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Selective attachment processes in ancient gold ore beneficiation ☆

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ABSTRACT

Ancient reports and mining relicts indicate that in antiquity technologies of high empirical level were used to enrich finely dispersed gold. This review describes the scientific bases behind these beneficiation technologies and confirms their historical significance. All of these ancient processes operate on the principle of selectively attaching finely dispersed gold particles onto a solid collector material via hydrophobicity, chemisorptive bonding, or electrical surface charges. This work begins by presenting the physical and chemical fundamentals of these processes. New research provides scientific explanations for several ancient variants of gold ore beneficiation that are discussed in the second section, including the dry and wet attachment processes used in pharaonic Egypt, sheepskins utilized as gold collectors in the Caucasian region, hemp utilized as a gold collector in Celtic Bohemia, and the use of gorse for gold beneficiation in the Roman Empire. The highest performing antique gold beneficiation technique was the use of gorse as a superhydrophobic gold collector and can be regarded as a precursor to the modern flotation process. The ancient processes demonstrate interesting correlations with modern gold ore beneficiation.

Contents

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1. Introduction

The appreciation of gold since prehistoric times has motivated man to expend significant effort in the recovery of this precious metal. The history of gold ore beneficiation includes developments in ancient Egypt (Klemm and Klemm, 2013) and Europe (Morteani and Northover, 1993) that occurred over multiple millennia. However, our knowledge of ancient beneficiation techniques remains incomplete. Much of this knowledge was likely lost due to wars and the decline of the pharaonic and Roman Empires. The few relicts of mining archaeology and ancient reports indicate that during antiquity, technologies of high empirical level were applied in addition to the well-known density separation technique. These techniques relate to the recovery of finely dispersed gold, which is a current issue of interest for modern mineral processing. Until now, portions of these ancient reports have been incomprehensible and mysterious. For example, Diodorus of Sicily (1st century BC) reported on the cleaning of gold concentrates using moist sponges, and Appian (2nd century AD) and Strabo (1st century AD) described the use of sheepskins for the enrichment of gold and referenced the legend of the golden fleece. Pliny the Elder (1st century AD) described the capture of gold particles on gorse. Further, archeological artifacts from Bohemia indicate the application of hemp in gold ore beneficiation (Morteani and Northover, 1993). Finally, an unusual report from pharaonic Egypt describes a bag or blanket with hanging ends in which the grains of gold were separated (Klemm and Klemm, 2013). In the 16th century, Agricola (1556b) reviewed the state-of-the-art gold ore beneficiation techniques, which were based on ancient traditions. However, he did not consider the aforementioned processes, indicating that they were forgotten during his time. A highly scientific analysis and discussion of these ancient techniques is still needed. This critical review describes the scientific bases behind these beneficiation technologies and confirms their historical significance. Furthermore, the question arises as to whether modern beneficiation techniques reflect this ancient knowledge and how this knowledge may stimulate current technology. All of these processes can be characterized as selectively attaching finely dispersed gold particles to a solid collector material via electrical surface charges, hydrophobicity, or chemisorptive bonding. The key to understanding this rich ancient knowledge provides the research into the hydrophobic effects, nanogold chemistry, and triboelectric properties of gold over the last decades. Therefore, the first section of this paper summarizes the relevant fundamentals.

2. Fundamentals

2.1. The properties of gold used for selective attachment processes

As shown in Fig. 1, the native gold particle sizes in gold ores span a wide range from millimeter-sized nuggets to nanogold, i.e., sizes <100 nm.

Various properties of gold can be utilized for beneficiation depending on the particle size. At particle sizes below 100 μm, the mass forces utilized in the gravity-hydraulic processes weaken, and surface forces become increasingly important (Allan and Woodcock, 2001). These surface forces cause selective attachment through electrostatic, hydrophobic, or adsorptive effects, which are described in the following section.

2.2. The electrostatic attachment of dry gold particles on keratin fibers

The metallic properties of gold, particularly its high electrical conductivity, enable electron transfer at the particle's surface. A triboelectric charge can develop if this charge is transferred to a contacting material. The magnitude of this charge depends on the position of the contacting material in the triboelectric series, which is based on its electrochemical surface potential. A connection between a gold conductor and a non-conductor, such as keratin fiber (hair, wool, silk), can exert strong effects. Fig. 2 presents the charge created by keratin hair in contact with gold depending on the contact time (Jachowicz et al., 1985).

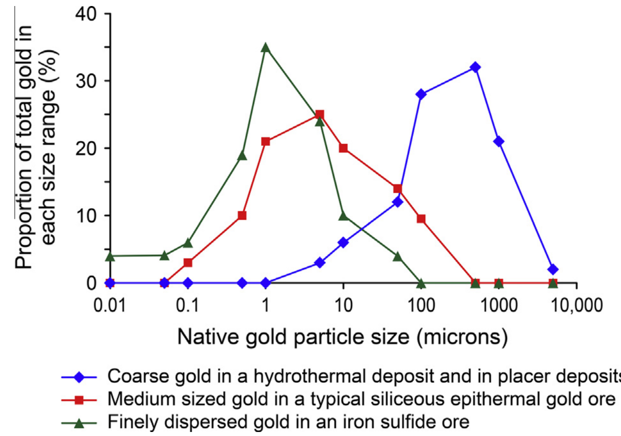

Fig. 1. The typical gold particle size distributions in gold ores, according to Allan and Woodcock (2011).

The charge is influenced by the intensity of the triboelectric contact, the humidity, and the chemical surface modifications of the two materials in contact. A sufficient charge results in an electrostatic attachment that can be utilized for selective dry gold separation. The sensitivity of the process renders the application of this technique difficult. In modern gold beneficiation, electrostatic separation via triboelectricity has been tested but has no practical use (Inculet et al., 1988). However, static electricity is an essential secondary effect in the winnowing or "dry washing" of gold (Wilson, 1961); a dry washer separates gold from sand using an air pulse through a porous blanket of wool or other fiber that has insulating properties. The wind removes the dried sand, leaving the heavier gold. The pulse causes the gold particles to impact the blanket, which results in a triboelectric charge and electrostatic attachment. Modern dry gold washing machines primarily use this method for prospecting and small mining operations in arid regions (McCracken, 2013). In ancient times, the electrostatic

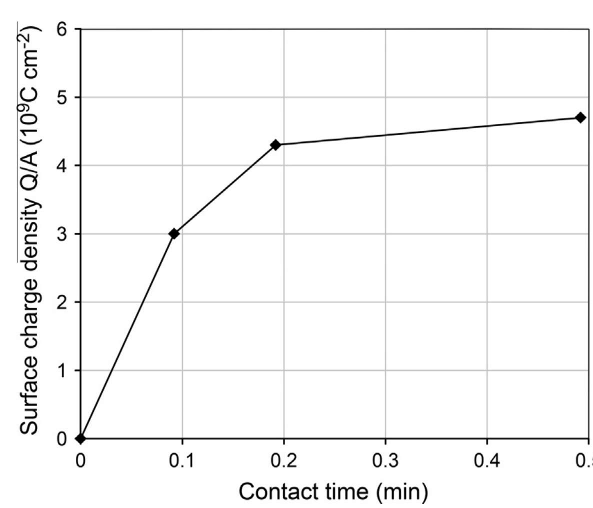

Fig. 2. The triboelectric charge of keratin hair in contact with gold, according to Jachowicz et al. (1985).