Bulletin de la Société belge de Géologie Bulletin van de Belgische Vereniging voor Geologie	98-1 98-1	pp. 63-72 pp. 63-72	Bruxelles 1989 Brussel 1989

THE USE OF HEAVY MINERALS AS PATHFINDERS FOR PLACER GOLD : A CASE STUDY IN THE DEPARTMENT OF MADRE DE DIOS (SE PERU)

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KEY WORDS

heavy minerals, placers, gold,multivariate analysis, Madre De Dios

MOTS CLES

minéraux lourds, placers, or, analyse multivariée, Madre De Dios, Pérou

ABSTRACT

A prospecting survey based on heavy mineral concentrates was carried out in the Department of Madre De Dios, where fine placer gold occurs in most of the rivers. The distribution of all heavy minerals was studied and the results were treated with multivariate statistical analysis.

Clear correlations exist between the gold concentration and the heavy mineral distribution of the sediment. The highest concentration of gold occurs in the upstream parts of the point bars where it is intensively correlated with zircon. In the downstream parts of the point bars the mineral suite shows higher contents of epidote, limonite, actinolite, andalusite and sphene. When the concentrations of those minerals exceed certain critical values they form an association which can be considered as characteristic for sediments with extremely low gold content.

Using multivariate techniques it is possible to distinguish from the concentrations of a few common heavy minerals gold bearing from barren sediments.

RESUME

Une prospection alluvionnaire a été effectuée dans le Département de Madre De Dios (sud-est du Pérou) où la majorité des rivières est aurifère. La distribution des minéraux lourds a été étudiée et les résultats traités à l'aide de l'analyse multivariée.

Des corrélations nettes existent entre la teneur en or et la distribution des minéraux lourds du sédiment. Les plus hautes concentrations d'or se trouvent dans les parties en amont des bourrelets arqués (point bars) où l'or est associé au zircon. Les parties en aval des point bars se caractérisent par une plus haute teneur en épidote, limonite, actinote, andalousite et sphène. Quand les concentrations de ces minéraux dépassent certaines teneurs critiques, l'association minéralogique devient typique de sédiments à très basse teneur en or.

En considérant les concentrations de certains minéraux lourds communs à l'aide de l'analyse multivariée, il devient possible de distinguer les sédiments aurifères des sédiments stériles.

1. INTRODUCTION

There have been many attempts to correlate placer gold values with sedimentological, chemical or mineral parameters.

In the Witwatersrand gold-uranium deposit of Ventersdorp Contact Reef MINTER (1970) states that major auriferous areas correspond with large maximum pebble sizes and with good pebble sorting. VOROB'YEV (1979) observed in beach placers containing gold that low metal concentrations were typical of the fine-grained sands and silts whereas the zones of coarser deposits were caracterized by the presence of higher contents of gold. BOGGS and BALDWIN (1970) came to the

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same conclusion during a study of the Sixes River, Southwestern Oregon, where the highest concentrations of gold were generally associated with the coarsest sediment. Those correlations can however not be applied to all deposits: results of a study on the Precambrian Tarkwaian Series of Ghana by SESTINI (1971) showed the absence of correlations between gold content and the average size and sorting of the pebbles in a small area of sampling. There was however a definite correlation between the higher gold values and the high degree of packing of the conglomerate.

SAAGER and ESSELAAR (1969) carried out an extensive investigation of the Basal Reef in the Welkom goldfield. A high correlation was found to exist only between gold and uranium and between gold and silver. LIEBENBERG (1973) studied a large number of reefs and found significant correlations between gold, uranium , chromium and zirconium, but neither of the last mentioned could be employed as an indicator of the first two, being present in too small quantities. LIEBENBERG found in the same study a definite correlation between the gold and the pyrite.

BOYLE (1979) and ROUTHIER (1963) mention that gold normally occurs with other heavy minerals such as magnetite, scheelite, barite etc. Gold is as well associated with zircon and monazite in the alluvial placers of Shri Lanka (DISSANAYAKE and NAWARATNE, 1981).

The aim of this research is to study the correlations between the gold and the other heavy minerals in a present meandering river system and to investigate if gold bearing sediments can be distinguished from barren sediments by their heavy mineral content (LANCKNEUS, 1988).

2. PRIMARY GOLD SOURCES

Primary gold in the Eastern Cordillera has been mined since pre-Colombian times.

Gold is there associated with quartz veins in Siluro-Devonian quartzites and sandy shales of the Ananea Formation where it occurs either in millimetre-sized particles located in the quartz microfissures or in fine specks scattered through the quartz (FORNARI, 1984).

Gold occurs also in the amphibolites of the Iscaybamba Complex and in sulphide exhalative sedimentary deposits of the Ananea formation in the Rinconada sector, 150 km North of Puno (FORNARI, 1984).

3. GOLD PLACERS OF MADRE DE DIOS

The present study was carried out in the alluvial plain of Madre De Dios, situated in the SE corner of Peru (fig. 1) (LANCKNEUS, 1987). Thousands of persons work in this giant alluvial placer deposit which contains enormous reserves of gold. The Mining Bank of Peru recorded in 1982 a production of 2689 kg of placer gold of which 75 % came from the region of Madre De Dios (FORNARI et al., 1984). This represents only a tiny fraction of the present reserves as methods of exploitation are extremely primitive.

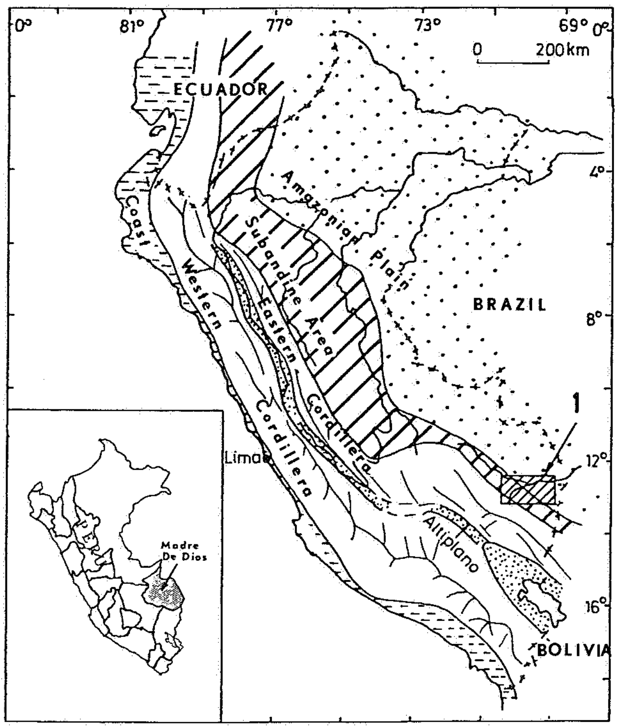

Figure 1. Megalandforms of Peru ; situation of study area (1)

The placer gold in the Department of Madre De Dios occurs in the present river beds and in the older Holocene sediments of the alluvial plain. The concentration of alluvial gold occurs mainly in the upstream parts of the point bars along the meanders. The sediments of the recent point bars show a mean gold content of 200-500 mg/m^3, whereas the older Holocene placers reach average gold contents of 2-4 g/m^3.

The gold particles have an average width of 135 m and a thickness ranging from 2 to 4 m. They present the morphological and chemical characteristics of particles that have experienced an extensive transport. A total of 32 heavy minerals were identified in the placer sediments. The most common are ilmenite, magnetite, hematite, zircon and epidote. From an economic point of view the only mineral which could be considered for exploitation as a secondary mineral together with the gold is the europium-rich dark monazite (LANCKNEUS, in press).

4. MORPHOLOGY AND GEOLOGY OF SE PERU

Our study area comprises two main morphostructural units which are the Sub-Andean area and the alluvial plain of Madre De Dios (fig. 1).

The Sub-Andean area may be considered as the piedmont zone of the Eastern Cordillera and consists mainly of Secondary and Tertiary strata, known as the Capas Rojas Formation (fig. 2). This entire sequence was folded by the late-Miocene phase of the Andean orogenesis (LAUBACHER, 1978). Upon this continental sequence lies a detrital formation of Pliocene age (Mazuko Formation), formed by the accumulation of vast quantities of sediments derived from the erosion of the Eastern Cordillera and deposited as piedmont fans (LAUBACHER et al., 1984). These deposits are gold bearing and form an intermediate host of detrital gold.

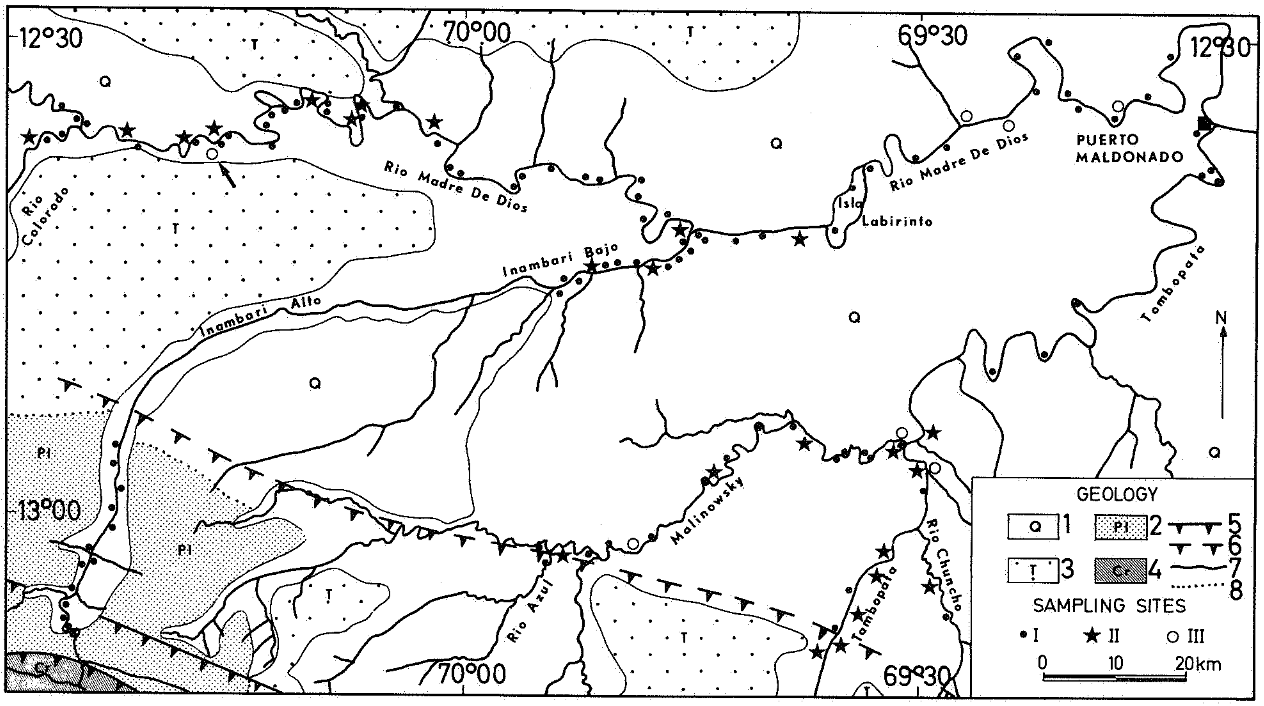

Figure 2. **Simplified geological map of Madre de Dios: (LAUBACHER, LAUBACHER *et al.*, 1984 ; ONERN, 1972)** : 1 : Quaternary alluvial deposits (Q) ; 2 : Mazuko Formation (Pl) ; 3 : Capas Rojas Formation (T) ; 4 : Cretaceous strata (Cr) ; 5 : reverse fault ; 6 : supposed reverse fault ; 7 : limit ; 8 : unknown limit.

The location of the sampling sites is shown as well. I : location of a single sampling point ; II : location of detailed sampling along the meander point bar ; III :location of detailed sampling along a vertical profile. The arrow indicates the position of the profile given in figure 3.

The alluvial plain of Madre de Dios consists of Quaternary alluvial deposits of sand, gravel, clay and loam. Few data are available about the thickness of the Quaternary deposits which are estimated between 30 and 40 m. A drilling operation by Andes Petroleum found the bedrock at a depth of 40 m (SANCHEZ, 1979). Figure 3 shows a verticale profile in the Holocene deposits of the alluvial plain. Note the highest concentration of gold in the sandy gravel layer and the still appreciable amount of gold in the sandy layer, caracterized by the complete absence of gravel elements (location of profile indicated on fig. 2 by arrow).

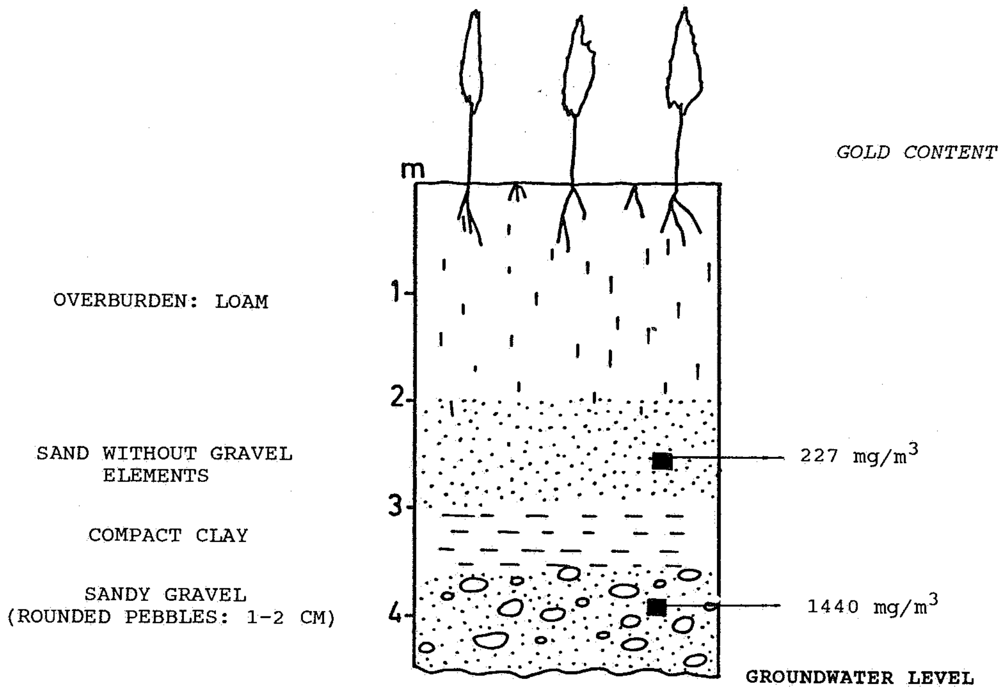

Figure 3. Verticale profile across the Holocene deposits of the alluvial plain.

It is probable that an important amount of the gold in the alluvial plain derives from the erosion of the Mazuko Formation.

5. SAMPLING TECHNIQUE AND ANALYTICAL PROCEDURES

Some 200 samples of alluvial sediment were collected in the river beds of the rivers Inambari, Madre De Dios, Malinowsky and Tambopata and in the alluvial plain (fig. 2). Sample sites were carefully chosen so that the relations between heavy mineral content and river morphology could be studied. A detailed sampling was for example performed along the point bars.

Each sample consisted of 20 to 60 kg of sediment depending upon local conditions. Most of the samples were taken from the superficial sediments of the meander point bars; some verticale profiles in the Holocene deposits were sampled as well. A first reduction of the sample volume was achieved on the field by panning after which the heavy minerals were separated from the light fraction by the use of the heavy liquid bromoform. Each sample was then split into 5 magnetic fractions (hand magnet and 0.4, 0.7, 1.5 and 1.5 Ampere current strength). The gold was separated from the other non-magnetic minerals by use of an elutriating tube similar in design to the apparatus described by FROST (1959) followed by final separation on a dry shaking surface. 90 % of the gold particles was recovered by means of elutriation and the remaining 10 % was recovered on the shaking surface. Representative heavy mineral grain mounts were prepared for each of the magnetic fractions. A hundred grains were identified and counted with the help of a polarizing microscope. The opaque minerals were counted with the binocular. The heavy mineral percentages were recalculated for the whole sample. The gold tenor was expressed in gr/m3.

6. RESULTS

6.1. Correlations

Relationships between different heavy mineral components can be studied in a number of ways. Let us here consider the correlation matrix (Pearson correlation coefficients) calculated on the 72 samples from the River Madre De Dios (table 1). The data of the variables showing a lognormal distribution were transformed by taking the logaritms of the original values (HOOGENDOORN, 1983, appendix 6).

	MAGNETITE	ILMENITE	HEMATITE	★ LIMONITE	★ TOURMALINE	ZIRCON	★ SPHENE	★ B LEUCOXENE	★ R LEUCOXENE	★ ANDALUSITE	★ STAUROLITE	GARNET	★ SPINEL	★ EPIDOTE	★ HYPERSTHENE	★ G HORNBLENDE	★ B HORNBLENDE	★ ACTINOLITE	D MONAZITE	★ GOLD
MAGNETITE	1																			
ILMENITE	0.15 72	1																		
HEMATITE	-0.20 72	-0.30 72	1																	
LIMONITE ★	-0.26 67	-0.40 67	-0.25 67	1																
TOURMALINE ★	-0.22 71	-0.28 71	-0.04 71	-0.24 66	1															
ZIRCON	-0.31 72	-0.18 72	-0.38 72	-0.24 67	0.13 71	1														
SPHENE ★	-0.34 72	-0.29 72	0.12 72	0.21 67	0.36 71	-0.02 72	1													
B LEUCOXENE ★	-0.24 72	-0.31 72	0.22 72	0.13 67	0.23 71	0.41 72	0.16 72	1												
R LEUCOXENE ★	-0.21 64	-0.13 64	0.05 64	0.14 59	0.39 63	0.11 64	0.27 64	0.45 64	1											
ANDALUSITE ★	-0.28 70	-0.42 70	-0.30 70	0.58 66	0.28 69	-0.14 70	0.38 70	0.04 70	0.15 62	1										
STAUROLITE ★	-0.46 34	-0.38 34	-0.29 34	0.59 33	0.22 34	-0.15 34	0.40 34	0.29 34	0.04 27	0.54 36	1									
GARNET	0.05 64	-0.28 66	-0.30 64	0.44 59	0.09 63	-0.46 64	-0.07 64	-0.03 64	0.04 56	0.28 62	0.34 33	1								
SPINEL ★	-0.23 56	-0.39 56	0.03 56	-0.29 56	0.33 51	0.00 56	0.22 56	0.20 56	0.25 50	0.31 54	0.39 26	0.09 51	1							
EPIDOTE ★	-0.45 72	-0.54 72	-0.05 72	0.46 67	0.32 71	-0.10 72	0.55 72	0.20 72	0.16 64	0.58 70	0.67 34	0.21 64	0.36 56	1						
HYPERSTHENE ★	-0.28 20	-0.36 20	-0.15 20	0.42 19	0.10 20	-0.33 20	0.28 20	-0.44 20	-0.07 17	0.28 19	0.21 14	0.21 17	0.50 17	0.35 20	1					
G HORNBLENDE ★	-0.49 71	-0.43 71	0.01 71	0.24 66	0.16 70	0.04 71	0.37 71	0.08 71	-0.04 63	0.46 69	0.50 33	0.15 63	0.28 55	0.50 71	0.20 20	1				
B HORNBLENDE ★	-0.29 64	-0.32 64	0.02 64	0.17 60	0.23 64	0.23 64	0.22 64	0.13 64	-0.04 57	0.32 62	0.38 30	-0.02 57	0.14 50	0.42 64	0.37 18	0.26 63	1			
ACTINOLITE ★	-0.21 72	-0.46 72	-0.21 72	0.35 67	0.13 71	-0.23 72	0.23 72	-0.10 72	0.21 64	0.40 70	0.43 34	0.38 64	0.29 56	0.46 72	0.76 20	0.30 71	0.14 64	1		
D MONAZITE	-0.19 72	-0.51 72	-0.16 72	0.33 67	0.20 71	0.13 72	0.10 72	0.21 72	0.22 64	0.49 70	0.54 34	0.23 64	0.08 56	0.48 72	0.07 20	0.34 71	0.23 64	0.36 72	1	
GOLD ★	-0.05 72	0.16 72	0.18 72	-0.31 67	-0.18 71	0.51 72	-0.27 72	-0.03 72	-0.17 64	-0.29 70	-0.09 34	-0.26 64	-0.24 56	-0.36 72	-0.11 20	-0.16 71	-0.02 64	-0.30 72	-0.15 72	1

Mineral★ : logaritmic transformed values

X.XX ← correlation coefficient
YY ← number of pairs

Table 1 - Correlation matrix. The correlation coefficients which are significant at the 97.5 % confidence level are underlined, the doubly underlined coefficients are significant at the 99.9 % level of confidence.

Four main correlation groups can be deduced from the correlation matrix (fig. 4). A first important group refer to the relations between the gold and the remaining minerals. Gold is strongly correlated with zircon. The correlation value of 0.51 may not seem very high, but we use the term "strongly" as the coefficient is significant at the 99.9% level of confidence. Other rivers in Madre De Dios show as well strong gold-zircon correlation coefficients (0.65 for the river Malinowsky and 0.75 for the river Tambopata). Negative correlations occur between gold and andalusite, limonite, epidote, actinolite and sphene which are all linked by significant correlations. This group of minerals is, in addition, also correlated with a number of other minerals. A second correlation group embraces the leucoxene varieties which show few correlations with the remaining minerals; brown leucoxene is however strongly correlated with zircon. A third correlation group consists of magnetite and ilmenite; they present strong negative correlations with most of the minerals of group 1 which are negatively correlated with gold. A last correlation unit comprises hypersthene correlated with spinel and actinolite.

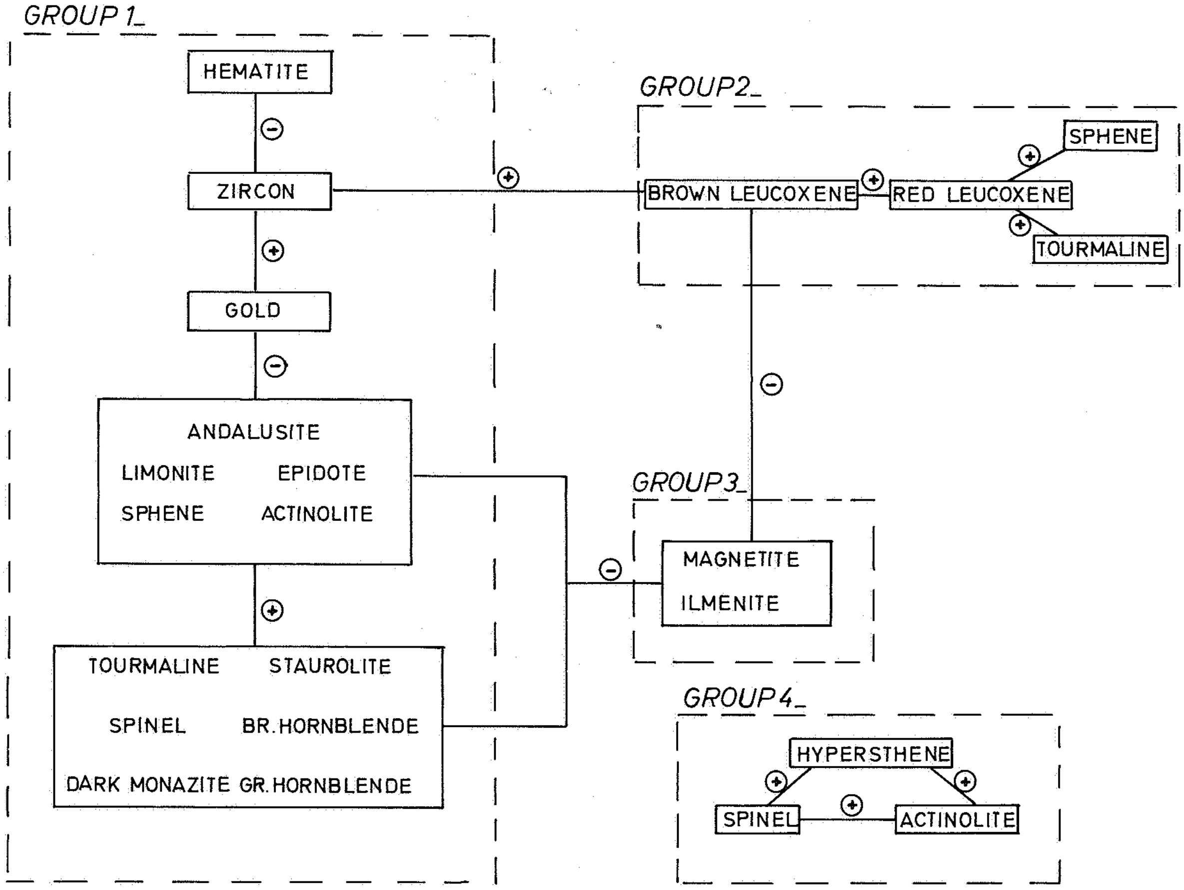

Figure 4. Main correlation groups deduced from the correlation matrix.

6.2. Factor analysis

Generally the mineral groups that can be derived from the correlation matrix are not well separated. Furthermore the significance of certain correlations is not clear. In order to obtain a clearer picture a principal component analysis and different types of factor analyses were performed (with and without rotation). The best results were obtained with a varimax rotated analysis, whose factor matrix is shown in table 2. Five factors were found with eigenvalues > 1.0 representing together 65 % of the total variance. The factor analysis was performed using the FACTOR program of the SPPS package (NIE *et al.*, 1975).

Two factors reflect clearly the differences in local hydrodynamic properties occurring along the meanders. The point bar heads of the meanders are characterized by higher contents of gold and zircon. Both minerals load high on factor 3 which can be considered as the point bar head factor or "gold factor". In the point bar tails the mineral suite shows higher contents of actinolite, limonite, andalusite, sphene and epidote. All these minerals have high loadings on factor 1 which can be regarded as the point bar tail factor or "barren factor". The two characteristic mineral associations of the point bar heads and point bar tails can be well appreciated on fig. 5. A map of the factor score distribution on factors 1 and 3 (fig. 6) illustrates the differences in heavy mineral content between gold bearing and barren samples. The separation of the samples in the factor distribution map is clearly associated with the geomorphological position of the sample (point bar heads and point bar tails) (fig.7).

The three remaining factors express regional associations. The six minerals loading high on factor 2 are characteristic for the River Inambari which flows into the River Madre De Dios. High loadings on factor 4 represent those minerals which are typical for the River Madre De Dios (fig. 8). A map of the factor score distribution illustrates this separation clearly (fig. 9). The samples taken upstream from the confluence of Inambari and Madre De Dios load high on the Madre De Dios factor whereas the samples taken downstream from this point are biased by the Inambari sediments and thus load high on the Inambari factor. The separation between the 2 groups is good although some overlaps do occur.

	F1	F2	F3	F4	F5	Comm
Magnetite	-0.65					0.50
Ilmentite	-0.31	-0.45			-0.82	0.99
Hematite		-0.49			0.56	0.60
Limonite	0.30	0.57				0.49
Tourmaline				0.44		0.29
Zircon			0.80		0.24	0.84
Sphene	0.63					0.58
Brown leucoxene				0.60		0.49
Red leucoxene				0.84		0.71
Andalusite	0.50	0.51				0.57
Staurolite	0.65	0.61				0.81
Garnet		0.59				0.45
Spinel						0.26
Epidote	0.71	0.35				0.73
Green hornblende	0.62					0.47
Brown hornblende	0.46					0.27
Actinolite	0.27	0.46				0.40
Dark monazite		0.60				0.51
Gold			0.66			0.51
Eigenvalue	5.7	2.7	1.6	1.3	1.1	
Total variance %	29.9	14.0	8.2	6.8	6.0	

Table 2 - Rotated factor matrix with eigenvalues and variance per factor and communalities. Only the significant loadings (> 0.20) are represented.

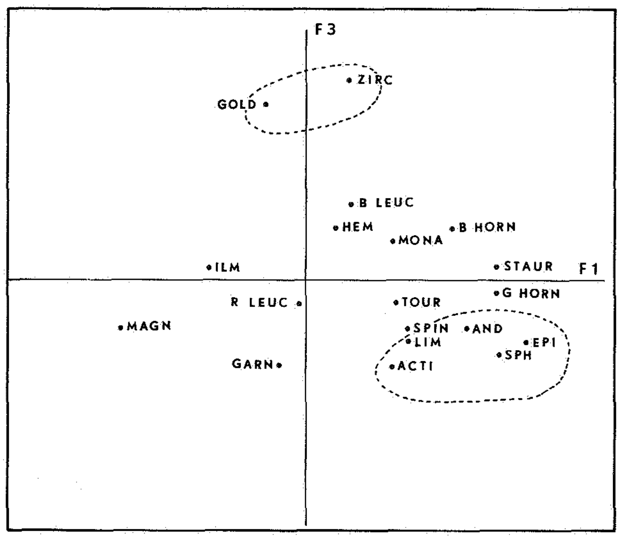

Figure 5. Loadings on factor 1 and 3, showing the two characteristic local mineral associations: (MAGN : magnetite, HEM : hematite, LIM : limonite ; ILM : ilmenite, ZIRC : zircon, B LEUC = brown leucoxene, R LEUC : red leucoxene, TOUR : tourmaline, STAUR : staurolite, AND : andalusite, SPIN : spinel, ACTI : actinolite, SPH : sphene, EPI : epidote, MONA : dark monazite, B HORN : brown hornblende, G HORN : green hornblende, GARN : garnet).

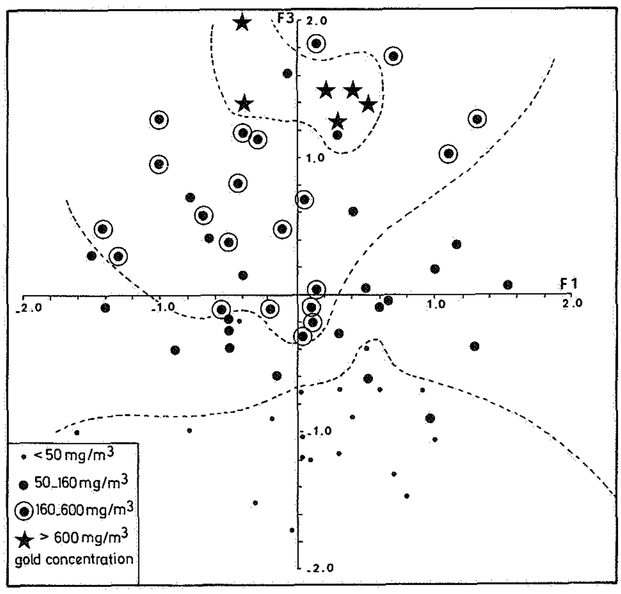

Figure 6. Distributions of scores on factors 1 and 3: Note the separation of samples as a function of their mineral content and their respective association with the gold tenor.

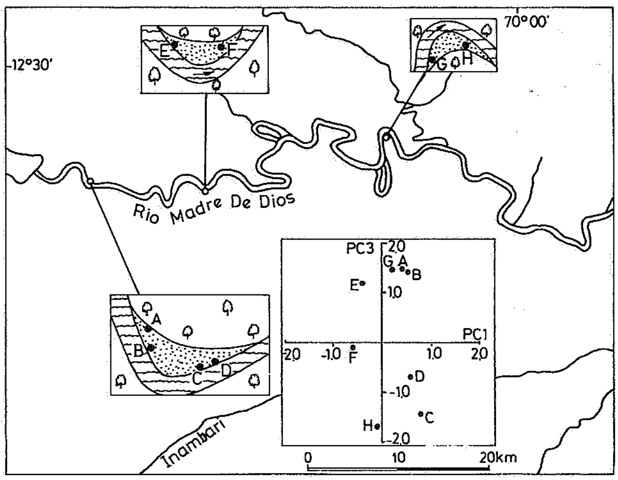

Figure 7. Geomorphological position of some samples along point bars and their c orresponding scores on factors 1 and 3.

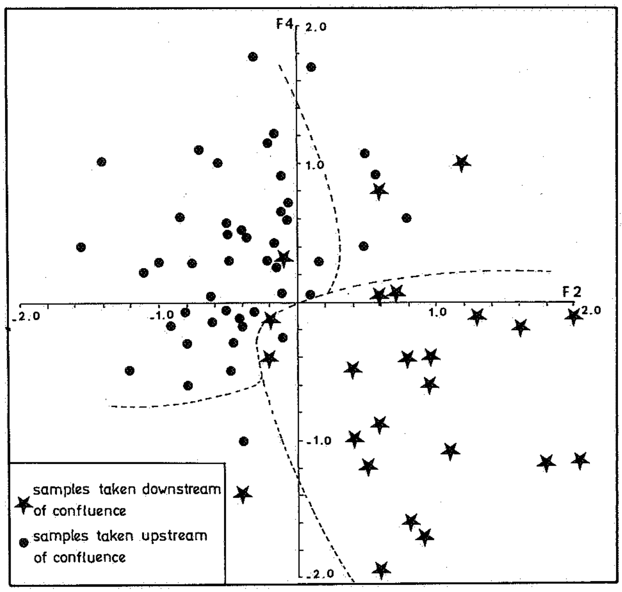

Figure 9. Distribution of scores on factors 2 and 4: illustrating the differences in heavy mineral content between the samples taken upstream and downstream of the confluence of the Inambari with the River Madre de Dios.

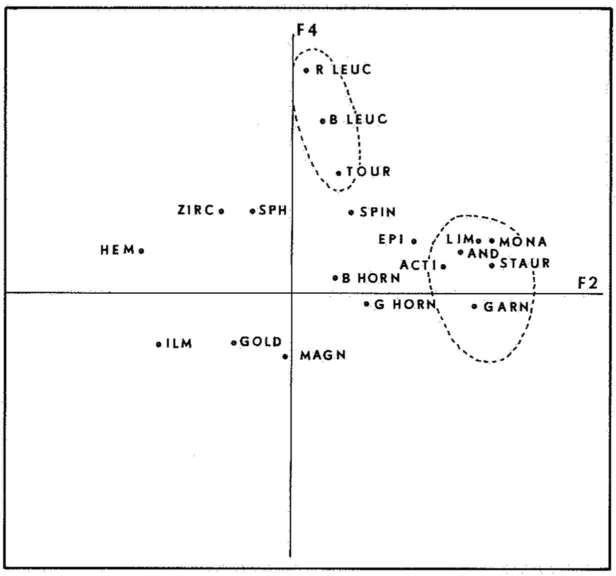

Figure 8. Loadings on factors 2 and 4, showing the characteristic mineral associations of the two river systems.

Let us now consider the distinction between barren and gold bearing sediments by means of their heavy mineral content.

6.3. Discriminant analysis

Discriminant analysis (DAVIS, 1973) permits us to find the linear combination of these minerals which produces the maximum difference between 2 previously defined groups. In our case those 2 groups are on the one hand samples with high gold content and on the other hand samples with low gold tenor. Once a set of minerals is found which provides satisfactory discrimination for samples with known gold content a set of classification functions can be derived which will permit the classification of new samples with unknown gold tenor. As not all of the heavy minerals are equally useful in distinguishing one group from another we eliminate those variables that are not especially helpful. In our case the discriminant function was formed with the following variables : zircon, limonite, andalusite, sphene, epidote and actinolite which are the characteristic minerals from the local associations deduced by factor analysis together with ilmenite and garnet. Gold is not considered as a variable and so the gold tenor of the sample does not influence the results of the discriminant analysis. The discriminant function was based on 20 reference samples of which 10 belong to sediments with high gold tenor and 10 to barren sediments. Discriminant scores were calculated and are visualised on fig. 10. As a test we also calculated the classification scores for 5 samples with high gold content and 5 samples with low gold content. The discriminant function was calculated by the DISCRIMINANT program of the SPSS package (NIE *et al.*, 1975).

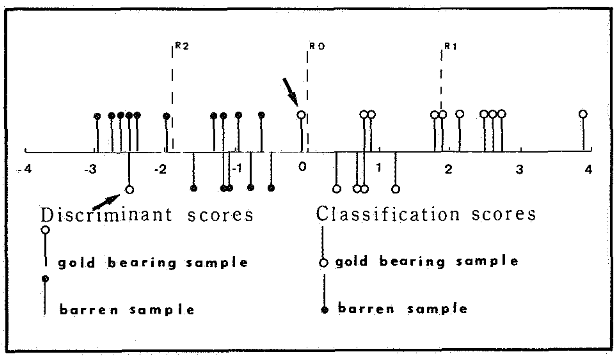

Figure 10. **Projection of discriminant and classification scores onto the discriminant function: R1 and R2 are the projections of the multivariate means of gold bearing and barren samples ; RO is the discriminant index. Only two samples were incorrectly classified (marked by an arrow on the figure).**

We see on fig. 10 that from the 20 reference samples 19 were correctly classified. This forms a first indication that our discriminant function was adequately chosen. This indication was confirmed by the classification scores where 9 samples out of 10 were correctly classified.

7. CONCLUSIONS

A study of associations between the different heavy minerals by means of a correlation matrix makes it possible to suspect the presence of several correlation groups. Those associations can have a local origin and in this case reflect small scale differences in hydrodynamic properties along the meanders. They can however be masked by regional associations. Such interferences upon local conditions occur for example at a confluence of 2 rivers where the mixing of sediments of different lithological origin results in a new heavy mineral distribution different than that from the upstream section.

The deduced correlations remain valid for the whole sampled length of the Madre De Dios (300 km) and for the adjacent alluvial plain. The other rivers of the area show slightly different associations but the main correlations, as between gold and zircon, remain correct.

Grain size measurements of the zircon grains and of the gold particles from different parts along the river and meanders show that both minerals have equivalent diameters (TOURTELOT, 1968).

Understanding the significance of the correlation groups and performing the separation between local and regional associations is of great importance for the identification of pathfinder minerals. Factor analysis permits this differentiation and demonstrates also clearly that the heavy mineral distribution varies in a predictable way with the gold tenor. Furthermore a detailed examination of the mineral composition by discriminant analysis permits the distinction between gold bearing and barren sediments. We are nevertheless completely aware of the fact that the actual gold particles are the best indicators for gold placers and we certainly do not claim to have found a new prospecting tool which will revolutionize the world of placer exploration. An advantage of the described method is however that the distinction between both types of deposits can be performed with the help of small samples as only a few common heavy minerals are used.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. M. Thorp of the University College Dublin for critically reading the manuscript and for his helpful suggestions. The field campaign in Madre De Dios was made possible by a grant from the "Belgisch Nationaal Fonds Voor Wetenschappelijk Onderzoek".

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