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Correlation between heavy mineral distribution and geomorphological features in the Plio-Pleistocene gold-bearing sediments of the Peruvian eastern Cordillera through principal component analysis

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Key words. — Placer, Heavy minerals, Principal component analysis, Gold, Geomorphology, Southeastern Peru.

Abstract. — The study of heavy mineral suites is often used together with other geological and geomorphological methods in placer prospection. However the results of the mineralogical determination expressed in percentage values of the identified species are generally not easy to interpret. The use of multivariate analysis reduces the complexity of a multidimensional data set, with as little loss as possible of the original information, and therefore can facilitate geological interpretation.

In the southeast of Peru, gold placers are located in glacial and fluvioglacial deposits in the high Cordillera and also in fluvial sediments in the Andean valleys and Amazonian piedmont. Principal component analysis (PCA) relationships are visualized on two dimensional diagrams and clustering of samples and variable associations leads to a better understanding of their geological significance; this study shows that various primary mineralization sources can be distinguished. In the glacial environment, economic concentration only occurs in close association with a primary mineralized zone. Mixings of flows are generally accompanied by a decrease in ore grade. In the Amazonian piedmont some grade increase in the Quaternary and present streams results from *in situ* reworking of the Pliocene sediments that therefore are "intermediate collectors" for the gold.

Relations entre la répartition des minéraux lourds des alluvions aurifères plio-quaternaires et la morphogenèse dans la Cordillère orientale du Sud du Pérou par l'analyse en composante principale

Mots clés. — Placer, Minéraux lourds, Analyse en composante principale, Or, Géomorphologie, Sud-Est Pérou.

Résumé. — Les minéraux lourds sont souvent utilisés, conjointement avec d'autres méthodes géologiques et géomorphologiques, pour la prospection des placers. Cependant les déterminations minéralogiques exprimées en pourcentage d'espèces identifiées ne sont généralement pas commodes à manier lorsque les données sont nombreuses d'où l'emploi des méthodes d'analyse factorielle permettant de réduire la complexité d'un ensemble de données, avec une perte minimale d'information.

Dans le Sud-Est du Pérou les placers se situent dans des matériaux glaciaires et fluvioglaciaires dans la cordillère ainsi que dans les sédiments fluviatiles des vallées andines et du piémont amazonien. L'emploi de l'analyse en composante principale sur les données minéralogiques et granulométriques a permis de confirmer l'existence de plusieurs sources d'or primaire et de montrer qu'il n'existe pas de relation simple et directe entre l'or des zones hautes de la cordillère et celui du piémont amazonien. En milieu glaciaire, des concentrations économiques ne se rencontrent qu'en étroite association avec des minéralisations primaires en roches; le mélange des décharges de matériaux détritiques de composition différente s'accompagne en général d'une baisse des teneurs. Dans le piémont amazonien, l'augmentation des teneurs résulte en partie de la remobilisation *in situ* de sédiments détritiques plus anciens déjà faiblement aurifères et qui jouent le rôle de collecteurs intermédiaires.

INTRODUCTION

In the eastern Cordillera of southern Peru, gold has been mined from primary vein deposits and more especially from alluvial placers since Inca times. Interest for gold prospection has been revived in recent years and a survey linked to the subject has been undertaken through a cooperation agreement between Institut Français de Recherche pour le Développement en Coopération (ORSTOM) and Instituto Geologico Minero y Metalurgico del Peru (INGEMMET) [Fornari *et al.*, 1982; Bonnemaison *et al.*, 1985].

In addition to the geological and geomorphological studies, voluminous samples (up to a hundred kilograms) were collected for gold evaluation, and various types of analysis undertaken on them, namely : grain size distribution of sediments, measurement of the gold content, morphological examination of the gold particles, separation and identification of the heavy minerals. The data concerning the heavy minerals form the basis of the present study using a statistical method which permits reduction of a large set of numerical data. This method permits to identify primary source zones and to describe the mechanism of the distribution of the different mineral suites in this Andean region with respect to the development of geomorphological features.

I. — GEOLOGICAL AND GEOMORPHOLOGICAL ENVIRONMENT OF SAMPLING SITES

The Ananea-Ancocala basin, the Quincemil basin and the Mazuko Amazonian piedmont which belong to the eastern Cordillera are characterized by extensive gold placers and therefore have been the subject of a more detailed study (fig. 1).

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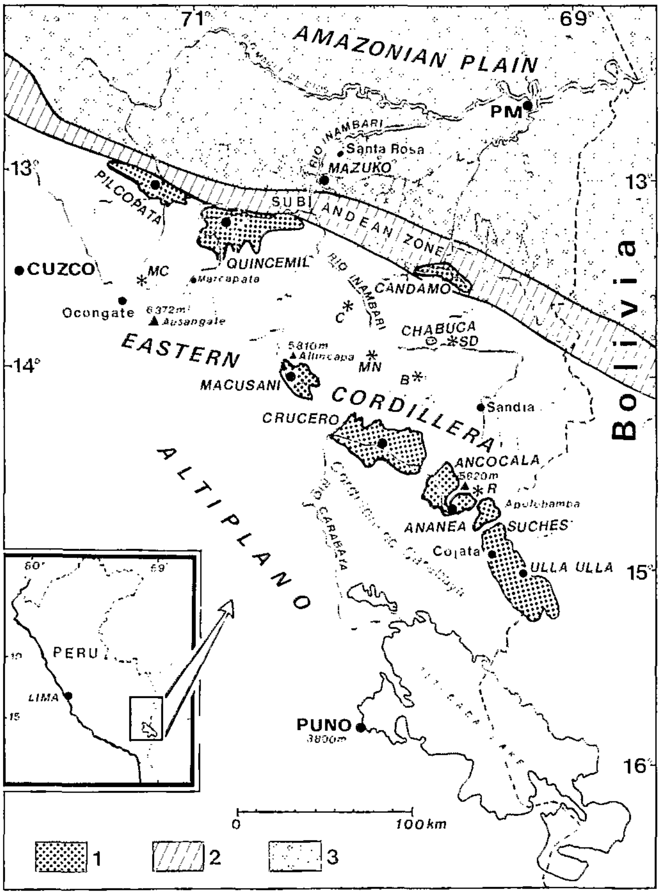

FIG 1. — Location map.
1 : Plio-Quaternary intramontane basins; 2 : sub-Andean foothill belt; 3 : Piedmont and Amazonian plain. *Altiplano slope basins* : Macusani, Crucero, Ancocala, Ananea, Cojata, Suches-Ulla Ulla. *Amazonian slope basins* : Pilcopata, Quincemil, Candamo, Chabuca. Star : primary gold mineralization of : *MC* : Manco Capac, *SD* : Santo Domingo, *C* : Candelaria, *MN* : Media Naranja, *B* : Benditani, *R* : la Rinconada, *PM* . Puerto Maldonado (town).

FIG. 1. — *Carte de localisation.*
1 : *bassins intra-montagneux plio-quaternaires*, 2 : *reliefs de la zone subandine*; 3 : *piémont et plaine amazonienne*. Bassins du versant altiplanique : *Macusani, Crucero, Ancocala, Ananea, Cojata, Suches-Ulla Ulla*. Bassins du versant amazonien : *Pilcopata, Quincemil, Candamo, Chabuca*. * : *minéralisations primaires de : MC : Manco Capac, SD . Santo Domingo, C : Candelaria, MN : Media Naranja, B . Benditani, R : la Rinconada, PM : ville de Puerto Maldonado (alt.)*.

1) The morphological-structural units in the eastern Cordillera of southern Peru

The eastern Cordillera trends approximately NW-SE in this region (fig. 1). In the south-west, it rises above a serie of basins (Macusani, Crucero, Ancocala, Ananea, Suches, Cojata) which separate it from the Carabaya Cordillera and from the Altiplano. The eastern Cordillera often rises above 5 000 m elevation and some peaks are even above 6 000 m in height. It is partly covered by glaciers which were much more extensive during the Plio-Quaternary glacial epochs. This massif is composed of a thick Paleozoïc series (mainly Ordovician and Siluro-Devonian); it consists of about 6 000 m of fine-grained sericite-quartz schists with intrusions of biotite-and muscovite-rich granite [Laubacher, 1978] and contains primary gold mineralizations [Fornari *et al.*, 1982; Fornari and Bonnemaison, 1984].

The northeastern slope of the Cordillera lowers down to about 1 000 meters above sea level. It is deeply dissected by entrenched rivers with more than 1 500 m steep valley sides. Some alluvial, conglomeratic and thick superficial deposits accumulated locally remain in the interfluves (e.g. Chabuca) in the Inambari river basin. Large amounts of gold bearing detrital sediments were trapped at the contact of the Sub-Andean reliefs at the foot of the Cordillera and accumulated in elongated basins (e.g. Pilcopata, Quincemil, Candamo) located at a height of 900-600 m. In the Sub-Andean zone, WNW-trending ridges and bars show structures (folds and thrusts) which affected Cretaceous and Tertiary sandstones and mudstones. These abrupt structures border the Madre de Dios Amazonian plain (250-300 m elevation).

a) *The Ananea Ancocala basin (fig. 2)*

The sediments contained in this basin (4 400 to 5 000 m elevation) mainly originate from the erosion of the Paleozoïc rocks surrounding the depression. The sedimentary sequence is composed of successive palustrine, fluvial, glacial and fluvioglacial deposits dating from Pliocene to Present [Fornari *et al.*, 1982].

Filling began with palustrine deposits interstratified with layers of microconglomerates (Arco-Aja Formation). They are conformably overlain by fluvio-torrential conglomerates (about 30 m thick). Some colluvial materials deposited on the margins of the basin. A cineritic level identified in the upper part of the palustrine sediments yielded a K/Ar age of 3.8 ± 0.4 Ma [Laubacher *et al.*, 1984].

These sedimentary deposits and the surrounding basement have been truncated by extensive development of pediments (erosive upstream, accumulative downstream) that appears to pre-date any identified glacial activity. This was followed by the glacial events, dissection and fluvial aggradation events. Three great glacial epochs have been identified. Only huge erratic blocks forming two parallel frontal arches attest to the oldest glaciation (Limata Glaciation) in the Ancocala basin. The second glaciation (Ancocala Glaciation) is characterized by morainal and fluvioglacial deposits truncated by a pediment which obliterated all previous glacial morphology; the remnants of this glacial epoch can still be observed in both the Ancocala and Ananea basins (Pampa Blanca area). The best preserved glacial and fluvioglacial deposits are linked to a third epoch (Chaquiminas Glaciation). It is characterized by the freshness of the glacial landforms and the weak weathering of the sediments. Conspicuous glacial-retreat forms remain in the main glacial valleys (e.g. Islapampa and lago Rinconada arc). Several retreat stages have been distinguished that lead to the presently reduced glaciers; this glacial recession occurred from about 40,000 B.P., as indicated by regional correlation with the ^{14}C ages of about 31,000-28,000 B.P., 14,000 B.P. and 28,000 B.P. obtained by Mercer and Palacios [1977] in the Ocongate massif, located about 200 km north-west of Ananea.

In the Ananea-Ancocala basin, the glaciers never covered the whole depression, and fluvioglacial and fluvial flows have always followed the Carabaya drainage axis, which migrated moderately. Sedimentary deposits associa-

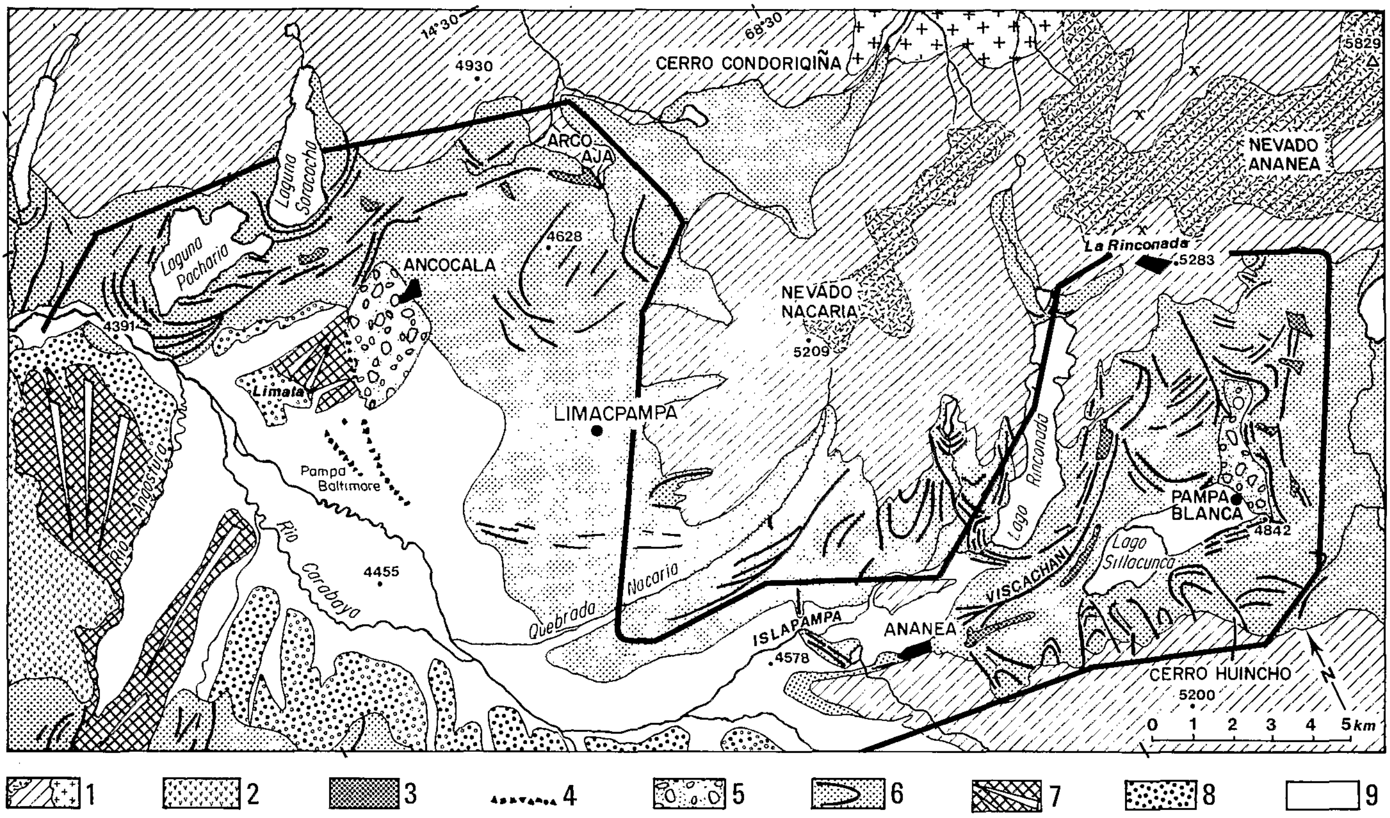

FIG. 2. — The Ancocala Ananea basin, (geology and geomorphology).
1 : Paleozoïc basement (crosses : granite); 2 : Cenozoïc ignimbrites; 3 : Arco Aja Formation; 4 : erratic blocks remnants of the Limata Glaciation; 5 : glacial and fluvioglacial deposits of the Ancocala Glaciation; 6 : glacial deposits, with main moraine crests, of the Chaquiminas Glaciation; 7 : main remnants of the pediment 6 and pediment 5; 8 : pediment-terrace 4; 9 : fluvioglacial and fluvial deposits (contemporaneous or younger than the Chaquiminas Glaciation). Fine dashed screen : main permanent glaciers (nevados). Frame outlines the sampled area.

FIG. 2. — *Le bassin d'Ancocala-Ananea (géologie et géomorphologie).*
1 : substratum paléozoïque (croix : granite); 2 : ignimbrites cénozoïques; 3 : formation Arco-Aja (Pliocène); 4 : blocs erratiques reliques de la glaciation Limata; 5 : dépôts glaciaires et fluvioglaciaires de la glaciation Ancocala; 6 : dépôts glaciaires de la glaciation Chaquiminas, avec les principales crêtes morainiques; 7 : reliques des glacis 6 et 5; 8 : glacis-terrasse 4; 9 : matériaux fluvioglaciaires et fluviatiles (contemporains ou plus récents que la Glaciation Chaquiminas). Trame tiretée : principaux glaciers (nevados); le cadre marque la zone échantillonnée.

ted with these glaciers are preserved in the form of stepped terraces above the present alluvial plain.

b) The Quincemil basin and the Mazuko piedmont (fig. 3)

On the northeastern piedmont of the eastern Cordillera, numerous placers are being or have been exploited for their gold deposits. They are located along the rivers, in inner basins (e.g. Quincemil basin) and at the river outlets on the piedmont (e.g. Mazuko area).

The Quincemil basin, about 50 km long and 15 km wide, includes a sedimentary sequence more than 300 m thick, probably Pliocene to Lower Pleistocene, which was deformed by compression [Laubacher *et al.*, 1982]. Bars and ridges of Cretaceous sandstones and of "Capas Rojas" (Palaeocene-Eocene red-beds) are locally partly fossilized by the detrital infill. The infill begins with a clay assemblage about 10 m thick, with abundant plant remains, including sandy and conglomeratic lenses (Huajumbre Formation). It is covered by a thick (300 m) conglomeratic accumulation (Cancao Formation) composed of blocks (up to more than 50 cm in diameter) as well as frequently contiguous and well imbricated pebbles.

The detrital filling of the basin has been deeply dissected by the incised valleys of the Marcapata river and its tributaries. This dissection phase is characterized by six main levels of alluvial terraces and alluvial fans which are particularly well developed in the eastern part of the basin.

At the outlet of the Quincemil basin, the Araza river (= Marcapata river) plunges into narrow gorges, cutting through the relief of the Sub-Andean zone. At Puente Inambari, it connects with the Inambari river which flows into the Amazonian plain upstream from Mazuko. The "Capas Rojas" red beds and a grey clastic formation composed of sands, clays and conglomerates, namely the Mazuko Formation [Laubacher *et al.*, 1982] can be identified above the Cretaceous sandstone along this valley, downstream from Puente Inambari. The Mazuko Formation is increasingly coarser to the top and could be synchronous with the Cancao Formation. It results from erosion of similar rock types [Laubacher *et al.*, 1982]. The

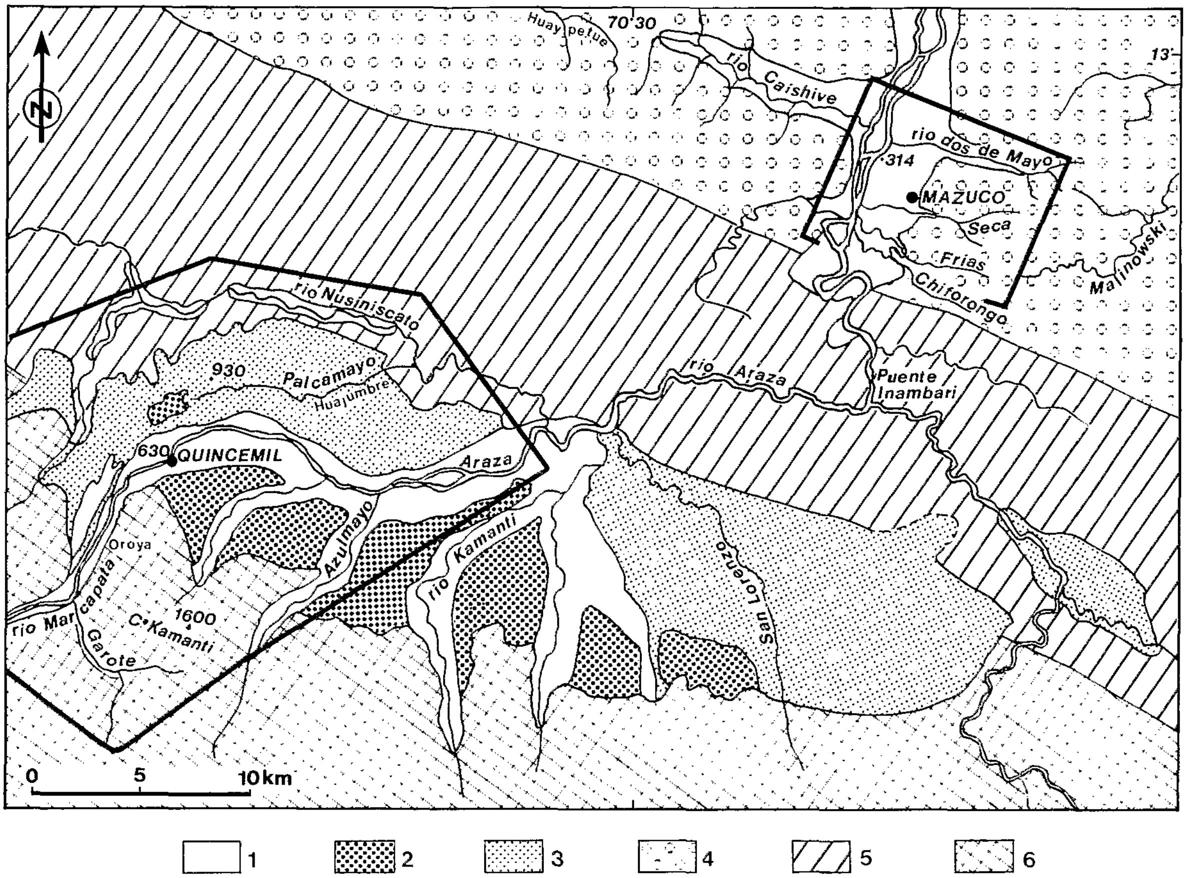

FIG. 3. — The Quincemil basin and the Mazuko piedmont.
1 : Pleistocene to Actual terrace; 2 : alluvial fan and pediment of the Quincemil basin (Pleistocene); 3 : Cancao Formation (Pliocene, ?); 4 : Mazuko Formation; 5 : Cretaceous and Tertiary outcrops of the sub-Andean zone; 6 : Paleozoïc basement. Frame outlines the sampled areas.

FIG. 3. — *Le bassin de Quincemil et le piémont de Mazuko*
1 : *terrasses pleistocènes à actuelles,* 2 : *cônes alluviaux et glacis du bassin de Quincemil;* 3 : *formation Cancao,* 4 : *formation Mazuko,* 5 : *Crétacé et Tertiaire de la zone sub Andine;* 6 : *sustratum paléozoïque. Le cadre marque les zones échantillonnées.*

Mazuko Formation exhibits slightly asymmetric folds trending N100°E to N110°E. This folding exerts a direct control on the network of autochthonous streams (e.g. Chiforongo, Quebrada Seca, Dos de Mayo, Caishive); these streams and their related terraces rework the Mazuko Formation along the synclinal axis. Downstream these terraces are connected with the alluvial sheets deposited along the Inambari river.

The compressive tectonic which folds the Mazuko piedmont, spread about 20 km northeastward during the Plio-Pleistocene; folding extended near Santa Rosa (fig. 1) where a new piedmont is constructed actually on the Amazonian plain.

2) Primary gold occurrences

In the Cordillera, primary gold mineralization occurs in several areas. Some are well located such as the gold-quartz veins of Manco Capac near the town of Ocongate, that of Candelaria, Benditani, Media Naranja (fig. 1); generally they are short (a few hundreds of meters) and narrow (20 cm-1 m); gold occurs as native gold in the quartz and the grade is about 10 g/t. Between 1890 and 1932 (?) the Santo Domingo mine produced about 500 kg gold annually and the grade attained 100 oz/t in the bonanzas; the main quartz vein was several kilometers long and 2-25 m thick. It was located in a fault striking NW-SE, parallel to the axial plane of an anticline. Presence of other primary occurrences are suspected such as the old pits of the Cerro Kamanti (fig. 3) which are located within the amphibolitic belt sandwiched between the Cordillera and the Sub-Andean zone [Fornari *et al.*, 1982]. Some have been more thoroughly investigated like the Rinconada deposit. There, the primary mineralization occurs as narrow bedding-parallel gold quartz veins; these veins show a close relation to a stratabound gold-bearing massive arseno-sulfide body [Fornari and Bonnemaison, 1984]; it is exposed over 300 m with a thickness of about 2 m within shales and sandstones of the Ananea Formation of Siluro-Devonian age. The granitic intrusion located near the Cerro Condoriquiña, which has produced thermal metamorphism in the Ananea Formation resulting in the presence of coarse andalusite and staurolite, contains minor occurrences of cassiterite [Petersen, 1962], in small quartz-tourmaline veins in places where the granite is greisenized.

II.2. — DATA PROCESSING AND INTERPRETATION

1) Sampling and analytical procedures

For this study 248 samples were used; 198 are located in the Ananea-Ancocala basin, 50 are in the Quincemil and Mazuko area (fig. 1, 2 and 3). The samples were selected on geological and geomorphological basis. In the field, sample locations were based on aerophotos at the 1/25 000 scale. The samples were collected from natural outcrops, on gravel pit faces, or from shafts.

Heavy minerals and gold contents were determined on samples of about 100 kg in average. First the samples were reduced in the field : they were washed in a 50 litres box with water to remove the clays and clean the grain surfaces; in the next step, the materiel was sieved through a 1.27 cm (1/2 inch) sieve and the coarse fraction discarded. The remaining material was carefully panned to obtain a pre-concentrate of heavy minerals. In the laboratory, the following procedure was used to estimate the free gold content : free gold was first collected by mercury; then the amalgam was dissolved in a nitric acid solution and the gold button was weighted (precision balance of ± 0.1 mg); the weight of gold was divided by the weight of the initial sample to calculate the grade.

The heavy minerals ($d > 2.9$) were also extracted from the pre-concentrate using standard methods [e.g. Parfenoff *et al.*, 1970]; It was necessary to clean the grains in dilute HCl and only light coloured mineral were counted; opaque minerals were only weighted but not identified (they consist mainly in abundant magnetite, ilmenite, pyrite and localy arsenopyrite). Densimetric and magnetic separations were made on three granulometric fractions of 500-300 µm, 300-160 µm and 160-50 µm; the finest fractions were generally more suitable for grain identification and counting.

In the Pampa Blanca area, it could be seen that the gold values obtained were in good agreement with those measured by the Natomas Company during their mining operation and Minero Peru's drilling campaign [Saenz Chavez, 1964; Kihien, 1985]. The values are generally less than a 1 g/t, the volume of minable low grade materials is of several millions of m^3.

2) Data processing

The initial file contains 19 observations (variables) made on each of the 248 samples selected from a larger data set. The variables considered are : percentage of 15 transparent heavy minerals, concentration rate of heavy minerals (i.e. ratio between the weight of the heavy minerals and the weight of initial sample), percentage of particles by weight with grain size less than 1 cm, percentage of particules by weight with size coarser than 5 cm in the initial sample, and gold content by weight. All the variables under consideration are quantitative and apparently none of them plays a preferential role a priori. Therefore we decided to process the data through a principal component analysis (PCA) technique [Klovan, 1966; Teil, 1975; Benzecri, 1980; Jambu and Lebeaux, 1983].

We considered both the R-mode, looking for relationships between the variables on the basis of all the samples, and the Q-mode factors which consider relationships between samples on the basis of all the variables. Variable or sample transformations before ACP calculation were not used nor factor rotations.

Firstly, the whole data were processed. Then, in order to evaluate possible effects of distortion due to the heterogeneity of the considered variables, we analyzed only the mineralogical composition of the samples. Finally, the inital data set was divided into two sets on the basis of geographical considerations, the first one comprising all the samples from the Ananea-Ancocala basin and the second one grouping all the samples from the Amazonian slope and its piedmont.

Data was processed at the Computing Center of the University of Toulouse; combined factorial plane projections of the six first factors were examined in detail, though only some projections for illustrative purpose were selected here. (Listing of the data files and calculation results can be provided on request).

3) The results

a) PCA of the total sample population

Considering all the variables for all the samples, the percentage of the total variance (eigen value) accounted to factor 1 amounts to 18.4 % and that of the first six factors amounts to 58.3 % (table I). One can notice that the amount of the total variance accounted by the first factors is low;

TABLE I. — Variables contributions for the first six factors, (accounting for 58.3 % of the total variance). PCA of the total sample population (248) considering all the 19 variables. *Variables :* g : fine fraction; G : coarse fraction; T : gold content; ML : heavy mineral ratio; Tour : tourmaline; Zir : zircon; Ru : rutile; A : anatase; Mo : monazite; Epi : epidote; Horn : hornblende; Gr : garnet; And : andalusite; Si : sillimanite; Stau : staurolite; Cas : cassiterite; Hyp : hypersthene; Aug : augite; Sp : sphene.

TABL. I. — *Contribution des variables pour les six premiers facteurs principaux, (représentant 58,3 % de la variance totale). ACP sur tous les échantillons (248) en utilisant les 19 variables.* Liste des variables : g : *fraction granulométrique fine;* G : *fraction granulométrique grossière;* T : *teneur en or;* ML : *pourcentage de minéraux lourds;* Tour : *tourmaline;* Zir : *zircon;* Ru : *rutile;* An : *anatase;* Mo : *monazite;* Epi : *épidote;* Horn : *hornblende;* Gr : *grenat;* And : *andalousite;* Si : *sillimanite;* Stau : *staurotide;* Cas : *cassitérite;* Hyp : *hypersthène;* Aug : *augite;* Sp : *sphène.*

Factors :	F 1	F 2	F 3	F 4	F 5	F 6
variance :	18.4 %	9.6 %	9.2 %	7.8 %	7.0 %	6.3 %
variables						
g	-0.72	0.32	-0.19	-0.19	0.17	0.36
G	0.82	-0.21	0.21	0.16	-0.11	-0.27
T	-0.16	-0.18	0.40	-0.14	0.12	0.18
ML	0.67	0.39	-0.08	-0.14	0.06	0.21
Tour	-0.33	0.10	-0.20	0.19	-0.04	-0.53
Zir	-0.56	0.19	0.72	-0.13	-0.07	-0.01
Ru	-0.24	0.43	0.08	0.38	-0.10	-0.36
An	-0.29	-0.05	-0.52	-0.53	0.03	-0.18
Mo	-0.29	-0.13	-0.49	0.43	-0.14	0.28
Epi	0.34	-0.60	-0.11	0.05	0.12	0.12
Horn	0.80	0.17	0.02	-0.08	-0.13	0.15
Gr	0.18	0.29	-0.31	0.12	0.36	-0.05
And	0.57	0.48	0.16	0.01	0.31	0.12
Si	-0.18	0.28	-0.24	0.48	-0.17	0.24
Stau	0.07	0.00	-0.08	0.28	0.20	-0.40
Cas	-0.10	-0.63	-0.23	0.19	-0.10	0.11
Hyp	0.06	0.20	-0.05	0.02	-0.70	0.03
Aug	0.18	0.12	-0.14	-0.25	-0.63	-0.14
Sp	-0.02	-0.02	-0.38	-0.54	-0.04	-0.24

this is due to the high number of variables used and the fact that these variables are relatively independant and not strongly correlated. The variables have a wide interval of variation (cf minimum and maximum in table II) and are more over scattered (cf mean and standart deviation in table II). This fact has to be reminded when looking to the ACP results, particularly in the case of gold grade (T) and concentration rate of heavy minerals (ML), because ACP uses a ponderation based on standart deviation to give the same "weight" to each variable, whatever his dispersion may be.

TABLE II. — Elementary statistic of the variables.
Variables as in table I: average, standart deviation, minimum and maximum values (range of variation).

TABL. II. — *Variation individuelle des variables.*
Moyenne, écart-type, intervalle de variation; mêmes variables que dans le tableau I.

variables	Mean	St. Dev.	Mini.	Maxi.
g	49.9	13.5	19	79
G	16.4	11.1	0	55
T [ppb]	450	1035	0	9500
ML	78.5	135.3	1	1000
Tour	9.1	10.9	0	70
Zir	32.8	28.9	0	99
Ru	1.3	2.8	0	17
An	5.9	10.1	0	68
Mo	4.0	5.6	0	43
Epi	22.6	19.7	0	99
Horn	5.0	12.3	0	60
Gr	1.4	4.2	0	37
And	8.1	15.7	0	83
Si	0.8	3.6	0	32
Stau	0.1	0.6	0	7
Cas	6.6	12.4	0	61
Hyp	0.3	1.4	0	13
Aug	0.4	1.8	0	21
Sp	0.2	1.9	0	27

It appears that the particle size largely contributes to the determination of factor 1. The contrasting characters on this factor are : the fine granulometric fraction and, with a less important contribution, abundance of zircon on the negative side and the abundance of hornblende, andalusite and a pronounced contribution of the concentration rate of heavy minerals and the coarse fraction on the positive side. On factor 2, epidote and cassiterite (on the negative side) are opposed to andalusite, rutile and the concentration rate of heavy minerals (positive values). Gold contents exert a considerable influence only in the factor 3; it contributes with zircon to the positive values of this factor.

Two main sample populations can be distinguished in the factor 1 vs factor 2 plane : the first one is composed of samples from the Amazonian slope of the Cordillera and the second one includes the samples from the Ancocala-Ananea basin (fig. 4); the two areas are practically not overlapping. For the samples from the Ancocala-Ananea basin additional distinctions appear : samples of glacial deposits from the Ancocala area, the Ananea area and the Pampa Blanca area, can be discriminated from the ones belonging to the resulting fluvial and fluvioglacial outwashes. The alluvium samples from the Carabaya river occupy a more central position. Age of the materials does not intervene in this discrimination. The samples of the Arco Aja Formation occupy the NW quadrant of the diagram and are partly mixed with the moraine ones toward the centre.

When only the mineralogical variables are considered (i.e. the proportion of the different heavy mineral species without taking into account gold content nor concentration rate of heavy minerals and granulometric criteria), the amount of variance accounted by the first six factors remains nearly the same (61.9 %), but the factor 1 explains only 14.6 % of the variance, and it is not very more important than the other following factors (table III). It appears that the factor 1 axis opposes hornblende, andalusite and epidote on the negative side, to zircon and, to a lesser extent, rutile and tourmaline on the positive side. Cassiterite, epidote, anatase and monazite largely contribute to define factor 2 axis (positive values), opposed to zircon, rutile and andalusite on the negative side. Comparison between table I and III shows that the order of the main variables contributions remains the same in both case.

In the plane defined by factor 1 and factor 2, the projection of the sample populations shows two principal groups : Amazonian piedmont and Quincemil basin samples on the one hand and Ananea-Ancocala basin on the other hand (fig. 5). These groups are the same as those defined when all the variables are included. Some overlap

TABLE III. — Variables contributions for the first six factors. (accounting for 61.9 % of the total variance). PCA of the total sample population (248) with only the 15 mineralogical variables. *Variables* : same as table I excluding g, G, T and ML.

TABL. III. — *Contribution des variables pour les six premiers facteurs principaux, (représentant 61.9 % de la variance totale). ACP sur tous les échantillons (248) en n'utilisant que les 15 variables minéralogiques.* Liste des variables : *comme dans tabl. I, mais sans* g : *fraction granulométrique fine.* G : *fraction granulométrique grossière.* T : *teneur en or et* ML : *pourcentage de minéraux lourds.*

Factors :	F 1	F 2	F 3	F 4	F 5	F 6
variance :	14.6 %	11.5 %	10.3 %	9.5 %	8.7 %	7.3 %
variables						
Tour	0.38	0.07	-0.37	-0.04	-0.13	-0.58
Zir	0.68	-0.49	0.42	-0.09	0.02	0.07
Ru	0.41	-0.38	-0.40	0.08	-0.06	0.07
An	0.16	0.45	-0.21	-0.61	-0.21	0.12
Mo	0.24	0.43	-0.48	0.32	0.24	0.19
Epi	-0.44	0.46	0.32	0.28	0.02	-0.17
Horn	-0.74	-0.24	0.01	-0.06	0.19	0.17
Gr	-0.31	0.11	-0.46	0.06	-0.33	-0.09
And	-0.64	-0.36	-0.30	0.03	-0.24	0.13
Si	0.17	-0.09	-0.52	0.29	0.25	0.38
Stau	-0.07	-0.02	-0.22	0.20	-0.24	-0.50
Cas	0.09	0.65	0.08	0.26	0.16	0.06
Hyp	-0.07	-0.17	-0.18	-0.16	0.72	-0.15
Aug	-0.20	-0.04	-0.13	-0.45	-0.53	-0.36
Sp	-0.04	0.28	-0.17	-0.66	-0.17	0.24

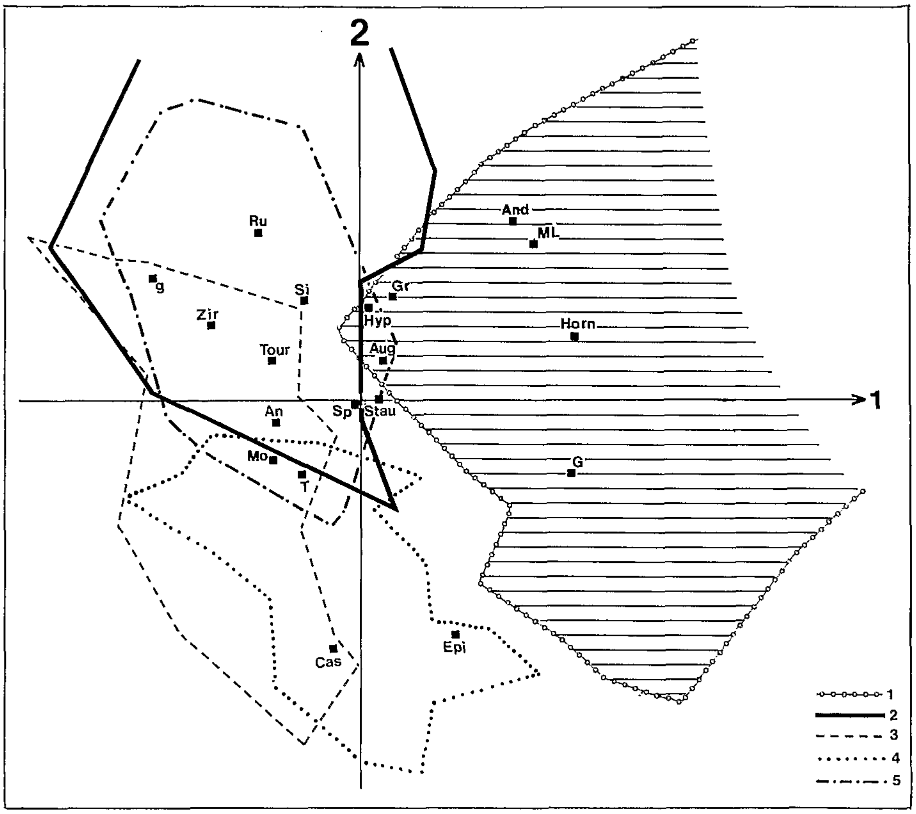

FIG. 4. — Principal component analysis of the total sample population (248) considering all the 19 variables.
Factor 1 versus factor 2 projection. *Projected variables :* same as table I. *Limits :* 1 : area includes the samples from the Amazonian piedmont and from the Quincemil basin; 2 : glacial deposit samples from the Ancocala basin; 3 : glacial deposit samples from the Ananea-Pampa Blanca basin; 4 : fluvioglacial deposit samples from Islapampa; 5 : fluvial and fluvioglacial deposit samples from the Carabaya river zone (limits were drawn on basis of individual plotting position of the samples, checking for the numerous superpositions).

FIG. 4. — *Analyse en composantes principales sur tous les échantillons (248) en utilisant les 19 variables.*
Projection suivant les axes factoriels 1 et 2. Liste des variables projetées : *cf. tableau I.* Limites : 1 : *secteur incluant les échantillons du piémont amazonien et du bassin de Quincemil;* 2 : *secteur incluant les échantillons des matériaux glaciaires du bassin d'Ancocala;* 3 : *secteur incluant les échantillons des matériaux glaciaires du bassin Ananea-Pampa Blanca;* 4 : *secteur incluant les échantillons des matériaux fluvioglaciaires d'Islapampa;* 5 : *secteur incluant les échantillons des matériaux fluviatiles et fluvioglaciaires de la zone du rio Carabaya (les limites des secteurs ont été établies d'après la position de chaque échantillon en controlant tous les points masqués).*

occurs however and in this figure population sorting is less efficient; some samples of the Ancocala glacial deposits therefore plot in the graph area occupied by the Amazonian samples, but their relative contribution is less important. Andalusite, common to both groups, causes superpositions.

When using only mineralogical variables, it also appears that samples from the same vertical section plot close to one another if they are in glacial deposits whereas a much greater dispersion occurs if they are in fluvial deposits.

b) PCA of the samples from the Amazonian slope and from the Piedmont

The PCA of all the variables for this geographical selected data set shows that the percentage of the variance corresponding to the first six factors amounts to 63.3 % (table IV). Factor 1 contrasts the abundance of the fine granulometric fraction and zircon, rutile, monazite on the positive side to abundance of the coarse granulometric fraction and hornblende on the negative side. Gold content also contributes largely to this factor on the negative side. Factor 2 contrasts epidote (on the positive side) to the high content of heavy minerals and to abundance of hypersthene and andalusite (on the negative side).

Despite the fact that few samples (50) were used, a pattern appears. The sample projections (fig. 6) separate the alluvium of the Quincemil basin and the Mazuko piedmont from the materials sampled in the Ocongate area and in the Marcapata valley upstream from La Oroya (village located at the inlet of the Marcapata river in the Quincemil basin, cf. fig. 3). The single sample of "Capas Rojas" red beds plots away from the cluster.

In the Quincemil basin, the samples of the basin infill (Cancao Formation) and those of the alluvial terraces enclosed in this formation are not separated; in the secondary valleys, such as those of the Yanamayo and the Palcamayo stream, samples of the Cancao Formation plot very close to those from the terraces of these streams.

In the Mazuko area, the samples of the piedmont conglomerates (Mazuko Fm) and those of the terraces deposits are very close to one another in a same valley. As

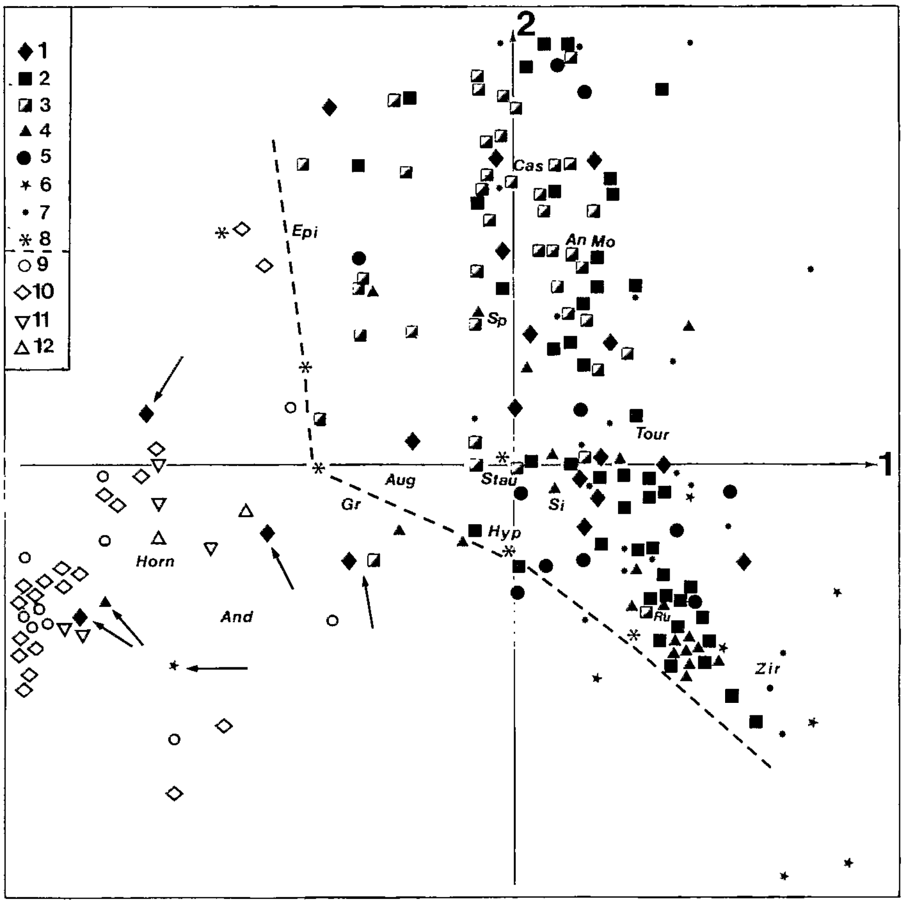

FIG. 5. — PCA of the total sample population (248) using only the 15 mineralogical variables.
Factor 1 versus factor 2 projection. *Projected variables :* same as table I excluding g, G, T and ML. *Projected samples :* 1 : Chaquiminas Glaciation moraines (from Ancocala area); 2 : Chaquiminas Glaciation moraines (from Ananea-Pampa Blanca area); 3 : Chaquiminas Glaciation fluvioglacial deposits; 4 : Ancocala Glaciation moraine and fluvioglacial deposits; 5 : Rio Carabaya fluvial deposits; 6 : pediment and pediment-terrace deposits (from Ancocala basin); 7 : Arco Aja Formation; 8 : glacial deposits from Ocongate region; 9 : Cancao Formation; 10 : alluvial terraces from Quincemil basin; 11 : Mazuko Formation; 12 : alluvial terraces from Mazuko piedmont. Filled symbols refer to the high Cordillera samples and open symbols refer to the Amazonian slope and Piedmont samples, also separated by the dashed line; arrows outline some "scattered" samples.

FIG. 5. — *ACP sur tous les échantillons (248) en n'utilisant que les 15 variables minéralogiques.*
Projection suivant les axes factoriels 1 et 2. Liste des variables projetées : *Cf tableau I, sans* g, G, T, *et* ML. Echantillons : 1 : *moraines de la glaciation Chaquiminas provenant de la zone d'Ancocala;* 2 : *moraines de la glaciation Chaquiminas provenant de la zone d'Ananea-Pampa Blanca;* 3 : *matériaux fluvioglaciaires de la glaciation Chaquiminas;* 4 : *moraines et matériaux fluvioglaciaires de la glaciation Ancocala;* 5 : *matériaux fluviatiles du rio Carabaya;* 6 : *matériaux des glacis et des glacis-terrasses (du bassin d'Ancocala);* 7 : *formation Arco Aja;* 8 : *matériaux glaciaires de la région d'Ocongate.* 9 : *formation Cancao;* 10 : *terrasses du bassin de Quincemil;* 11 : *formation Mazuko;* 12 : *terrasses du piémont de Mazuko. Les symboles pleins renvoient aux échantillons de la zone haute de la cordillère alors que les symboles évidés correspondent aux échantillons du versant amazonien et du piémont, aussi séparés par la ligne de tirets; les flèches indiquent quelques échantillons « mal » projetés.*

a whole, the samples from the Mazuko piedmont fall near the origin of the axis in the factor 1 versus factor 2 diagram.

c) PCA of the samples from the Ananea-Ancocala basin

This analysis brings out the second data group as previously defined (cf. fig. 4), the percentage of the variance accounted by the first six factors amounts to 56.2 % (table V). Fine granulometric fraction (lower than 1 cm) and heavy mineral contents form the main variables contributing to the negative values of factor 1 whereas abundance of the coarse fraction and cassiterite contribute to the positive values. On the factor 2 axis, monazite and epidote and, to a lesser extent, anatase and garnet on the negative side are opposed to zircon and to gold content, on the positive side.

In the factor 1 vs. factor 2 diagram (fig. 7), proportion of heavy mineral contents have an important discriminatory role because of their strong differences from one sample to another. In other respects, unlike the populations which have already been analyzed here, proportion of heavy mineral contents are strongly correlated with high proportions of the fine fraction in the sediments.

The same factor 1 vs factor 2 diagram shows that the samples of the most external morainal lobes from the Ananea basin and those of the resulting fluvioglacial outwash deposits can be clearly distinguished from the others. Some samples from the Carabaya river alluvium mix with this family. The samples from the Pampa Blanca area plot together in a well defined part of the diagram, irrespec-

TABLE IV. — Variables contributions for the first six factors, (accounting for 63.3 % of the total variance). PCA of the samples from the amazonian slope and the piedmont (50) considering all the 19 variables. *Variables :* same as in table I.

TABL. IV. — *Contribution des variables pour les six premiers facteurs principaux, (représentant 63,3 % de la variance totale). ACP sur tous les échantillons (50) de la zone de Quincemil et Mazuko en utilisant les 19 variables.* Liste des variables : *comme dans tabl. I.*

Factors :	F 1	F 2	F 3	F 4	F 5	F 6
variance :	17.9 %	12.6 %	10.6 %	8.0 %	7.7 %	6.6 %
variables						
g	0.80	-0.09	0.32	-0.16	0.10	0.17
G	-0.80	0.10	-0.24	0.14	-0.15	-0.19
T	-0.31	0.19	-0.08	-0.03	0.00	-0.04
ML	-0.02	-0.63	0.28	-0.38	-0.10	-0.04
Tour	0.32	0.08	-0.10	0.03	-0.30	-0.54
Zir	0.69	0.13	-0.29	0.14	-0.13	-0.35
Ru	0.54	-0.18	0.05	0.20	-0.35	-0.05
An	0.42	-0.15	-0.43	-0.21	0.48	0.07
Mo	0.57	-0.31	-0.21	-0.13	0.34	-0.02
Epi	-0.13	0.77	-0.11	-0.11	-0.04	0.52
Horn	-0.70	-0.37	-0.01	-0.39	0.13	-0.25
Gr	-0.17	-0.06	-0.01	0.64	0.45	-0.18
And	-0.11	-0.53	0.65	0.26	-0.04	0.15
Si	0.06	-0.34	0.16	0.36	-0.40	0.26
Stau	-0.07	0.00	0.26	0.46	0.61	0.02
Cas	0.03	0.13	0.00	0.23	-0.05	-0.40
Hyp	-0.24	-0.62	-0.52	0.19	-0.20	0.21
Aug	-0.02	-0.46	-0.76	0.11	0.04	0.19
Sp	-0.23	-0.16	0.21	-0.36	0.23	-0.26

TABLE V. — Variables contributions for the first six factors, (accounting for 56.2 % of the total variance). PCA of the samples of the Ananea-Ancocala area (198) considering all the 19 variables. *Variables :* same as in table I.

TABL. V. — *Contribution des variables pour les six premiers facteurs principaux, (représentant 56,2 % de la variance totale). ACP sur les échantillons de la zone de Ananea-Ancocala (198) en utilisant les 19 variables.* Liste des variables : *comme dans tabl. I.*

Factors :	F 1	F 2	F 3	F 4	F 5	F 6
variance :	13.3 %	11.7 %	9.2 %	8.5 %	7.2 %	6.2 %
variables						
g	-0.80	0.11	-0.39	-0.10	0.20	0.11
G	0.79	0.04	0.43	0.09	-0.17	-0.10
T	0.14	0.31	-0.15	0.15	0.34	0.15
ML	-0.52	-0.21	0.19	0.20	0.16	-0.08
Tour	-0.13	-0.26	0.48	0.15	-0.30	0.51
Zir	-0.02	0.96	-0.05	0.01	-0.04	-0.04
Ru	-0.17	0.22	0.50	-0.25	-0.36	-0.26
An	-0.28	-0.37	-0.32	0.41	-0.31	-0.30
Mo	-0.01	-0.44	-0.01	-0.45	0.10	-0.22
Epi	0.39	-0.46	-0.29	0.05	0.32	0.25
Horn	0.01	-0.26	-0.28	-0.49	-0.18	0.15
Gr	-0.34	-0.31	0.39	0.08	0.34	-0.13
And	-0.45	-0.27	0.46	0.05	0.22	0.08
Si	-0.23	-0.09	0.06	-0.65	-0.15	-0.23
Stau	0.10	-0.11	0.28	0.00	0.03	0.16
Cas	0.53	-0.40	-0.18	-0.08	0.17	-0.21
Hyp	-0.04	-0.02	-0.14	-0.47	-0.25	0.31
Aug	-0.11	-0.19	-0.19	0.20	-0.48	0.43
Sp	-0.11	-0.22	-0.26	0.38	-0.43	-0.37

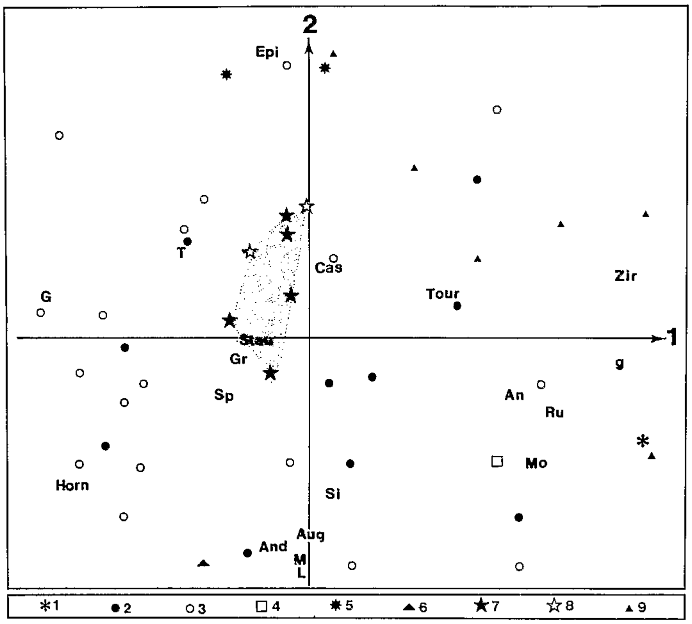

FIG. 6. — PCA of the samples from the Amazonian slope and its piedmont (50) considering all the 19 variables.
Factor 1 versus factor 2 projection. *Projected variables :* same as table I. *Projected samples :* 1 : "Capas rojas" (Cretaceous-Eocene red beds); 2 : Cancao Formation; 3 : Terraces of the Quincemil basin; 4 : Huajumbre Formation; 5 : Garote river alluvium; 6 : alluvium from upstream the Marcapata village; 7 : Mazuko Formation; 8 : Terraces of the Mazuko piedmont; 9 : Glacial and fluvioglacial deposits from the Ocongate region.

FIG. 6. — *ACP des échantillons du versant amazonien et du piémont (50) avec les 19 variables.*
Projection suivant les axes factoriels 1 et 2. Liste des variables projetées : *cf tableau I.* Echantillons : 1 : *« couches rouges » (Crétacé-Eocène);* 2 : *formation Cancao;* 3 : *terrasses du bassin de Quincemil;* 4 : *formation Huajumbre;* 5 : *alluvions du rio Garote;* 6 : *alluvions du rio Marcapata, en amont du village de Marcapata;* 7 : *formation Mazuko;* 8 : *Terrasses du piémont de Mazuko;* 9 : *matériaux glaciaires et fluvioglaciaires de la région d'Ocongate.*

tive of the age and morpho-sedimentary type of the materials. A third group includes samples of morainal sediments from the Ancocala area without age distinction; this group mixes with the samples from the bottom of the Arco Aja Formation as well as with those from the Limata pediment. The samples of the moraines collected near the Pacharia laguna and Soracocha laguna areas located farther north, plot on the same area as those from Pampa Blanca. The alluvium samples from the Carabaya river plain are not isolated relative to the other samples, but they tend to cluster in the central part of the diagram (fig. 7). The samples located close to the valley axis are most often influenced by the same variables which define the position of the Ananea-Pampa Blanca samples, even if they are situated farther downstream. On the contrary, the samples in a more lateral location from the main drainage axis plot with those of the glacial and fluvioglacial sediments observed in the neighbouring zones.

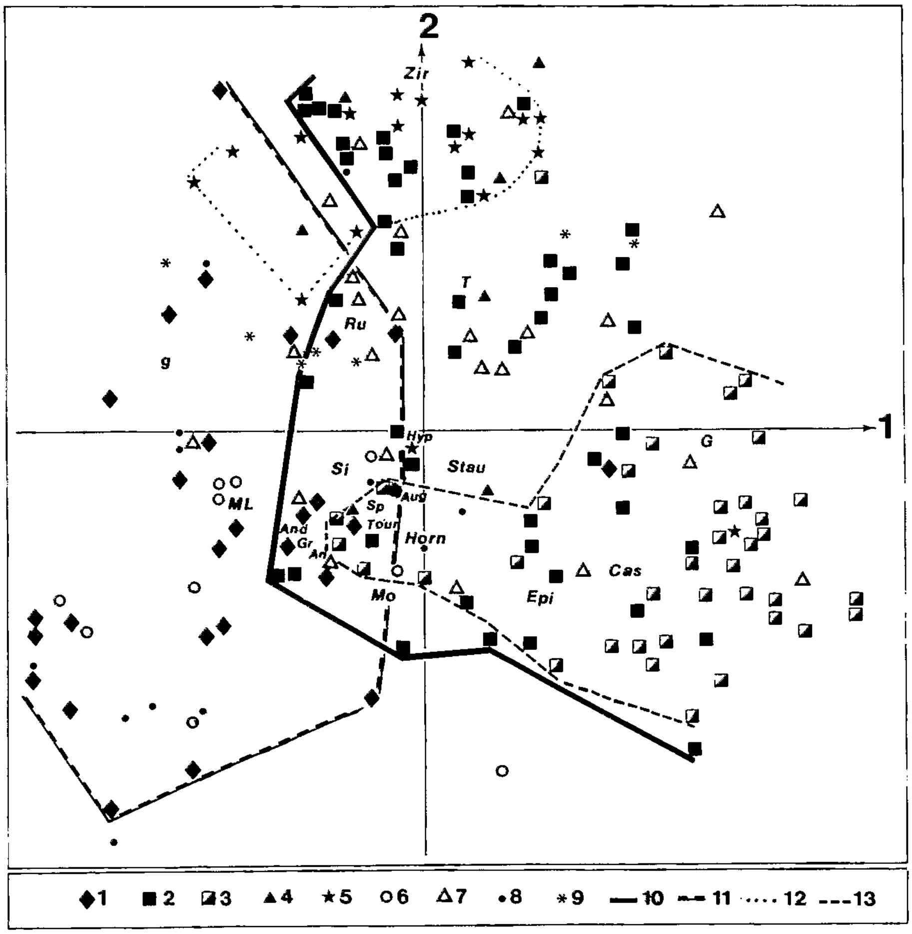

FIG. 7. — PCA of the samples from the Ananea-Ancocala basin (198) considering all the variables (19).
Factor 1 versus factor 2 projection. *Projected variables :* same as table I. *Projected samples :* 1 : moraines of the Chaquiminas Glaciation (from Ancocala area); 2 : moraines of the Chaquiminas Glaciation (from Ananea-Pampa Blanca area); 3 : fluvioglacial deposits of the Chaquiminas Glaciation (from Islapampa area); 4 : moraine of Ancocala glaciation; 5 : fluvioglacial deposits of the Ancocala Glaciation; 6 : pediment and pediment-terrace deposits; 7 : Rio Carabaya fluvial deposits; 8 : Arco Aja Formation (from Ancocala area); 9 : Arco Aja Formation (from Ananea-Pampa Blanca area); 10 : limit of the glacial materials from the Ananea-Pampa Blanca basin; 11 : limit of the glacial materials from the Ancocala basin; 12 : limit of the fluvioglacial deposits from Ancocala; 13 : limit of the external frontal moraine and fluvioglacial deposits from Islapampa area.

FIG. 7. — *ACP sur les 198 échantillons du bassin d'Ananea-Ancocala en utilisant les 19 variables.*
Projection suivant les axes factoriels 1 et 2. Liste des variables projetées : *cf. tableau I.* Echantillons : 1 : *moraines de la glaciation Chaquiminas provenant de la zone d'Ancocala;* 2 : *moraines de la glaciation Chaquiminas provenant de la zone d'Ananea-Pampa Blanca;* 3 : *matériaux fluvioglaciaires de la glaciation Chaquiminas provenant de la zone d'Islapampa;* 4 : *moraines de la glaciation Ancocala;* 5 : *matériaux fluvioglaciaires de la glaciation Ancocala;* 6 : *matériaux des glacis et des glacis-terrasses (du bassin d'Ancocala);* 7 : *matériaux fluviatiles du rio Carabaya;* 8 : *formation Arco Aja de la zone d'Ancacala;* 9 : *formation Arco Aja de la zone d'Ananea-Pampa Blanca;* 10 : *secteur des matériaux glaciaires de la zone d'Ananea-Pampa Blanca;* 11 : *secteur des matériaux glaciaires de la zone d'Ancocala;* 12 : *secteur des matériaux fluvioglaciaires d'Ancocala;* 13 : *secteur de la moraine frontale externe et des matériaux fluvioglaciaires de la zone d'Islapampa.*

III. — CONCLUSION : GEOMORPHOGENETIC INTERPRETATION

Analysis of the composition of heavy mineral suites and of their distributions in the gold-bearing alluvium of the eastern Cordillera shows that gold is hosted in sediments with different types of heavy mineral associations. In the Ananea-Ancocala basin, gold is present :

a) in glacial and fluvioglacial deposits, characterized by the abundance of zircon associated with subordinate rutile, tourmaline, anatase, epidote and monazite. This occurs in the Ananea-Pampa Blanca area, where gold content is about 0.5 g/m^3 and in the northern part of the Ancocala area (Soracocha and Pacharia laguna, fig. 2);

b) in deposits of glacial origin, characterized by andalusite, garnet, and rarely sillimanite in addition to the suite of minerals in (a); this occurs near the Ancocala village;

c) in glacial and fluvioglacial deposits characterized by the abundance of cassiterite with epidote, monazite, zircon and tourmaline; this is the case of the external moraine and outwash deposits of the Islapampa area (fig. 2).

Elsewhere in the high Cordillera gold is hosted in glacial and fluvioglacial deposits with very different heavy mineral suites. Near the town of Ocongate (about 200 km northwest of Ananea) the gold-bearing alluvia are characterized by the zircon-epidote association with subordonate augite, monazite, anatase, rutile and tourmaline.

In the basins located between the Cordillera and the Sub-Andean zone (e.g. Quincemil) and in the Amazonian piedmont plain (e.g. Mazuko), gold is located in river deposits characterized by the association of hornblende, andalusite, epidote and subordonate zircon and garnet. The ratio of zircon and garnet to hornblende increases toward the Piedmont.

On a scale of the eastern Cordillera of southern Peru, the use of the PCA outlines that :

1) the gold placers formed in the high part of the Cordillera and those formed in the Piedmont cannot be correlated; despite what is commonly believed that the gold of the Piedmont comes from the erosion of the whole cordillera;

2) in the cordillera there are several areas of primary gold mineralization with different mineralogical associations. Some are known such as the gold-quartz veins of Manco Capac or Santo Domingo. New areas have been inferred such as Cerro Kamanti within the amphibolitic belt which provides the hornblende dominated association. Others have been further investigated such as the Rinconada deposit. Its erosion provides gold and the zircon dominated mineralogical association of the recent deposits from the Ananea, Pampa Blanca area. The metamorphism of the Ananea Fm induced by the Cerro Condoriquiña granitic intrusion explains the presence of andalusite, staurolite and garnet in the alluvium from the Ancocala area. The PCA results may allow to discard the granitic area as gold source because the lack of relation between the gold grade and the minerals of thermal metamorphism and of tourmaline.

PCA can be used to demonstrate that in basins where evolution is controlled by glacial dynamics, as well as in all glacial environment [Cockfield, 1932; Sutherland, 1985], placers occur only near primary sources and indicate dispersive trend from those sources. Some information about the mechanism of placer formation appears. In the Ananea-Ancocala basin, the PCA results show a grouping of samples related to their geographical origin. Nature and age of the alluvium are not fundamental discriminating factors. The samples from the Ananea-Pampa Blanca area, those from the Ancocala area and those of the external morainic lobe from Islapampa area clearly separate. The samples of the Pliocene filling (Arco Aja Fm) are widely dispersed, but those from a precise area (e.g. Pampa Blanca) plot within the zone occupied by the samples of other sedimentary units of that precise area. Nevertheless the samples of the recent fluvial deposits from the Carabaya valley group in the central part of the graph (fig. 7); this indicates that their heavy mineral content results from mixing reworked from the different types of deposits present in the Ananea-Ancocala basin.

At the scale of a sample station (i.e. sampling a vertical section in the same sedimentary unit) the samples plot close to one another in the case of moraines; the same occurs with the pediment deposit samples. On the contrary, the samples of a same sedimentary unit from the Carabaya fluvial deposits show a strong dispersion, which indicates alluvial discharges from different origins. Fluvial materials deposited downstream from the fluvioglacial deposits consist of superposed discharges from variable composition and origin and such mixing implies a decrease in the ore grade by "dilution".

PCA of the whole sample population from the Amazonian slope shows that the Mazuko piedmont samples plot near the center of the diagram, therefore suggesting that the Mazuko region was an area of mixing.

In the Quincemil basin previous studies [Fornari *et al.*, 1982] showed an increase of the gold content in the alluvium of the recent terraces. Now, the PCA of samples from this basin shows that the samples collected along a same valley (e.g. the Palcamayo river) plot very close to one another; this indicates that the grade increase results from *in situ* reworking of the gold-bearing alluvium which produces a concentration of existing gold grains. The same process occurs in the autochthonous valley of the Mazuko piedmont and is linked with active tectonic process occurring there.

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