice from a number of sources. In the Leadhills region of Scotland, the Snar Water originates in high ground and flows northwards into a basin filled with glacial debris which it is currently eroding. Alluvial gold grains from the upper part of the river are similar to those from the rest of the Leadhills region and are locally derived. The gold from the lower reaches of the river differs markedly from that further upstream. The inclusions in typical Leadhills gold are predominantly arsenopyrite, pyrite, pyrrhotite and base metal sulphides with rare cobaltite and gersdorffite. In contrast, the gold from the lower Snar contains a much greater range of inclusions including platinum minerals, bismuth tellurides and copper and other selenides which are not recorded elsewhere in the Leadhills region (9, 31). In addition, the gold shows a greater range of silver contents and there are several grains with copper contents well in excess of those found in the typical Leadhills gold. The range of gold compositions and inclusions is not consistent with one single geological environment of mineralization. It would appear that the glacial till contains a range of different types of gold derived from unknown sources, some probably from a considerable distance away from the Leadhills region. An equally wide range of gold grain compositions and inclusion type is also recorded at a site in the upper Tweed basin about 15 km east of Leadhills where the river is also excavating a basin of glacial till down to bedrock (9).

A regional study of auriferous drainage in Zimbabwe included alluvial gold from the Sebakwe river. The population of 41 grains contains at least 17 different types of opaque inclusion (28), including, a range of complex copper minerals, bismuth tellurides and silver minerals, in addition to pyrite and base metal sulphides. The large variety of mineral inclusions is significantly greater than normally associated with gold formed during a single mineralizing event and suggests that either a single source containing multiple phases of mineralization or a number of discrete sources contribute to the alluvial gold in the drainage sediment. The latter is considered more likely given the large size of the river and the presence of a number of gold mines with contrasting mineralogy within its catchment.

Development of a Model for Mineralization Controls and a Strategy for Exploration

Identification of the inclusion signature of alluvial gold grains from the South Hams district of Devon, England, proved crucial in working out a model to explain its origin (15). Many of the gold grains from the area show complex patterns of chemical compositional variation (Plate 6). Palladium occurs as a minor alloy within the gold up to 11.9%, as inclusions of palladium-bearing minerals such as potarite, (PdHg), within gold grains and as discrete palladium-bearing minerals such as gold-bearing potarite (15). The inclusion suites are dominated by selenide minerals which are very common in gold grains from some localities. Sulphide and sulpharsenide inclusions are absent. In some cases it was possible to deduce from the compositional variation how a grain had crystallized. The gold grain chemistry and inclusion types seemed inconsistent with transport of gold as a bisulphide complex and deposition within the stability field of sulphide minerals as is postulated for the majority of types of gold mineralization. However, the observed features and mineralogy of the grains were consistent with transport of gold and palladium as chloride complexes in a solution of high E_h, similar to a model proposed for the formation of the Coronation Hill U-Au deposits of Northern Territory, Australia (32). In the case of the Devon gold mineralization, Leake *et al* (15) proposed that precipitation of gold and palladium would take place when E_h was reduced but still in conditions too oxidising for the precipitation of sulphides but allowing selenides to form (33, 34).

Although red beds of Permian age with which such oxidizing solutions were likely to be associated are absent from all but coastal areas of the South Hams district, geological reasoning suggested that the original interface between these rocks and the underlying Devonian rocks was not far above the present erosion surface. The mineralization which provided the source of the alluvial gold was thought to

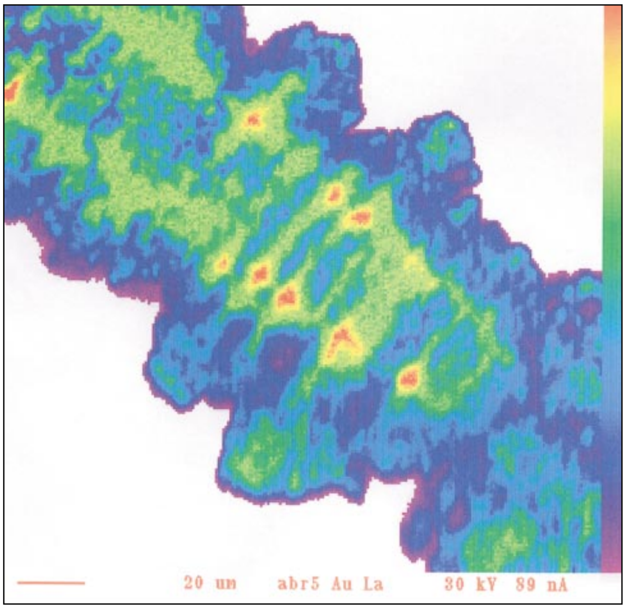

Plate 6

Microchemical map showing distribution of gold in dendritic alluvial gold/platinoid grain from South Devon. Rainbow scale represents increasing gold concentration originate by reaction of the gold-bearing oxidizing solutions circulating within the Permian red bed sequence and the more reduced rocks below or by reaction with more reduced solutions associated with these rocks. This model accounted for decrease in the intensity of mineralization with depth in structures within the Devonian strata and also for the complex pattern of growth zonation in many grains which reflects successive pulses of mineralizing fluids with differing physical and chemical properties. In particular the rapid precipitation of the gold due to abrupt changes in E_h also explained the highly crystalline and dendritic nature of many of the gold grains (Plates 3, 6). On the basis of this model, exploration effort was switched to the Crediton Trough further north in Devon which is filled with Permian red beds and associated alkaline basalt and lamprophyric lavas and where there are many kilometres of sub-cropping contact between the Permian red beds and underlying more reduced Carboniferous rocks. It was predicted that gold of the same type as that found in South Devon should also be in the Crediton Trough and at its contacts with the surrounding rocks. Subsequent exploration showed this to be the case (35) and interpretation of the inclusion assemblage in the alluvial gold from this area suggested an association with the alkali basalts which was subsequently proved as a result of drilling (36).

On the basis of these results, further exploration was carried out in Scotland in and around Permian red bed basins containing alkali basalts and this resulted in the discovery of widespread alluvial gold with palladium enrichment and a suite of selenide mineral inclusions generally similar to those found in Devon gold (29).

Regional Surveys of Alluvial Gold

Alluvial gold has been studied from 314 sites in Britain and Ireland and a regional pattern of the distribution of different types and the nature of the potential controls of the source mineralization has been established (8), or is in the process of being established. It is clear that, although there are several types of gold present, each can be equated with a particular geological environment. Moreover, similar gold is associated with similar geological environments even when geographically separated. Such a comprehensive data base is potentially of use, in association with other information in focusing exploration on a particular type of gold deemed to have been derived from mineralization with most potential to be of economic interest. However, this would only be applicable to mineralization containing grains of native gold large enough to be isolated and mounted for analysis.

Though the scale of investigations into alluvial gold from other countries is minor compared with that of Great Britain and Ireland, it is clear that comparable data can be obtained. Microchemical signatures of alluvial gold from Palaeozoic metasedimentary sequences in Malaysia, south east Australia and the Klondyke region of Canada are presented in Tables 2 and 3 and are similar to one of the types identified in Britain and Ireland. The inclusion suite is dominated by base metal sulphides and sulpharsenides with minor contributions from either antimony or tellurium-bearing minerals. In contrast, the inclusion assemblage found in gold from Fiji (Table 2), (derived from alkali epithermal and porphyry mineralization) is distinctly different, but similar to that of gold from Borland Glen in Central Scotland, which is associated with a volcanic sequence of intermediate composition (37).

Conclusions

1. Different styles of gold mineralization produce gold grains with different microchemical signatures.
2. The microchemical signature of a population of alluvial gold grains reflects the mineralogy of the source mineralization.
3. The technique of microchemical characterization permits assessment on the nature of source mineralization even before sources are discovered.
4. Interpretation of the microchemical signature(s) of alluvial gold help focus attention on types considered to be derived from mineralization with most potential economic importance. Information can be obtained at an early stage in the exploration process.
5. Extensive use of microchemical signatures has provided new insight into the origins of alluvial gold and the controls of source mineralization throughout Britain and Ireland. The same approach has been successfully applied to problems of origin of alluvial gold in more scattered areas in many other parts of the world.

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