The use of geometallurgy in the processing of a complex copper-gold ore deposit

R. Aliyev, F. Hedjazi, S.J. Westhead and A.J. Monhemius
Anglo Asian Mining plc
Baku, Azerbaijan

Abstract. The copper-gold ore deposit at Gedabek in western Azerbaijan is described, together with the various processes that are used to extract the gold, silver and copper from these ores. The processes include heap leaching, agitation leaching and flotation. Geometallurgy is used to classify the various types of ore found in this complex ore body and to determine the optimum processing route for each ore type. Examples of the ore classification system are given.

Keywords: Copper-gold ore processing; heap leaching; agitation leaching; flotation; Gedabek; Azerbaijan.

1 Introduction

The Gedabek Au-Cu-Ag deposit is located in the Gedabek Ore District in the Lesser Caucasus mountain range in north-western Azerbaijan. The Contract Area in which the Gedabek mine is situated is approximately 300 km^2 in size and is one of six Contract Areas held by the London-listed junior mining company, Anglo Asian Mining plc ("AAM"), under a Production Sharing Agreement with the Government of Azerbaijan (Figure 1). The AAM Contract Areas are located on the Tethyan Tectonic Belt, one of the world's significant Cu/Au-bearing metallogenic belts.

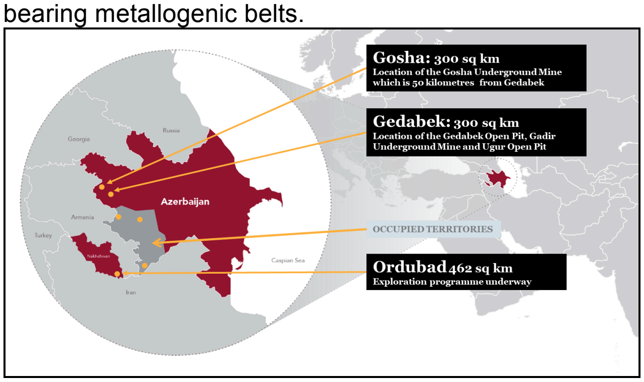

Figure 1. Map of Azerbaijan with locations of AAM Contract Areas

Exploitation of the ore at Gedabek has occurred intermittently since the Bronze Age. Old workings, adits and even pre-historic burial grounds can be identified in the region to this day. More recent mining activity began around 1849 when the Greek Mekhor Brothers, followed by the German Siemens Brothers Company in 1864, developed and operated the Gedabek Cu mine under an arrangement with Czarist Russian authorities. At least five large (>100,000t) and numerous smaller sulphide lenses were mined from 1849-1917, with exploitation ceasing at the onset of the Russian revolution.

During the 1990s, exploration work increased significantly at Gedabek, alongside attempts to reconcile then-current observations with historic production data. New adits were driven by Azergyzil (an Azeri government mineral resources agency) in 1995 and trenching and dump sampling was conducted.

After signing the Production Sharing Agreements, AAM decided to twin four diamond holes (originally drilled during the Azergyzil campaign) in order to ascertain the validity of previous drilling and assays. This proved positive; so too were results from grab and core samples taken during due diligence, with the result that, in 2009, AAM developed the Gedabek deposit into an open pit mine, marking the company as the first Au/Cu producer in Azerbaijan in modern times. The satellite mines of Ugur (open pit) and Gadir (underground) have since also been developed by AAM within the Gedabek Contract Area and all three mines are operated by the Azerbaijan International Mining Company ("AIMC"), a wholly-owned subsidiary of AAM.

2 Geology of the deposit

The Gedabek ore deposit is located within the large Gedabek-Garadag volcanic-plutonic system. This system is characterised by a complex internal structure indicative of repeated tectonic movement and multi-cyclic magmatic activity, leading to various stages of mineralisation emplacement. The Gedabek ore deposit is located at the contact between Bajocian (Mid-Jurassic) volcanic rocks and a later-stage Kimmeridgian intrusion (Late Jurassic). The mineralisation is dominantly hosted in the local rhyolitic porphyry (known onsite as the 'quartz porphyry' unit), bounded by the volcanics (mainly andesites) in the west and a diorite intrusion to the east. The principal hydrothermal alteration styles found at Gedabek are propylitic alteration (encompassing the orebody) with quartz ± adularia ± pyrite alteration (forming the deposit) and argillic alteration (confined to the centre of the orebody). Ore mineralisation is spatially associated with the quartz porphyry. Disseminated pyrite occurs pervasively through most of the deposit, with high concentrations of fine-grained pyrite found at its heart. Increased Au grades occur in the shallowest levels of Gedabek, predominantly in an oxidised zone in contact with the overlying waste andesites. A central brecciated zone continues at depth, as has been proven through exploratory drilling campaigns. Additionally, faulting running through the middle of the deposit has been shown to control the hydrothermal metasomatic alteration and associated Au mineralisation (causing the argillic alteration mentioned above).

The deposit geology was originally considered to be a "porphyry" style, whereas the current interpretation is that the deposit is HS-epithermal in nature. Mining of the deposit since 2009 has provided a vast amount of data about the nature of the mineralisation and its structural control.

3 Ore processing at Gedabek

When the Gedabek mine started up in 2009, the ore, which initially was mainly oxidic in nature, was treated by cyanide heap leaching to produce pregnant leach liquor, from which gold was extracted by fixed-bed resin ion exchange. Resin ion exchange was used at Gedabek, instead of conventional activated carbon, because of the elevated copper concentrations in the leach liquors from the heaps, which typically contained about 1000 ppm Cu. In spite of the high Cu/Au ratios in the Gedabek leach liquors, which usually ranged from 500 to 1000, the excellent selectivity of the Minix resin used in the process was such that the Cu/Au ratio on the loaded resin was about one. In order to prevent copper from building up in the recirculating leach liquors, a SART plant (Sulphidisation-Acidification-Recycling-Thickening) was incorporated in the circuit to remove copper from solution as a copper-silver sulphide concentrate. A description of the operations at Gedabek in the early years of the mine, prior to the introduction of the agitation leach plant, was given in a paper by Hedjazi & Monhemius (2014).

As mining progressed, the ore became less oxidised and harder in texture, with the result that gold recoveries in the heaps started to decrease. In 2012, it was decided that agitation leaching should be introduced to operate in parallel with heap leaching, with high grade ore (>1.5 g/t Au) going to agitation leaching and low grade ore (<1.5 g/t Au) going to heap leaching. Accordingly, a 100 t/h stand-alone agitation leach plant, including resin-in-pulp solution processing, was designed, built, and commissioned by July 2013. The way in which the agitation leach plant was integrated into the original heap leach operation is illustrated by the flowsheet shown in Figure 2.

Following the introduction of the agitation leach plant, soluble copper became a much more important issue at Gedabek. Grinding the ore to minus 75 μm for agitation leaching, instead of crushing it to minus 25 mm for heap leaching, exposed much more of the copper minerals to direct contact with the cyanide leach solutions, which increased the rate and extent of dissolution of copper. Furthermore, as the mine went deeper, the copper grades of the ore tended to increase. The result of these factors was that the consumption of cyanide and hence the overall operating costs for producing gold became unacceptably high, so that steps had to be taken to modify the process to bring down the costs. To do this, a little-used technique that had been invented at the beginning of the 20th century, in the early years of cyanide leaching, was adopted. The technique involved the addition of ammonia into the cyanide leaching system to suppress the dissolution of copper, without adversely affecting the extraction of gold. A full description of the agitation leach plant at Gedabek, together with a discussion of the effects of adding ammonia into the cyanide leach, was published in 2018 (Hedjazi & Monhemius, 2018).

After about one year of operation, ammonia additions at Gedabek were discontinued because the amount of soluble copper in the leach solutions had decreased naturally, due to changes in the ore mineralogy, which comprised more chalcopyrite and less cyanide-soluble secondary copper sulphide minerals.

The next development at Gedabek was the introduction in 2015 of a flotation plant to treat the tailings from the agitation leach plant to recover the copper sulphide minerals into a copper concentrate, together with some of the undissolved gold in the tailings. This additional process step increased the overall recoveries of both copper and gold. The plant was run in this configuration until the end of 2016 when, for operational reasons, it was decided to treat the stockpile of sulphide-rich ore that had been accumulated over several years. This change of feedstock necessitated a reconfiguration of the plant so that ore was first treated by flotation to produce a copper-gold flotation concentrate and then the flotation tailings were processed through the agitation leach plant to recover the gold remaining in the tailings by cyanide leaching.A paper comparing the performances of the plant in these two configurations was published in 2017 (Monhemius, Hedjazi & Saeedi, 2017).

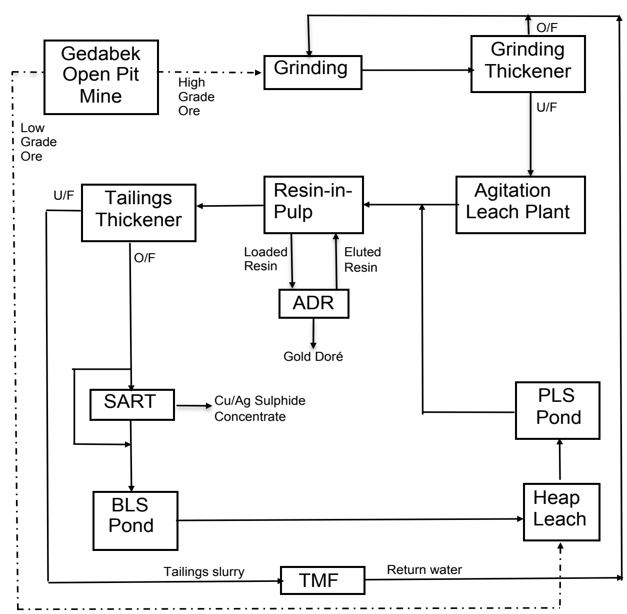

Figure 2. Flowsheet of the Heap Leaching and Agitation Leaching Circuits at Gedabek. (For key to acronyms, see Glossary)

In 2018, a second crushing and grinding circuit was installed, which enabled raw ore to be fed directly to the flotation plant, thus making flotation independent of the agitation leaching plant. The current set-up of the leaching operations at Gedabek closely resembles the pre-2015 configuration shown in Figure 2, but with the addition of an independent flotation plant operating in parallel. Furthermore, heap leaching has also undergone modification over the years. As well as using crushed ore (-25mm) as feed to the heaps, low-grade, run-of-mine (ROM) ore is also leached on separate heaps, without any prior size reduction.

Thus in the current processing set-up at Gedabek, ore coming from the mine(s) has to be directed to one of five possible destinations, namely: (i) agitation leaching (AGL); (ii) flotation (FLT); (iii) crushed ore heap leaching (HLC); (iv) run-of-mine heap leaching (HLROM); or (v) stockpile (SPF). These various process routes result in three marketable products: (i) gold doré; (ii) copper flotation concentrate with significant gold credits; and (iii) precipitated copper sulphide with silver credits from the SART plant. The metal recoveries achieved in these processes are shown in the following table:

Processes	Recovery %		
	Au	Cu	Ag
AGL	75%	30%	66%
HLC	60%	30%	7%
HLROM	40%	20%	7%
FLT	60%	83%	68%
SPF	60%	83%	68%

The decision on which of these processing routes is optimal for any particular batch of ore is based on geometallurgical factors, such as gold grade, copper grade, cyanide leaching amenability and consumption, and ore mineralogy.

4 The use of geometallurgy

A geometallurgical system has been created to classify Gedabek ores, based on geology, oxidation state and laboratory assay results. The first stage in the classification process involves logging the lithology and oxidation state of the material at the drill site. The dominant ore-bearing lithologies are 'quartz porphyry', 'andesite', 'gossan', 'fault' and 'dyke' and oxidation state is classified as either 'oxide', or 'sulphide'. After assaying, samples are assigned their assay result in the database; the attributing lithology and oxidation state are also allocated. Critical grade ranges of gold and copper have been established, and the data are separated into these as in the table below:

Au range		
Au	↓	0.3 - 1 g/t
Au	O	1 - 3 g/t
Au	↑	3 - 999 g/t
Cu range		
Cu	↓	0 - 0.5 %
Cu	O	0.5 - 1 %
Cu	↑	1 - 10 %

The ore material is then assigned a 'criteria code', as shown in the example in the following table:

lithology	*mineral_zone*	*AU range*	*CU range*	*criteria_code*
Quartz Porphyry	Oxide	↑	↓	QO1
Quartz Porphyry	Oxide	↑	O	QO2
Quartz Porphyry	Oxide	↑	↑	QO3
Quartz Porphyry	Oxide	O	↓	QO4
Quartz Porphyry	Oxide	O	O	QO5
Quartz Porphyry	Oxide	O	↑	QO6
Quartz Porphyry	Oxide	↓	↓	QO7
Quartz Porphyry	Oxide	↓	O	QO8
Quartz Porphyry	Oxide	↓	↑	QO9

The code is set-up in the format of 'Lithology/Mineral Zone/Au&Cu Range' and this coding can be applied to the whole dataset; hence:-

Lithology		Oxidation		Au range		Cu range		
Quartz Porphyry	Q	Oxide	O	↑	3 - 999 g/t	↓	0 - 0.5 %	1
AHQ-Contact rocks	A	Transition	T			O	0.5 - 1 %	2
Gossan	G	Sulphide	S			↑	1 - 10 %	3
Fault zone	F			O	1 - 3 g/t	↓	0 - 0.5 %	4
Dyke	D					O	0.5 - 1 %	5
						↑	1 - 10 %	6
				↓	0.3 - 1 g/t	↓	0 - 0.5 %	7
						O	0.5 - 1 %	8
						↑	1 - 10 %	9

For example, a sample comprising of transitional fault zone material assaying 2.5 g/t Au and 5% Cu would be assigned a criteria code of FT6. Metallurgical responses are obtained by subjecting each ore sample to a standardised cyanide leaching test to measure its gold and copper leaching recoveries and its cyanide consumption. These data are entered into the database and given a coding. By also adding empirical hardness ('soft', 'medium, or 'hard') to the coding, the classification can be used to guide drilling operations. This system alerts the driller to potential regions of increased hardness or abrasiveness that may impact drilling speed or the rate of drill bit replacement. It also has benefits in the crushing and grinding operations, where ore hardness can be used to estimate rate of steel grinding ball replacement (in the SAG and ball mills) or the frequency of part replacement or maintenance shutdown.

Since the introduction of flotation alongside leaching in the process plants, which was instigated in 2018, a simpler set of geometallurgical criteria was developed to determine the optimum process route, in which ore classification is based primarily on Au and Cu grades.

In general, all low gold grade ores are treated by heap leaching, either as crushed ore or run-of-mine (ROM) ore, except those with significant sulphidic copper grades, which are directed to flotation. For ores with higher gold grades, there are three processing alternatives, as described previously, i.e.

i) Integrated mode A: with agitation leaching (AGL) ahead of flotation (FLT)
ii) Integrated mode B: with FLT ahead of AGL
iii) Parallel mode: with the AGL and FLT plants operating independently in parallel. This configuration almost doubles the total throughput of ore.

The choice of which mode is used and for what period of time is based on the availabilities of the different type of ore and their metal recoveries and production costs in the various processes. The overriding objective is to maximize the NSR of the operations at any given time and this is the criterion that determines the selection of the processing route. Clearly, the market prices of gold, silver and copper and the selling terms of copper concentrates are important factors in this approach.

Currently, the processing plants are configured in parallel mode, with both agitation leaching and flotation being operated as independent units. The decision chart for parallel processing, which determines the optimum processing route for any particular ore type, as characterised by gold and copper assay values, is shown in Figure 3.

5 Conclusions

A geometallurgical system has been created to classify Gedabek ores, based on geology, oxidation state, metal assay values and cyanide leaching response data. This classification is used primarily to determine the optimum processing routes for different classes of ore, through the processing options available at Gedabek, which are heap leaching, agitation leaching and flotation. Other benefits of the ore classification system are manifested in improved drilling and blasting performance and in reduced costs for comminution.

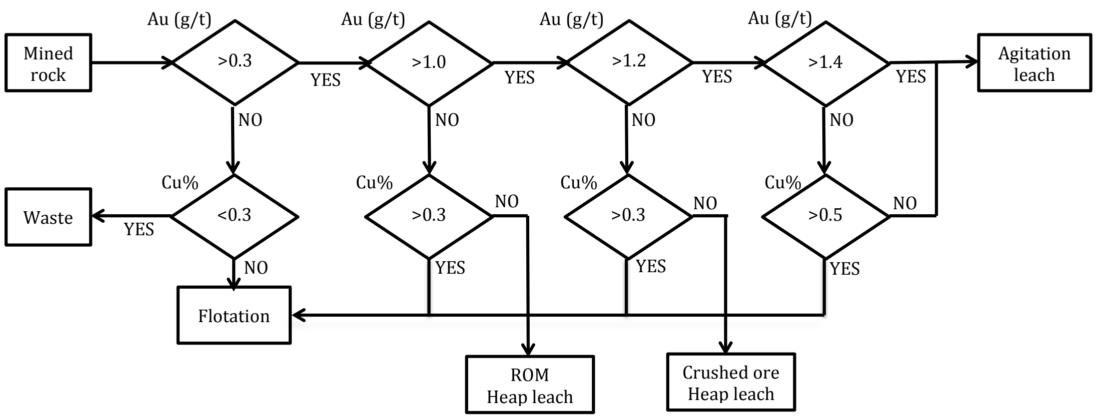

Figure 3. Decision chart to determine the optimum route for parallel processing based on gold and copper grades

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Glossary

AAM	Anglo Asian Mining plc.
ADR	Adsorption/Desorption/Recovery plant: where gold is eluted from the loaded resin and the stripped resin is returned to RIP, while the strip solution is electrowon to produce gold doré.
AGL	Agitation Leach plant.
BLS	Barren Leach Solution: recycled process solution used as feed to heap leaching.
FLT	Flotation.
HLC	Heap leaching of crushed ore.
HLROM	Heap leaching of run-of-mine ore
NSR	Net smelter return.
PLS	Pregnant Leach Solution: gold-bearing solution from heap leaching.
RIP	Resin-In-Pulp plant: where gold is extracted from the agitation leach pulp and the PLS.
SART	Sulphidisation/Acidification/Recycling/Thickening plant: where Cu and Ag are precipitated from the cyanide leach liquor to produce a mixed Cu/Ag sulphide concentrate.
SPF	Ore stockpile
TMF	Tailings Management Facility.

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