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A REVIEW OF GOLD PARTICLE-SIZE AND RECOVERY METHODS

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A REVIEW OF GOLD PARTICLE-SIZE AND RECOVERY METHODS

CJ Mitchell, EJ Evans & MT Styles

1. INTRODUCTION

This report reviews published literature concerning the particle-size distribution of gold occurring in alluvial and bed-rock deposits and the various methods used for its recovery. The aim of this review is to recommend methods for the recovery of fine-grained gold (generally less than 100 μm in size) as an alternative to the environmentally damaging use of mercury amalgamation. This work has been carried out as part of an ODA / BGS Technology Development Research (TDR) project R6226 "Mitigation of mining-related mercury pollution hazards".

2. PARTICLE-SIZE OF GOLD

Information on the particle-size distribution of gold is sparsely scattered throughout the literature and presented in various different forms. Many gold assays are carried out on sieved heavy mineral concentrates (HMC's). This is of limited use, to the current review, as coarse grained gold present in the ore will not be included in the analysis. This is simply due to the practicalities involved, often samples were pre-sieved on site to remove coarse material (for example >2 mm) and only the fine material was evaluated. Often laboratory evaluations will be geared toward the use of specific gold recovery techniques. Many of these techniques have their effectiveness limited to specific size ranges. Therefore the evaluation will often only be applicable to gold within that size range, regardless of the presence of finer (or coarser) gold.

Even where a complete gold particle-size distribution is quoted the information should be treated with caution. Gold generally occurs in minute amounts which requires (for statistical accuracy) large bulk samples to be collected for size analysis, especially to determine weight percentages of coarse gold grains (>500 μm). Various physical methods are used in order to separate gold for analysis, most commonly laboratory-scale gravity separators.

However for particles below approximately 75 μm the processing efficiency of most gravity separators starts to fall. Therefore it is important that the gold content of all separation products, middlings and tailings (waste products) as well as concentrates, are determined to ensure that an accurate gold particle-size distribution is produced for the whole sample not just for certain size ranges.

The size at which gold is considered to be "fine-grained" varies. The following classifications have been devised (Wang & Poling, 1983):

Russia		**Canada** (British Columbia)	
Fine gold	-315 +100 μm	Fine gold	-1.5 mm +350 μm
Minute gold	-100 +37 μm	Flour	-350 μm
Dispersible gold	-37 μm		

Others suggest that 75 μm or 100 μm (Stewart & Ramsay, 1993) should be the top size of fine-grained gold. This report will use 100 μm.

The particle-size distributions quoted for gold do not reflect the particle-size distribution of the ore. For example 50% of the gold by weight may exist in a size fraction that only represents 10% of the ore by weight. Also the variation in the weight distribution of gold with particle-size depends upon the nature of the ore (and for alluvial gold the source area). Some alluvial gold deposits may contain a significant amount of fine grained gold whereas others will contain virtually none.

2.1. Alluvial Gold

Generally the particle-size of alluvial gold falls into the range 5 mm to 100 μm. Several examples are given in the following Tables. The information given in Tables 1 to 6 is from a BGS study of alluvial gold. The samples were sieved in the field at 2 mm and hence will not contain gold grains larger than that, although it is unlikely that they are present. Grain size was measured by image analysis of grains hand picked for subsequent polishing and microanalysis. The minimum size is governed by that which could be manipulated and was considered large enough for polishing. Many samples actually contained a small proportion of finer grains that were not measured.

Samples purchased from artisanal alluvial miners and are shown with *. They often contained less fine gold than the samples collected by BGS staff and counterparts. This is due to both poor technique and, in some cases, poor equipment; African miners were seen using broken washing-up bowls and old ice cream tubs as pans. This explains the variation in data obtained for samples collected by different people in different ways and makes establishing the true natural variation very difficult.

As can be seem from most of the tables little information is available for gold finer than 100 µm. In part this may be due to the inefficiency of fine gold recovery in the studies referred to.

Table 1. Ecuador (Styles *et al*, 1992)

Sample	Size range (µm)	Average (µm)
EQ1*	153 - 2911	1393
EQ2*	186 - 2868	1607
EQ3*	980 - 3299	2288
EQ4*	608 - 3199	1552
EQ5*	544 - 3146	1431
EQ6*	555 - 4066	1898
EQ7*	123 - 3280	1347

Table 2. Mersing, Johore, Malaysia (Styles *et al*, 1994)

Site	Size range (µm)	Average (µm)
Kuala Mayang	312 - 893	631
Air Merah	208 - 481	342
Telok Bangka	110 - 727	385
Pulau Belanak	225 - 658	401

Table 3. Lubuk Mandi area, Terengganu, Malaysia (Henney *et al*, 1994)

Site	Size range (μm)	Average (μm)
Lubuk Mandi		
MA13*	560 - 1477	939
MA14	136 - 879	442
MA16*	136 - 1599	904
MA17*	476 - 3624	1332

Table 4. Zimbabwe (Styles *et al*, 1995)

Site	Size range (μm)	Average (μm)
Mazoe		
ZM5	212 - 1603	464
ZM89	30 - 550	249
ZM90	121 - 451	222
Chegutu-Chakari*	171 - 2486	1264
Kadoma*	217 - 2067	958
Kwekwe		
ZM28*	196 - 1961	865
ZM29*	365 - 2237	1047
ZM35	217 - 476	242
ZM73*	234 - 2428	1070
Silobela		
ZM33*	165 - 1944	313
ZM34*	256 - 1025	450
Zvishavane*	210 - 1239	585

Table 5. Penjom area, near Kuala Lipis, Pahang, Malaysia (Henney *et al*, 1995)

Site	Size range (µm)	Average (µm)
MA105	283 - 719	439
MA106	197 - 551	306
MA107	241 - 822	383
MA108	222 - 745	364
MA109	356 - 827	525
MA110	281 - 804	534
MA111	120 - 518	245

Table 6. Raub area, Pahang, Malaysia (Henney *et al*, 1995)

Site	Size range (µm)	Average (µm)
Luie River	215 - 519	386
Raub valley		
MA 86	149 - 787	332
MA87	132 - 306	203
MA88	208 - 726	404
MA89	197 - 575	359
MA90	110 - 844	369
20 km S of Raub		
MA92	215 - 394	270
MA93	146 - 308	225
MA94	132 - 461	273
10 km N of Raub		
MA100	266 - 575	413
MA101	405 - 723	528
MA102	253 - 390	308

Table 7. Mount Kare, SW of Porgera, Papua New Guinea (Bartram *et al*, 1991)

Particle-size	Weight Percentage
+5 mm	0.4
-5 mm +800 μm	29.6
-800 +250 μm	66.2
-250 +75 μm	3.6
-75 μm	0.2

Other placer deposits in Papua New Guinea have up to 50% fine gold <100 μm (Subasinghe, 1991).

Table 8. Average placer gold, Yukon, Canada (Clarkson, 1994)

Particle-size	Weight Percentage
+2.36 mm	10
-2.36 +1.4 mm	20
-1.4 mm +600 μm	30
-600 +300 μm	30
-300 +150 μm	10
-150 μm	Not quoted

Table 9 Placer gold, 'Middle Asia' (Solozhenkin *et al*, 1993)

Particle-size	Sample 1 Wt %	Sample 2 Wt %
+1 mm	-	-
-1 mm +400 μm	<0.1	0.22
-400 +200 μm	<0.1	0.65
-200 +100 μm	99.9	59.58
-100 +80 μm		39.53
-80 μm		0.02

In New Zealand placer deposits contain gold up to 95% <2 mm, 50 - 70% <1mm, mostly >200 µm (Braithwaite & Jury, 1993).

2.2. Bed-rock (& miscellaneous) gold

The particle-size distribution of bed-rock gold varies considerably with the type of gold deposit and is too diverse to generalise. Much of the information gathered here represents gold associated either with sulphide mineralisation or altered volcanic rocks/metasediments. Gold occurs in a wide range of particle sizes from ultrafine inclusions in pyrite (down to <1 µm, often called 'invisible gold') to native, or free, gold particles up to 1 mm in diameter and coarser. Several examples are given :

Table 10. Average from gold-rich quartz veins. Archean Basement, Dondo Mobi, Gabon (Leconte & Colin, 1989)

Particle-size	Weight Percentage
+500 µm	14
-500 +250 µm	5
-250 +125 µm	11
-125 +63 µm	6
-63 µm	64

2.2.1. Explosion breccia, Wau Valley, Papua New Guinea (Eltham, 1984). The gold occurs generally <100 µm, occasionally recrystallised as coarse grains (>100 µm).

2.2.2. Altered metasediments, Wafi River, Papua New Guinea (Erceg *et al*, 1991). The gold occurs as grains <3 µm in diameter associated with pyrite.

2.2.3. Mineralised turbidites, Peak Gold Mine, New South Wales, Australia (Davies, 1992). The gold ranges in size from 2 to 300 µm.

2.2.4. Mineralised volcanic rocks, Ladolam gold deposit, Lihir Island, Papua New Guinea (Moyle *et al*, 1991). The gold occurs as inclusions <5 µm within pyrite, as free gold up to 100 µm in oxidised ore and up to 500 µm in quartz veins.

2.2.5. Granulite, Renco Reefs gold mine, Zimbabwe (Leroy, 1995). The gold is fine grained (65% <15 μm) and 28% occurs as free gold associated with native bismuth.

2.2.6. Gold in glacial till overlying Archean greenstone, Ontario, Canada (Shelp & Nichol, 1987) is up to 90% <500 μm, mostly <125 μm.

2.2.7. Gold in streams draining gneiss & plateau basalts, Harris Creek, British Columbia, Canada (Day & Fletcher, 1989) is mainly <100 μm.

2.3. Summary of gold particle-size

The following table gives a summary of the overall range and average of the available particle-size data for alluvial and bedrock gold (the figures in brackets represent the particle-size which most of the data falls into).

Table 11. Summary of alluvial and bed-rock gold particle-size

Gold type	Particle-size Overall range	Average
Alluvial	30 μm to 4 mm (100 μm to 3.5 mm)	222 to 2.3 mm (300 μm to 1.5 mm)
Bedrock	<3 μm to >500 μm	<100 μm

3. GOLD RECOVERY METHODS

This section will briefly outline the various mineral processing methods commonly used to recover gold, giving an indication of the size-range of material processed and typical gold recovery figures. Panning is not considered as no 'hard data' was found. The methods considered mainly involve the physical separation of gold from 'gangue' (which ranges from vein material in bed-rock deposits to sand and silt grade material in alluvial deposits) using gravity-based processing methods. Gold has a high specific gravity (19.3 g/cm^3) in relation to most common gangue minerals (ranging from 2.65 to 3 g/cm^3) and is therefore eminently suitable for gravity processing. Considering the minute quantity of gold normally present in even the most auriferous ores (down to

1g/tonne in bed-rock and 0.25 g/tonne in alluvial deposits) gravity processing is virtually the only method effective at producing the concentration ratios required, especially with the high volume throughputs associated with alluvial mining.

Table 12. Particle-size range and typical efficiencies of gravity and chemical gold recovery methods

Method	Effective size range	Recovery efficiency
Sluice boxes (+ Reichert cones)	2500 to 100 µm	As low as 20% for -<100 µm gold to 96% for <1000 µm gold
Jigs	2500 to 75 µm	As low as 50% for 100 µm gold to 98% for 1000 µm gold
Shaking tables	3000 to 15 µm	As low as 20% for 20 to 40 µm gold up to 90% for gold >40 µm
Spirals	3000 to 75 µm	65 to 80 %
Rotating cones & Bowl concentrators	6000 to 30 µm	Up to 99%
Amalgamation	1500 to 70 µm	As low as 65% for <75 µm gold up to 98% for <500 µm gold
Cyanidation	Finer than 200 µm	At least 80% to 99%

N.B. Recovery data are specific to particle-size, ore nature and processing operation.

Certain gold grain characteristics influence the efficiency of gold recovery methods, particularly gravity separation. The influence of density upon the behaviour of a gold grain will lessen as the surface area to mass ratio increases. Gold is usually non-spherical, and it is typically flakier with decreasing grain size. This is mainly due to the malleability of gold, distorting rather than fracturing in response to loading and impact (during crushing and grinding of the ore, and alluvial transport). This irregular shape leads to porosity; cavities and pores are often infilled with lower density material lowering the density of the composite particle. The flaky shape, porosity and hydrophobic surface properties often cause gold to float. This is especially a problem for fine grained gold. Gold grain surfaces are often coated with an hydrophobic organic layer or iron oxide coatings and some are leached free of impurities (such as silver) leaving a rim of pure gold, all of these render the surface hydrophobic (Wang & Poling, 1983).

The mineralogical character of the gold is often not considered when planning a processing plant, especially if the gold responds well to standard gravity and cyanidation processes. However, if the gold recovery is poor (<80%) the ore is termed "refractory" and a detailed mineralogical investigation becomes necessary. This will involve the determination of the mode of occurrence of minute gold grains and the proportion of "invisible" gold. Gold usually occurs as "native gold". A solid solution exists with many heavy metals including electrum (Au, Ag), argentian gold (Au, Ag), cuprian gold (Au, Cu), palladian gold (Au, Pd), mercurian gold (amalgam) (Au, Hg) and Au-Ag-Hg alloy. Other gold-bearing minerals occur only in very small amounts including gold tellurides, gold selenides, gold sulphides and intermetallic compounds such as amalgam (Au, Hg), aurostilbite (Au, Sb) and maldonite (Au, Bi) (Petruk, 1989).

3.1. Sluice boxes

3.1.1. Riffled sluice boxes

The sluice box is by far and away the most commonly used means of concentrating gold from alluvial gravels. They are generally cheap to make, easy to operate and require minimal technical knowledge to maintain (Hancock, 1991). Essentially a sluice box consists of a sloping open rectangular flume with regularly spaced transverse bars, or 'riffles', through which a dilute slurry of water and alluvial gravel flows. Heavy minerals, including gold are usually captured in the upstream side of the riffles (or the downstream side depending upon the design of sluice box). These are regularly removed by raking or cleaning-out the sluice box riffles.

Sluice boxes are effective for the recovery of gold with particle-size from 25 mm to 100 µm. The efficiency of gold recovery varies from 80 to 100% in well operated sluices run by modern commercial companies to less than 50% in makeshift sluices run by small-scale miners. A typical small-scale operation would involve 2 to 3 people, with 1 digging and feeding the sluice, the second picking out stones and the third monitoring the wash water (Hancock, 1991). In New Zealand gold recoveries are up to 80%, the remainder is mainly finer than 250 µm and is physically recoverable by gravity separation (Fricker, 1986). In Yukon recoveries up to 98% are reported (Clarkson, 1994). The efficiency of gold recovery is influenced by a host of parameters:

i) The design of the sluice box, including the slope, width and length, and the type of riffles incorporated.

In Papua New Guinea sluice boxes consist of a wooden launder tilted 5 to 15° with transverse wooden slats (Subasinghe, 1991). In Yukon expanded metal riffles are incorporated into sluices operating at a relatively shallow slopes (7-12°) with feed rates of 20 m^3/hr and water flows of 40 l/s/m are used for recovering gold finer than 1 mm. Angle iron riffles used in sluices with steeper slopes (12-14°), faster feed rates, 40 m^3/hr and faster water flows, 80 l/s/m are used for recovering gold coarser than 1 mm. Flat bar riffles ('nugget trap') may be suitable for recovering gold coarser than 6 mm (Clarkson, 1994).

A porous matting is often used to line the floor between riffles, particularly in the lower part of the sluice box, in order to enhance the recovery of gold during operation. Oscillation of the sluice box during operation may improve gold recovery from alluvial gravel with a high proportion of heavy minerals or clay. However oscillation leads to reduced gold recovery from other alluvial gravels (Clarkson, 1994).

The recovery of gold increases with sluice length and particle-size as indicated here (Fricker, 1986):

Table 13. Gold recovery with increasing sluice length and particle-size

Sluice	**Gold recovery for a given particle-size**		
length	**-100 μm** wt %	**-250 +100 μm** wt %	**-1 mm +250 μm** wt %
0.5 m	4	34	50
1.0 m	5	50	68
1.5 m	6	58	78
2.0 m	7	59	80

ii) The particle-size range of the gold and the accompanying sediments.

The recovery of gold present in sand grade as compared to gravel grade material has been determined as follows (Fricker, 1986):

Table 13. Recovery of sand- and gravel-grade gold

Gold size	Gold recovery -4 mm sand Wt %	Gold recovery -16 mm gravel Wt %
0.1 mm	74	nd
0.2 mm	84	65
0.5 mm	92	85
1.0 mm	97	95
2.0 mm	100	99

Fine gold (<100 μm) is a problem for sluices and up to 60% of the total gold content reports to the tailings (i.e. is not recovered). Gold recovery efficiencies of up to 50% are achievable for material finer than 200 μm (Wang & Poling, 1983) and up to 40 to 50% for material finer than 100 μm (Subasinghe, 1991; Stewart & Ramsay, 1993). The 'slimes' content (this can mean material less than 10 μm in size to less than 75 μm in size) of the feed can adversely affect gold recovery. Scrubbing and screening prior to sluicing can improve gold recovery (by up to 20%) by freeing gold trapped in clay-bound and weakly cemented material (Clarkson, 1994). If no coarse-grained gold is present the sluice can be operated using conditions appropriate for the recovery of fine-grained gold. However if coarse-grained gold does exist the ore can be split into coarse and fine grained material. Gold can then be recovered from the coarse-grained material by using a second sluice operated using conditions appropriate for coarse-grained gold recovery. The treatment of coarse and fine material separately will increase overall gold recovery.

iii) The sluice feed and wash water rate

Sluices are often operated in an attempt to recover coarse- (nugget) and fine-grained gold in a single pass (Subasinghe, 1991). However these require distinctly different hydrodynamic conditions. Coarse gold is best separated using high feed rates, with steep sluice tilt and high riffles - the coarse gold drops out and finer gold remains entrained in the flow of material down the sluice. Fine gold recovery requires lower feed rates, shallower tilts and smaller riffles. Attempting to recover both coarse- and fine-grained gold at the same time will result in poor overall recoveries. A slower rate will improve recovery of fine gold but decrease the removal of gangue and reduce overall throughput. The effect of varying sluice feed and wash water is similar to that of varying sluice tilt. In many cases sluices are operated with water diverted from local streams and it is more practical to vary sluice tilt than the wash water rate. The steeper the tilt the faster the wash rate.

iv) The time interval between cleaning out the riffles

The sluice box is essentially a batch, or semi-continuous, process. In order to recover gold from the sluice box riffles the operation is halted. The sluice boxes operated in Papua New Guinea are operated for approximately a week between clean-out. The experience of the operator is important in deciding when to clean. Too long an interval will allow an excessive amount of solids to pack up against the riffles. This will stop gold being trapped and it will be displaced to the tailings. A shorter interval will result in improved recoveries but this has to be balanced against the time spent cleaning and decreased throughput (Subasinghe, 1991)

3.1.2. Pinched sluices (including Reichert cones)

A pinched sluice is similar to a riffled sluice box, minus the riffles, that tapers to the downstream end (Figure 1). During operation the minerals present in the feed slurry segregate with heavy minerals adjacent the floor of the sluice and progressively lighter minerals occurring at the top of the flow. The heavy mineral concentrate is separated by the use of an inclined plate over which the slurry flows from the end of the sluice.

A Reichert cone has a similar separating principle to that of a pinched sluice. It consists of a squat cone, as if the base of a pinched sluice had been stretched out into a circle. A slot near the base of the cone removes the concentrate, whereas the tailings, which are entrained in the flow, pass straight over.

Pinched sluices and Reichert cones are effective in the processing of material in the size range 3 mm to 30 μm. Typically used as a primary rougher (preconcentration of gold prior to gold recovery) or scavenger (reprocessing of waste to improve overall gold recovery) where high capacity, low operating cost is required. For example gold recoveries of 50 to 60% are achieved with Reichert cones at New Celebration gold

Mine in Western Australia (Martins *et al*, 1993). Used (to remove coarse gold) ahead of expensive stages such as froth flotation or chemical leaching, which work better on fine gold, they can save costs. The recovery of coarse gold requires ore to be ground to a size suitable for flotation or leach times to be extended. Up to 60% gold can be recovered by Reichert cones this way (Feree, 1993).

3.2. Jigs

A jig is described as a 'hindered settling device used to concentrate heavy minerals from feed material'. It consists of a shallow, flat tray with a perforated bottom plate through which water is pulsed up and down (Figure 2). This causes the heavy minerals to migrate downwards and the lighter minerals to remain at the top of the pulsing liquid. The heavy minerals are drawn through the base plate and the light minerals pass over the top as tailings.

Jigs are effective in the processing of material in the size range 25 mm to 75 μm. Material is best pre-screened and processed as separate coarse and fine fractions. Typically for gold below 100 μm recovery falls to less than 50%. In a combined sluicing-jigging operation gold recovery may be as high as 89 to 95% (Wang & Poling, 1983). In an Alaskan operation conversion of a sluice plant to a jig plant increased gold recovery by 37% (Fricker, 1986) and in a New Zealand operation a similar conversion increased gold recovery by 14% (Braithewaite & Jury, 1993). A Kelsey centrifugal jig has been used to concentrate fine gold-bearing sulphides from a process tailings stream with recoveries of >70% (Brewis, 1995). The following table compares gold recovery between a jig and a sluice at different grain sizes (Fricker, 1986):

Table 14. Recovery of gold using a sluice versus a jig

Particle -size	**Gold recovery**	
	Sluice Wt %	**Jig** Wt %
0.1 mm	20	48
0.2 mm	56	74
0.5 mm	88	95
1.0 mm	96	98

3.3. Shaking tables

The commonest form of shaking table used is the wet table (the 'dry' form is known as an air table, which uses air as the fluid separating medium). It consists of a flat table (or 'deck') with parallel riffles to trap the heavy minerals (Figure 3). The 'deck' is vibrated longitudinally and inclined laterally during operation. A perforated pipe feeds wash water from the upslope side. The slurried feed is introduced at the top upslope corner. The minerals in the feed segregate. The heavy minerals sink to the deck, migrate along the riffles and are discharged over the end of the deck. The light minerals, entrained in the water, pass straight over the riffles and down to the bottom and so to the tailings.

Shaking tables are effective in the processing of material in the size range 3 mm to 15 µm. Shaking tables have been used to recover 88% of the gold present in a concentrate produced on a spiral (Eltham, 1984). Wang & Poling (1983) record that up to 90% of gold coarser than 40 µm can be recovered, whereas typically only 20% of 20 - 40 µm gold can be recovered. The efficiency drops greatly below 40 µm. The following table gives the size distribution of gold present in a shaking table middling product from a commercial mine in Malaysia i.e. material that had passed over the table and was stockpiled for possible later reprocessing. Estimated assay of around 10 g/tonne is higher than the mined ore. There is considerable scope for increased yield with more effective processing.

Table 15. Particle-size distribution of gold in a middlings product from a gold mine in Malaysia

Particle-size (µm)	**Yield** (wt %)
+250 µm	35.3
-250 +120 µm	42.11
-120 +63 µm	21.81
-63 µm	0.75

3.4. Spirals

The spiral concentrator is described as a 'low feed rate, low feed density' flowing film gravity separator. It consists of a helical conduit of modified semi-circular cross-section, usually with between 3 and 5 complete 'turns' (Wills, 1992) (Figure 4). Material is fed onto the top of the spiral as a slurry with typically 25 to 30% solids by weight. As the material flows spirally downwards the particles stratify due to factors such as centrifugal force, differential settling, hindered settling and reverse classification. There is usually a density gradation across the profile of the spiral with heavy minerals concentrating next to the axis and minerals of lower density being swept to the outer edge. Concentrate, middling and tailing products are collected with the use of adjustable splitter plates.

Spirals are effective in the processing of material in the size range 3 mm to 75 µm (although up to 5 % 'slimes' can be tolerated with sufficient wash water). Spiral performance is controlled by : the diameter and pitch of the spiral; the pulp density (i.e. the solids content of the slurry); the location of the splitters and take-off points; and, the volume and pressure of wash water. In one operation hydrocyclones are used to deslime (removing particles nominally finer than 30 µm in this case) the feed to spirals (only rejecting gold finer than 14 µm) and this leads to spiral recoveries of up to 65% (Eltham, 1984). At New Celebration gold mine in Western Australia a series of rougher (producing gold pre-concentrates) and cleaner (removing impurities from gold concentrates) spirals consistently achieve gold recoveries of 70 to 80% (Martins *et al*, 1993). Spirals are also known to be used for the recovery of fine flat free gold (recoveries up to 85%) and gold finer than 37 µm (recoveries up to 50%) (Feree, 1993).

3.5. Rotating cones

Rotating cones find application in arid and semi-arid countries where water is at a premium. These concentrators use the least amount of water of any wet gravity separator and produce a high-grade concentrate in a single pass. They consist of a squat cone (included angles of 105° to 115°) which is tilted and rotated. A high-density pulp is introduced at the top edge of the cone and wash water at the bottom leading edge. As the cone rotates the heavy minerals migrate to the centre of the cone and are drawn off. The light minerals overflow the lower edge of the cone as a tailings.

Rotating cones are effective in the processing of material in the size range 3 mm to 30 μm. The concentrate grade is determined by : the slope of the cone; the grade of the ore; and, the residence time of the material in the cone during operation.

3.6. Bowl concentrators

Commonly used makes are the Knudsen and the Knelson bowl concentrators. A bowl concentrator consists of a rotating cylinder that segregates heavy minerals from light minerals by a combination of centrifugal force and wash water action. The Knelson bowl concentrator is claimed to recover "gold particles ranging from 6 mm to less than one micron in a single pass" (sales brochure). Recovery is effective down to approximately 30 μm.

Typically Knelson concentrators have been retrofitted to process flotation tailings to recover gold coarser than 100 μm and also to replace mineral jigs as a means of recovering coarse gold ahead of flotation and cyanidation. A fully-automated Knelson concentrator was installed at the Dome Mine, South Porcupine, Ontario in replacement for a jig circuit and exceeded jig gold recovery using only a tenth of the volume of jig feed (Brewis, 1995). A similar concentrator was installed at the Golden Giant mine in north central Ontario which, accompanied by a single stage of tabling, accounted for up to 30% of the overall gold recovery. This was free-gold recovered directly from the grinding circuit prior to cyanidation (Brewis, 1995). Removal of coarser free gold ahead of cyanidation leads to savings from lowered carbon stripping (recovery of gold from solution) and a consequent reduction in the use of cyanide acid and other consumables. Also removal of free gold grains ahead of the grinding circuit will ultimately improve flotation efficiency as there is a reduction in gold 'smearing' onto other minerals and effecting flotation properties.

3.7. Drum concentrators

The Mozley Multi-gravity separator (MGS) consists of a tilted drum that tapers slightly to the downslope end (Figure 5). The drum simultaneously rotates and is shaken longitudinally. Sample slurry is added to the upslope end and as it migrates down the drum it segregates into heavy and light minerals. The heavy minerals report to the inside wall of the drum, where they are pushed to the upslope end by scrapers. The light minerals remain entrained in the wash water and report to the downslope end. The MGS has been likened to a shaking table wrapped round itself into a drum.

The MGS can be used to process material in the size range 1 mm down to 1 μm. An MGS has been used to recover 76% of the gold present in a zinc flotation concentrate (Mozley sales literature).

3.7. Other gold recovery methods

3.7.1. Non-gravity methods

Magnetic separation - Magnetic separation is the process whereby minerals are separated by exploiting differences in their magnetic susceptibility. Magnetic separators, using either permanent magnets or electromagnets, can be used to process material in a wet or dry state at varying magnetic intensities (depending on the impurities to be removed). Magnetite often concentrates with gold, this is easily removed by magnetic separation which makes subsequent gold recovery more efficient (Wang & Poling, 1983). Magnetic separation is effective in the processing of material in the size range 2 mm to 70 μm for dry magnetic separation and down to 5 μm for wet magnetic separation.

Electrostatic separation - Electrostatic separation is the process whereby minerals are separated by exploiting differences in their electrical conductivity. Electrostatic separators use electrodes to create an electrical charge on the surface of minerals. The rate at which this charge dissipates controls the separation, conductive minerals lose the charge rapidly and non-conductive minerals slowly. If non-conductive heavy minerals occur with gold electrostatic separation can be used, leading to improved gold recoveries (Wang & Poling, 1983). Electrostatic separation is effective in the processing of material in the size range 600 μm to 70 μm.

Hydrocycloning - A hydrocyclone is a classification device used extensively in the minerals industry for the beneficiation of a wide variety of material and also for the dewatering of process products, for example ball mill discharge and flotation tailings. A hydrocyclone consists of a downward pointing cone through which a slurry is fed under pressure to produce a "whirlpool" effect. A separation of coarse from fine material is effected by the resulting centrifugal forces within the cone. A relatively coarse-grained product is discharged from the apex, known as the 'underflow' and a relatively fine-grained product is discharged from the base, known as the 'overflow'. Gold occurring in the underflow product may possibly exist as grains of free gold and may therefore be amenable to recovery by gravity processing. Hydrocyclones are effective in the processing of material in the size range 3 mm to 40 μm.

Compound water cyclones (a form of hydrocyclone composed of multi-angle cones) have been tested on fine feed material. Gold recovery of 63% was achieved with a sample containing 70% <75 μm (Wang & Poling, 1983). Pilot trials on sluice box tailings yielded gold recoveries of 92% (-840 μm) and 56% (-3 mm). It is recommended that they are used as a method of preconcentration ahead of more expensive methods such as jigs and spirals (Walsh & Rao, 1988).

Froth flotation - Froth flotation is a widely-used processing technique which exploits differences in the surface properties of minerals. Minerals with hydrophobic surfaces (either natural or due to chemical treatment) attach to air bubbles passing through a suspension and float to the surface to form a froth. Gold grain surfaces are often coated with an hydrophobic organic layer or iron oxide coatings and some are leached free of impurities (such as silver) leaving a rim of pure gold, all of these render the surface hydrophobic (Wang & Poling, 1983).

Froth flotation has the potential to be used for the recovery of fine gold. Desliming is usually required to remove material finer than 10 to 20 μm. Recoveries between 78% and 93% have been achieved (Wang & Poling, 1983). Flotation trials using amyl xanthate on different size fractions have reported gold recoveries of up to 90% (160 μm), 85 % (250 μm) and 70% (360 μm) (Lins & Adamian, 1993). Froth flotation trials have been carried out on material from old tailings ponds in Canada. The following collector combinations were tested: I) Aerofloat 208 (Sodium diethyl and sodium di-secondary butyl dithiophosphate), and ii) Aero 301 Xanthate (Sodium secondary butyl xanthate). A recovery of approximately 92% was achieved with material sized to 60 - 70% <75 μm. Sieve analysis indicated that 95% of the gold in the concentrate was <75 μm in particle-size (Cristovici, 1986). Froth flotation is effective in the processing of material in the size range 850 μm to 100 μm.

3.7.2. Chemical methods

Mercury amalgamation - Gold is commonly extracted from process concentrates using mercury which combines with gold to form an 'amalgam'. The gold is removed from the amalgam by evaporation of the mercury. Mercury is commonly added to sluice box riffles and also to grinding mills (Subasinghe & Maru, 1994). Also gold can be recovered from fine-grained tailings by washing them over a copper plate covered with mercury. Mercury amalgamation is effective for the recovery of gold from material in the size range 1.5 mm to 70 μm. Gold recovery efficiency falls for grains finer than 70 μm and typically only 65% of free gold grains finer than 75 μm are recovered. A recovery of up to 98% is quoted for one operation in Papua New Guinea (Eltham, 1984).

Mercury is occasionally poured between the riffles on a sluice box in an attempt to capture fine-grained gold. However the contact time between the mercury and the gold is not sufficient to allow amalgamation to occur. Often fine gold remains suspended in the flow of material above the riffles and does not come into contact with the mercury. Up to 30% of the mercury used in sluices in Papua New Guinea finds its way directly into local rivers. Passing the tailings over 'amalgamation units' or through mercury filled columns has been recommended as a method of recovering this fine gold. However these are ultimately unsatisfactory as they still pose a threat to the environment (Subasinghe & Maru, 1994).

Cyanidation - Cyanidation is the process whereby gold is recovered using a cyanide solution. Gold is dissolved using the cyanide solution and the resulting complex, $Au(CN)_2$, can be removed from solution by various methods (Deschenes, 1986):

i) The "Merill-Crowe" process, is used to remove the gold from the cyanide by cementation with powdered zinc.

ii) Activated carbon absorption (otherwise known as C-I-P, carbon-in-pulp) is used for the processing of ores with a high slimes content which are difficult to treat by the Merrill-Crowe process. The absorption of gold is either performed by:

- **Carbon-in-column** from solutions typically from heap leaching which are virtually free of suspended material,

- **Carbon-in-pulp** (CIP) from leach pulps typically slimes, ground ores and calcines. An alternative to CIP is RIP (Resin-in-pulp) which is easier to use and less sensitive to the influence of naturally occurring carbon.,

- **Carbon-in-leach** (CIL) whilst leaching is still in progress. Typically with ores containing carbonaceous material that could "rob" the gold from the "pregnant" (gold-bearing) solution.

The carbon is reactivated by heating to 600 to 900°C in a reducing atmosphere. Electrowinning (deposition of gold by electrolysis) and zinc cementation is used to recover the gold from the eluate.

Typical gold recovery efficiencies for cyanidation range from 95 to 99% (Marsden & Fuerstenau, 1993). Gold recovery is reported to be 80% from refractory gold ore residues from France (ground to 80% finer than 31 μm) (Lucion & Cuyper, 1993). Gold recovery is reported to be approximately 82.5% from the processing of uranium mill tailings at Cluff Lake, Saskatchewan. It was found that gold loss to tailings was associated with natural carbon present in the uranium tailings (Melis & Rowson, 1989). Cyanidation trials were carried out on material from old tailing ponds. A recovery of 90.5% was achieved using material 60% <75 μm (Cristovici, 1986). Cyanidation is more effective for finer grained gold as it relies on dissolution and is particularly effective for the recovery of gold finer than 200 μm. Free coarse gold is often recovered prior to cyanidation to avoid the cost of grinding and the extra reagents required.

3.8. Relative cost and environmental impact of gold recovery methods

Table 16 gives relative ranking to gold recovery methods in terms of their financial cost (capital and operating) and also their impact on the environment.

Table 16. Relative cost & environmental impact of gold recovery methods

Recovery method	Cost	Environmental impact
Sluice box	1	1
Jig	3	1
Shaking table	2	1
Spiral	3	1
Rotating cone	2	1
Bowl	4	1
Drum	4	1
Magnetic separation	4	1
Electrostatic separation	4	1
Hydrocycloning	2	1
Froth flotation	3 - 4	4
Amalgamation (mercury)	2	4
Cyanidation	3 - 4	4

N.B. Ranking from low (1) to high (4).

3.9. Typical large-scale gold processing flowsheets

3.9.1. Alluvial gold processing

Extraction - Typically by hydraulic sluicing or dredging.
Feed preparation - Drum scrubbing & trommel screening. Coarse material (>10 mm) to tailings. Fines dewatered by hydrocyclone. Fine screening (e.g. 500 μm) optional.
Primary processing - Riffled sluice or jig concentration. Coarse tailings removed.
Secondary processing - Shaking table or bowl concentrator. Fine tailings removed.
Fine processing - Spiral and shaking table concentration to process fine material.
Gold production - Amalgamation of concentrates with mercury to extract gold.

3.9.2. Hard rock gold processing

Extraction - Open cast bench mining or deep mining.
Feed preparation - Primary jaw or gyratory crusher (e.g. to <150 mm) followed by secondary milling (e.g. ball-, rod- or semi-autogenous milling). Size classification by screening or hydrocycloning.
Coarse processing (>500 μm) - Jig and shaking table or bowl concentration.
Fine processing (<500 μm) - Reichert cone concentration followed by spiral and/or shaking table concentration. Froth flotation of very fine material (e.g. <180 μm).
Gold production - Coarse concentrate by amalgamation. Fine concentrate by milling and CIP cyanidation.

4. RECOMMENDATIONS FOR FINE GOLD RECOVERY

The review of separation techniques shows that several methods are effective for the recovery of gold coarser than approximately 100 μm but for gold finer than approximately 50 μm only chemical methods are very efficient. The efficient recovery of gold coarser than 50 μm should be possible using simple gravity methods and some recommendations for possible implementation are given below. If there is evidence that there is significant gold finer than 50 μm a cyanide treatment of the fine tailings is necessary for recovery.

These recommendations apply to gold recovery by sluice box. Figure 6 summarises the main recommendations made for their use in small-scale gold processing.

4.1. Improvements to current practice

Optimise clean-out

The time interval between clean-out of sluice box riffles is dependent upon the nature of the material processed and the operating conditions applied. It is recommended that the time interval should be short enough to enhance the recovery of fine gold (that would otherwise be lost due to solids packed around the riffles). However this should be tempered by the requirement to maintain a relatively high throughput, which if reduced by too much cleaning will ultimately reduce gold production.

Appropriate configuration

It is recommended that the tilt of the sluice box should increase with increasing particle-size. Typically (in the Yukon, Canada) for material finer than 1 mm 7 to 12° is used and coarser than 1 mm 12 to 14°.

Appropriate operating practice

Appropriate feed and wash water rates are dependent upon the nature of the material being processed, especially the particle-size (and also the clay and /or heavy mineral contents). It is recommended that the feed and wash water rates are high enough to enable the efficient separation of coarse grained gold without excessive loss of fine grained gold.

4.2. Process modifications

Washing prior to sluicing

It is recommended that gold ore with a significant proportion of clay-bound and weakly-cemented material be washed ('scrubbed') and screened prior to sluicing. This will enable the liberation of gold trapped in clay.

Processing coarse and fine separately

Operating conditions appropriate for the recovery of coarse-grained gold are different to those for fine-grained gold. Typically material containing coarse and fine grained gold will be processed on the same sluice. This will invariably lead to a loss of gold. Ideally coarse gold should be recovered on a steep sluice using high feed and wash rates, whereas fine gold should be recovered on a shallower sluice using lower feed and wash rates. It is recommended that ore is screened prior to sluicing and the resulting coarse and fine streams be diverted down different sluices. This will improve overall gold recovery.

Expanded metal and angle iron sluice riffles

The use of alternative riffles will enable a higher recovery of gold. Expanded metal riffles are recommended for gold finer than 1 mm and angle iron riffles for gold coarser than 1 mm.

4.3. Efficient alternatives

Replace sluices with jigs

Jigs are efficient in the recovery of gold down to 75 μm and have been used to replace sluices, with a resultant increase in gold recovery.

Introduce shaking tables and bowl concentrators to concentrate fine gold

Shaking tables and bowl concentrators are efficient in the recovery of gold down to at least 40 μm and are used to process fine gold-bearing ore. It is recommended that these are considered for the recovery of fine gold that is not recovered by sluice box.

5. CONCLUSIONS

5.1. Alluvial gold has a particle-size range typically between 5 mm and 100 μm (however there is little information about the amount of gold finer than 100 μm). Hard rock gold has a wide range of particle-size depending upon the nature of the ore, and in some cases down to less than 5 μm.

5.2. Gold is usually recovered by a combination of physical and chemical processing methods. Commonly riffled sluice boxes and jigs are used to pre-concentrate heavy minerals (including gold) from gold-bearing ore. Shaking tables, spirals, rotating cones and bowl concentrators are used to upgrade this to a heavy mineral concentrate. Gold is commonly extracted from fine-grained concentrates by Carbon-in-pulp cyanidation and from coarse-grained concentrates by mercury amalgamation.

5.3. The efficiency of gold recovery depends upon the processing method and the proficiency of operation. A well operated modern sluice box can potentially recover up to 98% of gold coarser than 100 μm. However gold finer than 100 μm will be lost unless a fine processing method (e.g. shaking table or bowl concentrator) is used to reprocess the fine tailings.

5.4. If small-scale operators can be made to work at efficiencies close to that achieved by large companies, and in the laboratory, this will be as good as, and often superior, to mercury amalgamation.

5.5. Recommendations for the recovery of fine gold include improving current operating practice, modifying the process used, and introducing more efficient alternatives.

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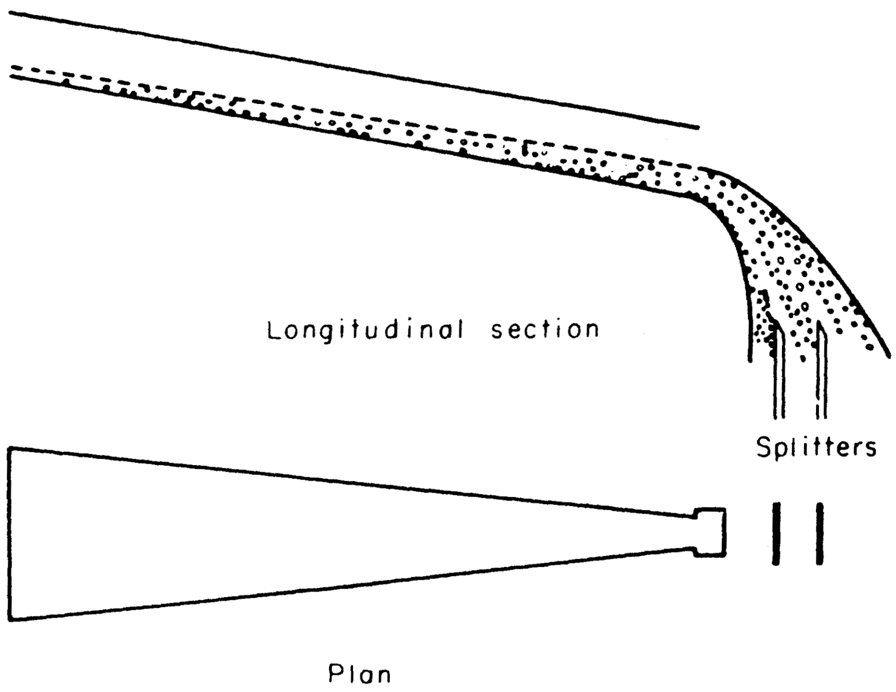

Figure 1. Schematic outline diagram of a pinched sluice

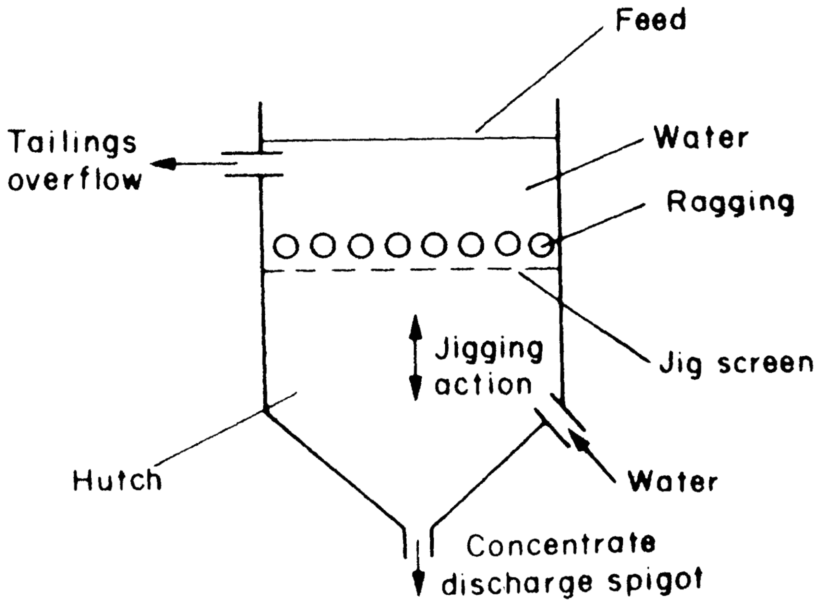

Figure 2. Schematic outline diagram of a mineral jig

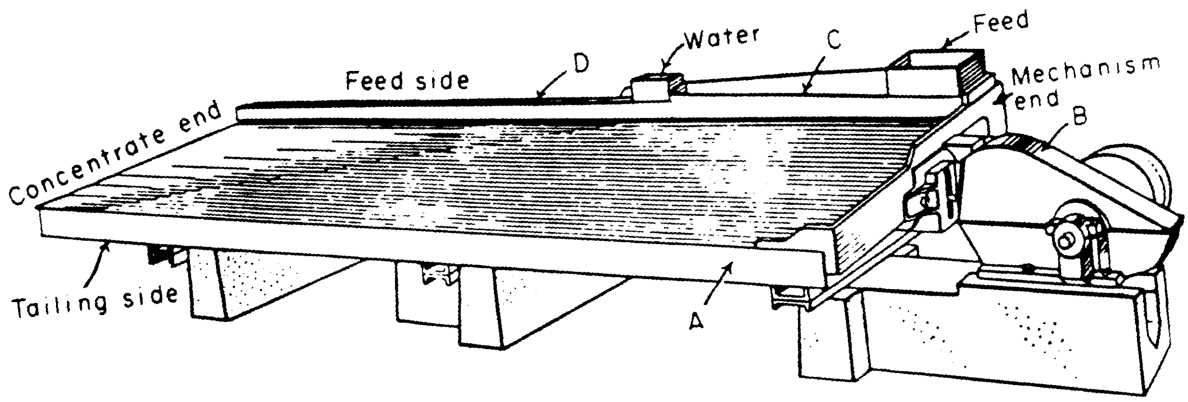

Figure 3. Schematic outline diagram of a shaking table

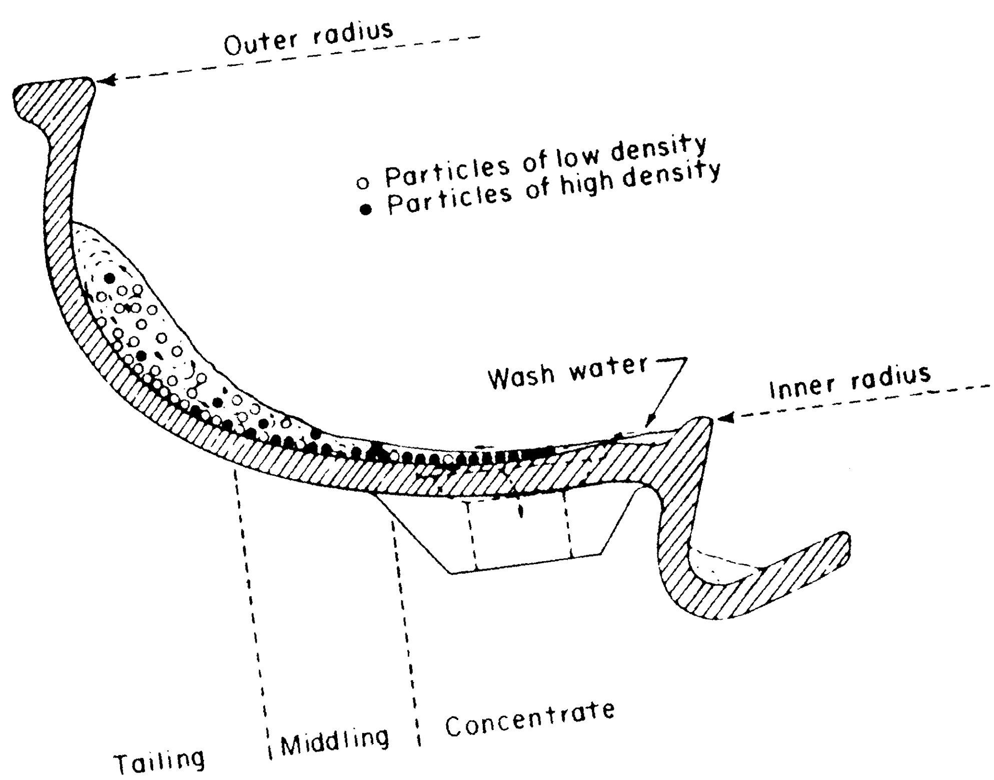

Figure 4. Schematic outline diagram of a mineral spiral (cross section)

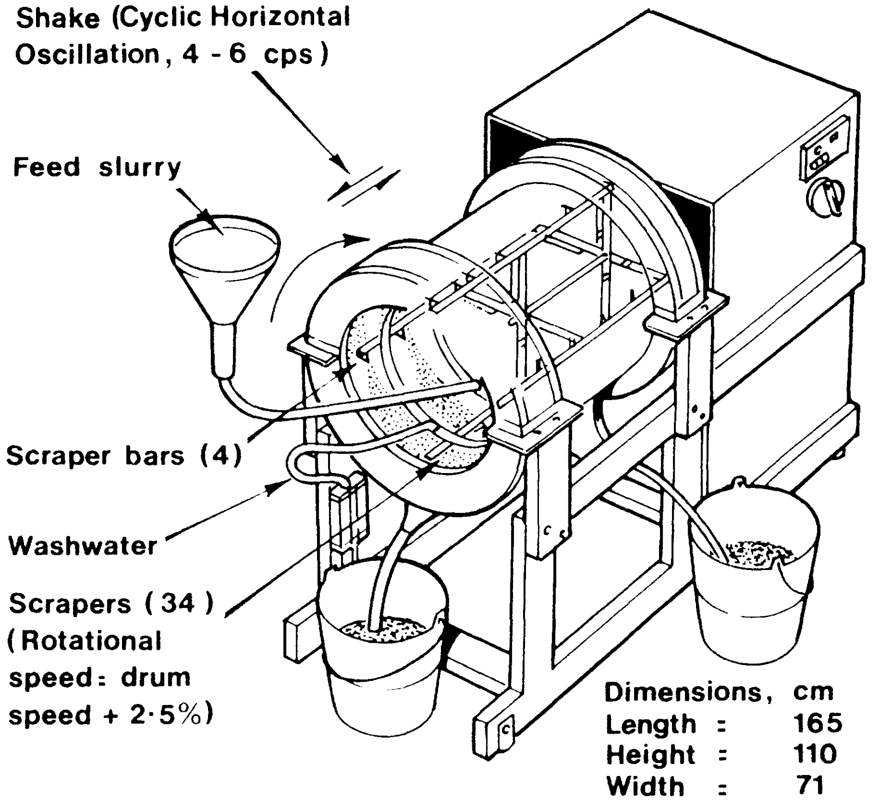

Figure 5. Schematic outline diagram of an MGS (Multi-gravity separator)

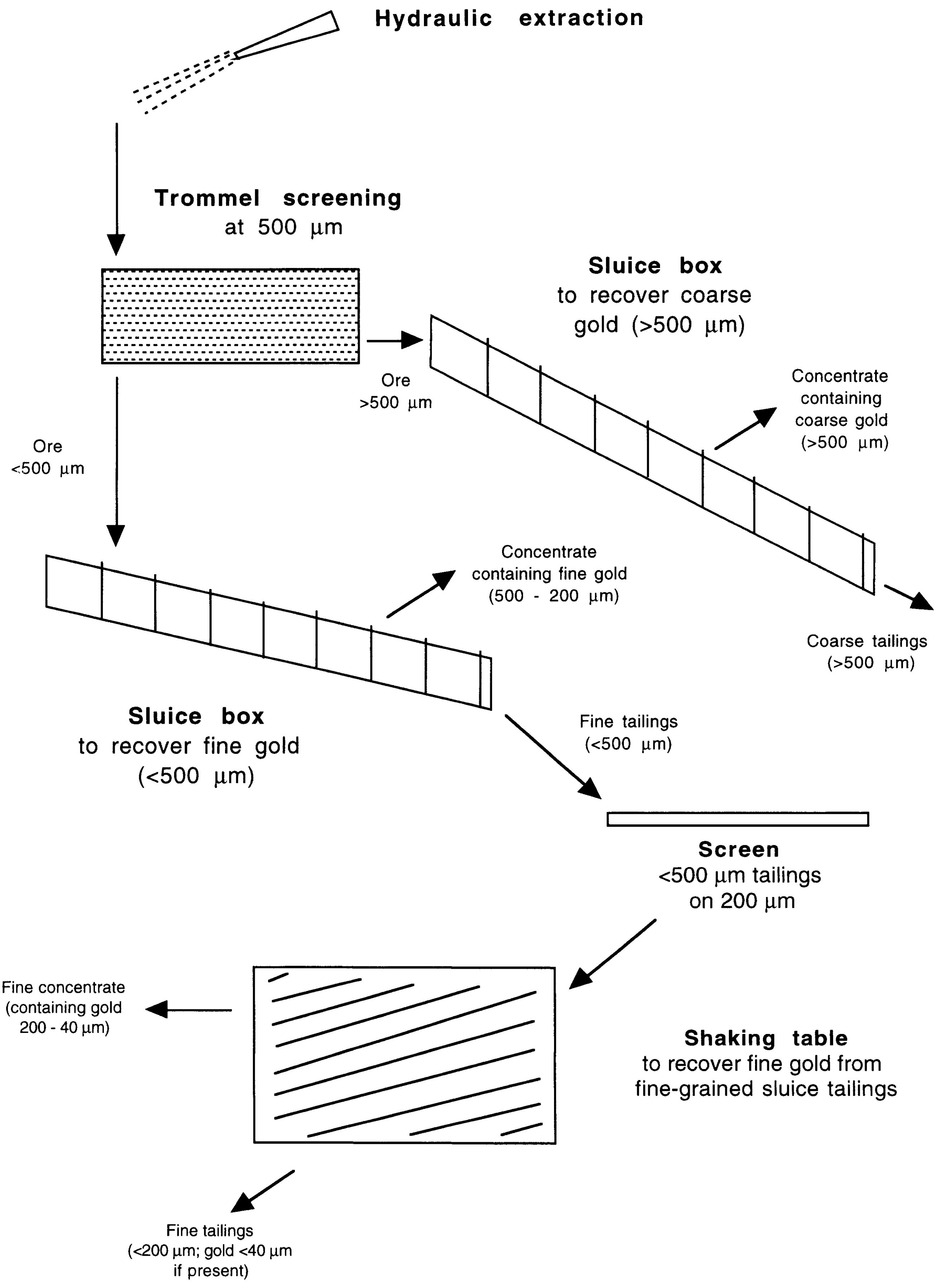

Figure 6. Recommended small-scale sluice box processing