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Geomorphological Control of Gold Distribution and Gold Particle Evolution in Glacial and Fluvioglacial Placers of the Ancocala–Ananea Basin – Southeastern Andes of Peru

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Abstract

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Gold placers are formed as a result of surficial processes but glacial and fluvioglacial systems are generally considered to be unfavourable for placer genesis. Nevertheless, some important glacial and fluvioglacial placers have been discovered and are currently being exploited in the Andes of Peru and Bolivia.

In the Plio-Pleistocene Ananea-Ancocala basin (4300-4900 m above sea-level), the gold content of the various formations indicates that only glacial and fluvioglacial sediments related to the Ancocala and Chaquiminas Glaciations (middle and upper Pleistocene) contain gold in any notable quantity. Local concentrations of economic interest occur only where a glacier has cut through a primary mineralized zone. Glacial erosion of dispersed primary mineralizations does not produce high-content placers of the kind found in fluviatile environments.

Gold distribution in tills is more irregular than in fluviatile sediments and no marked enrichment at bedrock occurs. The transition from a glacial to a fluvioglacial environment is characterized by an increase in gold content due to a relative concentration of the biggest gold flakes and by the appearance of a gold distribution pattern similar to that found in a fluviatile environment.

During their transport by glacial and fluvioglacial processes, gold particles acquire specific features; the size and morphology of a gold flake population are determined by the sedimentological and geomorphological environment in which the flakes are carried.

Introduction

Gold placers are the result of surficial processes and their genesis is related to the geomorphological evolution of the region. Most models for placer genesis (Lindgreen, 1911; Sigov et al., 1972; Yeend, 1974; Henley and Adams, 1979; Hérail, 1984) refer to fluviatile and marine beach environments, which are considered to be the most favourable for the concentration of detrital minerals. Moreover, glacial and fluvioglacial systems are generally considered to be unfavourable for the genesis of placers with economic potential (Cockfield, 1932; Blackwelder, 1932). Indeed, glacial action has been described as provoking the dispersion of

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pre-existing, available gold particle concentrations (Sigov et al., 1972; Boyle, 1979). The data concerning the distribution of heavy minerals and detrital gold in glacial deposits was obtained by studies whose object was to discover new primary mineralizations (Brundin and Bergström, 1977; Peuraniemi and Heinanen, 1985). No exploration of the tills for placers of economic interest has been carried out. Nevertheless, important glacial and fluvioglacial placers are exploited in New Zealand and in the Andes of Bolivia and Peru.

In the Andes of southern Peru and northern Bolivia (Fig. 1), gold placers are located both on the Amazonian slopes and on the southwestern (Altiplano facing) Cordilleran slopes (Fornari et al., 1982). Most of the gold production (several t yr^{-1}) comes from the placers of the Amazonian slopes and piedmont, however, glacial and fluvioglacial placers are also found in the Cordillera. Among them, the placers of the Ananea–Ancocala basin, in southeastern Peru, were exploited as early as the Inca period (Berthelot, 1978). During the twentieth century (from 1929 to 1937), mining activity increased considerably due to the use of monitors (hydraulicking) by the Sociedad Aurifera San Antonio de Poto in the Viscachani moraine area (Fig. 2). From 1960 to 1972, the Natomas Company produced about 350 kg of gold per year by dredging at Pampa Blanca. Since 1980, the Peruvian state company "Minero Peru" has resumed the exploitation of the Viscachani moraine area, by hydraulicking, with a gold production of about 150 kg yr^{-1}, and has carried out the exploration of other areas. The company announced the setting up of a dredging project in the Pampa Blanca area, with a planned production of 1100 kg yr^{-1} over a period of 12 years. Miners are still working on small claims using primitive methods; they produce 1–2 kg of gold per month, mainly during the rainy season (October–May). Field exploration has revealed reserves of several tens of millions of cubic meters of gold-bearing sediments with an average gold content of over 0.2 g m^{-3} (Saenz Chavez, 1964; Fornari et al., 1982; Bonnemaison et al., 1985; Kihien, 1985).

The purpose of this paper is: (1) to describe the pattern of gold distribution in glacial and fluvioglacial sediments of the Ananea–Ancocala basin; (2) to analyze the grain size and shape characteristics of gold particles which are found in the sediments of this basin; and (3) to examine the factors controlling the formation and evolution of gold placers in glacial and fluvioglacial geomorphological environments.

Geology and geomorphology of the Ananea–Ancocala basin

Along the southwestern flank of the eastern Cordillera (Fig. 1) a string of elongated basins extends from Peru (Macusani, Crucero, Ancocala–Ananea, Cojata) to the north of Bolivia (Suches, Ulla-Ulla, La Paz). These basins are filled with thick Pliocene and Quaternary sediments of which only some elements are auriferous.

The Ananea–Ancocala basin (4300–4900 m above sea-level) is 40 km long and 10–20 km wide (Fig. 2). To the north, it is bounded by a high ridge of the Apolobamba Cordillera (Nevado Ananea, 5829 m; Nevado Nacaria, 5209 m) consisting of Siluro-Devonian and Ordovician slates and quartzites, intruded by large plutons of biotite- and muscovite-rich granite (Cerro Condoriquiña). The Cerro Huincho (5200 m elevation) made up of upper Paleozoic sandstones, borders the basin to the south, and Cenozoic ignimbrites border the basin to the west. The known primary gold mineralizations occur only in the lower Paleozoic (Ananea Formation) in the form of concordant gold quartz veins parallel to bedding. In the Rinconada mine (Fig. 2), these veins are closely related to stratiform arseno-sulphide deposits (Fornari et al., 1982; Fornari and Bonnemaison, 1984). The upper Paleozoic rocks and the Cenozoic ignimbrites are sterile in gold.

The sedimentary filling of the Ananea–Ancocala basin (Fig. 3) consists of palustrine, al-

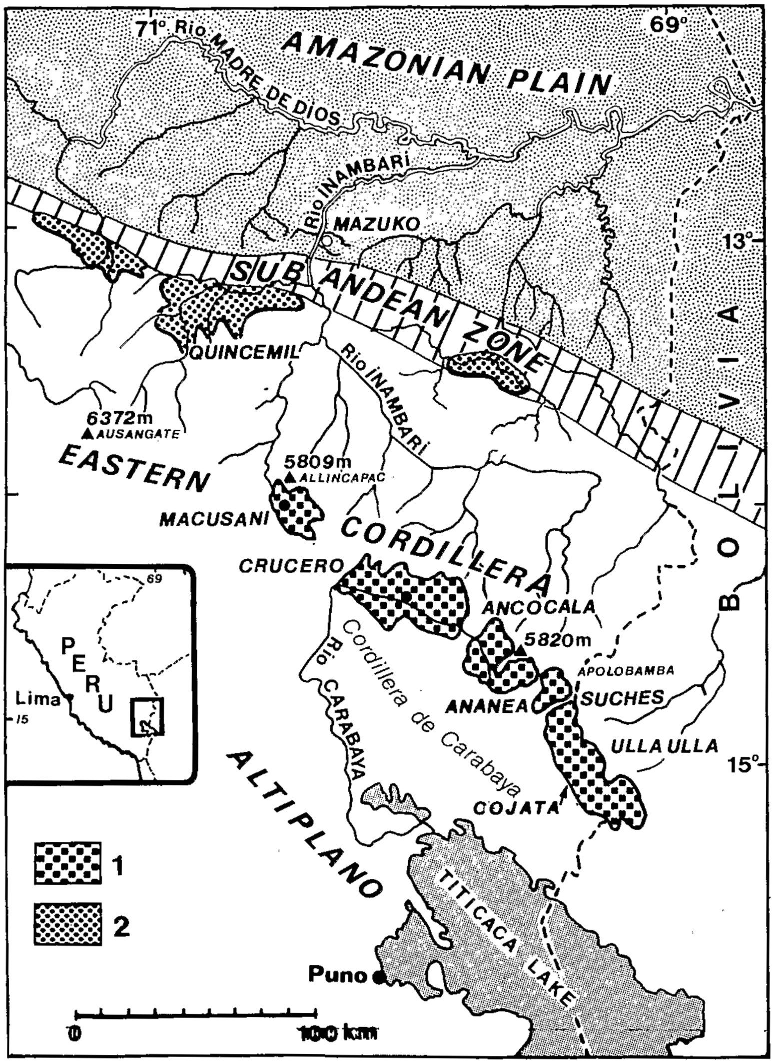


Fig. 1. General location of the study area. *1* = Plio-Quaternary intramontane basins of the Altiplano slope; *2* = Amazonian slope basins and sub-Andean foothill belt.

luvial, glacial and fluvioglacial sediments dating from the Pliocene age to the present (Fornari et al., 1982; Bonnemaison et al., 1985). The Arco Aja Formation is the thickest and corresponds to the oldest sediments of the basin fill. It consists of two members:

(1) The lower member is composed of grey clay with abundant plant remnants interbedded with layers of sand and gravel. This member is 70 m thick in the "Quebrada Arco Aja" outcrops (Fig. 2) and in the center of the basin the thickness reaches 150 m, as indicated by Resistivity Vertical Electrical Soundings (Carn et al., 1980). The sedimentological studies suggest deposition in a palustrine environment, locally and periodically interrupted by low energy fluviatile flows. An interstratified bed of cinerite found in the upper strata of this member gave a K/Ar age of 3.8 ± 0.4 m.y. (Laubacher et al., 1984).

(2) The upper member consists of more than 50 m of fluviotorrential conglomerates interbedded with debris flows. Relatively well rounded clasts (about 25–30 cm in diameter)

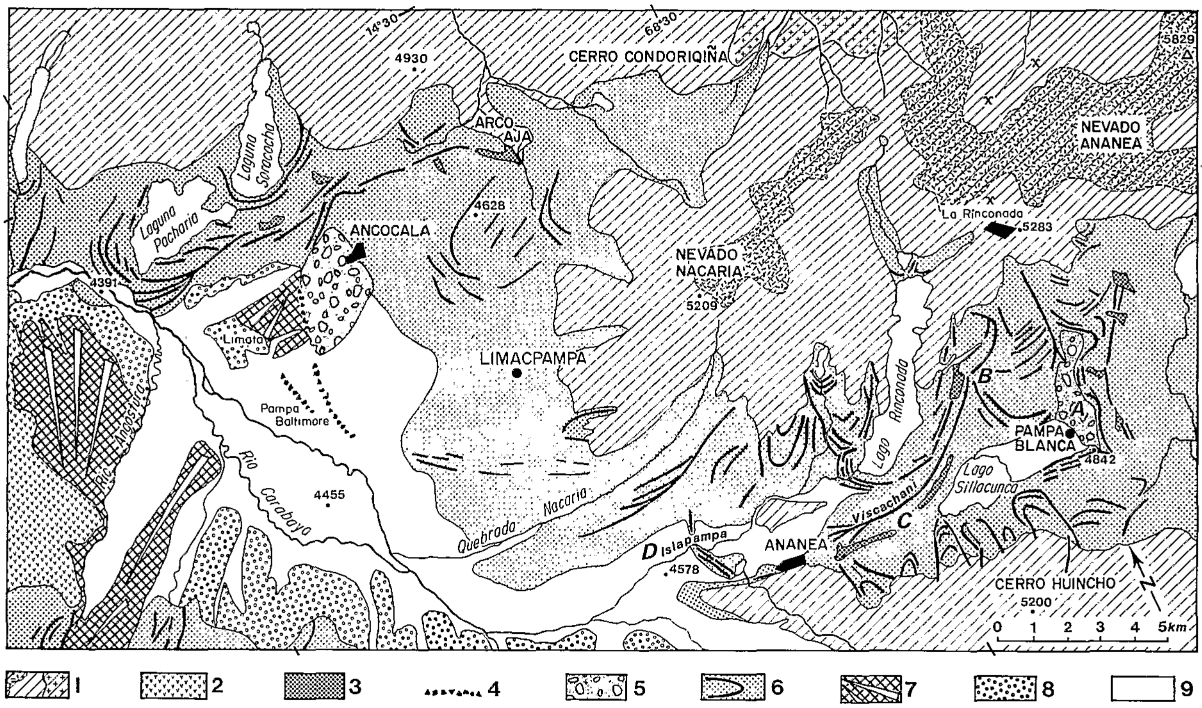


Fig. 2. Geology of the Ancocala–Ananea basin. *1* = Paleozoic basement (crossed area: granitic intrusion, stippled area: main permanent glacier); *2* = Cenozoic ignimbrites; *3* = Arco Aja Formation; *4* = erratic block trains of the Limata Glaciation; *5* = glacial and fluvioglacial deposits of the Ancocala Glaciation; *6* = moraines of the Chaquiminas Glaciation, with the main morainal crests; *7* = main remnants of the pediment P6 and pediment P5; *8* = Glacis-terrace T4; *9* = fluvioglacial and fluvial deposits (contemporaneous or younger than Chaquiminas Glaciation). *A*, *B*, *C*, and *D*, refer to Fig. 8.

are embedded in a matrix of mixed sand and mud. This member was probably deposited during a fluvioglacial episode.

The transition from the lower to the upper member occurs without any unconformity, but in places the conglomeratic unit is downcutting into the underlying palustrine deposits. The petrographic and mineralogical composition of the Arco Aja Formation indicates that its components originate from erosion of the rocky outcrops surrounding the basin. All these erosional products intermingle in the center of the basin.

A succession of glacial, fluvioglacial and fluviatile accumulation periods, separated by episodes of pedimentation and dissection, have shaped the upper part of the filling and explain the present morphology of the basin. The Arco Aja Formation and the ridges surrounding the basin are intersected by a pediment (P6) which is still clearly visible in the southwestern part of the mapped area (Fig. 2). Entrenched below the surface of P6 is a more recent pediment, called P5, which is characterized by an intense red weathering profile (3 m deep). On the surface of the P5 pediment as well as on recent terraces of the Rio Carabaya in Pampa Baltimore (Fig. 2), two trains of blocks (each train is several km long and each block over 10 m^3 in size) have been identified. These erratic boulders embedded in the weathering profile of the P5 pediment, are thought to be the products of a glacial phase (known as the Limata Glaciation) which occurred prior to the development of the P5 pediment.

The P5 pediment surface, like the older deposits, is uncomformably covered by tills and by proximal fluvioglacial sediments which correspond to a more recent period referred to as the Ancocala Glaciation. These sediments are

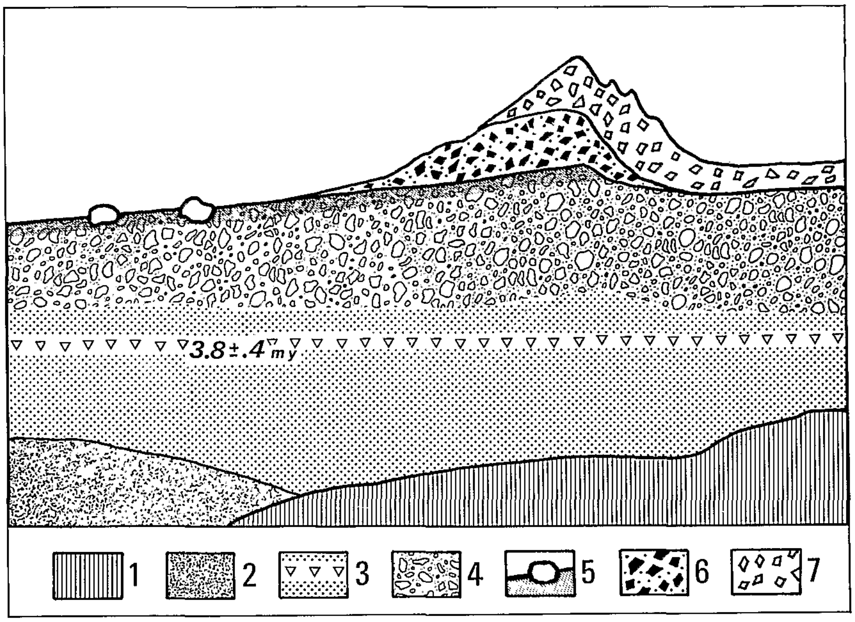


Fig. 3. Stratigraphic sketch of the sedimentary infill of the Ananea–Ancocala basin. *1* = Paleozoic basement; *2* = Cenozoic ignimbrite; *3* = Arco Aja Formation: palustre lower member, with dated cineritic level; *4* = Arco Aja Formation: conglomeratic upper member; *5* = pediment P5 surface and erratic blocks of the Limata Glaciation; *6* = moraine of the Ancocala Glaciation; *7* = moraine of the Chaquiminas Glaciation.

themselves dissected and partly covered by more recent glacial and fluvioglacial sediments attributed to the Chaquiminas Glaciation (Fig. 3). The erosional discordance that separates the Ancocala sediments and the Chaquiminas sediments is outlined by a locally well preserved paleosol. The Chaquiminas Glaciation is characterized by the freshness of the glacial landforms and the mild weathering of the sediments. Distinct glacial-retreat forms are still to be seen in the main glacial valleys and can be correlated with various recession stages (e.g. Islapampa and Laguna Rinconada arcs) which have led to the presently restricted glaciers (Fig. 2). On the basis of regional considerations, some correlations can be established with other chronologically better constrained formations in northern Bolivia (Ballivian et al., 1978; Gouze et al., 1986) and the Ausangate massif in southern Peru (Fig. 1) (Mercer and Palacios, 1977). In these two areas, the oldest stages of the last glaciation are older than 35,000 BP and the recessional stages are dated between 16,000 BP and 10,000 BP.

The Chaquiminas Glaciation tills are also separated from the Ancocala Glaciation tills by an erosionally discordant surface with a paleosol. This indicates that the tills of the last two glaciations originate from erosion of the glaciated mountains surrounding the basin and not from the reworking of the sedimentary fill of the basin.

Methods of sampling and analysis

In the Ananea–Ancocala basin, 297 samples representing all the alluvial formations were collected from natural outcrops, on gravel pit faces and from shafts. Sample selection was based on geological and geomorphological criteria; each sample consisted of a "heavy" sample of about 100 kg on average and a "light" one of 25 kg.

Using the "heavy samples", the gold content is determined as follows. The samples are reduced in the field. The sediment is washed in a 50-l box and passed through a 1.27 cm (1/2 inch) sieve and the coarse fraction is discarded. The remaining material is carefully panned. In the laboratory, water and mercury are added to the panning preconcentrate in a 2-l glass bottle; generally 10 g ($\pm$0.1 mg) of mercury is used; however, the weight of mercury is adjusted to about 1/10 of the weight of the panning preconcentrate. The bottle is shaken for 2 h to ensure amalgamation. After washing and decantation, the mercury amalgam is dissolved in a solution of nitric acid (1 N), the remaining gold button is weighed (precision: $\pm$0.1 mg) and the gold content calculated. Where necessary, a weight correction corresponding to the mercury loss is calculated. The gold values are given in g t^{-1}, but in order to compare them with other data obtained by mining in the same region, they are also converted into g m^{-3}, assuming an average sediment density of 2. Our data agree with those obtained during subsequent mining in the area.

Using the "light samples" of about 25 kg, gold particles are concentrated first by moderate panning in the field and then in the laboratory using heavy liquids; they are then separated under a stereomicroscope for further examination. An analysis of grain size is carried out, followed by a systematic description of the surface morphology using criteria established by Hérail (1980, 1984) i.e. the general shape and the outline, edge and surface aspects are all described. The flatness index (F.I.) defined as the ratio $(L+b)/(2t)$ where L is the length, b the breadth and t the thickness of gold particle, is also calculated.

Gold content and factors determining gold content variation

The gold content of various formations sampled (Table 1) indicates clearly that only the glacial and fluvioglacial deposits related to the Ancocala and Chaquiminas Glaciations contain gold in notable quantities. However, not all the moraines are gold-bearing. There are wide areas of very poor or barren sediments, such as the Nacaria, Limacpampa, Laguna Soracocha and Laguna Pacharia areas; moreover all the sediments originating from the south and southwest source area are barren (Fig. 4).

Within the whole basin gold distribution is controlled by the origin of the sediments. Principal component analysis (PCA) performed on mineralogical variables (light-coloured heavy mineral suites only) makes it possible to separate different mineral suites (Delaune et al., 1989). In the factor-1 versus factor-2 projection plan (Fig. 5), the Pampa Blanca and Ananea moraine samples were separated from the samples of Ancocala moraine area. Mineral checking indicates that minerals such as garnet and andalusite, coming from the Condoriquiña batholith and its metamorphic aureole, are present as well as those characteristic of the mineralogical background of the Ananea Formation (zircon, tourmaline, epidote). However, the samples collected in the Nacaria and Limacpampa areas which feature the same mineralogical suite, and which plot in the northwestern quadrant of the graph, are very poor in gold or completely barren. This is due to the fact that the primary gold mineralizations are clearly defined. Only the moraines coming from the Rinconada area and from the Cerro Condoriquiña region are auriferous.

Analysis of the petrographic and mineralogical composition of the sediments shows that the alluvia with low gold contents are the product of the mixing of several flows and hence the dilution of any auriferous flow. This is the case for the Arco Aja Formation and for some alluvia of the Carabaya river which is the main drainage axis of the basin. On the PCA graphs (Fig. 5) the samples from the lower part of the Carabaya plain and those from the low terraces (poor in gold) plot in the central part of the graph. This shows that these samples are not "preferentially attracted" by any of the minerals that contribute to the definition of the factors. This behaviour indicates a mixture of sediments from different source areas and it is

TABLE 1

Gold grade distribution in the Ancocala–Ananea basin

Formation			Percent of gold-bearing samples	Mean grade (mg m^{-3})
Arco Aja	Lower member (palustre)		11	trace
	Upper member (conglomerate)		57	6
Ancocala Glaciation	Moraine	Ancocala village area	100	120
		Pampa Blanca area	100	258
	Fluvioglacial	Pampa Blanca area	100	314
Chaquiminas Glaciation	Moraine	Ancocala village area	100	158
		Soracocha–Pacharia area	48	7
		Pampa Blanca area	100	156
		Islapampa area	100	83
	Fluvioglacial	Islapampa area	100	93
Fluviatile		Carabaya river	56	40

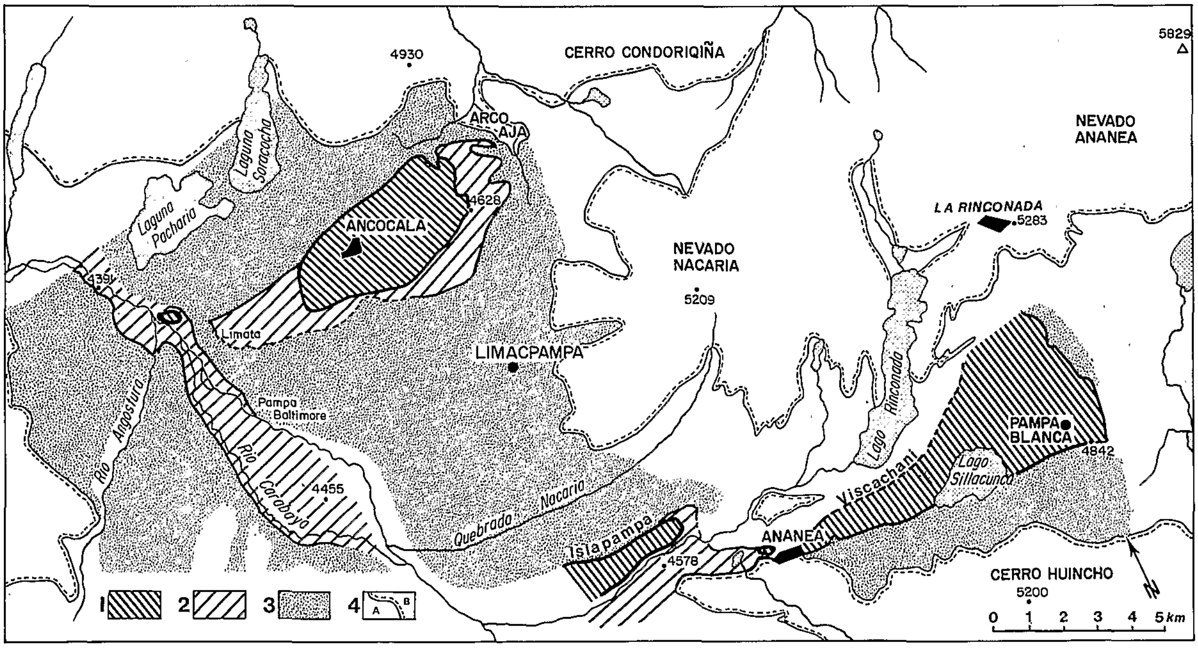


Fig. 4. Map of gold contents of the sediments from the Ancocala–Ananea basin. *1* = more than 100 mg m^{-3}; *2* = between 20 and 100 mg m^{-3}; *3* = lower than 20 mg m^{-3}; *4* = *A* not sampled, *B* Paleozoic basement.

this mixing which leads to the dispersion of the gold particles and to a decrease in gold content.

The same effect can be seen in the Arco Aja Formation, but in addition to the flow diversity, the unfavourable sedimentary environment (palustrine and fluviatile environment of low

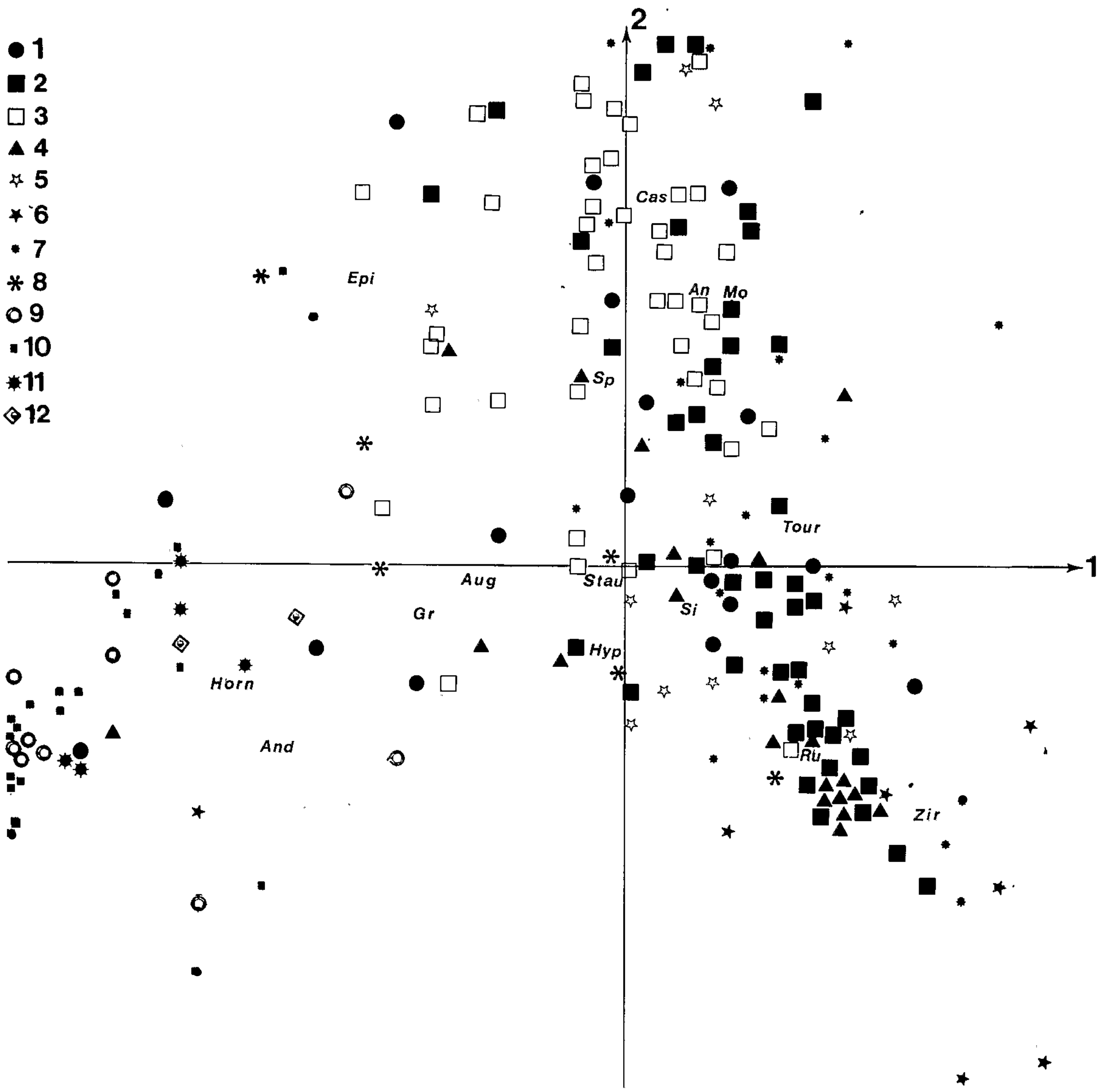


Fig. 5. Principal Component Analysis of the samples from the Ananea-Ancocala basin (198) considering 19 mineralogical variables. Factor-1 versus factor-2 projection. Projected variables: *Epi*=epidote; *Ru*=rutile; *Zir*=zircon; *Gr*=garnet; *Sp*=sphene; *An*=anatase; *Mo*=monazite; *Tour*=tourmaline; *Cas*=cassiterite; *Si*=sillimanite; *Stau*=staurolite; *And*=andalusite; *Horn*=hornblende; *Hyp*=hypersthene; *Aug*=augite; *T*=gold content by weight; *ML*=heavy minerals ratio (i.e. ratio between the weight of the heavy minerals and the weight of the initial sample); *g*=fine fraction; *G*=coarser than 5 cm fraction. Projected samples: *1*=moraines of the Chaquiminas Glaciation (from the Ancocala area); *2*=moraines of the Chaquiminas Glaciation (from the Ananea-Pampa Blanca area); *3*=fluvioglacial deposits of the Chaquiminas Glaciation (from the Islapampa area); *4*=moraine of the Ancocala Glaciation; *5*=fluvioglacial deposits of the Ancocala Glaciation; *6*=pediment and glacis-terrace deposits; *7*=fluvial deposits of the Carabaya river; *8*=Arco Aja Formation (from the Ancocala area); *9*=Arco Aja Formation (from the Ananea-Pampa Blanca area); *10*=limit between the Ancocala and the Ananea-Pampa Blanca basin; *11*=Ancocala village area; *12*=external frontal moraine and fluvioglacial deposits from the Islapampa area.

energy) contributes to the very low gold content of this formation.

On a sedimentary and geomorphological unit scale, gold distribution is determined by sedimentological variations. When all the samples collected in the sediments of the basin are considered, differences in the gold values become apparent (Table 1).

The examination of gold content in a single sedimentary unit reveals that the gold content is lower in the downstream tills and higher in the upstream tills and in the proximal fluvioglacial sediments (outwash deposits) (Fig. 6). Ancocala Glaciation deposits appear richer than the Chaquiminas Glaciation deposits (Table 1) but this fact can be explained only because the proximal facies are preserved. In the tills, the gold is distributed at random and the gold content shows no signs of increase at the bedrock.

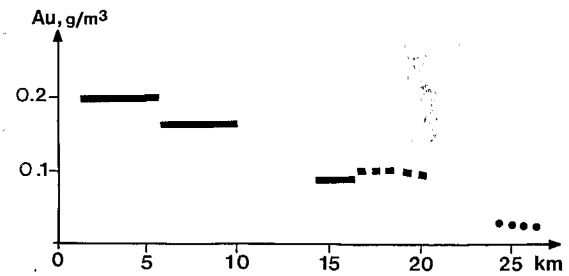


Fig. 6. Variations of the mean gold contents with the downstream distance. A decrease appears for the Viscachani moraine (bold line), the Islapampa fluvioglacial material (dashed line) and the Carabaya fluvial material (dotted line).

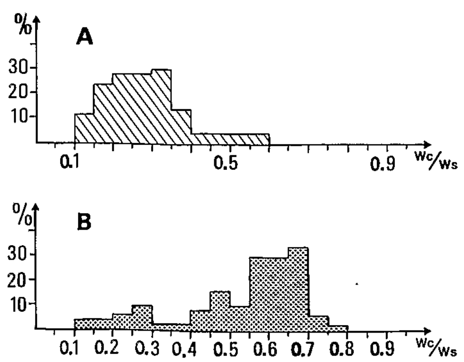


Fig. 7. Granulometry of moraine and fluvioglacial material. (A) In the moraine, the weight of the clast size fraction is lower than 50% of the weight sample and it shows roughly normal distribution curve; (B) in the fluvioglacial material the weight of the clast size fraction is generally above 50%. *Wc* = weight of the clast size fraction (> 4 cm); *Ws* = weight of the sample; diagram A = 38 samples, diagram B = 41 samples, corresponding to a total weight of 6571 kg.

The transition between tills and proximal fluvioglacial sediments is accompanied by an increase in gold content of 20% for Ancocala Glaciation deposits located in the Pampa Blanca area. A similar increase of 12% occurs between the Islapampa terminal moraine ridge and the associated fluvioglacial outwash (Fig. 2). However, in the fluvioglacial sediments the gold content increases only in comparison to the terminal moraines. This enrichment does not lead to the formation of placers as rich as those found in the upstream part of the till (Fig. 6). Fluvioglacial reworking mechanisms are characterized by a loss of fine material and a relative increase in the weight of the clast size fraction elements (Fig. 7). In the Islapampa area, this sedimentological evolution is accompanied by an increase in the average size of the gold particles. In the fluvioglacial deposits, the number of gold particles is lower than in the tills, but they are bigger and heavier which explains the increase in the gold grade. The smallest gold particles are carried off downstream by meltwater and may then become trapped in distal fluvioglacial sediments.

Morphometry and morphology of gold particles

Gold grain size

Measurement of the gold particles shows that they are small; 83.5% are less than 300 μm long and only 1.16% are longer than 1 mm. The size frequency distribution graph shows that 91% of the flakes are less than 400 μm long and 49% between 100 and 200 μm long. Measurements by Minero Peru also indicate the abundance of finer gold particles (Kihien, 1985). Nuggets are almost nonexistent (during a two-year period of exploitation only one, measuring about 1.5

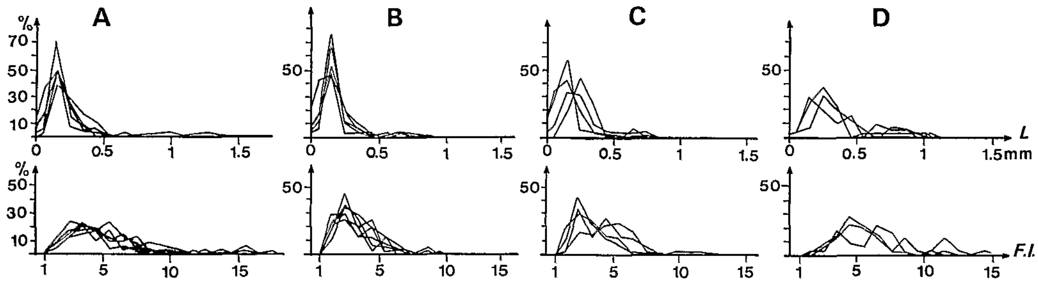


Fig. 8. Gold particles granulometry and Flatness index variations of the glacial and fluvioglacial deposits from the Ananea–Pampa Blanca area. (A) Moraine of the Ancocala Glaciation; (B) moraine of the Chaquiminas Glaciation (upstream); (C) moraine of the Chaquiminas Glaciation (Viscachani area); (D) fluvioglacial material from Islapampa. The Flatness Index (F.I.) increases with the transportation distance (sampled area located in Fig. 2).

cm and weighing 9 g, was recorded).

However, the grain size of gold varies according to the type of the gold-bearing sediment. In the tills, small particles dominate (Fig. 8A and B) and in some samples 80% of the particles are less than 200 μm long. Along a lateral moraine, the average size of the gold particles increases from upstream to downstream by a factor of two. In the Ananea lateral moraine, located on the left bank of the Rinconada lake valley (Fig. 2), the average particle size is about 130–150 μm upstream whereas it is 300–310 μm 10 km downstream. This evolution in the size of the particles is accompanied by a marked intersample heterogeneity. The size distribution of the particle population does not vary much from one sample to another upstream (Fig. 8B), but differences between samples become notable downstream (Fig. 8C). The average particle size is bigger, in the proximal fluvioglacial sediments, with 25% of the particles measuring between 300 and 500 μm (Fig. 8D). Moreover the size frequency distribution curves show that a significant proportion of flakes are more than 500 μm long.

Downstream, in the distal fluvioglacial and fluvial deposits, the gold size distribution decreases rapidly and the gold grade in the samples collected is low.

Flatness index (F.I.) of the gold particles

In the Ananea–Ancocala basin, the gold particles are not very flattened; the average value of the F.I. is about 4. The lowest values correspond to the upstream moraine (Fig. 8B) and the highest values are found in the fluvioglacial sediments (Fig. 8D). In these latter sediments, half of the particles have a F.I. higher than 5 and only a few of them are not very flattened. A different pattern appears in the case of Ancocala Glaciation samples from the Pampa Blanca area, where small flakes are predominant but where the F.I. distribution curves are smoother (Fig. 8A).

These F.I. values are significantly lower than in the fluviatile placer of the Amazonian piedmont where the average values obtained in the Quincemil basin and in the Mazuko area are about 12. In the fluviatile placers located in the northwest of Spain, the average value of the F.I. is about 7 to 9 (Hérail, 1984) for an estimated transport distance of 15–20 km, comparable with the distance covered by the gold particles in the Ananea–Ancocala basin.

Morphological characteristics

In the Ananea Formation, part of the gold from the primary sources fills intergranular fissures and characteristic crystal outlines are recognisable (Fig. 9A and B). In the western part of the Rinconada area, where the still-active San Andrés glacier crosses over the primary gold mineralization outcrops, samples were taken from the present frontal moraine. In these samples, the gold particles, which had undergone

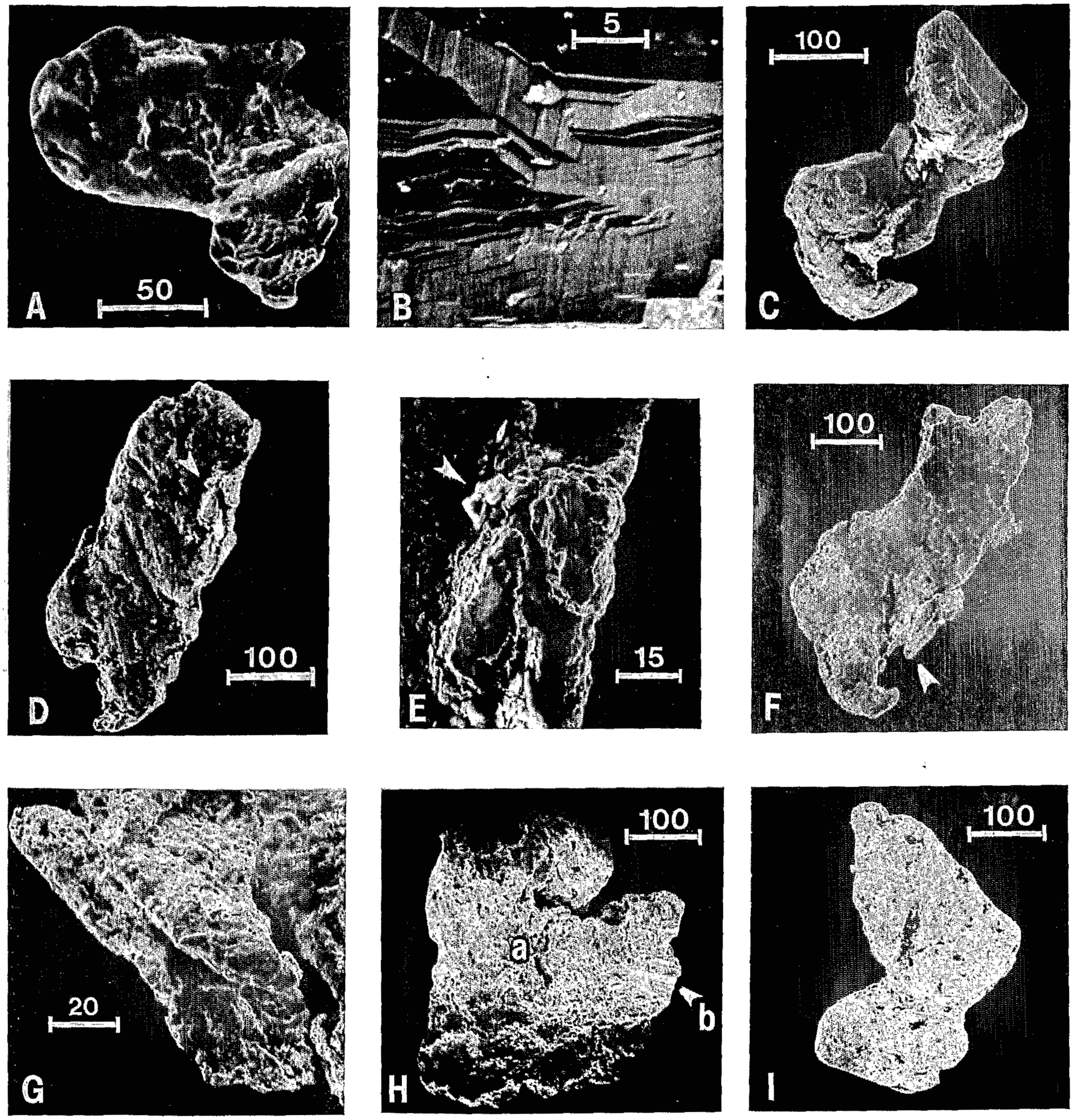
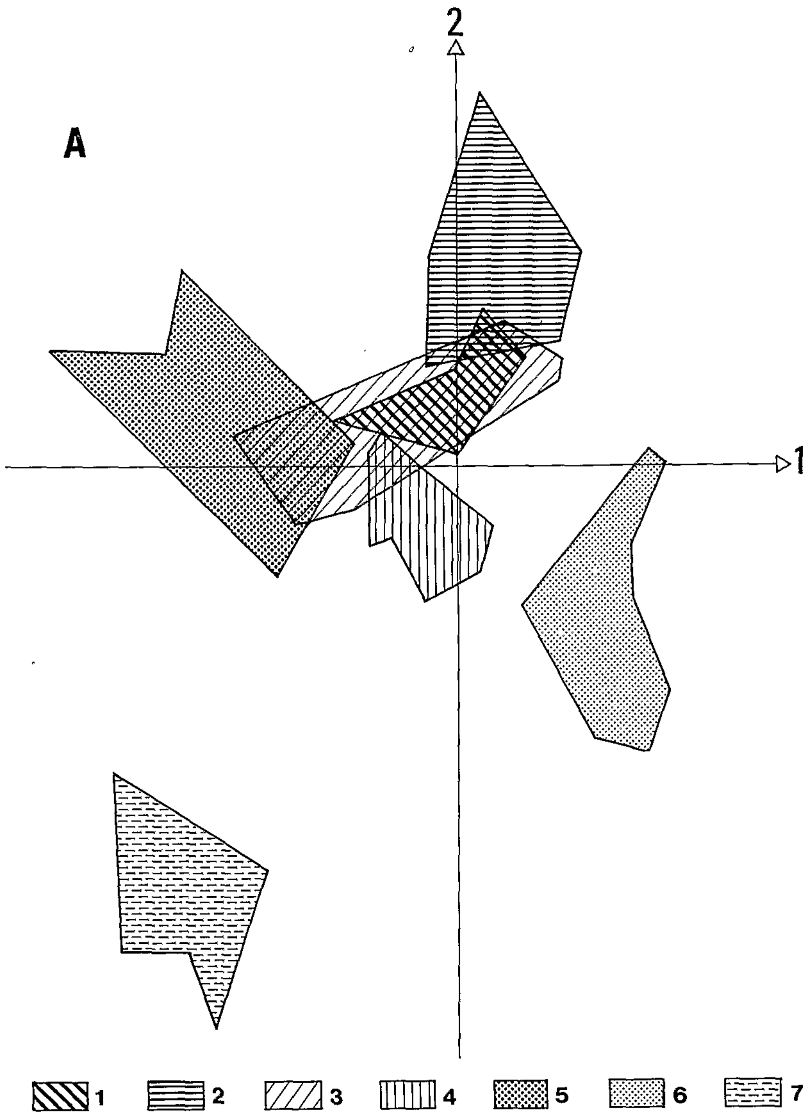


Fig. 9. Exoscopic characteristics of gold particles (SEM photomicrograph, scale bar in micrometres). During the fragmentation of the veins of la Rinconada, where gold fills up cracks in the quartz, the released gold particles may be quite rounded but they never show any mechanical deformations (A). On their surfaces, original crystalline growth structures can be observed, (B) = detailed from (A). In the moraines, upstream, gold particles still showing plain crystalline shapes (C), even if sometimes striated. Rapidly, downstream, gold grains take on more rounded shapes and are characterized by deep stripes, crushing marks (D), and the abundance of quartz fragment embedded in the gold, (E) = detail from (D), quartz appears in white. The edges of the grains are not blunt and roll-ups are frequently observed, (G) = detail from (F). Near the Ananea village, after about twelve kilometres of transport in the moraine the particles retain very irregular shapes (H) but roll-up forms are fewer, the rolled-up and turned-up gold particles being progressively stuck to the grain, (H) point *a*; the crush marks remain important, (H), point *b*. It is only in the fluvioglacial sediments that gold particles occur with regular shapes, a smooth surface and blunted edges (I).



short transport of about 1 km together with the till material, still exhibit fresh crystal outlines (Fig. 9C), but they are characterized by the abundance of wide and deep striation marks, crush marks and rolled-up edges (Fig. 9D and E). These features, often accompanied by very small embedded quartz inclusions, are typical of the gold particles contained in the moraine (Fig. 9F, G and H). Such features have never been observed on gold particles which have evolved in a fluviatile environment (Hallbauer and Utter, 1977; Hérail, 1984; Lankneus, 1987). The abundance of these features on gold particles seems to be characteristic of glacial transport (Hérail, 1988). Their systematic description can be used in order to distinguish, in mixed samples (Giusti, 1986), the particles that evolved in a strictly glacial environment from the ones submitted to a different evolution.

The features induced by glacial process in the gold particles disappear progressively downstream; in the fluvioglacial sediments rounded flakes appear (Fig. 9I), more flattened and already exhibiting fluviatile morphologies such as

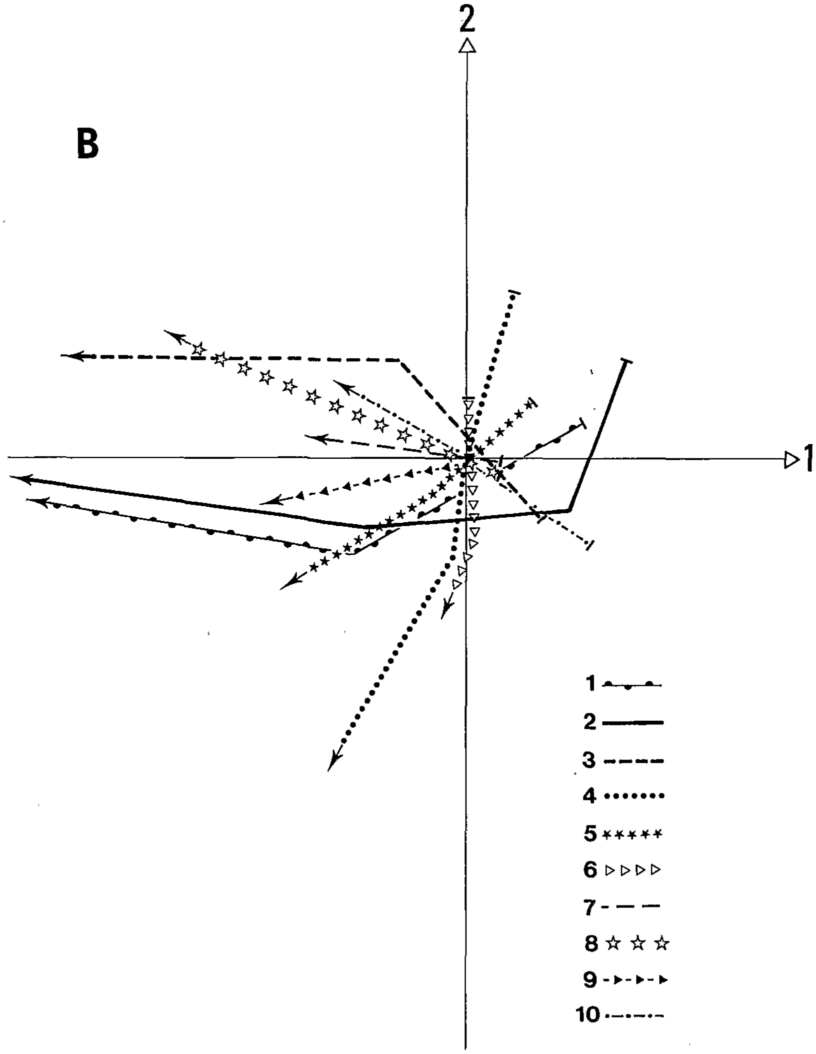


Fig. 10. Morphology of the gold particles from the Ancocala–Ananea basin and from the Mazuko piedmont. Factor analysis of correspondence; factor-1 versus factor-2 projection. (A) Plot of the gold particles from different populations; *1* = gold particles from the moraine of the Ancocala Glaciation; *2* = gold particles from the upstream moraine of the Chaquiminas Glaciation from the Ananea–Pampa Blanca area; *3* = gold particles from the downstream moraine of the Chaquiminas Glaciation from the Ananea-Pampa Blanca area; *4* = gold particles from the moraine of the Chaquiminas Glaciation from Ancocala area; *5* = gold particles from the proximal fluvioglacial material (transport distance in front of the glacier lower than 3 km); *6* = gold particles from the distal fluvioglacial material (transport distance of 10–15 km); *7* = gold particles of the fluvial material from the Amazonian piedmont of Mazuko. (B) Classification of the samples by the granulometric and morphometric characters: *1* = breadth; *2* = length; *3* = thickness; *4* = flatness; *5* = striation marks; *6* = impact; *7* = turning up; *8* = brushing up; *9* = redoubling; *10* = irregular outline.

narrow striation marks, bendings and rolled-up edges. These modifications affect the majority of particles after a transport distance of about 25 km.

Morphological and morphometrical criteria were used to compute a Factor Analysis of Correspondence; together with the particles from the Ananea–Ancocala basin we also examined particles from the Amazonian fluviatile piedmont of the Mazuko area (Fig. 2) in order to obtain a better assessment of the effects of glacial and fluvioglacial processes on gold particles. The particle population is clearly structured and its diversity can be explained by several key factors. In the factor-1 versus factor-2 main plane (Fig. 10A), the Amazonian piedmont samples are separated from the Ananea–Ancocala glacial and fluvioglacial samples. The factor-1 axis contrasts to the particles of the fluviatile and distal fluvioglacial sediments (from the Rio Carabaya plain) with those of proximal fluvioglacial sediments. The factor-2 axis separates the upstream facies samples from those downstream in the Chaquiminas moraine. It appears also that for the first factor (Fig. 10B), the large particles are apart from the small ones; moreover the thin particles contribute to the positive values of this first factor. Morphological features such as rolled or brushed up particle edges and, less importantly, the existence of striation marks on the particles surface also contribute to this factor. The main variables which contribute to factor 2 are the evolution of the flatness index and the presence or absence of impact marks caused by transport in turbulent flow.

Conclusions

(1) Glacial erosion leads to gold dispersion. The existence of economic conentrations in such environments occurs only in the vicinity of a primary mineralized zone. Unlike fluviatile environments, the erosion of dispersed primary mineralizations by glaciers does not produce rich placers. In the Ananea–Ancocala basin, this feature is apparent in the occurrence of two mineralized trains of economic interest, isolated from each other by materials which are very poor in gold.

(2) In the Ananea area tills, the gold content decreases rapidly downstream as the distance from the primary mineralizations increases.

(3) In contrast to the findings for fluvial placers, gold distribution in glacial sediments is not controlled by specific sedimentary structures; neither is there an increase in gold content at the bedrock contact.

(4) During transport by glacial processes, gold particles become slightly rounded and acquire specific features (rolled edges, crush marks,...) which allow them to be distinguished from particles which have evolved in other geomorphological environments.

(5) The transition from a glacial to a fluvioglacial environment is characterized by: (a) a local increase in the gold content due to a relative concentration of the biggest particles, produced by the reworking of the sediments by meltwater; (b) the appearance of a gold distribution pattern similar to that found in fluviatile environment; and (c) the gradual appearance of particles exhibiting a morphology comparable to that characteristic of fluviatile sediments (high degree of flatness, striation marks, bendings and sandwiched structure).

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