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Morphology and chemistry of placer gold grains – indicators of the origin of the placers: an example from the East Sudetic Foreland, Poland.

JAN WIERCHOWIEC

Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, PL-02-089 Warszawa, Poland.
E-mail: janzloz@geo.uw.edu.pl

ABSTRACT:

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The gold in the vicinity of Głuchołazy – Prudnik (the East Sudetic Foreland) is associated with Pliocene piedmont fans and Pre-Pleistocene river systems, primarily with the paleobeds of the Prudnik river and its tributaries. The morphology (roundness, flatness index and particles folding), surface textures and chemical composition of the gold particles suggest that the placer gold occurrences in the East Sudetic Foreland are multicycled (recycled paleoplacers) and multisourced. The most significant primary gold source was the sedimentary and epimetamorphic cover of the Żulova granitoids, eroded and removed during the Neogene. The majority of the gold was transported (redeposited) in a suspended form as flakes, scales, small grains and gold dust. This entered the river directly as a result of erosion of auriferous sediments. The homogeneous, porous, gold particles were formed in the weathering zones of polymetallic veins and other types of mineralization. Coatings of both crystalline and amorphous gold on particle surfaces suggest chemical accretion of authigenic gold on to pre-existing grains. Some porous gold particles may have been formed post-depositionally as the result of precipitation from colloidal solutions.

Key words: Placer gold, Morphology, Surface textures, Chemical composition, Origin, East Sudety Mts., Poland.

INTRODUCTION

The morphological characteristics of placer gold evolve during fluvial transport as a function of transport distance and fluvial dynamics (YEEND 1975, YOUNGSON & CRAW 1999). Numerous studies have described these characteristics, interpreting them in terms of placer-source relationships (e.g., TISHCHENKO 1981, HÉRAIL & *al*. 1990, LOEN 1995), gold particle origin (YOUNGSON & CRAW 1993, 1995; EYLES 1995) and relationships between average shape (flatness, roundness) and transport distance of the particles from the lode source (KNIGHT & *al*. 1999). Quantitative or qualitative data are fitted into classification schemes based on various particle parameters such as size, shape, sphericity, or surface texture (impacts, striations, recrystallization features).

The composition and internal structure of gold particles evolve also during fluvial transport (HÉRAIL & *al*. 1990, EYLES 1995). In general, the primary lodes gold have lower Au content (fineness) than placer gold from the same source. Detailed microprobe investigations have shown that the fineness increase is due to the formation of a high fineness enrichment rim, whereas the cores of the placer gold grains keep a composition similar to the primary mineralization sources (DESBOROUGH 1970). Consequently, the composition of the core or the average composition of placer gold particles enables recognition of the type of source mineralization (MOSIER & *al*. 1989), recognition of multiple sources, and discriminates between gold of primary and secondary origins (LEAKE & *al*. 1998, CHAPMAN & *al*. 2000).

The author considers that the combined analysis of the gold grains' morphology, chemistry and internal structures allows reconstruction of the history and origin of the placers. Previous studies on the source of gold in the auriferous clastic sediments near Głuchołazy assumed that either it was transported mechanically from eroded pre-Tertiary deposits (mostly vein), or resulted from reworking of pre-existing Tertiary gold-bearing gravels.

SAMPLING AND ANALYTICAL METHODS

Samples were collected from some 6.4 m^3 of auriferous sediments washed from 21 outcrops of Pliocene piedmont fans and 11 drill holes in Quaternary deposits. Ten litre samples were reduced in the field by sieving, and the remaining materiel was panned. Gold grains were then picked up from heavy mineral concentrates by hand-picking using a binocular microscope.

The long (a), intermediate (b), and small (c) axes of 464 gold particles were measured under a low-powered binocular microscope fitted with a micrometer ocular, in order to classify their shapes using a Zingg shape classification diagram (ZINGG 1935) and calculate the Cailleux flatness index [F.I. = (a+b)/2c] (CAILLEUX 1945). The Cailleux index is a measure of the transport-induced mass redistribution (i.e., shape change) of gold grains by progressive hammering and/or folding in the fluvial system. It was used for Bolivian (HÉRAIL & *al*. 1990) and New Zealand (YOUNGSON & CRAW 1999) placer gold. Particle roundness (after POWERS 1953) was visually determined under a binocular microscope.

Of the 464 Au grains, 65 representing different morphological classes from Pliocene piedmont fans to Holocene alluvial sediments, were examined and photographed under the SEM in secondary electron mode, mounted in transoptic plastic and polished. Great care was taken to ensure that sample preparation artifacts resulting from the difficulty of polishing gold were avoided. That concerned particularly the redistribution into fractures and holes of micron-sized polishing debris which can be mistaken for 'new' gold, and localized smearing, which can create both the impression of an inhomogeneous element distribution and obscure internal textural features.

To obtain detailed information about surface characteristics, internal structure and chemistry of gold grains, a method involving the JSM-35 (JEOL) scanning electron microscope coupled with an Oxford Instruments energy dispersive X-ray microprobe Link-ISIS, was applied. The composition of gold particles was determined under the following conditions: accelerating voltage-20 kV, counting time 50 s and a 5 µm beam diameter.

The surface layers and sectioned, polished grains were analyzed for Au, Ag, Pd, Pt, Hg, Fe, Cu, Zn, Pb, Bi, Se and Te. The detection limits were between 0.05 and 0.3 wt % depending on the particular element. The intensities of the characteristic radiation were corrected for absorption, fluorescence and atomic number difference according to ZAF FLS standards. Back-scattered, X-ray spectra and single element scans were employed to observe internal structures within gold grains resulting from variations in the concentration of alloying elements.

Each of 32 particles representing the placer gold from Pliocene piedmont fans to Holocene alluvial sediments was analyzed by microprobe once in the center of the section exposed. Random analyses were made just inside the outer edge of the core. Where rims were sufficiently well developed, they were also analyzed (26 rims). Inhomogeneities and other unusual features were examined where possible.

THE GOLD-BEARING HORIZONS AND THEIR RELATIONSHIP THROUGHOUT GEOLOGICAL TIME

The gold-bearing occurrences in the Głuchołazy – Prudnik area are associated with Pliocene and Quaternary fluvial sediments overlying the Tertiary sediments of the Poznań Series or Palaeozoic metamorphic rocks (Text-fig. 1).

The richest gold-bearing horizons are associated with Pliocene piedmont fans and Pre-(Eo-) Pleistocene river systems (the preglacial 'white gravels' series), primarily with paleobeds of the river Prudnik and its tributaries. The Pliocene to Pre-Pleistocene development of the river network in East Sudetic Foreland has been discussed by WROŃSKI (1975), DYJOR & *al*. (1978), PRZYBYLSKI & *al*. (1998) and WIERCHOWIEC (2000).

The series of the Pliocene piedmont fans and Pre-Pleistocene, preglacial 'white gravels' come most probably from the Tertiary weathering mantles of the Sudety Mts. Progressive, late Cenozoic uplift resulted in the deposition of alluvial fans along the mountain front. The fan deposits were strongly eroded and reworked during the Pre-Pleistocene and Pleistocene.

During the Pre-Pleistocene, the Prudnik river and its tributaries flowed generally to the east, forming a widespread alluvial surface in the eastern part of the Sudetic Foreland (Text-fig. 1).

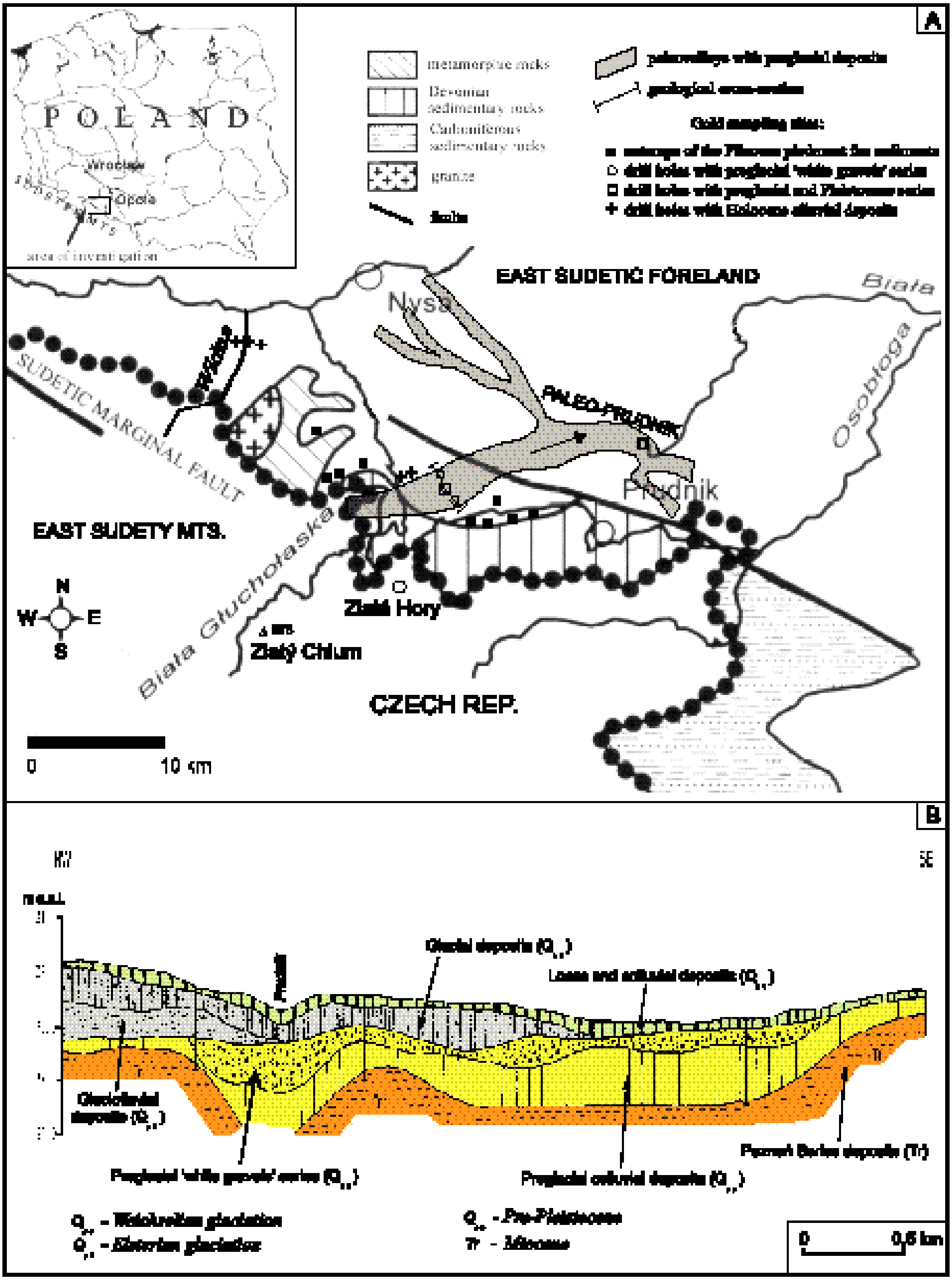

Fig. 1. A – Simplified geologic map of the East Sudety Mts. and its foreland, showing the approximate extent of paleovalleys with preglacial deposits and most of the gold sampling sites for this study; B – geological cross-section through the buried paleovalley of the river Prudnik; all lines between units are unconformities

During the Cromerian and Holstein interglacials, the rivers eroded deeply the older deposits. Low gold contents are characteristic of Holocene alluvial sediments of the Biała Głuchołaska and Prudnik rivers.

Five gold-bearing horizons were distinguished in the studied area (Text-fig. 2), although never encountered in a single section.

Petrological analysis of auriferous sediments

Pliocene piedmont fans (I – lowermost gold-bearing horizon) consists of massive, coarse grained, angular clasts with high kaolinite matrix contents. The thickness of these sediments varies from 1.0 to 2.5 m, increasing locally up to 20 m. The clasts are composed, up to 85%, of milky-white quartz and quartzites (which are the local bedrock), small amounts of siliceous schists, granitoids and metamorphic rock fragments. Occasionally gravel beds contain clay intraclasts. The heavy minerals are composed mostly of opaque minerals (16-54%), zircon (5-28%) and rutile. Other major minerals are garnet, epidote and staurolite with lesser amounts of amphiboles, tourmaline, kyanite and pyroxenes. The gold grade in the piedmont fan sediments is low, <100 mg/m^3, ranging to a maximum of 200 grains/m^3 in intercalated gravel beds.

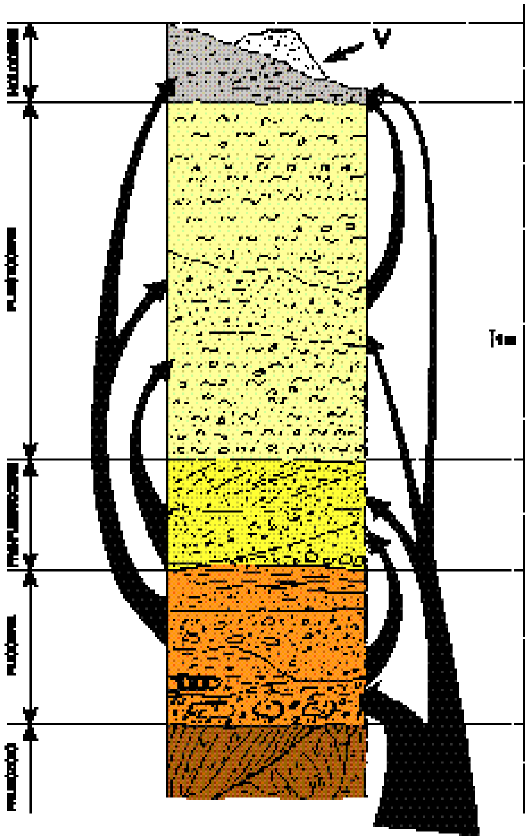

Fig. 2. Stratigraphic section of auriferous sediments with redistribution paths of gold through horizons described in the text

The second gold-bearing horizon (II) is represented by Pre-Pleistocene, preglacial 'white gravels' series. These sediments comprise strongly reworked, quartz-rich material and a kaolinite matrix. The gold-bearing beds are formed usually of well stratified deposits that consist of well-rounded to sub-rounded gravels of varying grainsizes from cobble to granule. The thickness of these sediments varies from 1 to 14 m. They are composed mainly of milky-white quartz and quartzites (80-90%), associated with siliceous schists and granitoids. The heavy minerals fraction of the 'white gravels' series is dominated by staurolite, with a large admixture of zircon, epidote, garnet, kyanite and amphiboles, and contains much less opaque minerals than older fan sediments. This series is the richest gold-bearing horizon in the studied area containing Au grades that range between 370 mg/m^3 near its base, to <100 mg/m^3 in its upper part.

The distribution patterns of the heavy minerals suggest that the Tertiary and preglacial sediments contain predominantly products from the destruction of the epimetamorphic cover of the East Sudetic granitoids, and to a lesser extent, the granitoids themselves.

Overlying the 'white gravels' series is a widespread deposits representing Pleistocene fluvial, glacial and fluvioglacial sediments (III gold horizon). The Au grade in this gold-bearing horizon is much lower: 10-60 grains/m^3, ranging to a maximum 60 grains/m^3 in the fluvial gravel beds.

The Pleistocene (Saalian and Weichselian age) alluvial sediments of the Biała Głuchołaska, Prudnik and Złoty Potok rivers are well exposed in terraces along the river valleys. Petrographic studies of these deposits indicate the predominance of local rocks (quartz, quartzites, metamorphic schists and granitoids), although a small admixture of glacially-derived rocks is present (1-5%).

The fluvial Pleistocene sequences are up to 30 m thick and comprise pebbles, pebble sands with single cobbles or coarse-grained sand and some layers of fine-grained deposits (sandy silts, silts and clays). Pebbles and pebble sands are mainly massive and imbricated. The maximum size of a single cobble is 25 cm. The fine-grained beds range from a few centimetres up to 50 cm and have limited lateral extent.

The fourth gold-bearing horizon (IV) is represented by the Holocene alluvial sediments of the Biała Głuchołaska, Prudnik and Złoty Potok rivers. Gold content is generally low, <100 mg/m^3. Local enrichments in gravels have been encountered, however, with gold contents up to 240 mg/m^3. These sediments are 1-8 m thick and commonly bipartite. Their lower parts are composed of pebbles or coarse-grained sand with single cobbles and layers of sandy silts and clays, whereas the upper parts of the alluvial deposits are formed of matrix-supported diamictons. The coarse-grained sediments comprise only local components (metamorphic schists, quartz, quartzites and granitoids). The composition of heavy mineral assemblages is variable, consisting mainly of garnet (6-44%), staurolite (4-38%) and zircon with a considerable admixture of opaque minerals, amphiboles, rutile, epidote and kyanite. Less common are tourmaline, sillimanite, andalusite and pyroxenes.

The uppermost, Vth horizon is of artificial origin related to extensive mining activity. The auriferous sediments are composed of tailings and wastes of ancestral mining activity mixed with Quaternary deposits.

GOLD GRAIN CHARACTERISTICS

Size distribution

Gold grains from the studied sediments are consistently fine grained (<1.5 mm), and bimodal, being either 150-250 μm or 250-500 μm (Text-fig. 3). Size distribution is always more or less normal about the mode, although a very subtle coarse skew is apparent in some populations. Distributions with this range and form are typical of the East Sudetic placer gold at all locations sampled during this study, although rare placer gold nuggets up to 1783 g are known (MORÁVEK 1992).

Gold from Pliocene piedmont fan sediments falls within a compact, more or less normal distribution with a pronounced mode in the 250-500 μm fraction. Gold in the preglacial 'white gravels' is dominated by small grains as in piedmont fan sediments, but there is a coarse-skewed distribution which incorporates grains of >1 mm range. In the Pleistocene series, there is still a mode of fine grained gold with the same grain size range as the fan sediments, but a second mode occurs in the 500-750 μm fraction. In the Holocene alluvial deposits, the mode 250-500 μm range is also visible, and a new fine grained (<150 μm) mode is developed.

Grains from the piedmont fans, 'white gravels', Pleistocene and Holocene sediments each display the same 250-500 μm 'piedmont fan mode', and this strongly suggests a Pliocene piedmont fan deposits parent, recycled several times.

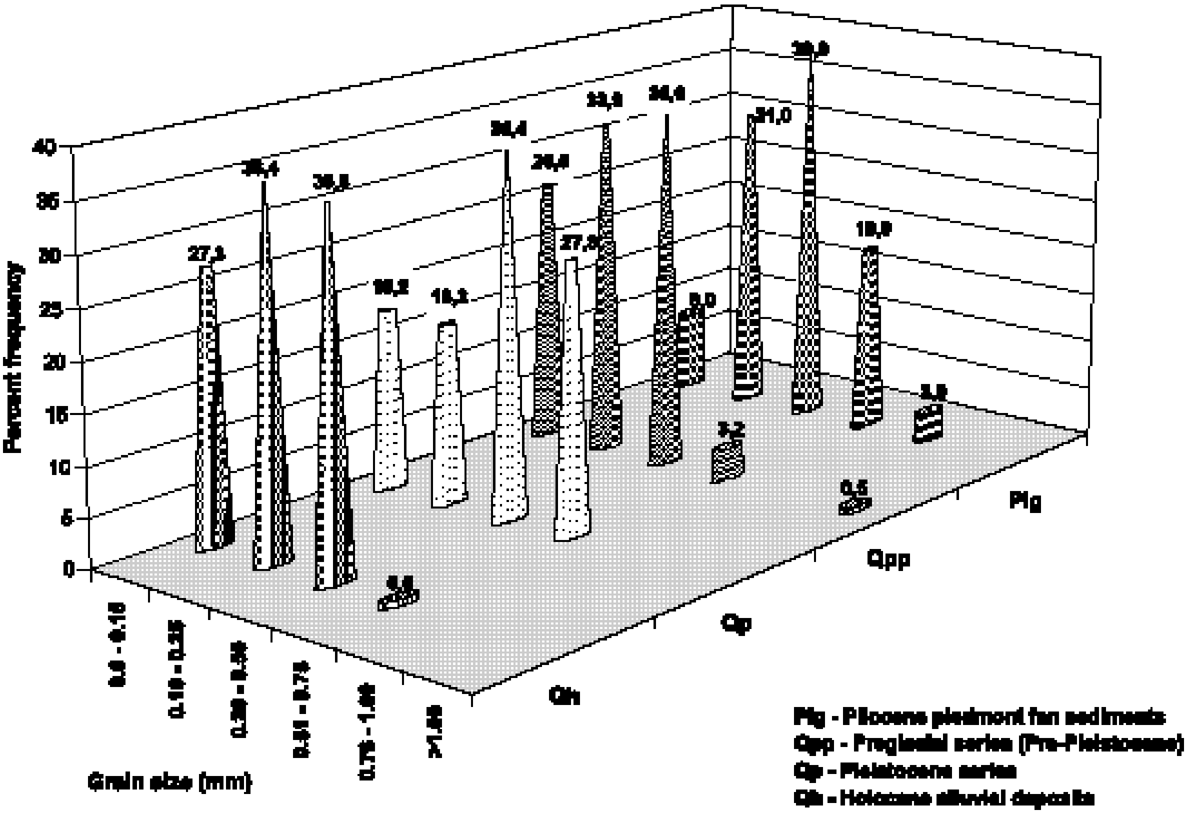

Fig. 3. Gold grain size distributions; location of gold sampling sites in Text-fig. 1

Grain shape and surface textures

The shape of gold particles is usually described by the following parameters: flatness, roundness and some specific morphological features, such as folding and 'sandwich structures'. One other feature related to shape is the surface texture.

The shape characteristics of placer gold can be used to estimate the distance of transport or a hydraulically equivalent cumulative distance for recycled paleoplacer particles and for predicting gold grains behavior in fluvial systems. The most useful descriptors are flatness, roundness and folding (Loen 1995, Youngson & Craw, 1999). Thus, any description and interpretation of placer gold shape (morphology) should include at least these three parameters.

Two processes involved in the evolution of placer gold particle shapes are hammering and abrasion. These processes both decrease the mass and increase the roundness of the gold particles.

Particle rounding results mainly from abrasion of particle edges and in-folding of delicate protrusions. Hammering also removes and deforms the protuberances in angular particles and consequently is the cause of rounding.

The data of Tishchenko (1981) and Knight & *al.* (1999) suggest that flattening of particles in the 0.05 to 1.5 mm size range are mainly the result of hammering. This flattening tends to focus abrasion (rounding) on the rim of the a-b plane of particles, but results in relatively minor textural changes on faces perpendicular to the c-axis. Knight & *al.* (1999) noted that both gold particle roundness and flatness increase rapidly within the first 3 km from the source. After approximately 5 km, the flatness continues to increase slowly whereas roundness remains essentially unchanged. Roundness is a more sensitive estimator for distances less than 5 km and less reliable than flatness for distances greater than 5 to 10 km.

Particle shape

Gold particles from all locations have relatively limited varieties of shapes in three dimensions (Pl. 1). As a

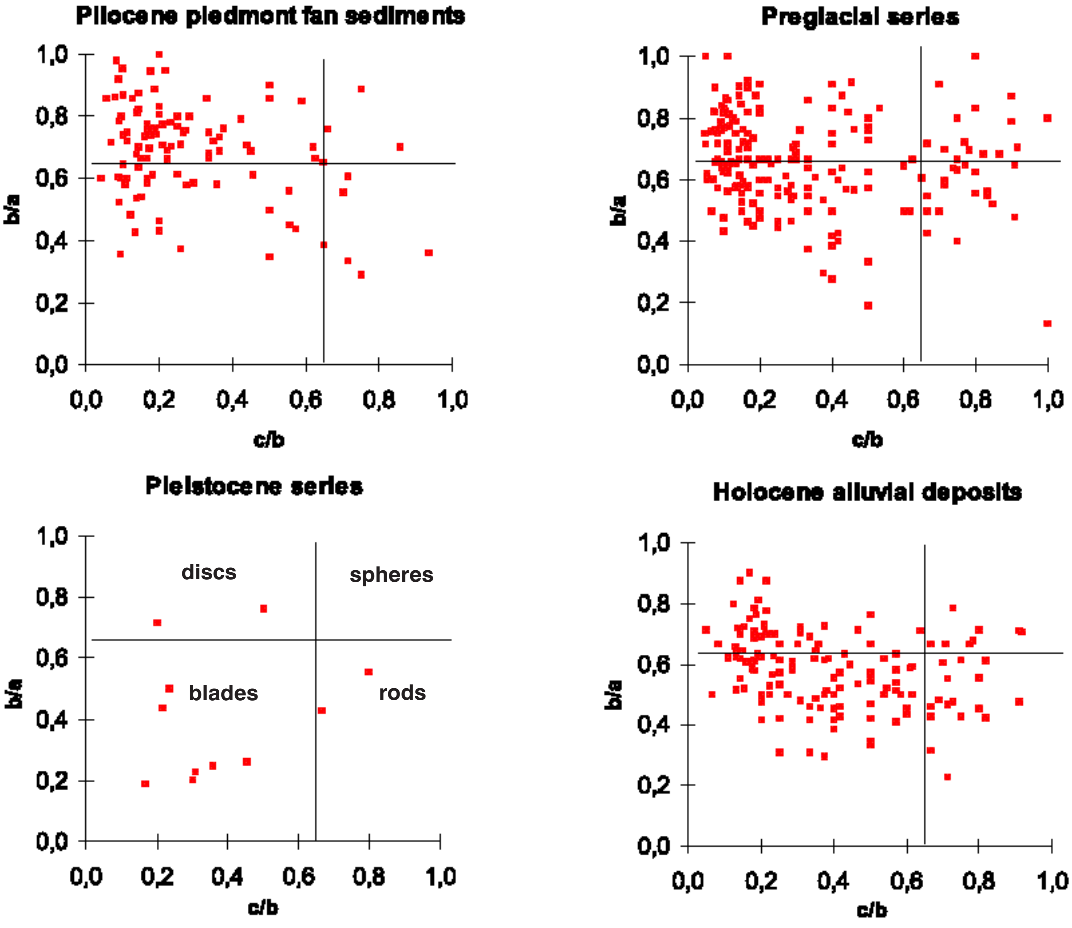

Fig. 4. Zingg shape classification diagram of 464 gold particles illustrating the distribution of shapes with a dominance in the oblate (discs and blades) field

result, it is possible to describe them in terms of shape classification schemes such as those commonly used for silicates and assume a limited number of primary shapes (e.g., ZINGG 1935, POWERS 1953).

The intermediate axis/long axis (b/a) and short axis/intermediate axis (c/b) ratios of 464 gold grains plotted on a Zingg shape classification diagram (Text-fig. 4) indicate that the majority of particles plot into the oblate (discoidal) and triaxial (elliptical) fields. Spherical and rod-like particles are present in low numbers. Within the preglacial, 'white gravels' and Holocene alluvial deposits the commonest shape is elliptical (scales). In contrast, discoidal grains predominate in piedmont fan sediments.

More than 80% of gold particles from the 'white gravels' and Holocene alluvial deposits have shape characteristics typical of fan sediment gold grains. The remainder are either rod-like particles, produced from rounded discoidal flakes, which have been hammered and folded during transport (Pl. 1, Figs 4, 5), or rarely, irregular grains with angular appendages (Pl. 1, Fig. 1). Appendages show sign of abrasion, or have angular to only locally rounded rims.

Particle roundness and flatness

Histograms of roundness data for gold particles from the studied sediments show, that the most common are rounded (up to 74.5% of the total grain population in preglacial 'white gravels') and well rounded grains (up to 55.4% in Pleistocene deposits). Subangular particles are rare; subrounded are also present in low numbers. Very angular and angular grains are absent (Text-fig. 5).

The above data show that grain distribution in younger host sediments (Pleistocene and Holocene deposits) trend progressively toward the well rounded category, probably as a result of an extensive reworking of older deposits and recycling.

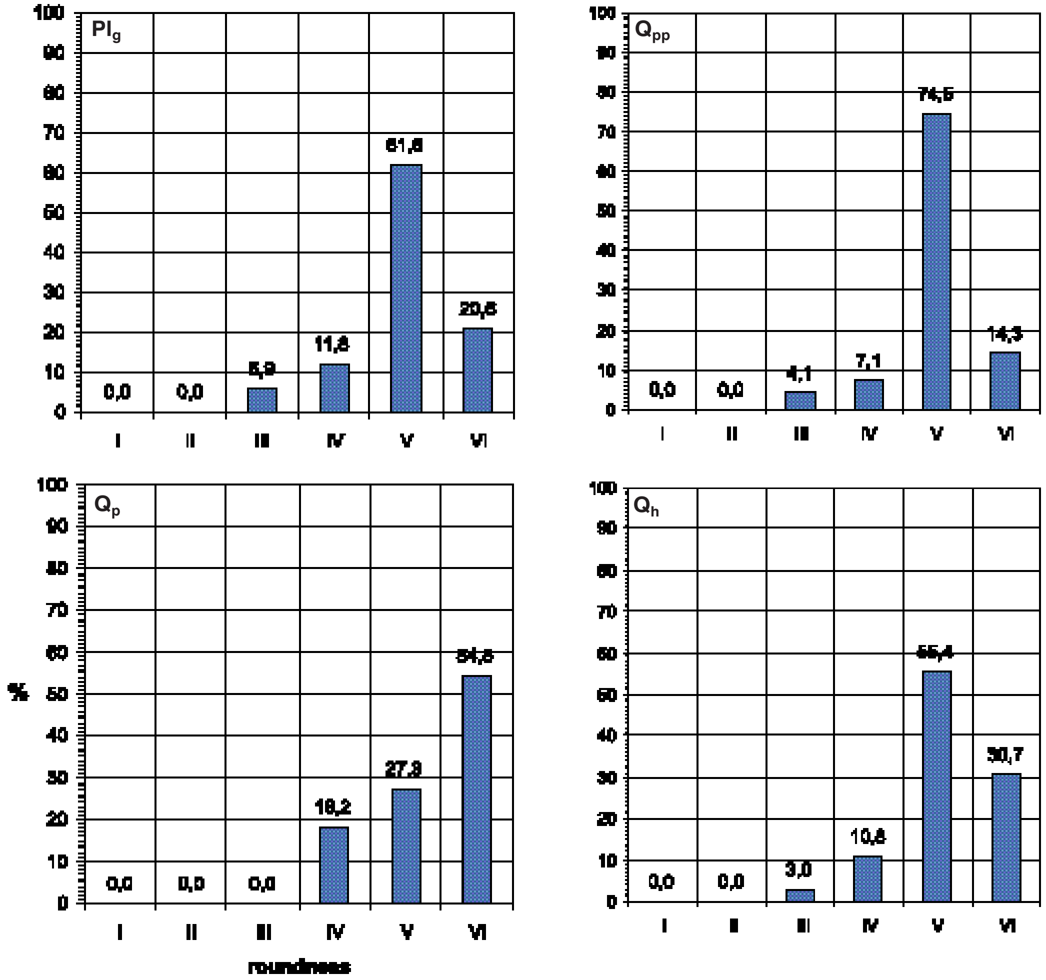

Fig. 5. Histogram of roundness data (after POWERS, 1953) for gold particles in studied auriferous sediments; gold-bearing horizons are denoted as in Text-fig. 3; roundness categories are represented by numbers (I-VI): I = very angular, II = angular, III = subangular, IV = subrounded, V = rounded, VI = well rounded

The Cailleux flatness index (F.I.) for gold particles sampled from the Pliocene piedmont fan sediments, preglacial 'white gravels', Pleistocene series and Holocene alluvial sediments ranges from about 1 to as much as 32, with a predominance of grains with F.I. maxima <10 (Text-fig. 6). Most of these are flattened particles which have been rethickened by folding (Pl. 1, Figs 4-7), but some are not folded and show little evidence for any significant flattening (Pl. 1, Fig. 1). These latter particles are probably derived from either local primary or relatively proximal paleoplacer sources.

LOEN (1995) reported that flatness index maxima show a gradual increase with increasing transport distance, from about F.I. = 2 in bedrock deposits, to F.I. = 45 over transport distances of several tens of kilometers. Similar conclusions were made by HÉRAIL & *al.* (1990) for Bolivian placers.

The full range of flatness index for individual samples can represent several gold subgroups. The gold subgroups distinguished in the studied sediments are: (1) particles transported as free gold from local, primary sources, (2) particles transported substantial distances as inclusions within ore clasts before being released, (3) particles recycled into the trunk rivers from paleoplacers, (4) particles recycled from till (Pleistocene and Holocene auriferous sediments) and (5) particles rethickened to subcritical flatness index by folding.

There is no correlation between flatness and roundness for gold in Pliocene piedmont fan sediments and preglacial series (Text-fig. 7) because of significant particles folding (described below). A positive correlation between flatness index maxima and rounding is apparent however for gold particles in the Pleistocene and Holocene gold-bearing horizons. Gold grains from these sediments have been reflattened after folding. In general, if particles have an anomalously low flatness index but are well rounded and underwent flattening, then they are likely to have been recycled from a paleoplacer.

No correlation between the distribution of flatness index values and lengths of the a-axis was recognized

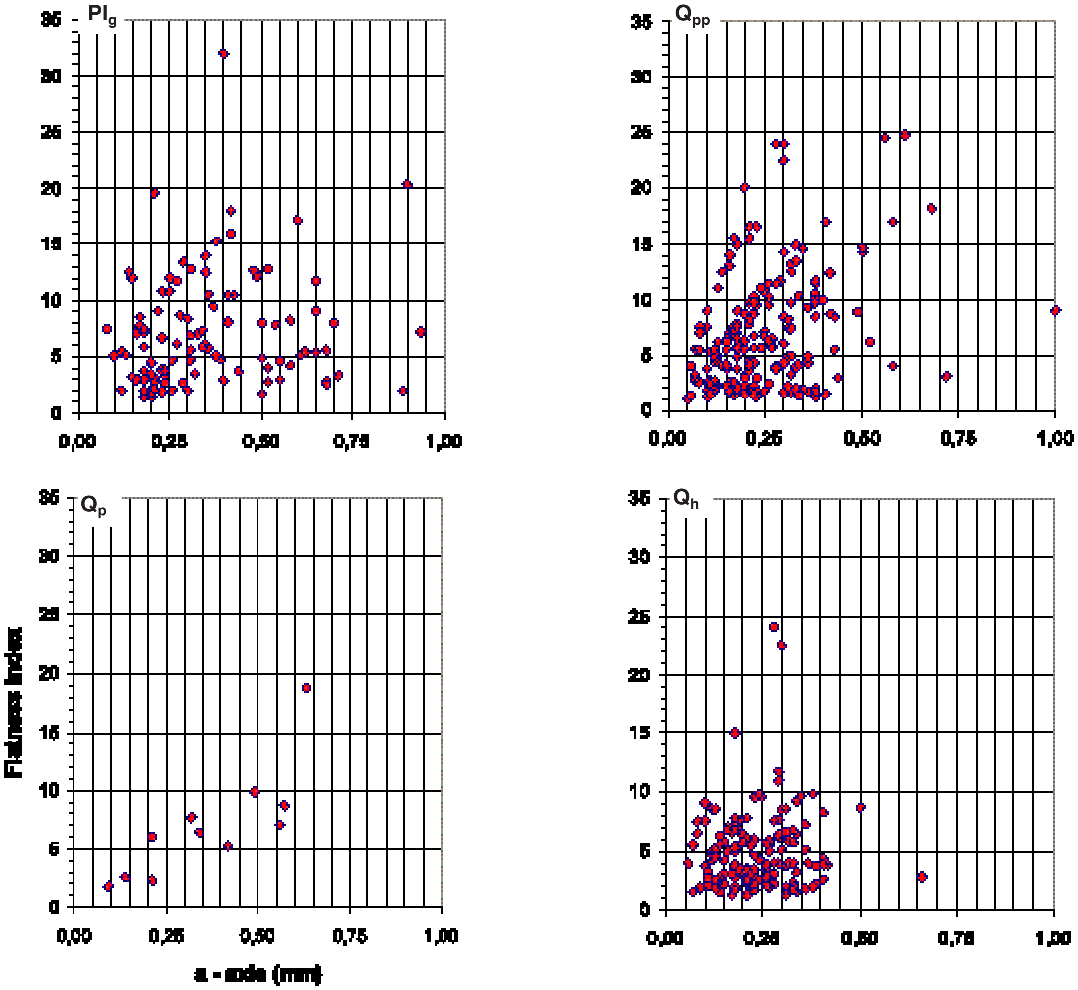

Fig. 6. Cailleux flatness index [F.I. = (a+b)/2c] vs. a-axis length for gold particles in studied sediments; gold-bearing horizons are denoted as in Figure 3

(Text-fig. 6). Consequently, it is assumed here that the interpretation of flatness is independent of whether gold samples are randomly chosen or sieved.

Particle folding

A feature of studied sediments is the presence of folded gold particles. Although reflattening after folding commonly removes much of the evidence, folding can nevertheless still be recognized from certain morphological features. These include the preservation of fold hinges, represented by straight edges on discoidal and elliptical particles (Pl. 1, Figs 3, 6) and remnants of curved sutures where the prefold particle edge has been hammered into the face of the a-b plane (Pl. 1, Fig. 7). Folding may also be recognized in polished sections of some particles (Pl. 4, Figs 3, 4).

The proportion of folded particles increases within the Quaternary deposits, particularly in preglacial 'white gravels' series, where more than 40% of particles are folded or multiply folded ('sandwich structures'). Some particles have been folded then reflattened, or repeatedly folded (Pl. 1, Fig. 6). Others have been folded over completely and slightly twisted about their a axes (Pl. 1, Fig. 5).

A feature of these folded gold particles is the presence of peculiar 'envelope-like' and 'sandwich-like' gold grains (Pl. 1, Figs 7, 8). The 'envelopes' form as a result of intense deformation of particles with impact pressing of prominences and uneven pitted surfaces with mineral inclusions. In contrast, the 'sandwiches' are due to deformations in the marginal parts of the grains with anomalously high flatness index. Gold particle edges have been hammering into the face of the a-b plane (Pl. 1, Fig. 8).

The increase in the proportion of folded particles, 'envelopes' and 'sandwiches' in preglacial series is probably caused by the susceptibility to folding that results from

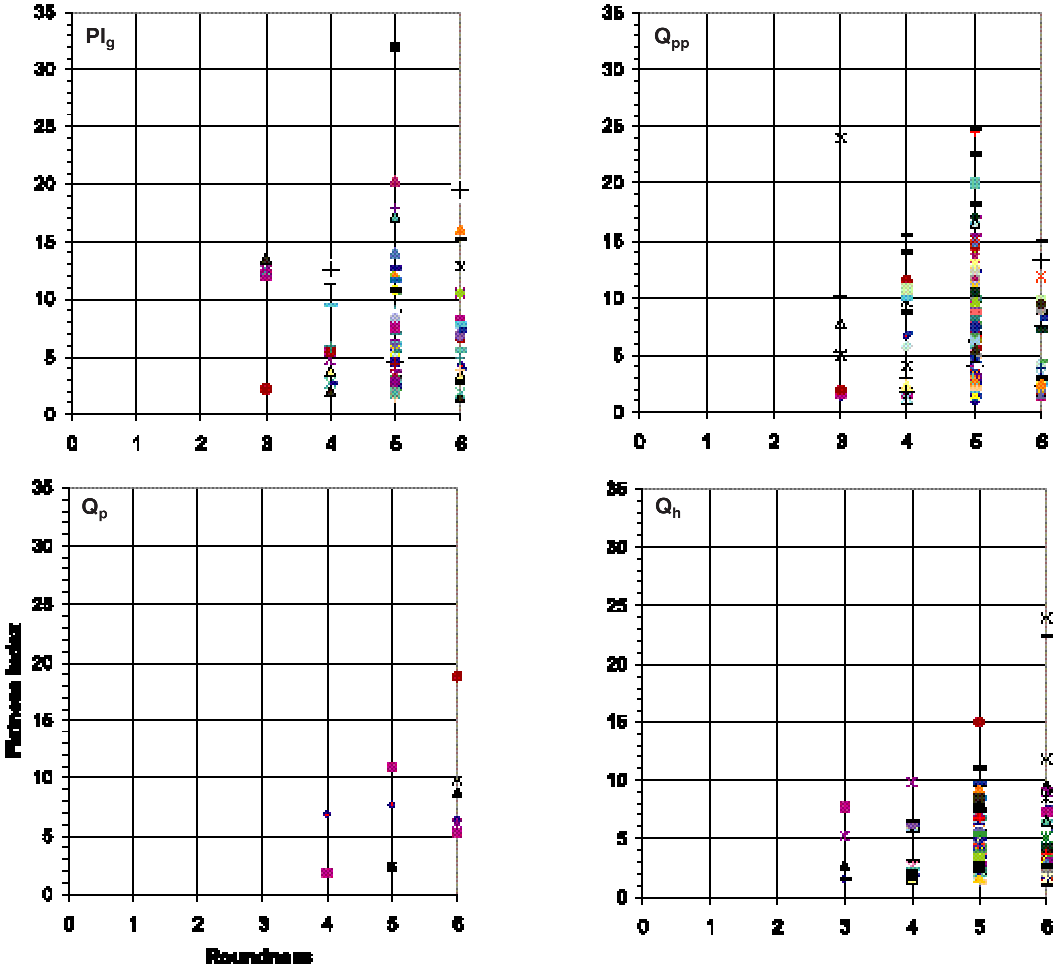

Fig. 7. Roundness vs. Cailleux flatness index [F.I. = (a+b)/2c] for gold particles in studied auriferous sediments. Gold-bearing horizons are denoted as in Figure 3. Roundness values (1-6) represent: 1 = very angular, 2 = angular, 3 = subangular, 4 = subrounded, 5 = rounded and 6 = well rounded

the extreme flattening associated with relatively long-distance transport.

HÉRAIL & *al*. (1990) noted that after transport over a distance of about 60 km the grains have been flattened so much by hammering that they are easily folded upon themselves to form 'sandwich structures'. Similar conclusions were made by TISHCHENKO (1981), who suggested that a high proportion of folded particles in some recycled Siberian placers was caused by significant transport in previous placer cycles.

The data above show that grains from different host sediments are very similar in character, probably as the result of extensive reworking of deposits and recycling. An abundance of a relatively simple 'two-dimensional' population dominated by flakes, and an increase in the proportion of folded discoids and elongate or irregular particles produced by folding of highly flattened grains (elliptical), suggest that such particles have been exposed to lengthy transport. Such an evolutionary trend in grain form is known from Cenozoic placer gold deposits in New Zealand and Canada (YOUNGSON & CRAW 1993, 1995; EYLES 1995).

Surface texture

The texture of the surface is one other feature related to shape of gold particles. It records both hammering and abrasion and will rapidly evolve in response to the change in size distribution of the host sediment and stream energy (YEEND 1975).

The surfaces of the most of the rounded and folded gold particles bear a rough microrelief with depressions caused by the hammering of moving detritus transported together. A common feature of the surface texture of the grains examined in this study are shallow hammer-marks, scratches or furrows, irregular surface pits and abraded embayments up to 10 μm across (Pl. 2, Figs 1-3). Because they change rapidly, surface textures record probably the last abrasion event. The features of the surface texture are masked sometimes by ferric oxides (limonite and hematite), manganese oxides and clay minerals, which form thin films (coats) or small assemblages (Pl. 1, Fig. 5).

Both hammering and abrasion cause smearing, best seen in cross section (Pl. 4, Figs 5, 7). Smearing can generate cavities and trap host particles (quartz, heavy minerals, limonite) in the gold (Pl. 2, Figs 4, 5). Some of the grains show marks of pressing due to which numerous inclusions are overprinted by surrounding prominences of host gold particles (Pl. 2, Fig. 6). No primary mineral inclusions were observed on gold grain surfaces. These inclusions (mainly quartz, sulfide minerals, and iron oxides) are mostly lost within 10 to 20 km of fluvial transport and this loss increases with distance (LOEN 1995).

Beyond the common texture features related to mechanical deformations, on the surface of rare, multilobed and irregular grains were described characteristic textures which can represent authigenic gold precipitated from solution on to preexisting grains.

Two distinctive textures are observed on some irregular gold particles. The first one is the 'lattice intergrowths'. It consists of layers of elongate, thin (a few microns), crystalline plates, tens of microns in length (Pl. 3, Figs 1-3). Crystals grow on each other sequentially. The plates can be uniformly orientated or intergrown in a variety of orientations. There are numerous pores and fractures between individual crystals. Growths at angles around 70° are common (Pl. 3, Fig. 4).

The lattice intergrowths often show signs of abrasion or other transport damage. Because of the malleability of gold, the surface expression of the intergrowths is very easily destroyed during transport. Nevertheless, their presence can often still be detected, and some gold grains preserve the multilayered structure and remnants of intergrowths on their surfaces. Abraded surfaces show commonly a tabular, terrace-like structure with relief of a few microns, representing possibly former bladed intergrowths (Pl. 3, Fig. 5).

The second texture is a highly porous encrustation of amorphous, wormlike blebs of gold, a few microns across, which coat partially the surface of grains, and fill cavities (Pl. 3, Fig. 6).

The author considers it unlikely that delicate crystal textures such as lattice intergrowths and worm-like encrustations, coating the surface of a gold particle, could survive fluvial transport. It is possible, therefore, that grain mass made of Au crystals with the above textures were formed in the sediment and had not undergone long-distance transport. The gold was added authigenically as a result of precipitation from colloidal solutions.

Colloidal gold can originate chemically, by the breakdown of complex gold compounds, and mechanically (BOYLE 1979, BENEDETTI & BOULEGUE 1991). Gold may be abraded as a consequence of its softness and high density during transportation due to sediment movement, resulting in the formation of new, colloidal particles. As the result of changing physical and chemical conditions, gold can be precipitated from solution on the surface of larger particles to form characteristic worm-like encrustations and lattice intergrowths, similar to that described above.

Gold grain chemistry

The internal chemical composition of gold grains in the 0.15 to 1.00 mm size range was studied by X-ray microprobe analysis. Of the 12 elements tested, only Au, Ag and Te were detected. A small amount of Cu, Fe and Se (<1 wt %) is present in a few grains.

Sixty detailed analyses of the 32 gold grains from throughout the gold bearing horizons show significant variations in the silver distribution. The range of this distribution in gold particles from Pliocene piedmont fan series and the preglacial 'white gravels' is always similar to that for gold from younger host sediments (Pleistocene and Holocene). Some of the gold grains from the piedmont fan series differ markedly from those in the 'white gravels', however, in that they are approximately homogeneous in composition.

Three different gold generations were distinguished on the basis of their internal chemical composition:

1. low silver gold (Ag content <0.5–3.7 wt %),
2. high silver gold with Ag content 8.5–18.7 wt %,
3. electrum (Ag content >20.0 wt %).

In addition, one grain of gold-bearing silver (kustelite) with Ag content 51.4 wt % was obtained from the Holocene deposits.

Differentiation in the composition of gold particles is a result of different gold sources or their different genesis. The internal chemical composition of gold provides good information on the mechanism of transport from hard rock to alluvium. One must take into account, however, only the values in the inner zone of gold particles and disregard the grain borders where silver (the other major element) has been leached. It is also important to recognise that the decrease in Ag content in placer gold is not due to progressive leaching of Ag in the secondary environment with distance from a source but reflects primary variations in gold composition instead.

Most of the placer particles have a nearly pure, chemically resistant, protective gold rim surrounding, or partly surrounding, a core of varying composition (DESBOROUGH 1970, GIUSTI 1986, YOUNGSON & CRAW 1993, 1995; EYLES 1995, KNIGHT & *al.* 1999). The core appears to have been unchanged by its passage downstream and can therefore be used to characterize/identify the primary (lode) source of placer gold.

Low silver gold

The low silver gold grains examined in this study are compositionally homogeneous and did not display cores of contrasting composition. The majority are nonporous, massive particles (Pl. 4, Fig. 1), or rarely ameboid, pore-rich forms (Pl. 4, Fig. 2). The lack of a compositionally distinct core in these grains may result from near-total leaching of their silver content. Polished sections have almost certainly cut some grains without intersecting a core, however, and some of the low silver gold particles probably represent such sections.

High silver gold

The high silver gold particles differ markedly from low silver particles in that they are inhomogeneous, with distinct core and rim (Pl. 4, Figs 3-7). Gold grains are commonly highly deformed, and in some cases have a 'sandwich' form (Pl 4, Figs 3, 4). Their cores are nonporous with irregular, sharp, ragged boundaries against the rim. Some of the gold particles contain two or more cores of similar or slightly differing composition (Pl. 4, Figs 4, 6). In numerous grains from both Pliocene piedmont fan sediments and the Quaternary deposits, cores are reduced in size to remnant ragged areas, a few to tens of microns across (Pl. 4, Fig. 7).

Rims which enclose grain cores either completely or partially are composed of zones of essentially pure gold (typically >99.5 wt %) and commonly have porous structure (Pl. 4, Figs 3, 6). In the few cases where pure gold was detected, it occupied only very small, isolated portions of the grain margins (Pl. 4, Fig. 8).

There has been discussion in the literature as to whether low Ag rims on gold grains are due to addition of gold (to make a larger grain) or leaching of silver (to make a smaller grain) (DESBOROUGH 1970, BOYLE 1979, KNIGHT & *al*. 1999).

There is evidence for gold addition in the studied sediments, but there is also evidence for leaching of silver. Delicate crystal textures such as lattice intergrowths (Pl. 3, Figs 1-3) and highly porous encrustations of amorphous, wormlike blebs of high purity gold, which coat the grain surfaces (Pl. 3, Fig. 6), could not survive transport in a high energy environment.

In grains where the outer rim envelopes directly a high Ag core, compositional SEM images of gold particles (Pl. 4, Figs 3-7) show the irregular boundary with numerous depressions and embayments. This may represent a leaching 'front', which transgressed into the grain. Occasionally enrichment rims form pseudoveinlets penetrating the grains which resemble replacement, cementation or reaction zones (Pl. 4, Figs 3, 4).

Gold in the rim of such grains is partly added, and partly reprecipitated or recrystallised with associated loss of Ag. The association of pure gold rims with both authigenic addition and silver leaching textures suggests that both processes could have occurred.

GENESIS OF PLACER GOLD-CONCLUSIONS

The morphology (roundness, flatness index and particles folding), surface texture and chemical composition of gold particles suggest that the placer gold occurrences in the East Sudetic Foreland are multicycled and multisourced.

Today, there are no large primary gold deposits in close proximity to the studied placer gold occurrences. Minor quartz veins with reported gold (Zlatý Chlum) and polymetallic vein-type deposits (Zlaté Hory), are known from epimetamorphic and metamorphic rocks surrounding the East Sudety Mts (Text-fig. 1). The gold amount contained in these mineralizations is very small and is spatially limited. Native gold reported from these occurrences is extremely small: most grains are below 0.02 mm in diameter. Hence, this type of occurrence can not be regarded as a major source for the alluvial gold of the East Sudety Mts.

It is suggested therefore that the principal source for the placer gold were the sedimentary and epimetamorphic covers of the Żulova granitoids which were completely eroded during progressive, Neogene uplift (Text-fig. 8). This inference is supported by the high content of milky quartz in gold-bearing horizons.

The compositionally homogeneous, pore-rich gold particles were formed probably in the weathering zone of polymetallic veins and other types of mineralization. Gold was liberated from its host minerals and concentrated secondarily within enrichment zones.

During the Pre-Pleistocene, piedmont fans with gold

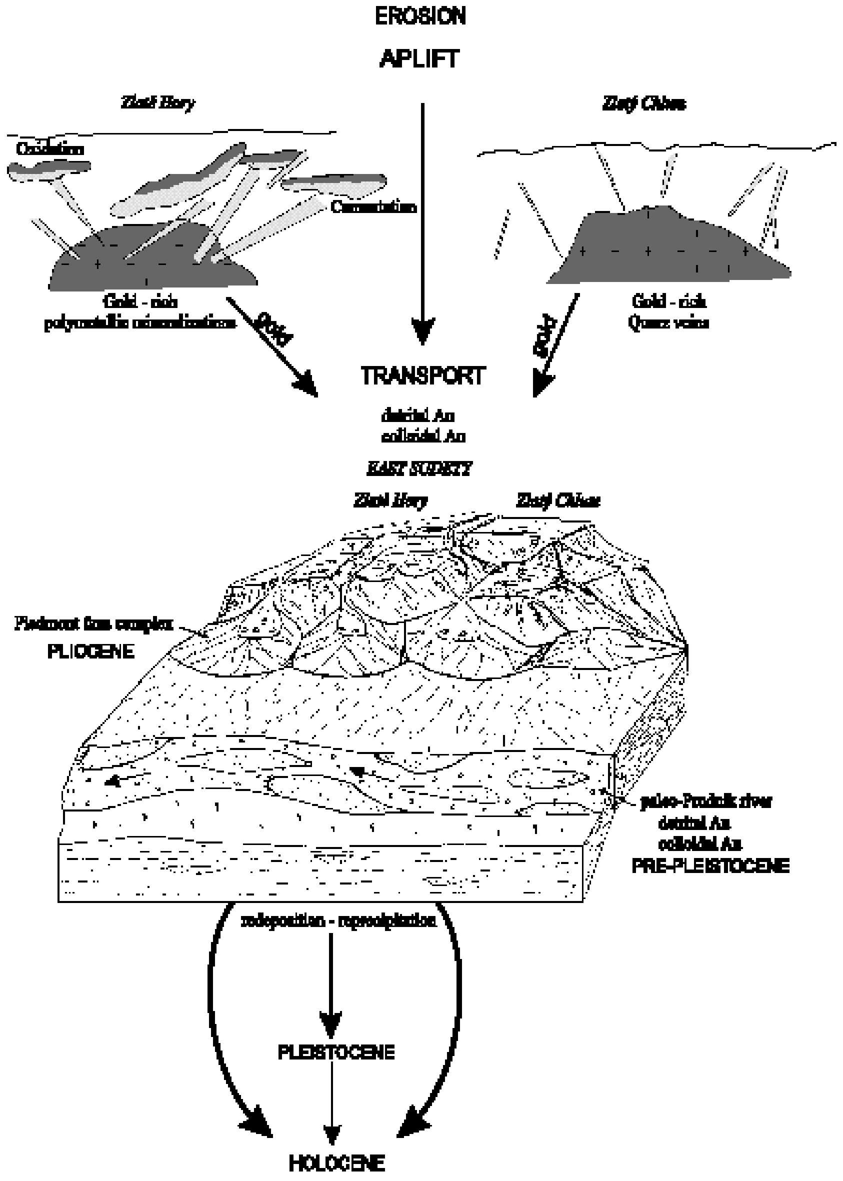

Fig. 8. Simplified model for evolution of placers in the East Sudety Mts.

were extensively reworked, removed and redeposited by the rivers of pre-Prudnik, Biała Głuchołaska, and their tributaries. This process evolved during Pliocene and continued into the Pre-Pleistocene time (paleobed of the river Prudnik) (Text-fig. 8).

The majority of the gold was transported presumably in a suspended form, as flakes, scales, small grains and gold dust. This entered the river directly as a result of erosion of auriferous sediments. A simple evolutionary trend in gold grain form toward a relatively simple 'two-dimensional' population (flakes, scales) and increase in the proportion of folded particles, 'envelopes' and 'sandwiches' suggest significant transport and/or paleoplacers recycling.

Gold could have also been dissolved, transported and under favourable chemical conditions, and reprecipitated. It is unlikely that delicate crystal textures, such as lattice intergrowths and encrustations of worm-like masses coating the surfaces of gold grains could survive fluvial transport. Au was added authigenically as a result of precipitation from colloidal solutions.

Some amoeboid, porous gold particles, without any signs of mechanical abrasion, could have been formed chemically, during diagenesis. In some locations, the diagenetic migration and reprecipitation of gold was promoted by two periods of subaerial exposure of gold-bearing sediments during the Pleistocene and Holocene, as well as by paleohydrological changes caused by glaciation.

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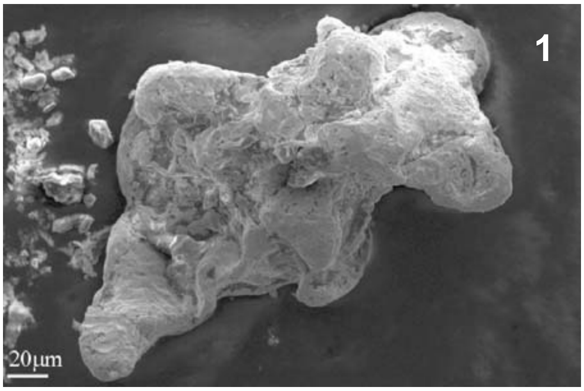
PLATES 1-4

PLATE 1

Secondary electron images of typical fluvial gold particles from studied gold-bearing sediments; scale as shown

1 – irregular grain with angular appendages and locally rounded rims (Qh)
2 – branched particle showing evidence of abrasion and rounding (Plg)
3 – elliptical particle with straight edges (fold hinges) (Qp)
4 – rod-shaped particle produced by folding of discoid (Qpp)
5 – rod-like particle which have been twisted about its a axis. Note freshly deposited ferric oxides and clay minerals coating the surface of gold grain (Qpp)
6 – typical platy particle from Qpp; it has been folded during fluvial transport. Note fold hinges and pitting on the grain surface.
7 – 'sandwich-like' particle. Note remnants of curved sutures where the prefold particle edge has been hammered into the face of the a-b plane (Qpp)
8 – 'envelope-like' particle with marks of intense deformation (Qh)

Abbreviations in the text: Plg – Pliocene piedmont fan sediments, Qpp – preglacial 'white gravels' series, Qp – Pleistocene series, Qh – Holocene alluvial deposits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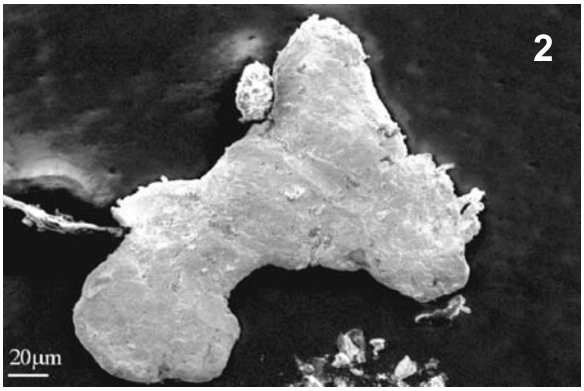
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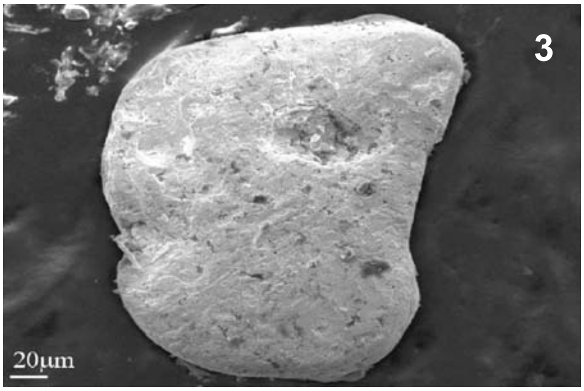
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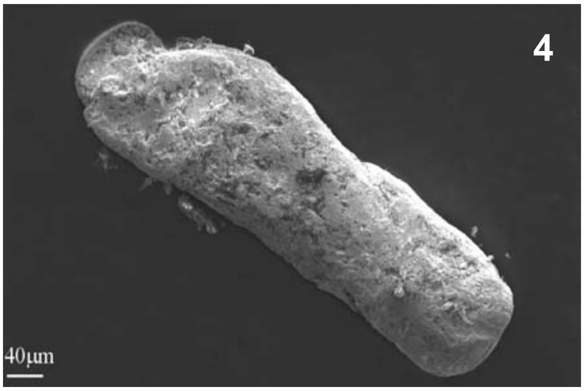
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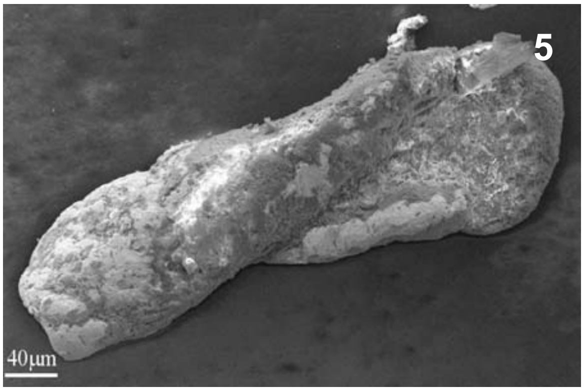
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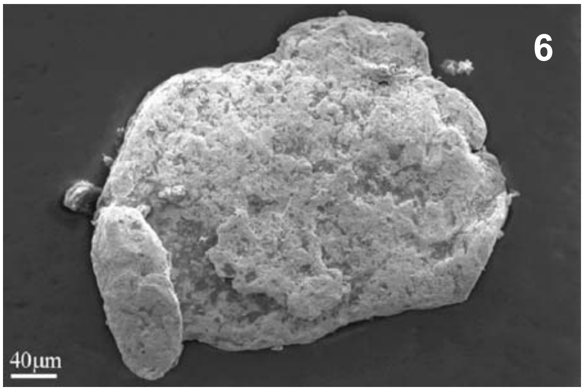
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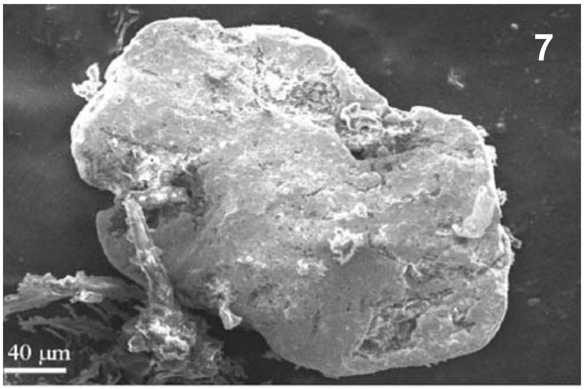
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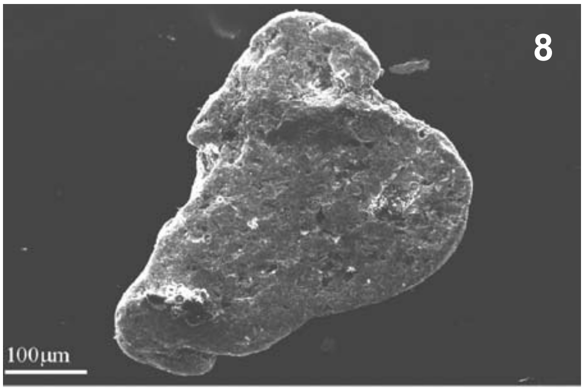
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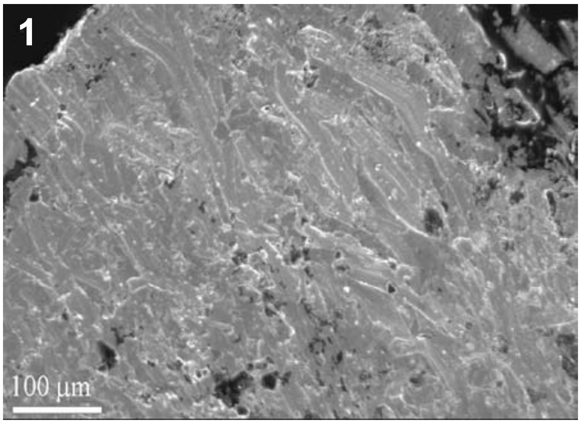
PLATE 2

Secondary electron images of the surface texture of gold particles deformed by hammering, abrasion and smearing; scale as shown

1 – scratches and furrows; these features record the last abrasion event
2 – composite surface texture with hammermarks and pits of an unknown origin
3 – abraded embayments that are partly obliterated by hammering and abrasion
4-5 – generated by smearing irregular surface pits with trapped a quartz-clay inclusions
6 – mineral inclusions ‘overpressed’ by surrounding parts of gold particle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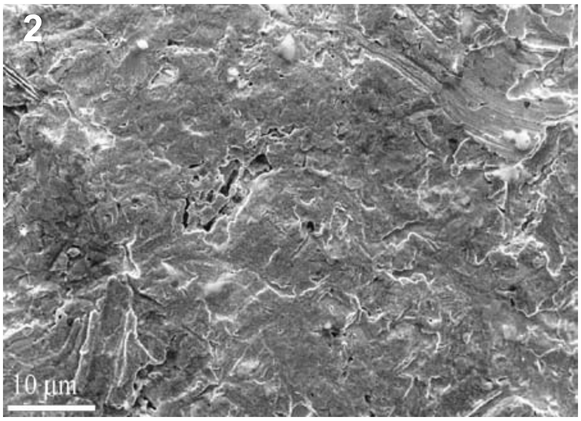
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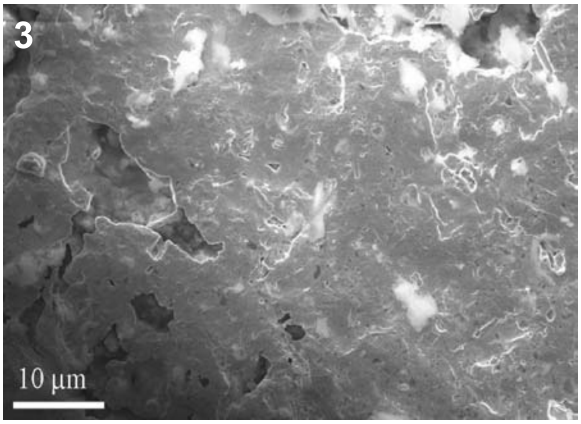
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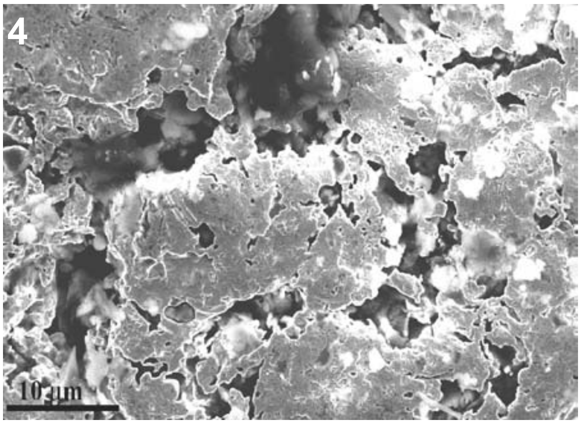
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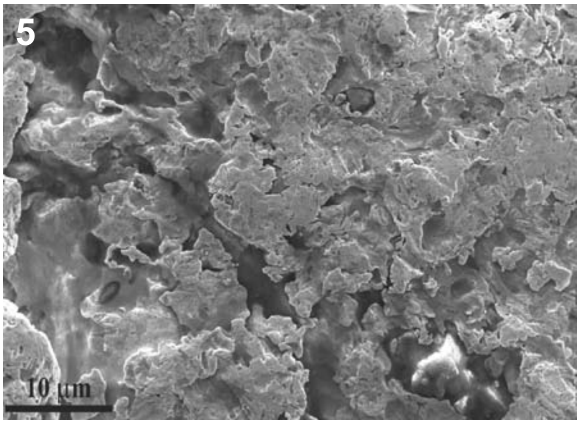
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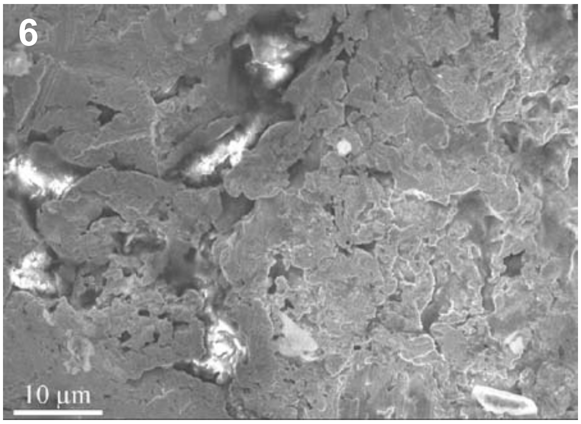
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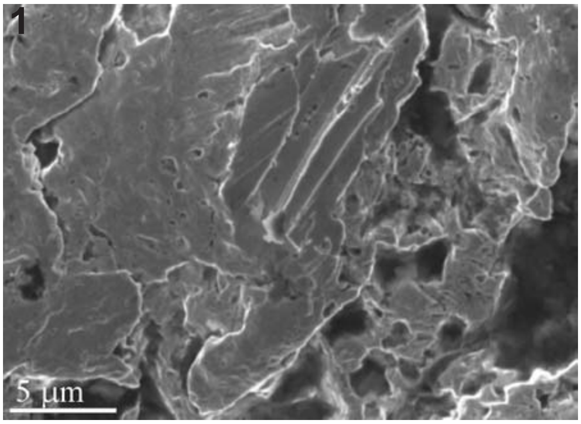
PLATE 3

Secondary electron images of textures representing authigenic gold precipitated on the preexisting gold particles; scale as shown

1-2 – ‘lattice intergrowths’; note layered structure with thin, elongate, crystalline plates
3 – remnants of intergrowths and the multilayered structure
4 – uniformly orientated growths at angles of around 70º
5 – tabular, terrace-like structure representing former bladed intergrowths
6 – porous encrustations of amorphous, wormlike, blebs of gold filling cavity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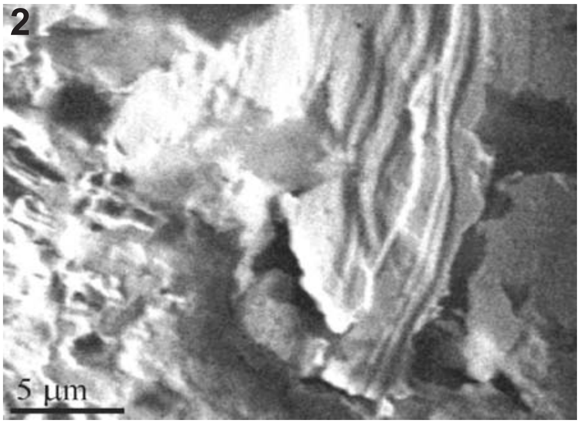
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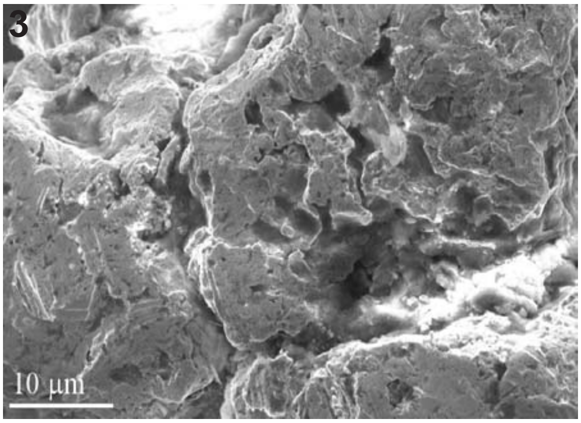
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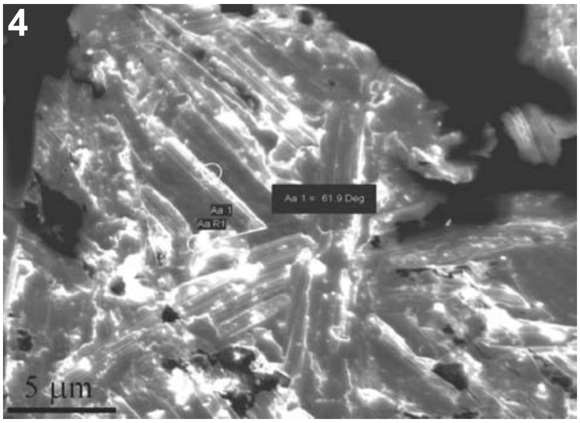
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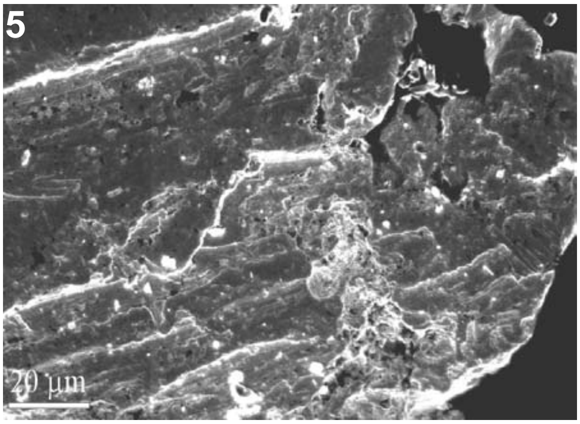
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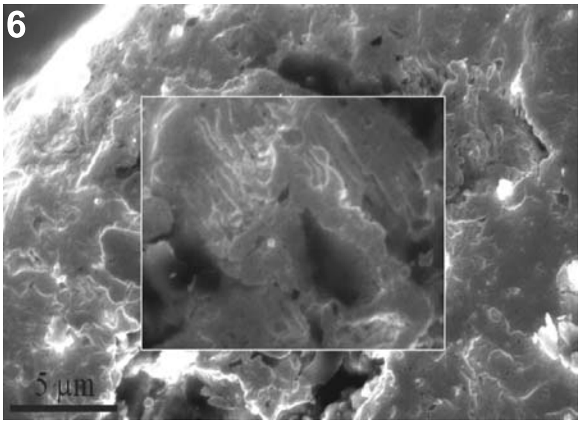
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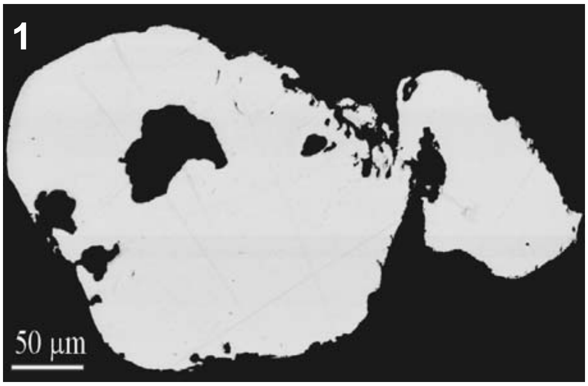
PLATE 4

Compositional, back-scattered electron images of internal structures on polished (sectioned) gold particles. The lighter the tone the higher the fineness. Scale as shown

1 – the compositionally homogeneous, massive (nonporous), low Ag gold grain (Plg)
2 – homogeneous, pore-rich, low Ag particle (Qpp)
3 – high Ag, 'sandwich-like' particle with the pore-free core and the pore-rich rim (Qpp)
4 – deformed particle consists of three cores surrounded by high purity Au rim (Qpp)
5 – inhomogeneous high Ag particle. Note the sharp core-rim contact and ragged boundaries between the rim and core (Qh)
6 – typical multiple cores particle from Qpp. Note high Ag, the pore-free cores surrounded by pores, pure gold rim (Qpp)
7 – well-rounded particle with multiple cores reduced to remnant ragged areas (Qp)
8 – irregular, high Ag grain with angular appendages. Note the presence of small isolated portions of pure gold on grain margin (Qh)

Abbreviations in the text: Plg – Pliocene piedmont fan sediments, Qpp – preglacial 'white gravels' series, Qp – Pleistocene series, Qh – Holocene alluvial deposits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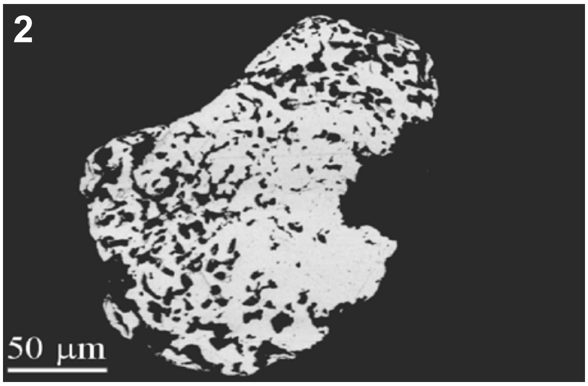
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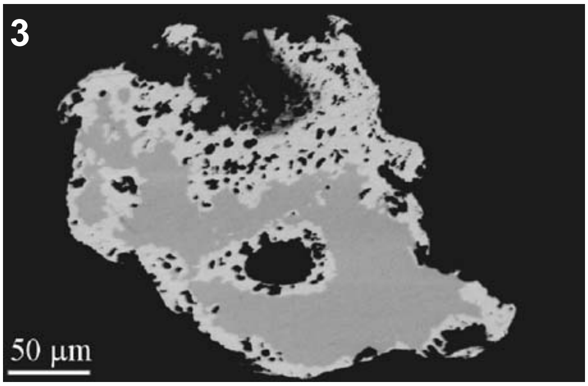
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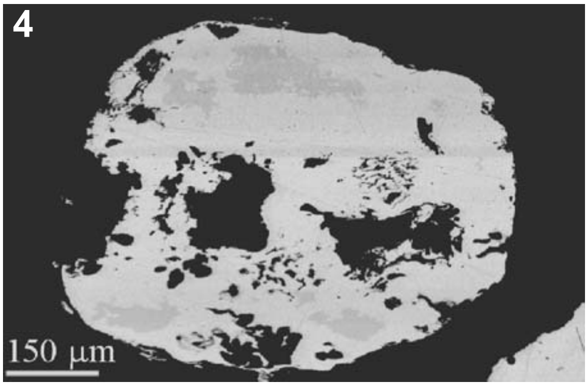
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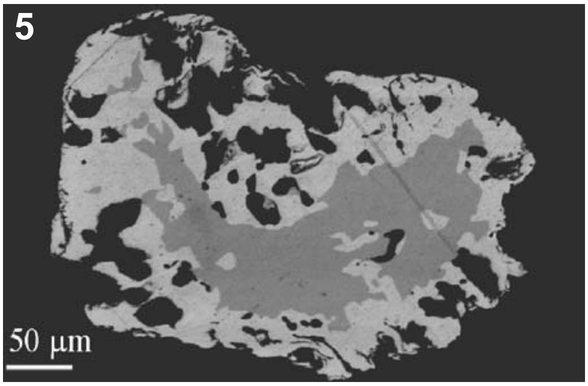
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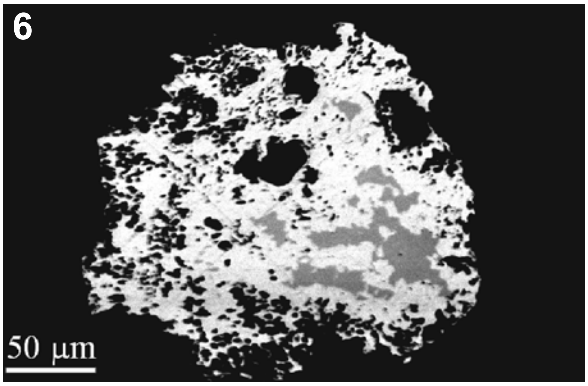
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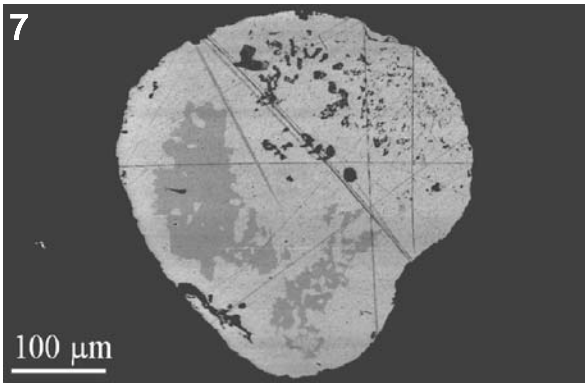
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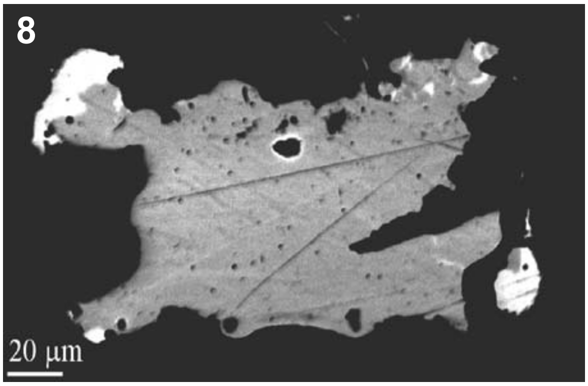
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