

TREATMENT AND MICROSCOPY OF GOLD AND BASE METAL ORES.

(Script with Sketches & Tables)

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CONTENTS

(Script)	page
1. Gold ores and their metallurgical treatment	2
1.1 Gravity processes	2
1.2 Amalgamation	2
1.3 Flotation and subsequent processes	2
1.4 Leaching processes	3
1.5 Gold extraction processes	4
1.6 Cyanide leaching vs. thio-compound leaching	5
2. Microscopy of gold ores and treatment products	5
2.1 Tasks and problems of microscopical investigations	5
2.2 Microscopy of selected gold ores and products (practical exercises)	6
3. Base metal ores and their beneficiation	7
3.1 Flotation	7
3.2 Development of the flotation process	7
3.3 Principles and mechanisms of flotation	7
3.4 Column flotation	9
3.5 Hydrometallurgy	10
4. Microscopy of base metal ores and milling products	10
4.1 Specific tasks of microscopical investigations	11
4.2 Microscopy of selected base metal ores and milling products (practical exercises)	13
5. Selected bibliography	14
 (Sketches & Tables)	
Different ways of gold concentration	15
Gravity concentration of gold (Agricola)	16
Gravity concentration of gold ("Long Tom")	17
Shaking table	18
Humphreys spiral concentrator	19
Amalgamating mills (Mexican "arrastra", Chilean "trapiche")	20
Pressure oxidation flowsheet	21
Chemical reactions of gold leaching and cementation	22
Cyanide solubilities of selected minerals	23
Heap leaching flowsheet	24
Carbon in pulp process	25
Complexing of gold by thio-compounds	26
Relation gold content / amount of particles in polished section	27
Economically important copper minerals	28
Common zinc minerals	29
Selection of flotation reagents	30
Design and function of a flotation cell	31
Column cell flotation	32
Flowsheet of a simple flotation process	33
Flowsheet of a selective Pb-Zn flotation	34
Locking textures	35



1. Gold ores and their metallurgical treatment

Only a few minerals are important as gold carriers. Native gold is by far the most important, followed by gold tellurides. Other gold compounds are economically irrelevant. There is a series of minerals that can carry gold as a physical constituent such as pyrite and arsenopyrite.

The mineralogy determines the recovery process of gold. Two types of gold ores can be distinguished: **Non refractory** ores and **refractory** ores. Non refractory gold ores permit a straightforward recovery by a relatively simple conventional technology. Refractory gold ores, however, require rather sophisticated recovery techniques. **Different ways of gold concentration (p15).**

1.1 Gravity concentration

Gravity concentration is the oldest technique for gold recovery. It makes use of the high specific gravity of gold that amounts to 19.3. The devices developed and used for gravity concentration are innumerable. The most common ones are: Sluice boxes, rocker boxes, shaking tables, jigs, spirals, centrifugal concentrators, and dry washers. The limits of gravity concentration are mainly determined by the size and shape of gold particles: Particles of less than 30 microns size can hardly be recovered by gravity and tiny flakes do not settle as fast as rounded grains.

The flow sheet of a gravity process is rather simple. It generally consists of a conditioning and sizing of the feed material followed by one or two stages of gravimetric gold recovery. **Gravity concentration of gold, Agricola (p16), "Long Tom" (p17). Shaking table (p18). Humphreys spiral concentrator (p19).**

1.2 Amalgamation

The **amalgamation process** is based on the low surface tension between gold and mercury, which permits gold particles to be wetted and enclosed exceedingly well by the liquid metal forming an amalgam. The physical properties of an amalgam permit its recovery by elutriation (desliming), cycloning or another gravity process. Filter pressing removes surplus mercury. Heating of the filter cake evaporates the mercury, and the remaining material is a gold concentrate that can be smelted down to a gold bullion. **Amalgamating mills: Mexican "arrastra", Chilean "trapiche" (p20).**

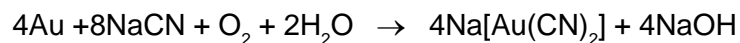
1.3 Flotation and subsequent processes (refractory ore processing)

The flotation process is described in detail in chapter 3.3. Native gold, gold tellurides, and sulphides that contain finely disseminated gold can be floated and recovered in a concentrate. In gold metallurgy flotation is often used as a pre-enrichment process for refractory ores. Subsequent stages of gold recovery may require oxidation and leaching steps. Regrinding of an auriferous sulphide concentrate can create access for a leaching solution and permit the gold to be recovered. If this is not the case, the auriferous sulphides have to be chemically destroyed to liberate the gold. This can be achieved by **roasting** or **pressure oxidation** that transform leaching resistant gold carriers into porous oxides or oxidic residues that can be leached. A third alternative to degrade gold carriers is **bio-oxidation** by means of Thiobacillus and Leptospirillum bacteria. **Pressure oxidation flowsheet (p21).**

1.4 Leaching processes

Leaching is a hydrometallurgical method that permits the beneficiation of gold ores from deposits which would else be uneconomic because of their fine gold distribution or their relatively low gold grades. Leaching processes, however, are not limited to such ores.

The **chlorination process**, which is obsolete by now, used chlorine gas that was conducted through wet, precrushed gold ore forming soluble gold chloride that could be washed out with water. The dissolved gold was eventually precipitated from the aqueous solution by ferrous sulphate. The rather common **cyanide leach process** is based on the selective solubility of gold in a weak cyanide solution. The chemical principles of gold leaching by sodium cyanide are the following:



The essential requirements for a good gold recovery are adequate cyanide and oxygen levels as well as a p_{H} – value between 10 and 12. The normal cyanide consumption per tonne of ore is in the order of 100 – 500g. The presence of cyanide soluble minerals, so called cyanicides or cyanide killers (e.g. secondary copper sulphides) increases cyanide consumption; under certain conditions cyanide consumption can reach levels that render a leaching operation uneconomic. The approximate tolerable level for cyanide soluble copper is definitely below 0.5%. **Cyanide solubilities of selected minerals (p23).**

Presuming ideal conditions the solubility rate of pure metallic gold is 3,25mg/cm²/hour. At such a rate a gold grain of 30 microns size would dissolve within 9 hours, a 150 microns diameter gold particle would need almost 45 hours. Therefore leaching processes are often combined with gravity circuits that serve for the recovery of coarse gold particles.

A cyanide leaching process can be conducted under different technical conditions. An effective technique for well leachable high grade gold ores is **agitation leaching**. Thereby an ore pulp with grain sizes of < 100 microns is permanently agitated during its leaching in special tanks (e.g. Pachuca tanks). The leaching period is generally less than 24 hours. The gold recovery lies usually above 90%.

A second technique is **vat leaching**, which also requires well leachable ores. The required grain sizes of < 1 cm are much coarser as compared to agitation leaching because in vat leaching the ore is not agitated in the leaching tanks and only coarse material warrants a good permeability. Grain sizes of < 2 mm are disadvantageous as they tend to block the free circulation of the leaching agent. The leaching period is 2 – 4 days and gold recovery lies in the order of 70 – 80%.

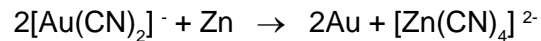
The cheapest but slowest technique is **heap leaching**. It is a process usually applied to low grade gold ore. Basically the ore is piled to a given height on an inclined impermeable surface, a so called leach pad. A sprinkler system provides a continuous spray of alkaline cyanide solution that percolates through the ore dissolving the gold. The gold bearing or pregnant solution is collected and pumped to a gold recovery plant. The amount of material contained in a heap can reach more than 100.000 t. The leaching time ranges from several weeks to a few months. The gold recovery hardly exceeds 70%. **Heap leaching flowsheet (p24).**



1.5 Gold extraction

After dissolving the gold by a cyanide solution the metal can be extracted from the liquor by **cementation** or **adsorption**.

Cementation of dissolved gold from the leaching solution is performed by pulverised zinc (Merrill-Crowe process).



As soon as the zinc dust is added almost the complete gold content of the liquor is immediately precipitated and the cementate can be filtrated and melted to a gold bullion. Before smelting the cementate is washed with acid in order to remove the remainder of zinc.

The **adsorption** of gold from cyanide solution makes use of the natural affinity of gold for carbon. During adsorption the entire gold cyanide complex becomes attached to the carbon. The gold attached to the carbon is then desorbed by a cyanide solution from which it can be recovered by electrolysis. The desorbed or “stripped” carbon can be regenerated by heating it at approx. 600 °C for 30 minutes in absence of air. From a head value of approx. 2g of gold per tonne of solution a carbon loading of up to 15 kg gold per tonne of carbon is achieved leaving as little as 0,01g of gold per tonne of solution in the tailings.

There are essentially three process varieties that use carbon adsorption:

- The **carbon in pulp (CIP) process**,
- The **carbon in leach (CIL) process** and
- The **carbon in column (CIC) process**.

During the **CIP process** activated carbon particles are added to the leached pulp in a counter current circuit. The counter current principle is important because the amount of gold adsorbed on the carbon is in equilibrium with the residual gold concentration in the solution, and therefore the low gold concentrations in the final stage can be adsorbed only if the pulp in this stage is contacted with unloaded carbon. The considerable difference in grain size between carbon and pulp particles permits an easy separation of the two by sieving. Whereas pulp particles generally do not exceed 100 microns, the carbon granules appear in fractions between 1 and 3 mm. **Carbon in pulp process (p25).**

The **CIL process** and the **CIC process** are essentially variations of the carbon in pulp technique that are used under special conditions.

In principle adsorption can also be accomplished by **ion exchange technology** with artificial resins. The disadvantages of the existing resins, however, prevented their wider spread use (they are expensive, most of them are non selective for gold and difficult to strip, and if they are selective and easy to strip their loading capacity is very low).

1.6 Cyanide leaching vs. thio-compound leaching

In recent years **thiourea and thiosulphate leaching** gained a certain attractivity because it was believed that less toxic or non-toxic reagents are involved. An additional argument for thiourea or thiosulphate are their high leaching rates that can reach 250mg/cm² per hour exceeding cyanides almost by a factor of 100. The technical implementation of a thio-compound leaching process, however, implies a series of problems and therefore we see very few operations that apply thiourea as an alternative lixiviant. Another adverse factor are the high costs for the reagents because of high reagent consumptions as compared to sodium cyanide. The gold leaching reaction by thiourea and thiosulphate is very sensitive to p_H and redox potential and both chemicals are intrinsically unstable decomposing readily to substances that are unable to leach gold. **Complexing of gold by thio-compounds (p26)**. This means that process control is difficult and reagent recycling is very limited if not impossible. The seemingly low toxicity of the two compounds as compared to cyanide is only valid regarding their lethal toxicity. Decomposition of thio-compounds generates a series of partly highly toxic products that must not be released into the ecosystem. In addition to this thiourea is suspected to be carcinogenic.

2. Microscopy of gold ores and treatment products

Gold minerals and especially native gold can generally be identified very well by ore microscopy because of their distinctive optical properties. Nevertheless gold microscopy has its peculiar difficulties. Above all ranges the usually low gold content of the ores, which makes it often hard to find any gold in polished section. This can often be achieved only after time consuming studies of several sections. Another complicating factor consists in the frequently small sizes of gold particles, which require the use of high magnifications.

Gold tends to show an irregular distribution in the ore. This is the case on macroscopic and even more so on microscopic scale. The fact that gold cannot be detected in the very first section of an high grade ore must not lead to the conclusion that it occurs in a submicroscopic form, e.g. in sulphides. Once detected we shall find that there are local concentrations or clusters, often in association with specific properties of the ore such as siliceous or ferruginous parts or in zones of microfracturing. These environments can be looked after in order to observe microscopic gold more easily. If, however, no gold minerals can be found after the study of a reasonable amount of sections, electronoptical and microanalytical investigations should be considered. By using these tools submicroscopical or chemically bonded gold will generally be detected. **Relation gold content / amount of particles in polished section (p27)**.

2.1 Tasks and problems of microscopical investigations

The main task of gold ore microscopy with regard to metallurgical treatment is the assessment of all relevant parameters that influence the recovery process. The mineralogy of the ore determines the recovery process. The decisive mineralogical factors are in particular:

The mineral assemblage (native gold, gold tellurides, auriferous sulphides; acid generating and oxygen consuming minerals such as pyrrhotite, marcasite, and melnicovite pyrite; cyanide soluble copper minerals such as chalcocite, digenite, covellite or stibnite; clay minerals; carbonaceous matter)

Textures and particle sizes of the gold minerals (free or locked gold; native gold at grain sizes that permit gravity concentration or sizes that require a leaching process)

It is often useful to study the intermediate products and tailings of a gold recovery process in order to discover the reasons for potential gold losses. When refractory ores are roasted prior to cyanidation “flash roasting” may convert the enclosing sulphide into a non porous iron oxide that shields the gold inclusions from cyanide solutions.

2.2 Microscopy of selected ores and products

Callion / Australia ++ (2 sections): Auriferous limonite concentrate; gold is associated with limonite in which it occurs as rather small inclusions; isolated colloform textures of the gold indicate a simultaneous precipitation of gold and iron hydroxides rather than in situ relics of gold inclusions in former pyrite.

El Callao / Venezuela +++ (7 sections): Gold is associated with quartz (3 sections) and pyrite (2 sections). Auriferous pyrite concentrates (2 sections); gold occurs intergrown with pyrite, both in coarse lockings and as tiny inclusions.

Hillgrove / Australia +++ (2 sections): Auriferous sulphide concentrates; gold occurs intergrown with accompanying pyrite, arsenopyrite, and stibnite.

Kotchbulak / Uzbekistan +++ (4 sections): Native gold and gold tellurides.

Rheingold / Germany +++ (2 sections): Gold gravity concentrate; flakes and grains.

Salsigne / France + (3 sections):

Sol de Oro / Peru ++ (4 sections): Auriferous crude ore; gold occurs as inclusions in primary ore (pyrite) as well as in supergene ore (quartz and limonite).

- + traces of gold
- ++ accessory gold
- +++ abundant gold

3. Base metal ores and their metallurgical treatment

In early days of mining ores could be enriched only by hand picking and gravity concentration. These simple techniques limited the ores that could be used by mankind to a few types. Those were all fairly coarse and easy to separate from barren gangue. Most of the base metal sulphides mined today would have been useless because of their fine and complex nature. Only after the invention of a new technology called **flotation** the development of a new type of base metal deposits became possible.

Flotation works well with most sulphide ores and is definitely the most widespread recovery method for base metal ores. Of course it is no remedy for all types of ores. There is a series of oxides and sulphates that possess high metal contents. In deposits where they represent the main ore other recovery methods may have to be applied (many important porphyry copper deposits e.g. contain such minerals as Antlerite or Brochantite which are best recovered by leaching and precipitation with scrap iron).

In recent years **hydrometallurgy** has gained a growing importance in mineral beneficiation. Hydrometallurgical methods permit the utilization of low grade or mineralogically complex material whose conventional treatment would be uneconomic or technically difficult. **Economically important copper minerals (p28). Common zinc minerals (p29).**

3.1 Flotation

Flotation is a technology for the separation of fine particles of different materials. It is widely used in a variety of fields such as recycling of plastics, paper, etc. At present flotation is the only process available that permits the production of ore concentrates from those fine grained base metal sulphides mined today at the majority of deposits.

3.2 Development of the flotation process

The beginnings of flotation technology date back to the middle of the 19th century, when it was realized that metallic minerals become preferentially wetted by oil and gangue minerals preferentially by water (HAYNES, 1860).

In 1877 BESSEL patented a process that shows already all the essentials of a modern flotation. The process had been developed for the recovery of graphite mined at the Bavarian deposit of Kropfmühl. An aqueous slurry of ground graphite ore with additives of oil or grease was heated to boiling in order to generate steam bubbles. The oily graphite flakes would then get attached to the bubbles and float to the surface where they could be recovered in a graphite rich foam.

The following development of flotation technology took place mainly in Australia and the United States of America. In the twenties of the past century KELLER made use of xanthates as collectors for sulphides. The xanthates are well defined water soluble reagents that replaced the different types of oil with their rather inconsistent properties. Xanthates still remain the most common sulphide collectors.

3.3 Principles and mechanisms of flotation

Flotation is based on differences in the physico-chemical surface properties of minerals. These properties are either already existent or they are induced by corresponding reagents.

A flotation system consists of three different phases represented by water, air, and solid particles. The process takes place in flotation cells. In those cells the fine grained solids are maintained in suspension by agitators or impellers. At the same time a continuous stream of air bubbles rises from the bottom to the top of the cell. For mineral separation certain minerals have to attach to the bubbles which take them to the surface. There the bubbles have to form a stable froth that can carry the floated mineral particles until they are removed from the top of the cell. **Design and function of a flotation cell (p31).**

Before submitting an ore to flotation it has to be ground to floatable grain sizes. In order to defy the laws of gravity with the help of an air bubble a mineral particle must not exceed certain dimensions, which depend on the specific gravity of the mineral. The upper size limit rarely exceeds 500 microns and is usually below 300 microns. Optimum results are generally obtained with particle sizes ranging from 10 to 100 microns. With particles below 10 microns there are phenomena that strongly affect flotation: Extremely fine particles, so called “slimes”, tend to lose their chemical identity in favour of physical forces that become more and more dominant.

The floatability of a mineral mainly depends from its ability to adhere to air bubbles. This ability is controlled by the surface properties of the mineral. Mineral particles that get readily attached to air bubbles are water repellent or **hydrophobic**, those that do not attach are **hydrophilic**.

More or less polar minerals such as most sulphides have to be conditioned by chemical reagents, so called **collectors**, before they can be recovered by flotation. The collectors are added to the pulp in special conditioning tanks. Collectors are complex organic chemicals that usually possess a polar and a non polar end. The polar end is adsorbed to the polar mineral surface leaving the non polar end toward the water. So the conditioned mineral achieves a water repellent characteristic and gets easily picked up by a rising air bubble. There are also non polar collectors that render a mineral hydrophobic by covering its surface with a thin film. The consumption of a xanthate collector per tonne of ore lies between 20 and 200g.

In addition to collectors **frothers** have to be added to the pulp to create persistent bubbles and to produce a froth stable enough to carry the load of floated minerals at the top of the flotation cell. Generally, frothers are surface active agents that are adsorbed to the air-water interface reducing the surface tension and thereby stabilising the air bubbles. Common frothers are pine oil, alcohols, and certain soaps. The consumption of pine oil ranges between 10 and 100g per tonne of ore.

Finally there are a series of chemical reagents known as **regulators** or **modifiers** that are used to enhance or diminish the floatability of minerals thereby permitting the selective flotation of particular minerals. The regulators are subdivided into **activators** and **depressors**, **p_H-regulators** and **deflocculants**.



Activators make a mineral surface more amenable to the adsorption of a collector. They are generally soluble salts which ionise in solution e.g. copper sulphate that activates sphalerite due to its copper ions during flotation with xanthates.

Depressors prevent undesired minerals from floating. They render a mineral surface inactive to a collector by forming a coating on it. Thus the collector cannot connect and the mineral becomes unfloatable.

In selective flotation a strict p_H control is essential. P_H -regulators such as lime or sulphuric acid provide an optimum p_H environment that is needed for flotation of a particular mineral. Generally there is a critical p_H above which a mineral will not float.

Dispersing agents or defloculants are used to control an accumulation of ultra fine particles ("slimes"). These slimes would otherwise adsorb on the surfaces of the minerals to be floated and affect the selectivity of a flotation process. Additionally they would increase the consumption of flotation chemicals by adsorbing them to their large specific surfaces. The amounts of modifiers used per tonne of ore vary as widely as their applications; they range from several grams to a few kilograms. **Selection of flotation reagents (p30).**
Flowsheet of a simple flotation process (p33).

Flotation is a continuous process. The crude ore which has been ground to an appropriate grain size gets to a **conditioner** where flotation chemicals are added. The conditioned ore pulp is then pumped to the **rougher flotation** in which all floatable minerals are recovered. The portion of hydrophobic minerals in the pulp decreases from the first to the last flotation cell of the rougher stage because they are floated in each cell. Theoretically only gangue minerals remain in the pulp which is pumped to the tailings. The relatively impure preconcentrate of the rougher cells then gets to a **cleaner flotation** in which gangue particles that floated with the ore minerals are depressed to the tailings. The tailings of the cleaner stage can be passed through an additional **scavenger flotation** in which the few ore particles still remaining in the pulp can be recovered. Until a final concentrate is obtained the pulp has often passed several cleaner and recleaner stages. This is done to produce a concentrate as clean as possible and to minimize losses in ore recovery. **Flowsheet of a selective Pb-Zn flotation (p34).**

If the ore contains more than one type of valuable mineral we can usually decide between two options. The first is to recover all the valuable components by **collective flotation** in one single product called **bulk concentrate**. This can often be done by a simple flotation plant. The second option to recover different minerals from one ore is a **selective flotation** that produces **selective concentrates**. Such an operation requires much more sophisticated installations. Usually the valuable minerals are recovered in sequence, one by one. In sulphide flotation the most hydrophobic or the easiest to float are recovered first, followed by the flotation of minerals that are more difficult to float.

3.4 Column flotation

Column flotation is special technique that has been developed fairly recently as an alternative to conventional flotation. It is mainly used in the cleaning applications of sulphide flotation, where its ability to wash the froth off entrained gangue particles results in a higher grade product. In addition to this distinct advantage over conventional technology column flotation possesses significantly lower capital and operation costs and permits a superior process control. **Column cell flotation (p32).**



Column flotation is carried out in tower like flotation cells. The cells are usually round and can measure over 10m in height and over 3m in diameter. Instead of an impeller that agitates the pulp and disperses the air, air is introduced at the bottom of the cell either by an internal sparger or an external bubble generator. The ore pulp is fed in the upper part of the column. As the bubbles rise up through the pulp they get in contact with the descending solids and contact is made in the **collection zone**. After attaching to the bubbles the ore minerals rise into the **cleaning zone**, where the mineralised froth is cleaned by a downward flowing stream of wash water. The wash water removes the rest of undesired hydrophilic gangue particles that may have got to the cleaning zone. It is essential that sufficient wash water is added to ensure that the flotation process is performed under a **positive bias**, i.e. the tailings stream flow that leaves the cell at the bottom is greater than the inflow of feed material.

3.5 Hydrometallurgy

Hydrometallurgical processes are becoming more and more important. They involve leaching the metal content from the ore, from a concentrate or from process side products in an aqueous solution. After purifying the solution to remove deleterious elements the required metal is isolated and can be extracted.

Bioleaching of low-grade ores is another example of hydrometallurgy. In this case bacterial action liberates metal ions from the ore. Bio-leaching has been successfully applied to sulphide ores, gold bearing pyrites and arsenopyrites.

Teck-Cominco developed a new, low cost process (**HydroZinc Process**) for the direct extraction of zinc metal from sulphide ores. The new process involves bio-leaching of ore in heaps with naturally occurring bacteria, followed by neutralization, solvent extraction and electrowinning. The process is a direct ore to metal procedure, which does not require grinding and flotation. It is applicable to a variety of zinc ores and, last not least, it is environmentally sound with no sulphur dioxide emissions involved.

The **Albion Process** was developed by Mount Isa Mines in order to optimise metal recovery from the extremely fine-grained ore of the McArthur River deposit in Australia's Northern Territory. The process requires ultrafine grinding of an ore or concentrate to particle sizes of 80% less than 20 microns. The resulting slurry then undergoes autothermal oxidation in open agitated tanks (the oxidation of sulphide minerals as an exothermic process is self-sustaining and needs no external energy). After oxidation the slurry is leached with sulfuric acid in leaching tanks and the leached slurry is neutralised to precipitate impurities, ideally to produce a goethite residue. Harmful impurities such as arsenic are fixed in the neutralised solids as ferric arsenate. The neutralised slurry is subsequently thickened, and vacuum filters are used to produce a filter cake. The filter cake is then converted back into a slurry and sent for cyanidation for gold and silver recovery. The filtrate undergoes conventional solvent-extraction and electrowinning to recover metals such as copper, zinc and nickel. Base-metal recoveries for the Albion process are typically in excess of 95%, and those for gold and silver are 90-95%.

4. Microscopy of base metal ores and milling products

The mineralogical composition and texture of a sample can be obtained only by its microscopic examination. Microscopy may be complemented by other methods of investigation such as X-ray diffractometry, spectography or microanalysis but it cannot be replaced because no other method allows us to recognise minerals in their natural form.

4.1 Specific tasks of microscopical investigations

The systematic treatment of an unknown ore is impossible without accompanying mineralogical, particularly ore microscopical investigations. Of course microscopy must not be limited to crude ores or mill feeds but accompany the whole treatment process by studying all its intermediate and final products. Together with metallurgical bench scale tests ore microscopy forms an integral part of the **predictive metallurgy**, which tries to foresee the metallurgical behaviour of an ore and the quality of its concentrates. Thus microscopy plays a decisive role in generating parameters that are needed to decide the feasibility of a mining project and to select an appropriate ore dressing process. Thereby microscopy bases essentially on the determination of the **mineral inventory** and the **mineral textures and lockings** of an ore and its treatment products.

The determination of the mineralogical composition or **mineral inventory** is certainly the first thing to do when investigating an unknown ore. It allows to establish important parameters that have an impact on the metallurgical treatment, which a chemical analysis alone cannot provide. On the contrary, a mineral inventory is indispensable to understand and explain the chemical analysis. While a chemical analysis does not tell how the analysed elements occur in an ore, microscopy shows the minerals that are formed by these elements. It shows whether deleterious elements such as As, Bi, and Hg can be eliminated by metallurgical measures or if they will report to the concentrates attracting **smelter penalties**. The penalties are deductions from the original concentrate value which may represent a substantial reduction in the revenues of a mining operation.

The importance of a proper mineral inventory can best be explained by a few examples: It is obvious that alteration phenomena affect the surface and therefore the specific behaviour of minerals during the recovery process. It is clear that sulphide ores require other treatment techniques than oxide ores. And it is also understood that the metal recovery from complex polymetallic ores differs substantially from that of simple monomineralic ones.

It makes a difference whether the copper carrier of an ore is chalcopyrite or if it is bornite. Although both minerals are treated by the same process the copper grade of a chalcopyrite concentrate hardly exceeds 30% whereas with bornite one easily obtains a concentrate containing over 40% copper. Relative to the copper contents the sulphur contents are higher or lower, a fact that is important for smelters that have to control their sulphur gas emissions.

There are minerals that affect a beneficiation process: Certain types of pyrrhotite as well as melnicovite pyrite tend to decay rapidly into sulphates after being exposed to air. The generation of large surfaces during the comminution of the ore often accelerates this oxidation process dramatically with the effect of a steep drop in the p_H value of the ore pulp that requires immediate action.



Certain elements reduce the quality of the mill products if they cannot be eliminated during flotation: Iron contents in zinc ores e.g. may originate from independent minerals such as pyrite, pyrrhotite, and magnetite or may be an integral part of the sphalerite lattice. In latter case they cannot be eliminated by means of flotation and will reduce the value of the corresponding zinc concentrate. The same is true for arsenic in copper ores; it may be bound to arsenopyrite that can be depressed during copper flotation or it may occur together with copper in the same mineral e.g. as enargite or tennantite.

The determination of **mineral textures and lockings** is the second important task of ore microscopy. It indicates the **liberation size** of a mineral which is the key parameter in ore grinding. Ore grinding which is expensive, is best performed according to the principle **as fine as necessary and as coarse as possible**, and it is the ore microscopy that provides the required supervision. Once an optimum liberation for mineral separation is obtained the ore must not be ground any further. The quantitative microscopical assessment of mineral lockings is the only appropriate tool to evaluate directly the efficiency and economy of a grinding process and to warrant its permanent control and optimisation. **Locking textures (p35).**

The following examples illustrate the metallurgical impact of mineral textures and lockings: A well known and frequent phenomenon in ore microscopy are tiny chalcopyrite inclusions in sphalerite forming an emulsion-like texture. In metallurgy this texture is called “chalcopyrite disease” and it cannot be cured because the chalcopyrite inclusions are resistant to grinding. It makes the sphalerite inclined to float with the copper minerals and it is responsible for copper losses in the zinc concentrate.

Another example that shows the limits of grinding are accessory bismuth minerals that often occur in the form of milling resistant inclusions within galena or chalcopyrite leading to painful smelter penalties for the affected concentrates.

Whenever colloform mineral textures appear we have to envisage problems due to poorly crystallised sulphides that tend to decay during the recovery process contaminating the ore pulp with all sorts of metal ions that lead to an erratic flotation behaviour.

Summing up the facts and examples just given it can be stated that ore microscopy is an indispensable and effective tool for the evaluation of an ore and its milling products. It can make very concrete predictions on the metallurgical behaviour of minerals and on the quality of the planned products. It can give specific recommendations to the metallurgist enabling him to elaborate an optimum treatment process for a given material. It helps to avoid unpleasant surprises by identifying metallurgical problems at an early project stage, and in extreme cases ore microscopy can even decide if an ore is amenable to beneficiation or not.

4.2 Microscopy of selected base metal ores and milling products (practical exercises)

Artjomovskoje / Kazakhstan (6 sections): Ore feed, Cu-conc, Pb-conc, Zn-conc, pyrite concentrate, tailings.

Bo Yai / Thailand (13 + 8 sections): Pb-Zn ore. Zn & mix conc, size fractioned.

Bou Grine / Tunisia (5 + 5 sections): Zn-Pb ore, size fractioned; Zn conc, size fractioned

Castellanos / Cuba (31 sections): Zn-Pb-Cu ore.

Cayeli / Turkey (18 sections): Cu-Zn-Pb ore.

Gataga Project / Canada (10 sections): Zn-Pb ore with abundant globular pyrite.

Sta. Lucia / Cuba (2 sections): Zn-Pb ore; fraction 75-63 micron: comparison between crushing and grinding.

Song Toh / Thailand (16 + 11 sections): Pb-Zn ore. Pb, Zn & mix conc, size fractioned.

Sotiel / Spain (24 sections): Ore feed, Cu-conc, Pb-conc, Zn-conc, pyrite concentrate, tailings.

Escondida / Chile (2 sections): High grade Cu-conc.

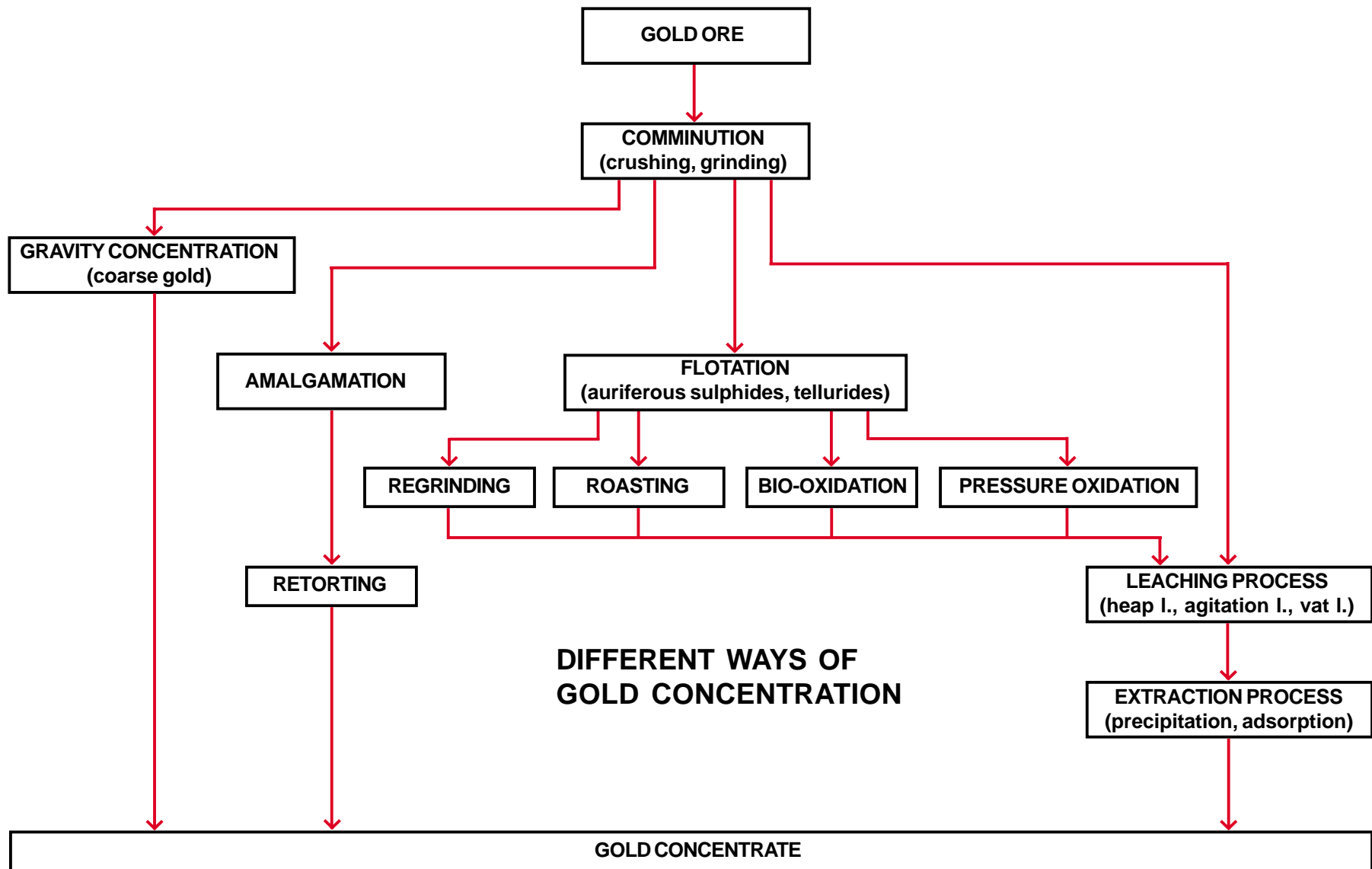
Ertsberg / Indonesia (2 sections): High grade Cu-conc.

Ok Tedi / Papua NG (2 sections): Medium grade Cu-conc.

Neves Corvo / Portugal (2 sections): Lower grade Cu-conc.

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GRAVITY CONCENTRATION OF GOLD (Agricola, 1556)

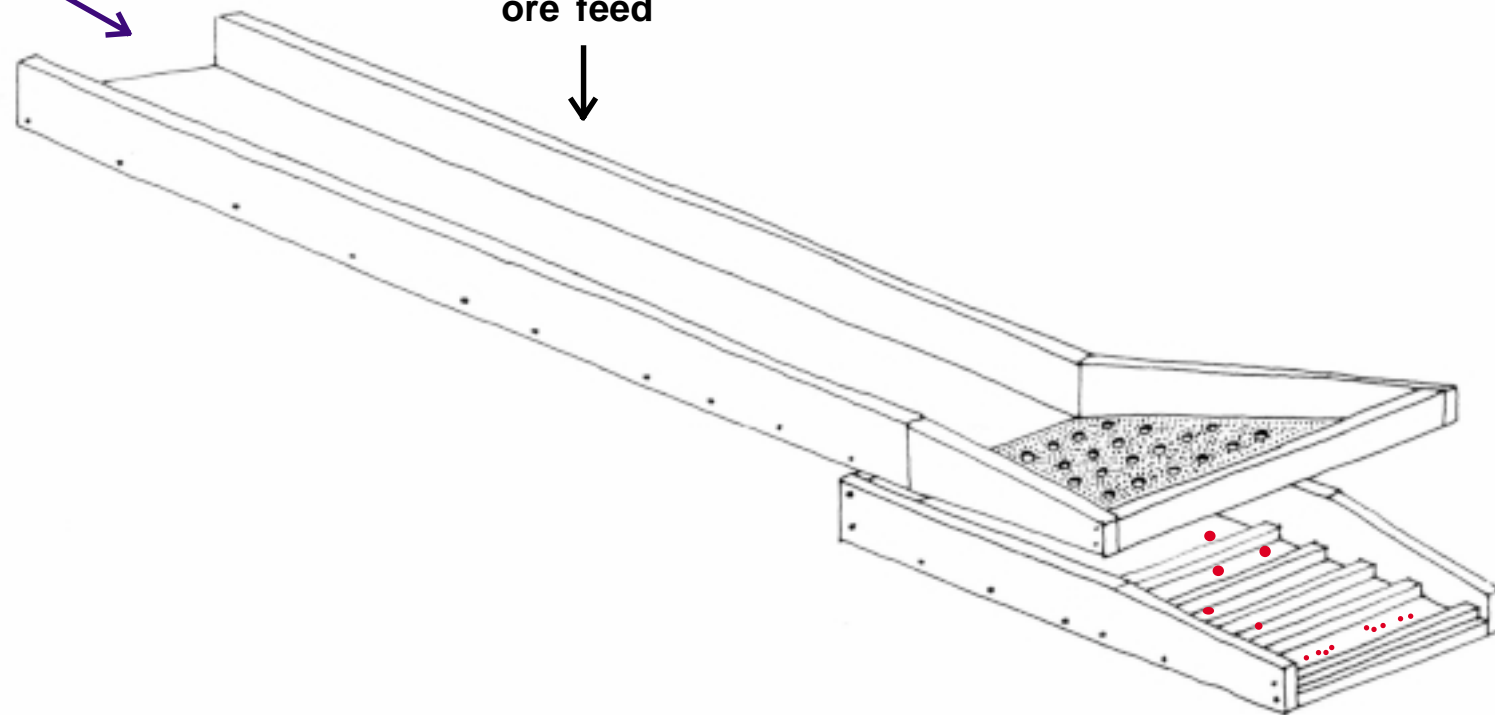
A sluice box is coated with a cloth serving as a trap for tiny gold particles. The particles are recovered by changing and washing the cloth at certain time intervals.



water inflow



ore feed



recovered gold

GRAVITY CONCENTRATION OF GOLD

“Long Tom”, a sluice box used by the Californian “Forty-Niners”

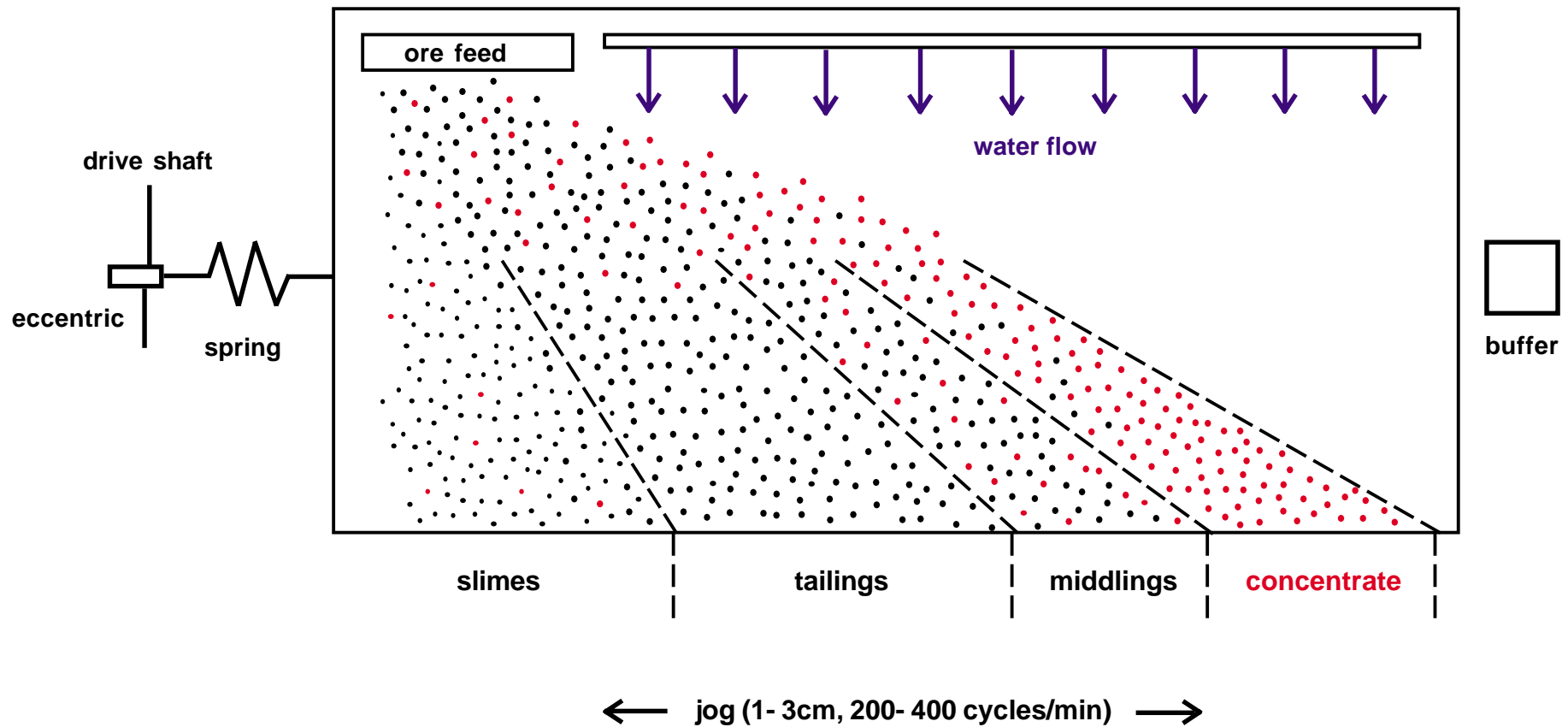


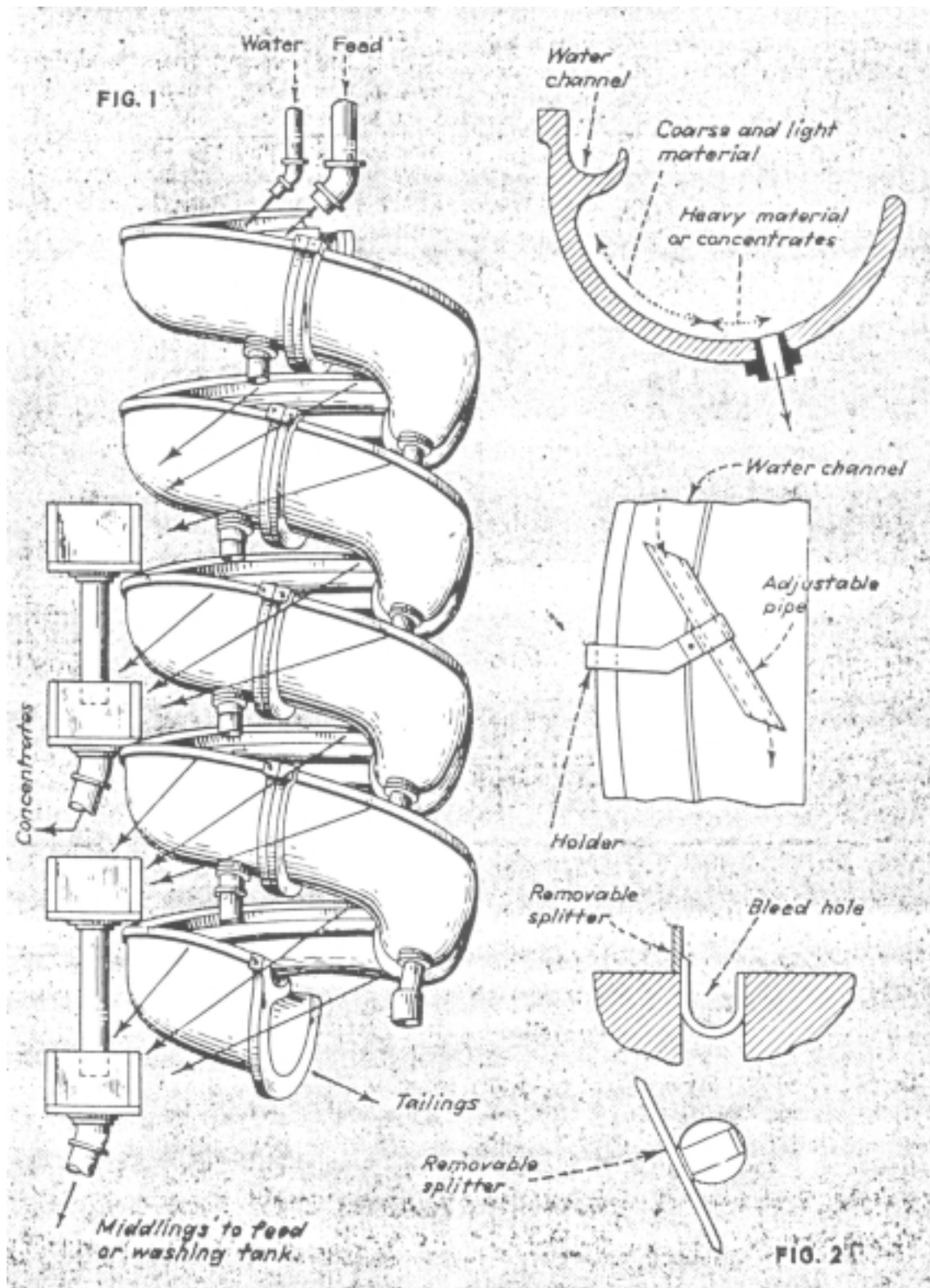
LEHNE & ASSOCIATES
APPLIED MINERALOGY

www.isogyre.com

GRAVITY CONCENTRATION OF GOLD

Working principle of a shaking table (table sizes of approx. 50x100cm - 200x500cm)

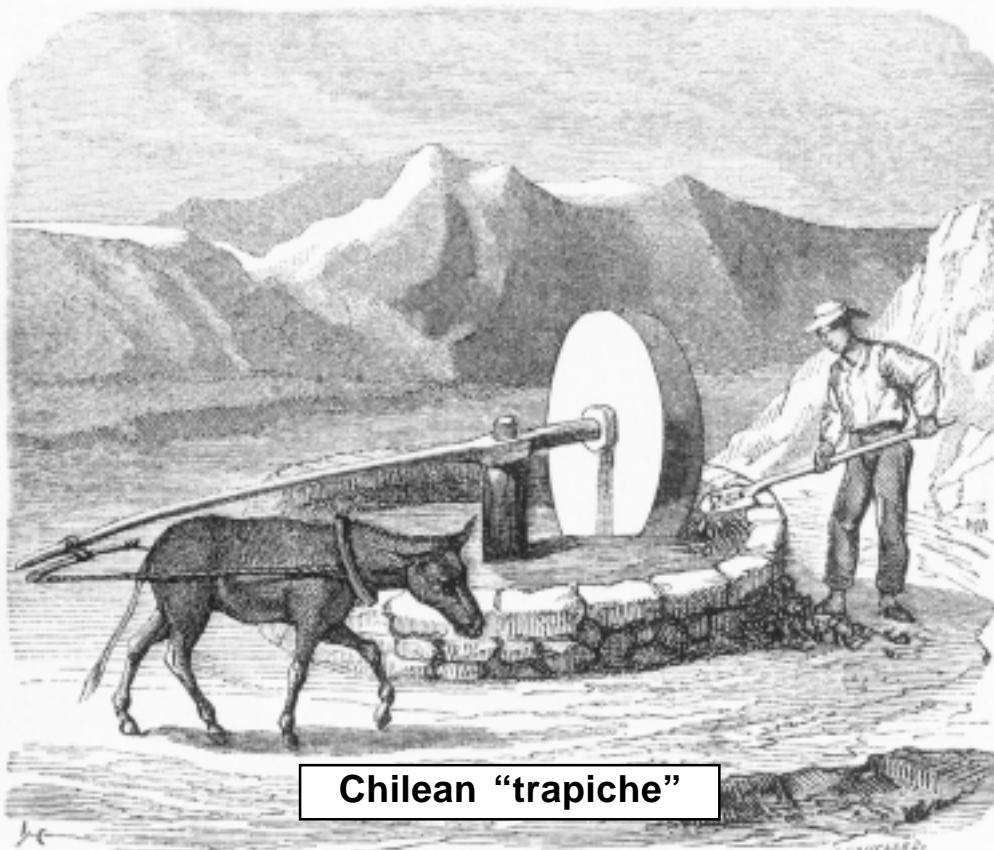
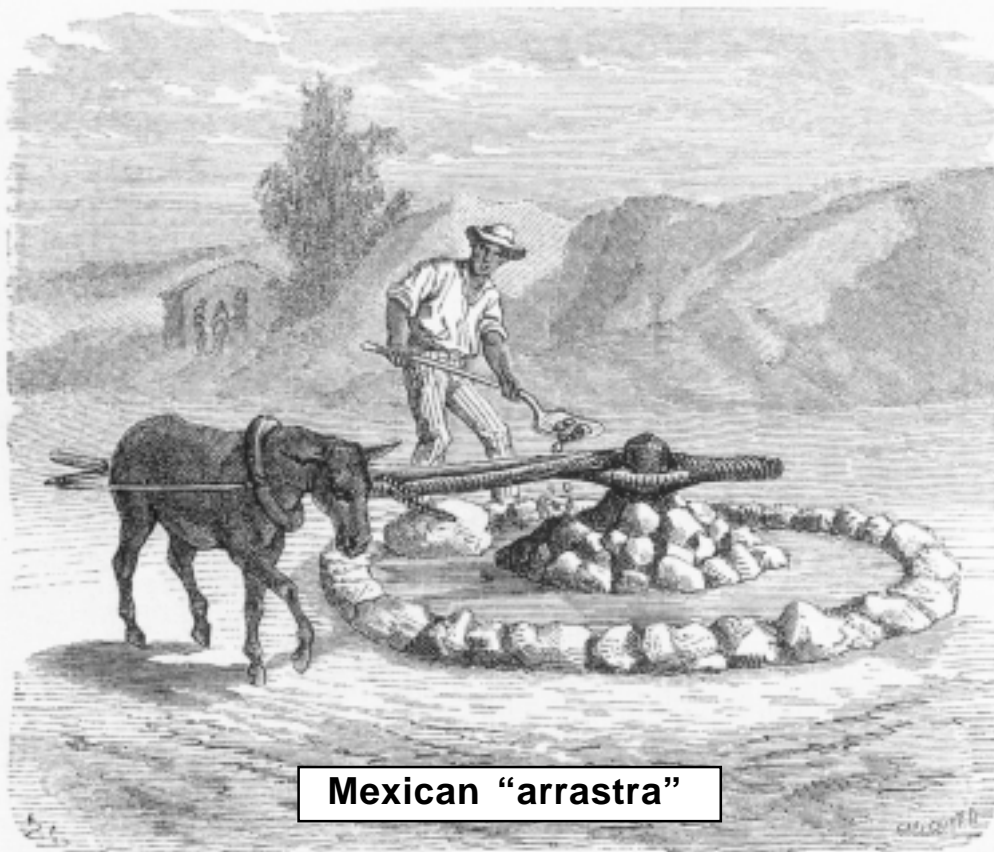




HUMPHREYS SPIRAL CONCENTRATOR

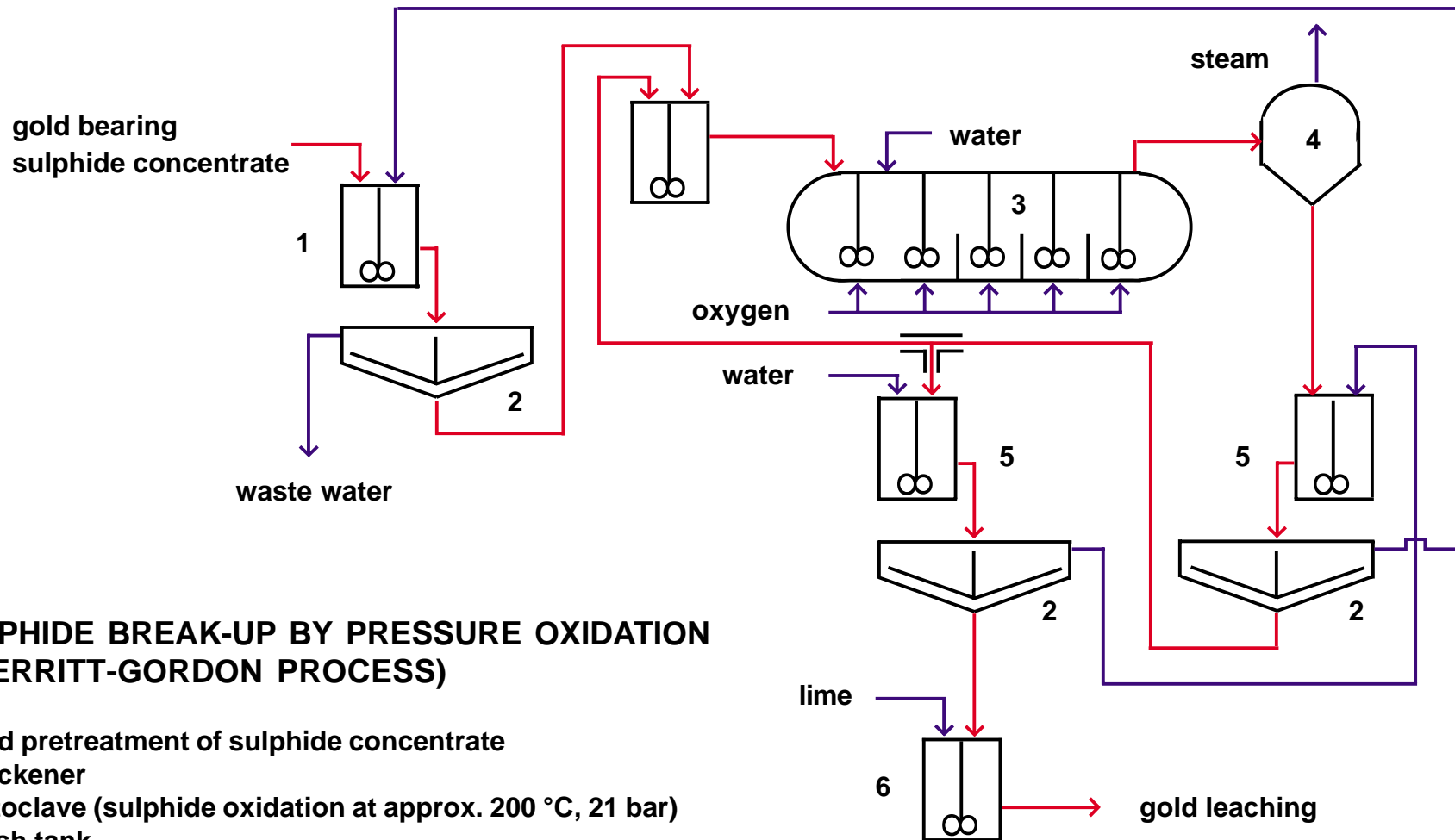
Sketch from the original patent
by I. B. Humphreys (1943)





Source: Eisenbibliothek Schaffhausen



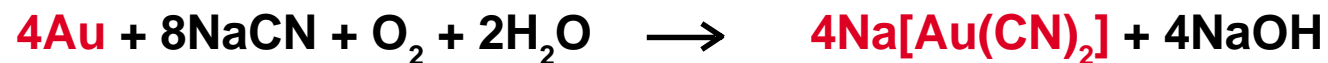


SULPHIDE BREAK-UP BY PRESSURE OXIDATION (SHERRITT-GORDON PROCESS)

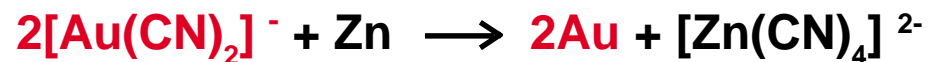
- 1 Acid pretreatment of sulphide concentrate
- 2 Thickener
- 3 Autoclave (sulphide oxidation at approx. 200 °C, 21 bar)
- 4 Flash tank
- 5 Countercurrent washing circuit for oxide pulp
- 6 Neutralisation of oxide pulp

CHEMICAL REACTIONS OF GOLD DISSOLUTION AND PRECIPITATION

1. Dissolution of gold by sodium cyanide



2. Cementation of gold from solved cyanide complex by zinc dust
(Merrill-Crowe process)

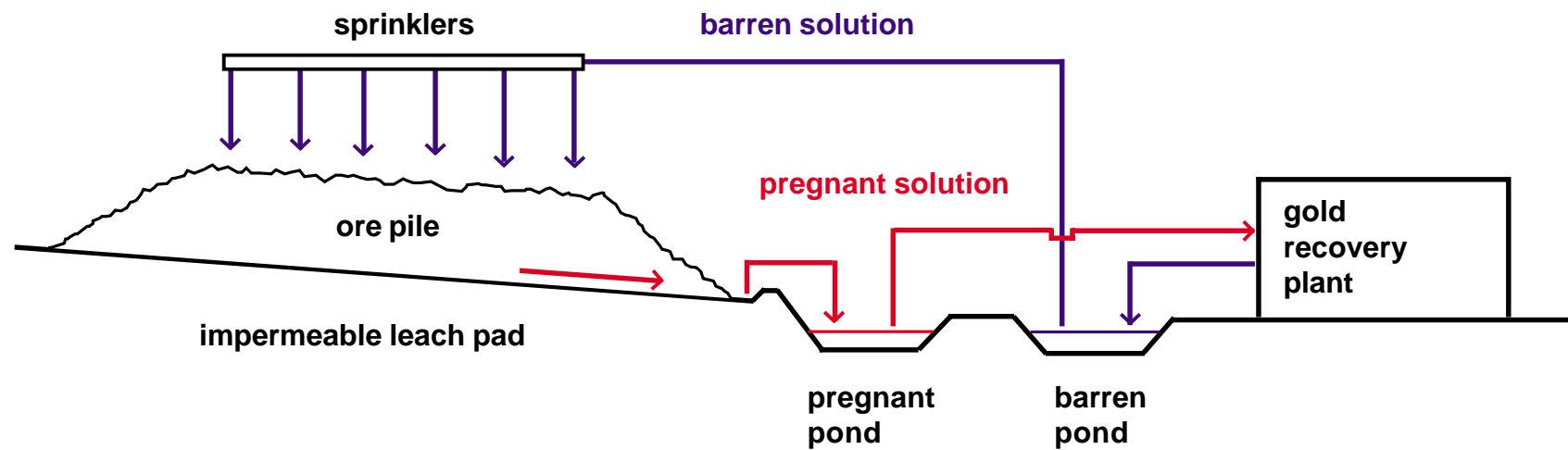


CYANIDE SOLUBILITY OF COPPER MINERALS

Mineral	Chemical formula	Extraction [%] *)
Chalcopyrite	CuFeS_2	5,6 (8,2)
Chrysocolla	$\text{CuSiO}_3 + \text{aq.}$	11,8 (15,7)
Tetrahedrite	$\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$	21,9 (43,7)
Enargite	Cu_3AsS_4	65,8 (75,1)
Bornite	Cu_5FeS_4	70,0 (100)
Cuprite	Cu_2O	85,5 (100)
Copper (native)	Cu	90,0 (100)
Chalcocite	Cu_2S	90,2 (100)
Malachite	$\text{Cu}_2(\text{OH})_2\text{CO}_3$	90,2 (100)
Azurite	$\text{Cu}_3(\text{OH})_2[\text{CO}_3]_2$	94,5 (100)

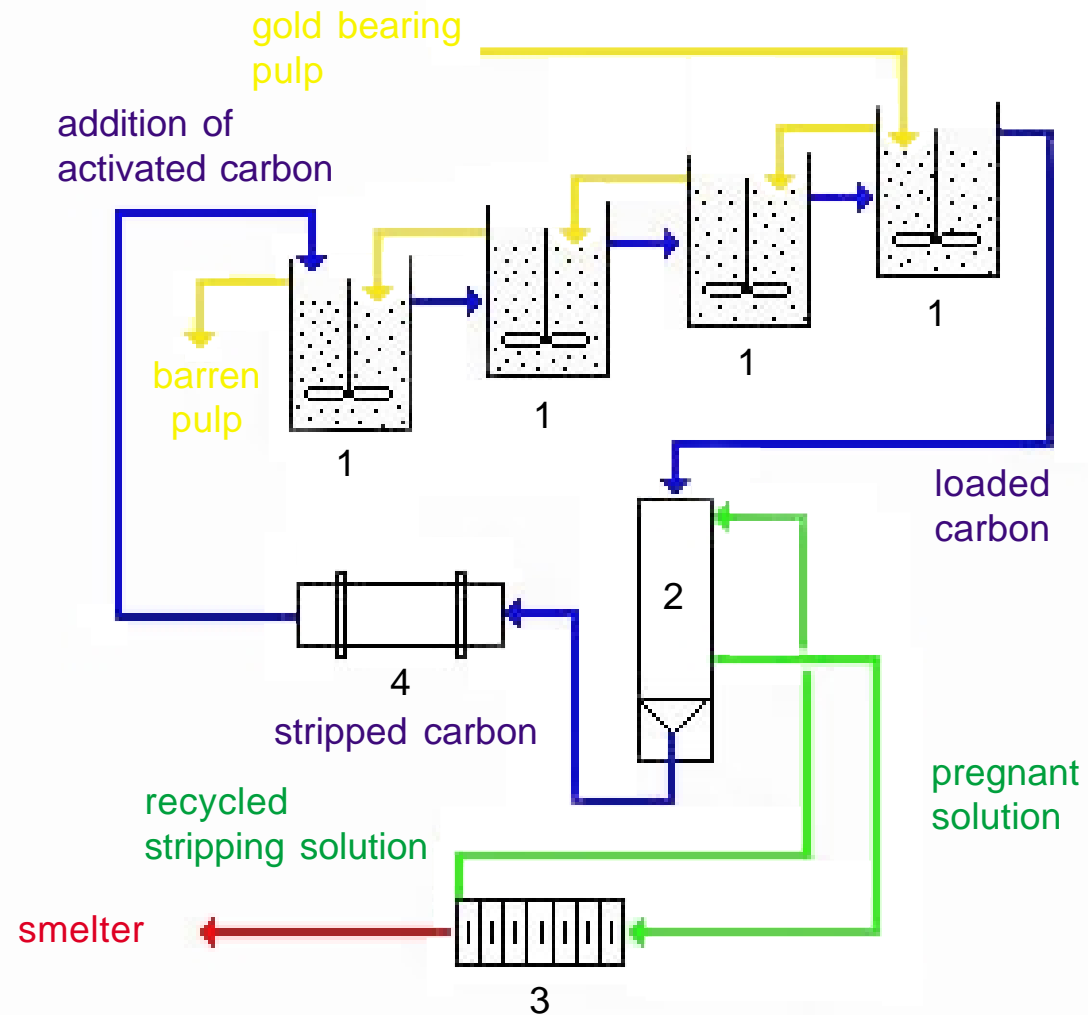
*) Leaching parameters: Mixture of copper mineral and quartz
 < 150 microns
 Copper grades between 0,2 and 0,3%
 Agitated solution containing 0,1% NaCN
 Pulp density 9%
 Leaching temperature 23°C (45°C)
 Leaching time 24h
 (Leaver & Woolf, 1931)

SIMPLIFIED FLOWSHEET OF A HEAP LEACHING OPERATION



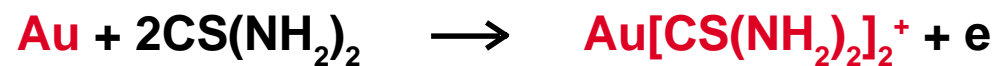
CARBON IN PULP PROCESS

- 1 Adsorption agitators
- 2 Desorption unit
- 3 Electrolytic cells
- 4 Carbon regeneration



COMPLEXING OF GOLD BY THIO-COMPOUNDS

1. Complexing of gold by thiourea



2. Complexing of gold by thiosulphate



RELATION BETWEEN GOLD CONTENT (10 PPM) AND NUMBER OF GOLD PARTICLES IN POLISHED SECTION

Fraction [microns]	Total number of grains	Number of gold grains *)
420 - 210	2 000	< 0,01 (< 0,01)
210 - 105	8 000	< 0,01 (0,01)
105 - 53	32 000	0,02 (0,04)
53 - 26	125 000	0,09 (0,16)
26 - 13	500 000	0,35 (0,65)
13 - 7	1 000 000	1,40 (2,60)

*) The figures refer to the theoretical number of gold particles or particle equivalents exposed on the surface of a 2 cm diameter section in mixtures of quartz and pyrite (values in parentheses) respectively at a gold content of 10 ppm.

(Jones & Gavrilovic, 1968)

ECONOMICALLY IMPORTANT COPPER MINERALS

Mineral	Chemical formula	Copper content [%] *)
Copper (native)	Cu	99
Chalcocite	Cu ₂ S	79
Digenite	Cu ₉ S ₅	78
Covellite	CuS	66
Bornite	Cu ₅ FeS ₄	63
Enargite	Cu ₃ AsS ₄	48
Tennantite	Cu ₁₂ As ₄ S ₁₃	42 - 52
Tetrahedrite	Cu ₁₂ Sb ₄ S ₁₃	30 - 45
Chalcopyrite	CuFeS ₂	34
Cubanite	CuFeS ₃	23
Cuprite	Cu ₂ O	88
Tenorite	CuO	80
Malachite	Cu ₂ (OH) ₂ CO ₃	57
Azurite	Cu ₃ (OH) ₂ [CO ₃] ₂	55
Chrysocolla	CuSiO ₃ + aq.	30 - 36
Atacamite	Cu ₂ Cl(OH) ₃	59
Brochantite	Cu ₄ SO ₄ (OH) ₆	56
Antlerite	Cu ₃ SO ₄ (OH) ₄	53
Chalcanthite	CuSO ₄ · 5H ₂ O	25

*) rounded down to the nearest whole number

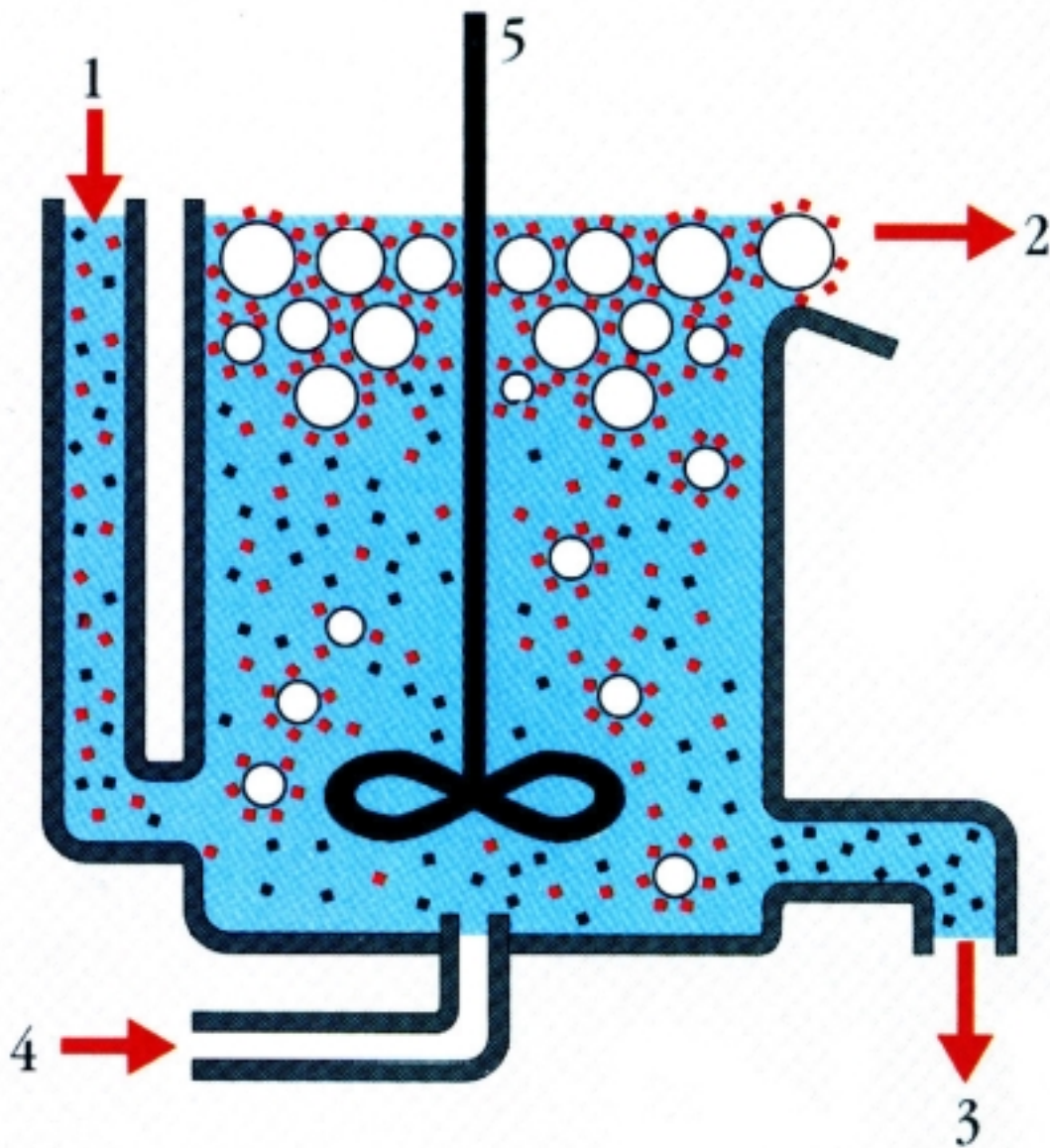
COMMON ZINC MINERALS

Mineral	Chemical formula	Zinc content [%] *)
Sphalerite	α -ZnS (cub)	38 - 67
Wurtzite	β -ZnS (hex)	48 - 67
Zincite	ZnO	80
Gahnite	Zn Al ₂ O ₄	13 - 35
Franklinite	Zn Fe ₂ O ₄	5 - 27
Willemite	Zn ₂ [SiO ₄]	58
Hemimorphite	Zn ₄ (OH) ₂ [Si ₂ O ₇] · 5H ₂ O	54
Smithsonite	ZnCO ₃	52
Hydrozincite	Zn ₅ (OH) ₆ [CO ₃] ₂	59

*) rounded down to the nearest whole number

SELECTION OF FLOTATION REAGENTS

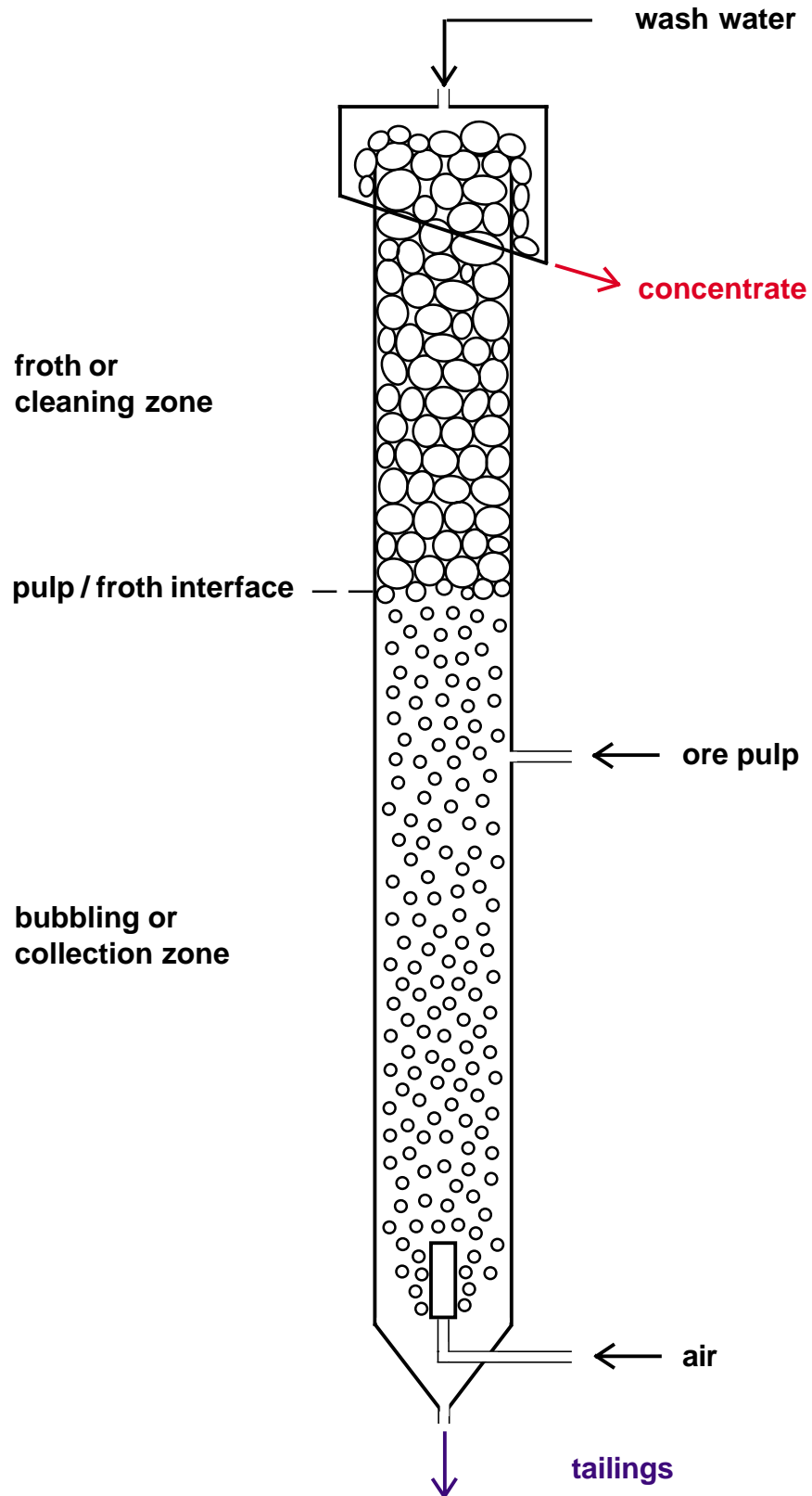
COLLECTORS (promoters)	APPLICATION
Xanth(ogen)ates	Sulphide flotation
Dithiophosphates	Sulphide flotation
Carboxylates (fatty acids, soaps)	Carbonate/oxide/sulphate flotation
Alkyl ammonium salts	Silicate/oxide flotation
FROTHERS	
Aliphatic alcohols (methyl isobutyl carbinol)	Frother
Cyclic alcohols (pine oil, eucalyptus oil)	Frother, collector
Aromatic alcohols (cresols, xylenols)	Frother
REGULATORS (modifiers)	
Lime	pH - increase, depressor for pyrite
Caustic soda	pH - increase, disperses gangue
Sulphuric acid	pH - decrease
Copper sulphate	Sphalerite activation
Sodium sulphide	Activation of oxidised minerals
Cyanides	Depressor for sulphides
(Di)chromate	Depressor for galena
Sodium silicate	Depressor for quartz and slimes
Quebracho extract	Depressor for calcite
Organic colloids (dextrin, starch)	Depressor for gangue and slimes

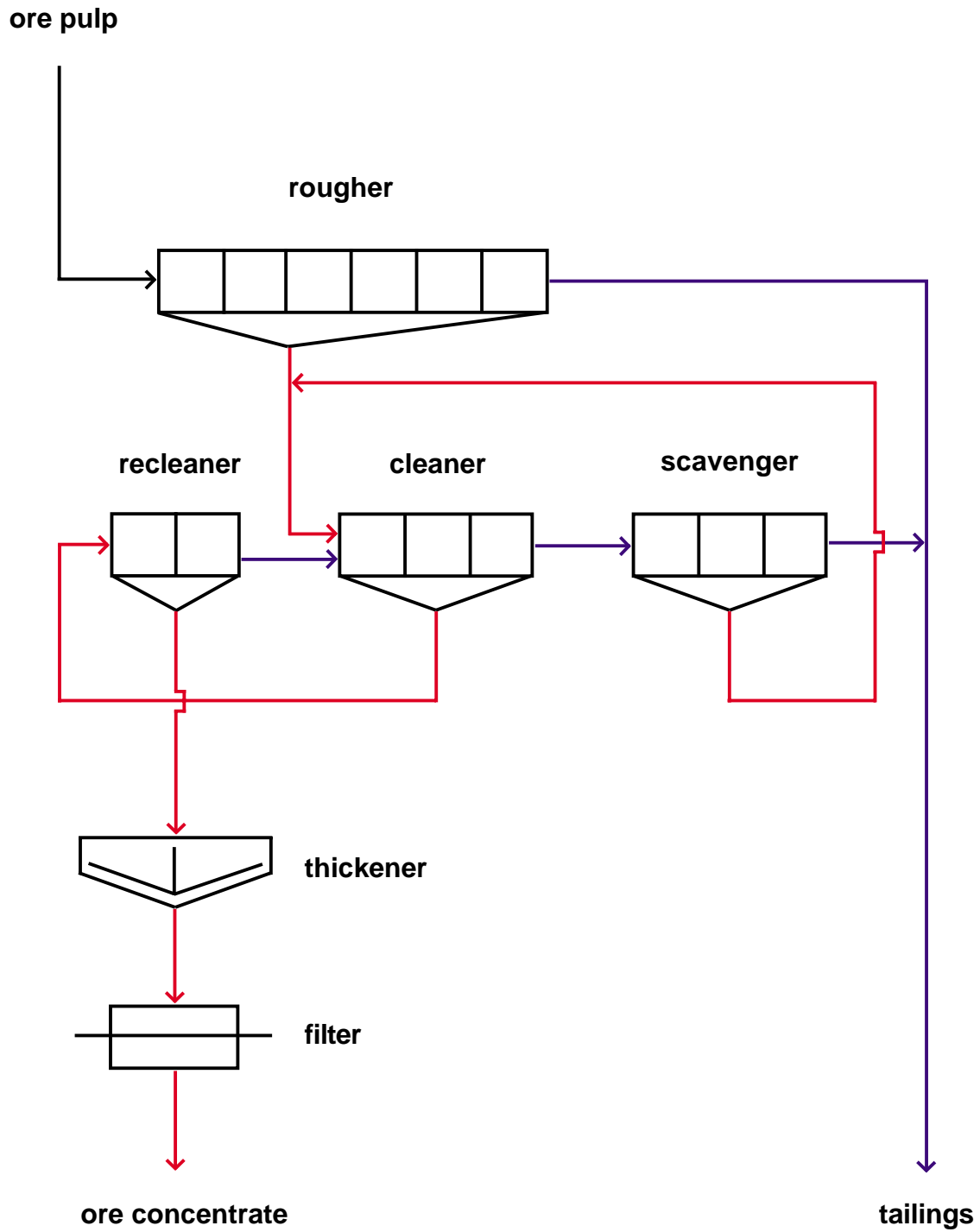


DESIGN AND FUNCTION OF A FLOTATION CELL

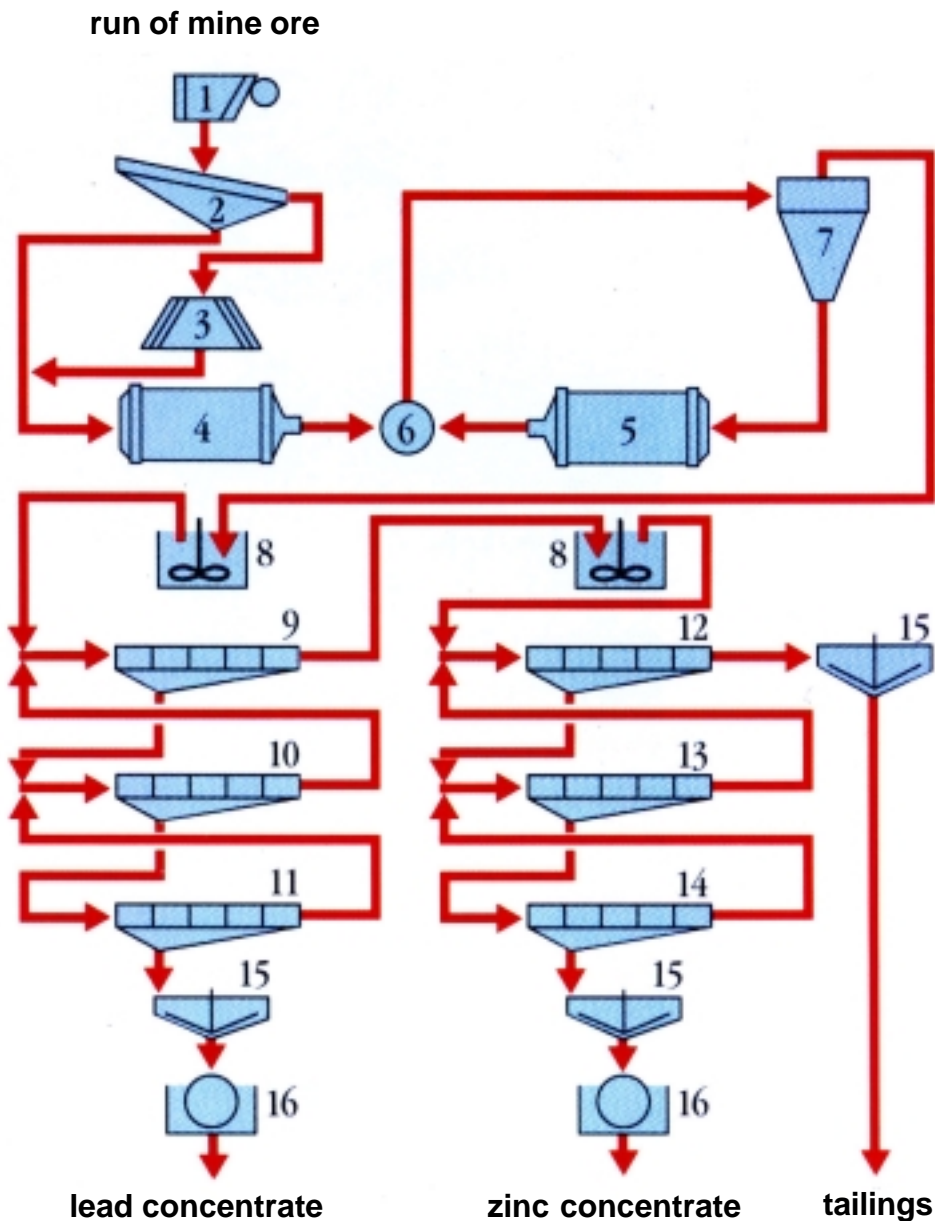
- 1 Ore pulp feed
- 2 Ore concentrate
- 3 Tailing
- 4 Air supply
- 5 Agitator

COLUMN CELL FLOTATION





**FLWSHEET OF A
SIMPLE FLOTATION PROCESS**



FLWSHEET OF A SELECTIVE Pb-Zn FLOTATION

- | | |
|---------------------|---------------------------|
| 1 Jaw crusher | 9 Pb-rougher flotation |
| 2 Sieve | 10 Pb-cleaner flotation |
| 3 Cone crusher | 11 Pb-recleaner flotation |
| 4 Rod mill | 12 Zn-rougher flotation |
| 5 Ball mill | 13 Zn-cleaner flotation |
| 6 Pump for ore pulp | 14 Zn-recleaner flotation |
| 7 Hydrocyclone | 15 Thickeners |
| 8 Conditioners | 16 Filters |



1a



1b



1c



1d



2a



2b



3a



3b



3c

LOCKING TEXTURES

A geometric classification of basic intergrowth patterns of minerals according to Amstutz, 1960

