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CASE STUDIES

Laboratory Investigation of the Acid Drainage Potential of Host Rock and Waste in the Sariguney Gold Deposit, Gorveh, Western Iran: Implications of Static and Preliminary Kinetic Chemical Tests

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Abstract

Geochemical and mineralogical assessments indicate that the Sariguney gold deposit has a high potential for acid rock drainage (ARD) due to sulfide mineralization. Among 185 analyzed samples from the ore, low-grade ore, and waste rock groups, classification based on net acid-producing potential (NAPP) and pH results from the net acid generation (NAG) test categorized 31% of the waste rocks as high acid-forming (high-PAF), 13% as potentially acid-forming (PAF), and 56% as non-acid-forming (NAF). On average, the sulfur contents in the ore, low-grade ore, and waste samples were 2.6%, 1.3%, and 0.9% by weight, respectively, with corresponding NAPP values of 77, 32, and 18. Thus, the high-grade ore materials have a high potential for acid generation due to their high sulfur content and limited acid neutralization capacity (ANC). Approximately two-thirds of the low-grade samples, despite being classified as high-PAF and/or PAF, exhibit only a short lag period before acidification begins. Additionally, most of the NAF rocks contain less than 0.5% sulfur and have an ANC below 15 kg H_2SO_4/t, meaning that when mixed with acid-generating materials, they provide only limited additional neutralization and primarily dilute the acidic waste. Moreover, the exposure of waste dumps and low-grade ore stockpiles to atmospheric conditions, along with the retention of high-PAF surfaces within the open pit, poses a potential ARD risk. However, stockpiled run-of-mine (ROM) ore, which typically remains stored for only a few days, does not present a major concern. Given the insufficient neutralization capacity in most samples, delays in ore processing could lead to acidic conditions developing within weeks to months. Therefore, to control this phenomenon and mitigate its environmental impacts, management strategies such as selective extraction of low-grade ore, minimizing sulfide oxidation, strategic placement of high-ANC rocks (e.g. as intermediate or final covers in waste dumps), and conducting specialized tests (such as column tests to determine lag time) are essential.

Keywords Sulfide mineralization · Acid neutralizing capacity (ANC) · Net acid production potential (NAPP) · Net acid generation (NAG) · Sariguney · Iran

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Introduction

With the formation of acid rock drainage (ARD), depending on the type of mineral deposit, metals such as copper, zinc, lead, nickel, cadmium, cobalt, mercury, aluminum, manganese, uranium, and metalloids such as arsenic, antimony, and selenium enter the solution through the weathering process (Nordstrom 2011). Acid drainage and the dissolution of metals resulting from it are considered some of the most costly and serious environmental challenges in metal mining (Chopard et al. 2017; Jamieson et al. 2015).

Evaluation of the potential and rate of acid rock drainage from mine wastes is essential for effective prevention and management. The prediction of mine drainage can be carried out through static and kinetic mineralogical and/or chemical tests (Plante et al. 2012; Sobek et al. 1978; Stewart et al. 2006;). The geochemical behavior of mine waste and its acid production potential are influenced by several intrinsic mineralogical characteristics, such as iron sulfide content, ore and carbonate-gangue textures, particle size, oxidation state of sulfides, and chemical composition (S, C, CO_3, metals), which are assessed through static tests (Bennett et al. 1997).

Static methods provide a rapid assessment of pH, which is primarily influenced by the balance between the oxidation rate of acid-generating sulfides and the dissolution of acid-neutralizing minerals. In contrast, kinetic tests provide information on mineral reactivity and the release rates of chemical species (Elghali et al. 2023; Plante et al. 2012; Shu et al. 2001).

One of the chemical static test methods is the calculation of acid–base accounting (ABA) and the direct oxidation method using hydrogen peroxide, which also includes the net acid generation (NAG) test (Abrosimova et al. 2015). Standard ABA tests may not account for the role of hydroxides and sulfates of Fe(III) and Al (e.g., jarosite, alunite, schwertmannite) as well as metal chlorides and sulfates (e.g. eriochalcite, chalcanthite, rhomboclase) in producing acidity through equilibrium reactions. These reactions can either release substantial acidity in acid rock drainage (ARD) systems through dissolution-equilibrium reactions or transform into secondary insoluble minerals (Dold 2017).

The Sariguney gold deposit is one of the most noteworthy gold deposits discovered in Iran and is considered a world-class deposit. Along with several other gold mines in western Iran, it is located within the Sanandaj-Sirjan metallogenic zone. Gold mining in Sariguney occurs through both open-pit and underground methods. Gold extraction from ore materials is performed using the heap leaching method, as there is no smelter plant. Diamond drilling has delineated an exploitable reserve of 52 million metric tons (Mt) of oxidized ore with an average gold grade of 1.77 g/t and a cutoff grade of 0.5 g/t. This deposit extends over an area of 0.72 km^2 and reaches a depth of 350 m (Wilkinson and Bartran 2003).

At the Sariguney gold mine, the mineral reserve is divided into an oxide zone and a sulfide zone. Open-pit mining has been going on since 2014, and the surface oxide reserve is almost depleted. Mining operations are now continuing in the transitional zone from oxide to sulfide. The ore processing includes crushing, grinding, and heap leaching (cyanidation). In sulfide ores (unlike oxide-silica ores), the gold is mostly free incorporated within the structure of sulfide minerals such as realgar, orpiment, stibnite, pyrite, cinnabar, and galena. In this type of ore, a small amount of gold becomes soluble in the cyanidation process, and its processing requires the use of pre-treatment methods such as bio-oxidation, pressure oxidation, and roasting, which reduce the economic feasibility of gold recovery (Ghobadi 2022).

In this study, samples were collected from the primary host rock units of the mineralized material at various exploration borehole depths (prior to extraction) and from high-sulfide tailings (often of low grade) that were stockpiled at the mine site due to issues encountered during the alkaline leaching process in extraction. The climate of the Sariguney mine area is classified as warm and dry, with an average annual temperature of 11.13 °C, an average annual precipitation of 367.62 mm, and an average annual relative humidity of 40.6%.

A comprehensive set of static tests (ABA and NAG) and targeted kinetic tests (NAG kinetic with continuous monitoring of pH and temperature, and acid buffer characteristic curve (ABCC)) were conducted to assess the acid generation potential of the primary rock units in the Sariguney area and to examine the distribution of acid-producing and non-acid-producing waste rocks. In this context, the reactivity of sulfide and carbonate minerals in the waste rocks and economic grade ore was studied under controlled laboratory conditions to provide an initial estimate of their geochemical behavior in the natural environment. Additionally, the enrichment of certain elements in these materials has been identified, since these could greatly affect the quality of drainage and mine runoff. Finally, the geochemical implications of these findings for on-site water management, including the need for long-term management of ARD from waste dump sites and mine pits, have been assessed.

Geological Setting

Sariguney is classified as a vein-hosted epithermal gold deposit, which originated within a late Miocene volcanic complex consisting of latitic to trachytic rocks (Shahbazi et al. 2021). It is located on the common boundary of

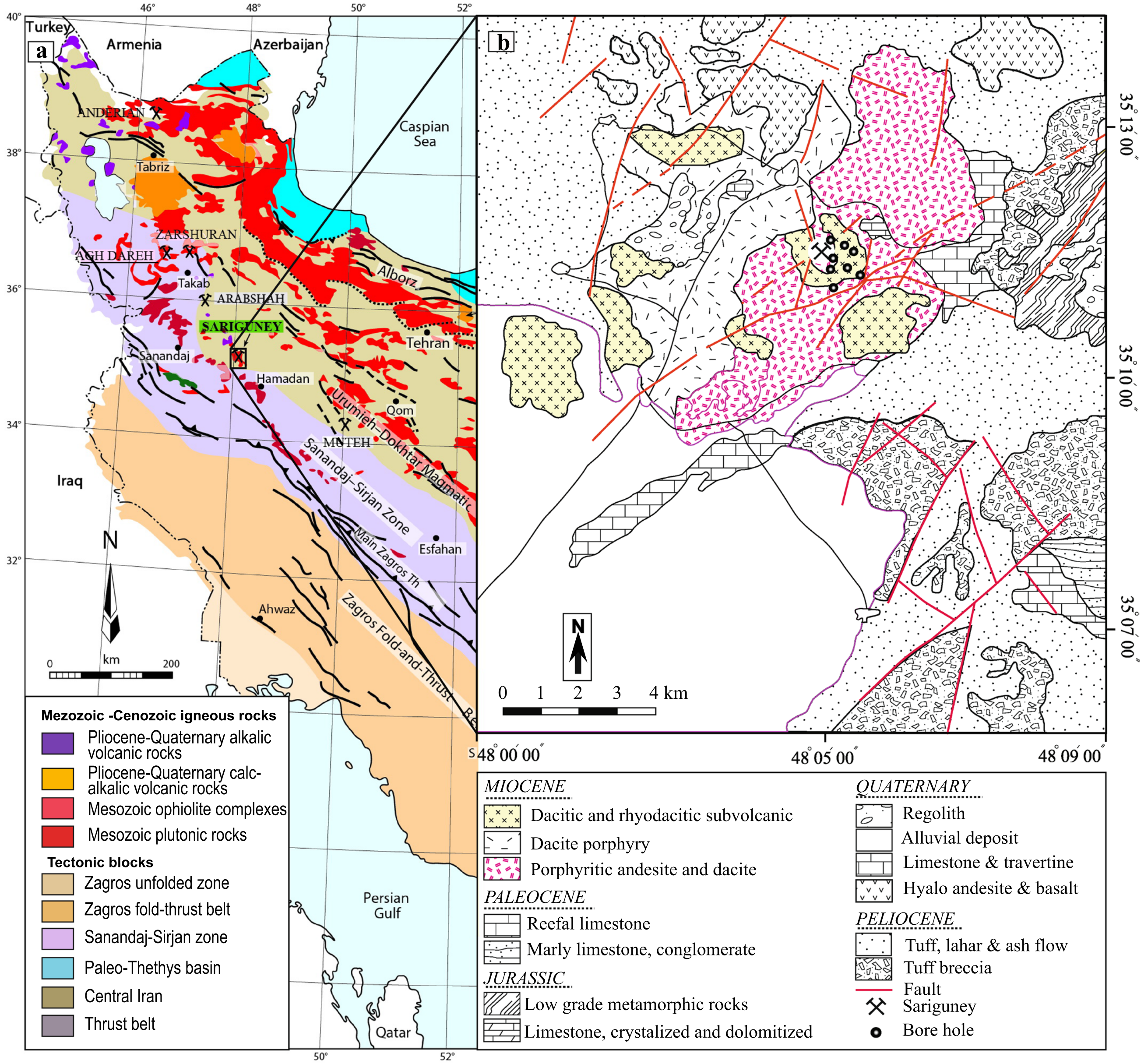

Fig. 1 **a** A simplified map of Iran showing its geological and tectonic zones (adapted from Richards et al. 2012) and the locations of gold prospects and mines (Shahbazi et al. 2021), including the study area in western Iran. **b** A geological map of the Sariguney deposit, highlighting the selected borehole locations within the deposit

Urmia-Dokhtar and Sanandaj-Sirjan structural zones, and at the southeastern end of the Qorveh-Takab magmatic belt, ≈ 42 km southeast of Qorveh city, Kurdistan, west-central Iran (Fig. 1a).

This magmatic belt is a key metallogenic province that hosts several epithermal gold deposits in Iran, including Dashkasan (Kouhestani et al. 2012), Zarshuran (Mehrabi et al. 1999; Tale Fazel et al. 2023), QolQoleh (Aliyari et al. 2009), Miverood, Aghdareh (Daliran et al. 2002), and Arab Shah (Afzal et al. 2017). The region's bedrock primarily consists of Jurassic limestone and some clastic sediments and metamorphic rocks. These rocks are overlain by Oligomiocene to Pleistocene andesitic volcanics and intruded by porphyritic andesite-dacite stocks, which outcrop in Sariguney as the main host for gold mineralization (Niroomand et al. 2013; Richards et al. 2006; Fig. 1b).

The Sariguney gold deposit represents a low-sulfidation epithermal system, with a core enriched in gold, antimony, and mercury, surrounded by an arsenic halo and further encircled by a halo of lead, silver, zinc, and copper (Granian

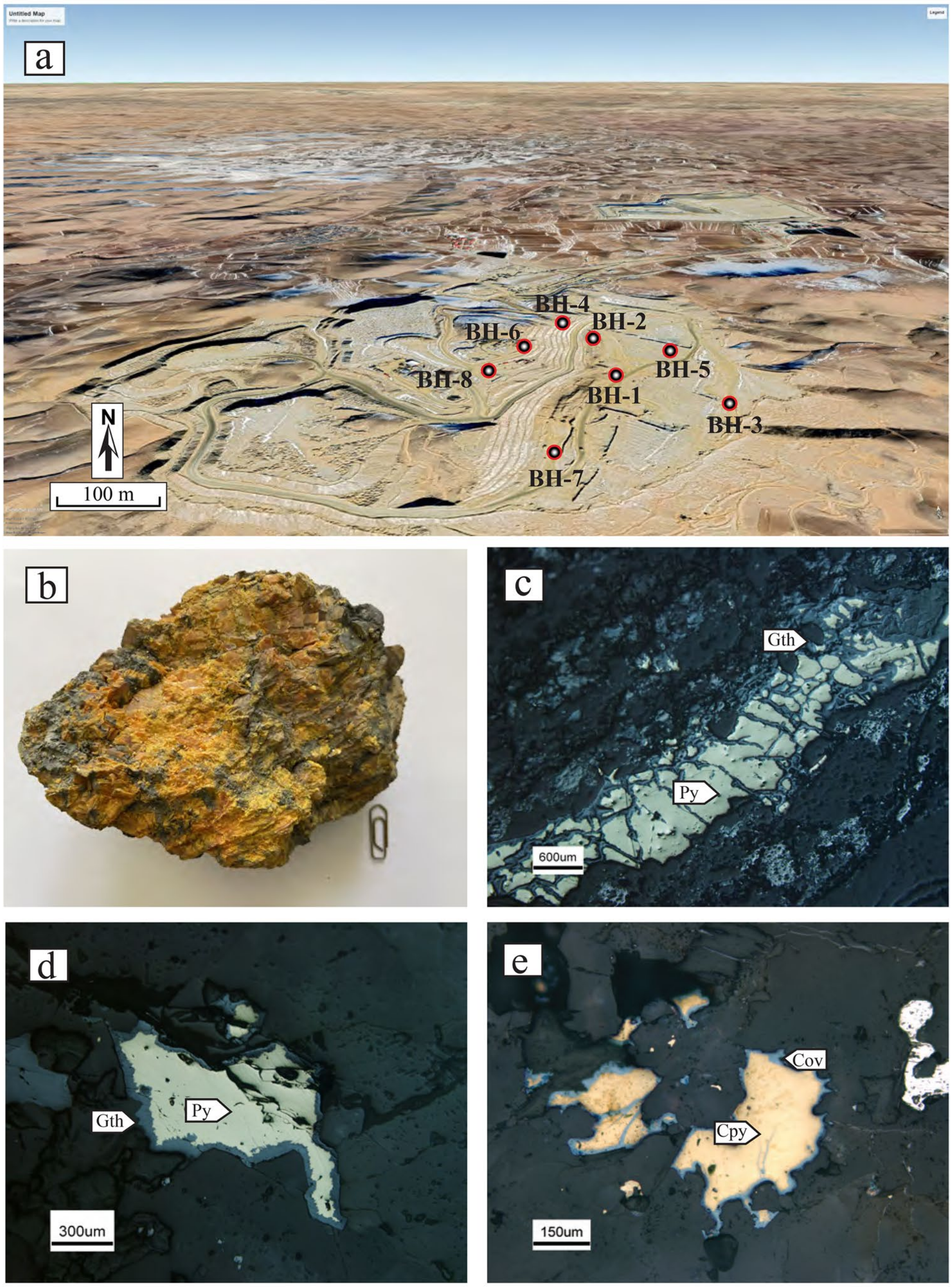

Fig. 2 Photographs and photomicrograph of Sariguney gold deposit: **a** Field view of google earth image showing boreholes and sampling locations, **b** realgar and orpiment hand-specimen identified as ore-grade samples, **c** pyrite veinlets occur as fracture filling **d** Gothite is inferred to be a product of oxidation of pyrite, **e** Chalcopyrite occurs as disseminated grains and is typically replaced by covellite

et al. 2015; Niroomand et al. 2013). Field observations and ore microscopy reveal that the sulfidic veins contain minerals such as pyrite, stibnite, realgar, orpiment, galena, sphalerite, chalcopyrite, cinnabar, and tennantite (Fig. 2). These ore types are also associated with gangue minerals, including sericite, quartz, chalcedony, carbonate, biotite, hornblende, tourmaline, and secondary iron hydroxides.

The Sariguney epithermal gold deposit occurs on a volcanic hillside with a NNE-SSW trend, ≈ 1.2 km long and 450 m wide, extending vertically down at least 300 m. It consists of a central high-grade mineralized zone, about 75 m wide with a maximum width of 150 m, and two smaller high-grade zones (Wilkinson 2005). These zones are surrounded by a lower-grade mineralized halo. The high-grade zones have an average gold grade of about 2–2.5 g/t, while the low-grade halo zone contains an average gold grade of 0.7–0.8 g/t.

Core logging observations indicate that the high-grade zones, consisting of tourmaline-quartz breccia units, were formed during hydrothermal alteration accompanied by silicification. Beneath the main epithermal mineralization, a weak hypogene copper mineralization exists, starting around 300 m below the surface. This zone has an average copper grade of 0.1–0.2% and gold grade of 0.3–0.6 g/t (Shahbazi et al. 2021).

Material and Methods

Sampling and Sample Processing

The samples analyzed and examined in this study were primarily collected from the drill cores of eight key boreholes selected from a total of 46 boreholes drilled across the main lithological units, including oxidized zones, sulfide zones, and altered rocks of the Sariguney deposit. In total, 185 drill cores and waste rocks were prepared for geochemical testing by Environmental Geochemistry International Pty Ltd (EGi). Based on gold assay data and defined extractable zones, these samples were categorized into three groups: ore-grade (18 samples), low-grade ore (40 samples), and waste rock (127 samples). Each drill core sample typically represented a 1-m interval of the drill run. Out of 127 waste samples, 50 surface samples from high-sulfide waste (stockpiled at the extraction site) were collected. The process of preparing the samples involved crushing (using a jaw crusher and cone crusher) half of the core until it reached a size < 2 mm. The crushed rock was then sub-sampled using a riffle splitter, and finally further pulverized. Approximately 300 g of crushed material and 150 g of pulverized material were provided to EGi for geochemical testing.

Analytical Procedures

The geochemical evaluation of the samples included the determination of the following parameters: total sulfur, maximum potential acidity (MPA), acid neutralizing capacity (ANC), ANC/MPA ratio, NAPP, NAG, ABCC and multi-element composition.

Sulfur Content and Maximum Potential Acidity (MPA)

The total sulfur content of each sample was measured using the Leco furnace method. The MPA is the maximum quantity of acid that could be produced by the sulfur in a sample, assuming all sulfur is present as reactive pyrite. The MPA of each sample was calculated based on the total sulfur content using Eq. 1. This equation multiplies the total sulfur content of the sample by a stoichiometric factor of 30.6 (Schumann et al. 2012). This calculation is based on the assumption that all total sulfur is present as pyrite and that the oxidation of 1% sulfur yields 30.6 kg/ton of sulfuric acid in waste materials.

$$\text{MPA}\ \left(\text{kg H}_2\text{SO}_4/\text{t}\right) = (\text{Total \%S}) \times 30.6. \tag{1}$$

Static Test Procedures and the Calculation of NAPP

Static tests, including ANC and NAG, were conducted on powdered samples. Initially, the acid–base accounting (ABA) test was performed as the primary static assessment to quantify the maximum acid neutralization capacity and acid generation potential. In this framework, the ABA results provide the essential basis for the reliable interpretation of extended NAG test outcomes rather than being validated by them. The acid produced by pyrite oxidation partially reacts with carbonate and/or silicate minerals in the sample. This inherent acid buffering is quantified as ANC, expressed in the same units as MPA. The ANC value was measured using the modified method by Sobek, which involves reacting a sample with a known quantity of acid and back-titrating of the acidity to calculate the amount of acid consumed by the sample. A mixture of 4 mL of 0.5 M HCl and 20 mL of distilled water was added to 5 g of pulverized (particle size < 75 µm) and dried (at 105 °C for 4 h) sample in a 50 mL beaker. The mixture was heated to 85 °C for 2 h with occasional agitation until reaching pH 2.0 (Shu et al. 2001). The resultant supernatant was then filtered through a Whatman 45 paper filter. Following pulp filtration, 5 cc of the acidic solution was titrated with 0.1 M NaOH titrant to pH 7.0 at room temperature. ANC was calculated in terms of kg H_2SO_4/t using the formula:

$$\text{ANC}\ \left(\text{kg H}_2\text{SO}_4/\text{t}\right) = \left[(\text{N.V})_{\text{HCl}} - (\text{N.V})_{\text{NaOH}}\right] \times 50/\text{w} \tag{2}$$

where V and N represent volume and normality, respectively, and www is the weight of the sample in grams. The conversion factor 50 transforms the units to kg H_2SO_4/ton.

Net acid production potential (NAPP) is the potential amount of acid a sample may produce after considering its ANC. It is calculated by subtracting ANC from MPA (EPA 1993; Lawrence and Wang 1996; Plante et al. 2012; Schumann et al. 2012equation 7). A negative NAPP value indicates that the material has sufficient buffering capacity to neutralize the acid produced, while a positive NAPP value suggests the material may produce acid.

$$\text{NAPP}\ \left(\text{kg H}_2\text{SO}_4/\text{t}\right) = \text{MPA} - \text{ANC} \tag{3}$$

Net Acid Generation (NAG)

In our study, we employed the net acid generation (NAG) test as an alternative approach to estimate a sample's potential to form acid. This method involves the reaction of the sample with hydrogen peroxide, which rapidly oxidizes any

Table 1 Classification scheme for drill core samples

ARD Category	Description	Criteria
High-PAF	Strongly sulfidic rock with a high acid potential	*NAPP > 30 kg H2SO4/t* and NAGpH ≤ 4.5
PAF	Sulfidic rock that is likely to be acid forming	*NAPP 0 to 30 kg H2SO4/t* and NAGpH ≤ 4.5
NAF	Rock that is likely to be non-acid forming	*NAPP < 0 to –100 kg H2SO4/t* or NAGpH > 4.5
AC	NAF rock with a high carbonate content	*NAPP < –100 kg H2SO4/t*

PAF = potentially acid forming, NAF = non-acid forming, AC = acid-consuming, NAPP = Net acid producing potential

sulfide minerals present. The test provides a direct measurement of the net acid generation capacity of the sample. According to Johnson and Taylor (2023), if the pH of the reacted sample is 4.5 or below (NAG pH ≤ 4.5), the sample is classified as acid generating. While alternative threshold values (such as 4.0, 5.0, or 6.0) may be applicable depending on the hydrogen peroxide concentration, the selected criterion in this study aligns with the experimental conditions established in reputable sources. The samples previously prepared for the ANC procedure were used for the NAG test. To determine the net acid generation, 250 mL of 15% H_2O_2 was added to 2.5 g of sample in a 500 mL beaker and placed under a fume hood for 24 h to complete the reaction; then the resulting solution was heated for 2 h. After cooling the solution, the NAG pH and EC values were recorded by Metrohm-827 and S230 pH and conductivity meter (Shu et al. 2001; Weber et al. 2005).

Kinetic NAG Testing

The kinetic net acid generation (NAG) test evaluates the reactivity of sulfides within a sample and offers a rapid, qualitative assessment of the probable lag time for acidification under field conditions. This method is like the standard NAG test but includes the continuous recording of pH and temperature during the test.

Measurement of Acid Buffering Characteristic Curves (ABCC)

The ABCC measurement involves gradually acidifying a sample with a dilute acid solution to ≈ pH 3 over a 16 to 24-h period. This method is less aggressive than the ANC tests and typically focuses on more accessible carbonates such as calcite and dolomite. These minerals, when present in sufficient quantities, can buffer waste rock at near-neutral pH levels, which is crucial for maintaining low metal solubilities. According to Price (2009), the ABCC method, with its more precise reflection of the gradual acidification process, allows for a more accurate assessment of the acid production potential of samples.

Multi-Element Composition

To assess the multi-element composition of each sample, 1.2 g of dried and powdered sample was digested using concentrated hydrochloric and nitric acids in a 3:1 ratio in a 100 mL conical flask. The digestion was carried out on a hotplate at 100 °C for 2 h. After allowing the hot solution to cool, it was filtered through Whatman 42 filter paper. Element concentrations for all samples (n = 185) were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES, Varian 730ES), while sulfur was assessed using IROES (LECO RC-412) at Genalysis Laboratory Services Pty Ltd, Australia.

ARD Classification Scheme

The classification of each sample into one of the four categories was based on both NAPP and NAG pH values. The criteria used to define each category are given in Table 1.

At a general level, the high-PAF category allows for identification of rock that is particularly hazardous in terms of ARD potential and that may require a higher level of management within waste dumps (i.e. encapsulation). The definition of high-PAF rock is material that has a NAPP greater than 30 kg H_2SO_4/t. This refers to the potential acidity that may result from the oxidation of rock containing at least 2% pyrite (or 1% sulfur).

The sulfide content of NAF rocks may be negligible or, when sulfide mineralization is present, their intrinsic ANC is considered sufficient to buffer any acid that may be generated by sulfide oxidation. Typically, this samples would include limestone or dolomite, or rock that has a high proportion of calcite ($CaCO_3$) or magnesite ($MgCO_3$). The criterion used to define AC rock is an NAPP value less than −100 kg H_2SO_4/t. This definition means that the rock contains > 10% calcium carbonate.

As noted above, both NAPP and NAGpH were used to classify the Sariguney samples (Fig. 3). Usually, a positive NAPP suggests a material could be a source of ARD whilst a negative NAPP suggests it is not. However, experience has shown that samples that have a NAPP close to zero may not reliably indicate the acid forming potential of a given

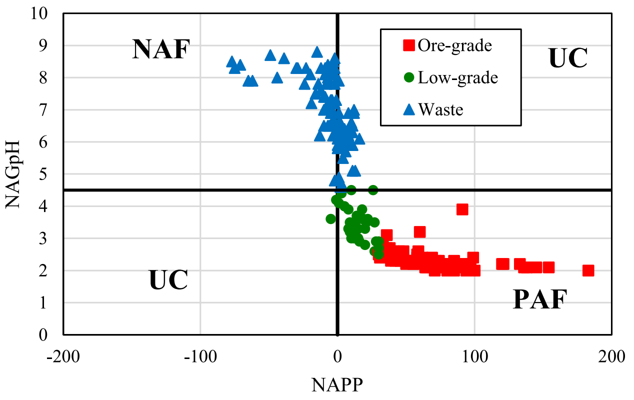

Fig. 3 Geochemical classification plots with different ARD categories for: **A** Ore-grade, **B** Low grade and **C** Waste samples, based on NAPP and NAGpH values (after Smart et al. 2002). Field symbols: NAF (non-acid forming), PAF (potentially acid forming), and UC (uncertain)

sample. This uncertainty occurs when sulfides other than pyrite are present in a sample, or when some sulfur exists in the form of sulphate. Also, oxidized rocks in the weathered zone typically have a slightly positive NAPP value, despite essentially lacking the ability to produce and neutralize acid. In such cases, the NAGpH value is used as an indicator to determine the potential for acid production.

Results and Discussion

The classification scheme outlined earlier was applied to the different lithologies from the Sariguney deposit (Fig S-1). Table 2 is a summary of the distribution of samples between the four ARD categories from each material type and measured statistics parameters.

Static Tests Assessment and Comparison

Ore-Grade Samples

Samples were defined as ore if they were representative of mineable zones averaging greater than 1 gt^{-1} of gold. Overall, the results indicate that the ore-grade material has a moderate to high sulfur content, little if any ANC, and a moderate to high acid generating potential. The overall range for the ARD parameters measured were summarized in Table 2. The ore-grade samples were taken from the oxide, transition, and primary rock zones of the Sariguney deposit. There were seven oxide samples, six transition samples, and five primary (or fresh) samples. The term “oxide ore” usually implies the rock is weathered and oxidized, and thereby usually non-acid forming. However, it is understood that at Sariguney, the “Oxide Zone” refers to ore where the metallurgical recovery of gold by cyanide leach is > 80%. This definition does not exclude the possibility of some sulfides being present and the testing carried out confirms the presence of sulfides in oxide ore as well as in transition and primary ore samples. The sulfur content of the oxide ore samples ranged from 0.22 to 3.92% S, and the average was 1.8% S. This represents a high potential for acid generation by some “*oxide*” ore. Furthermore, the ANCs of the “oxide” samples were essentially negligible, ranging from 0 to 3 kg H_2SO_4/t.

Figure 4a presents an acid–base plot specifically for the ore-grade samples classified as high-PAF ore. Of the seven samples described as “*oxide*” ore, five were classified as high-PAF, one as PAF, and one as NAF. The one “oxide” sample classified as NAF actually falls on the positive side of the NAPP = 0 line. Although the positive NAPP suggests that the sample may be acid generating, the sulfur content was low and the ANC was negligible. This suggests that the sample displayed minimal acid generation and acid neutralization properties, rendering it essentially barren in this regard. The NAG test result confirmed that this sample

Table 2 Summary of ARD classifications and parameters for ore-grade, low-grade ore, and waste sample types

Material Type	No. of samples	Distribution of Samples							
		High-PAF	PAF	NAF	AC	Sulfur (%)	MPA (kg H_2SO_4/t)	ANC (kg H_2SO_4/t)	NAPP (kg H_2SO_4/t)
Ore-Grade	18	88%	6%	6%	0%	0.22 to 4.52 (Avg. = 2.6)	7 to 139 (Avg. = 79)	0 to 9 (Avg. = 2)	6 to 138 (Avg. = 77)
LG Ore	40	45%	22%	33%	0%	0.06 to 4.49 (Avg. = 1.3)	2 to 137 (Avg. = 39)	0 to 58 (Avg. = 7)	−39 to 136 (Avg. = 32)
Waste	127	31%	13%	56%	< 1%	0.01 to 6.01 (Avg. = 0.9)	0 to 184 (Avg. = 28)	0 to 115 (Avg. = 11)	−115 to 183 (Avg. = 18)

PAF = potentially acid forming, NAF = non-acid forming, AC = acid-consuming, MPA = maximum potential acidity, ANC = acid neutralizing capacity, NAPP = net acid producing potential, LG = low grade ore samples, Avg = Average

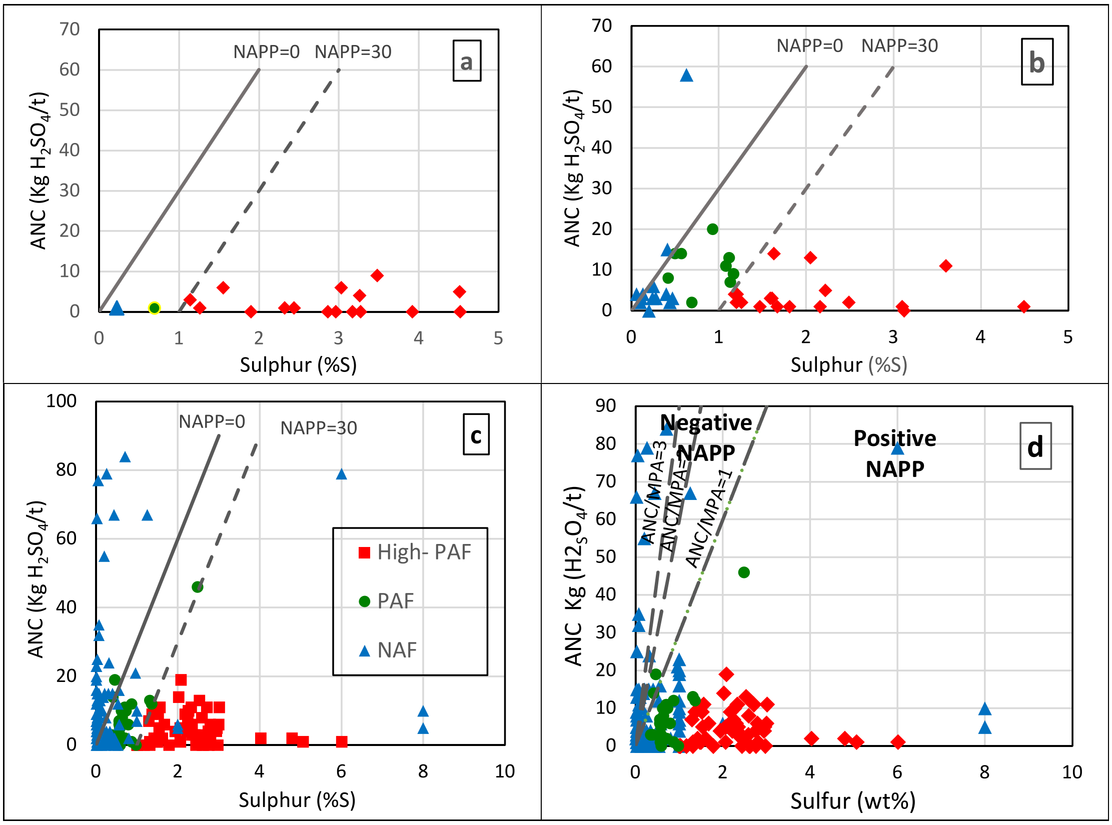

Fig. 4 Geochemical classification plots with the different ARD categories for **a** ore-grade, **b** low grade and **c** waste rock samples on their wt.% sulfur and ANC values. **d** Samples are plotted in either the positive or negative NAPP field (after Smart et al. 2002)

did not acidify when reacted with hydrogen peroxide (i.e. NAGpH was > 4.5) and so the sample was classified as NAF.

Low-Grade Samples

Forty samples were identified as representing low-grade ore (from 0.5 and 1 gt^{-1} of gold). The results suggest that most low-grade ore, if it were selectively stockpiled for the purposes of future processing or heap leach treatment, would have a considerable sulfide content and the potential for ARD generation. The range and the average for the various ARD parameters measured are presented in Table 2.

Figure 4b illustrates the acid–base plot for the low-grade ore samples. It is notable that ≈ two-thirds of the low-grade ore samples were categorized as acid generating, with a large portion falling into the high-PAF category. The availability of ANC in the low-grade ore samples was low and it is expected that most of the low-grade ore classified as high-PAF would have a relatively short lag prior to acidification.

Approximately one-third of the low-grade ore samples were identified as NAF. The ARD characteristic that tends to separate NAF low-grade from acid generating material is a low sulfur content, rather than a high ANC. The sulfur contents of samples classified as NAF were typically < 0.5%S, and their ANCs were typically < 6 kg H_2SO_4/t. These characteristics suggest that NAF low-grade, if blended with acid generating rock within a stockpile or dump, will provide little additional buffering capacity. As such, NAF low- grade will tend to "dilute" the acid rock rather than provide extra neutralizing capacity.

Waste Rock

All samples not specifically identified as ore-grade or low-grade were designated as waste rock. This assessment encompassed a total of 127 waste rock samples and their range of ARD characteristics are exhibited in Table 2.

Figure 4c illustrates an acid–base plot representing the waste rock samples. The waste rock samples tested were fairly evenly divided between acid generating and non-acid generating categories. The occurrence of a significant proportion of acid generating samples suggests that waste rock, like low-grade ore, will likely be a source of ARD if exposed to atmospheric conditions.

As indicated in Fig. 4c, most of the NAF samples contained < 0.5% S. The ANCs of NAF samples were also

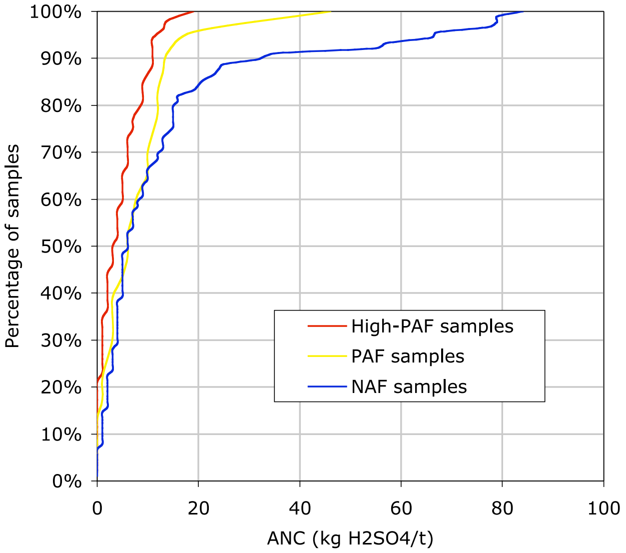

Fig. 5 Percentile distribution of ANC values for waste rock samples, showing that at least two-thirds of the samples within each ARD waste category had ANCs < 10 kg H_2SO_4/t

typically low, (i.e. typically 15 kg H_2SO_4/t) but there were some samples with moderate to high ANC. It is expected that the higher ANC materials would provide some ARD control if blended with acid-generating rock within the waste dumps. However, the overall effectiveness may be limited by the availability of such material within the deposit. Figure 4d is another representation of the classification of whole rocks based on their weight percentage (wt.%) sulfur and ANC values, where the samples are plotted in two NAPP positive and negative sections. The variability and reactivity of ANC within waste rock is discussed further below.

Variability of ANC.

The results of drill core testing suggest that most of the rock that will be mined from the Sariguney deposit will have a low ANC. The low ANC of the ore will probably not be of concern assuming that the residence time in ore stockpiles is relatively short (i.e. days to weeks). However, the low ANC of the waste rock, and also low-grade ore that is stockpiled for an extended period (i.e. many months to years), may influence how such materials are managed to minimize the potential for ARD generation.

Figure 5 shows the distribution of ANC values for the waste rock samples. At least two-thirds of the samples within each ARD waste category had ANCs < 10 kg H_2SO_4/t, which means such materials only have the capacity to neutralize acidity generated by less than 0.3% S as pyrite. This suggests that a small percentage of NAF waste will have moderate to high acid neutralizing capacity, but the usefulness of this higher ANC material for control of ARD in waste dumps will depend on the actual amounts present within the orebody, how it is scheduled, and whether it can be identified in mineable blocks.

Reactivity of ANC

In addition to measurement of ANC, a number of samples were selected to determine their acid-buffering characteristics when exposed to increasing acidity under controlled laboratory conditions. The ABCC provides an indication of the readily-available buffering capacity within a sample, which typically results from carbonates such as calcite and dolomite. A total of 12 drill core samples were selected, with ANCs ranging from 1 to 115 kg H_2SO_4/t. Nine samples were representative of waste rock, two represented low-grade ore, and one represented ore. For discussion purposes, some of the curves are also illustrated in Fig. 6.

Figure 6a presents two sample ABCC curves: one for rock with an ANC close to zero and another within the range of 5 to 20 kg H_2SO_4/t. Most rocks in the Sariguney deposit are expected to be represented by one of these two curves. In rocks with ANC near zero, the pH drops immediately after acid addition, indicating the absence of carbonate minerals and a high potential for ARD generation under atmospheric conditions. Additionally, the figure displays an ABCC curve for a sample with an ANC of 12 kg H_2SO_4/t, which is close to the average ANC of the tested waste rock samples. In this case, a stable level at around pH 8 is observed, attributed to the buffering effect of soluble carbonate minerals. This buffering capacity remains relatively constant in samples with ANC between 5 and 35 kg H_2SO_4/t, providing an immediate buffering potential of approximately 3 to 5 kg H_2SO_4/t.

As indicated in Fig. 4, a small percentage of the waste rock samples tested had moderate to high ANCs (i.e. ≈ 15% of the NAF waste rock samples had ANCs > 20 kg H_2SO_4/t). ABCCs were determined for a selection of the NAF samples with higher ANCs to assess the reactivity of the carbonate mineralization providing the buffering capacity.

Figure 6b shows the ABCCs for three NAF samples with ANCs of 55, 79, and 115 kg H_2SO_4/t, respectively. The curves show that most of the ANC present in these samples was readily available at circumneutral pH. Under the test conditions imposed, the three samples buffered the equivalent of 31, 49, and 85 kg H_2SO_4/t, respectively, above pH 6. The high reactivity of the ANC at circumneutral pH suggests that buffering is probably due to calcite or dolomite. A typical ABCC for pure calcite is included in Fig. 6b for comparison. The results indicate that the higher the ANC, the more closely the ABCC reflects the buffering characteristics of calcite.

Overall, these findings suggest that NAF rock with higher ANCs can be effectively mixed with acid-generating rock to minimize ARD generation. However, the usefulness of this

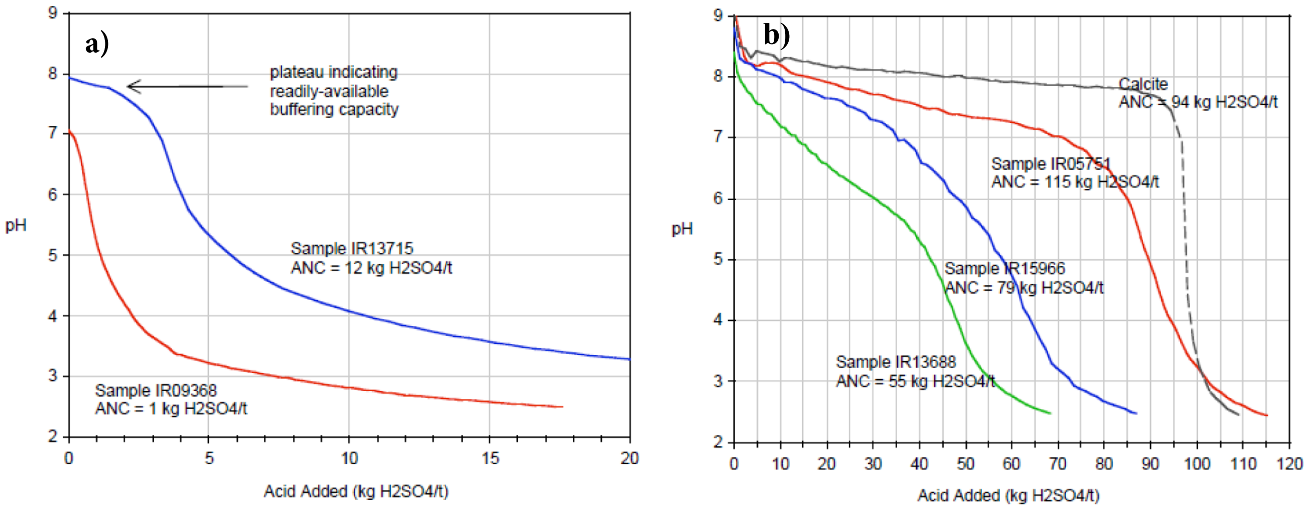

Fig. 6 Typical ABCCs for sample with: **a** low ANC vs. virtually no ANC; **b** moderate to high ANC

Table 3 Median sulfur and ANC values for waste rock samples

Parameter	Waste ARD Category			
	All waste Samples	High-PAF (High acid)	PAF (Acid)	NAF (Neutral)
Sulfur (%S)	0.42	2.3	0.62	0.08
ANC (KgH_2SO_4/t)	5	4	6	6

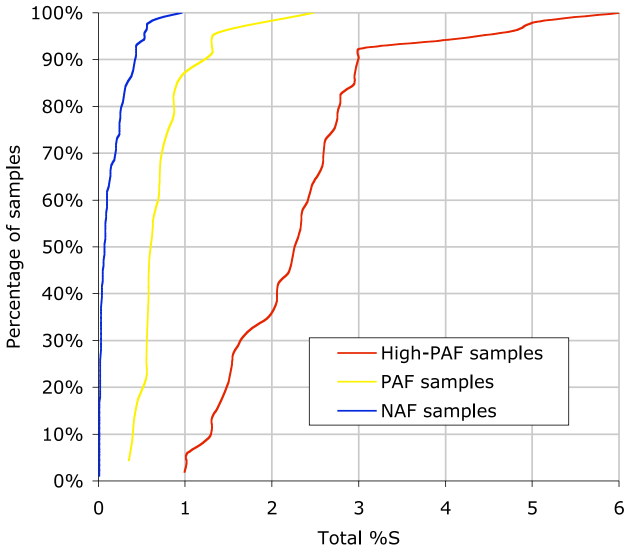

Fig. 7 Percentile distribution of sulfur contents in waste rock samples

strategy will probably be restricted by the limited amounts of higher ANC rock within the deposit. More selective use of higher ANC rock could involve placement in drainage lines, use as intermediate cover layers over acid-generating rock, or as final capping for waste dumps. It could also be judiciously blended with a larger volume of acid-generating rock to increase the lag phase to allow sufficient time for over-dumping, rather than producing an overall NAF blend.

Variability of Sulfur

The acid-forming potential of rock within the Sariguney deposit is primarily determined by the sulfur content, rather than ANC. The disparity in the sulfur content of waste rock compared to ANC is illustrated by the median sulfur and ANC values in Table 3. Whereas the median ANC changes little between the high-PAF, PAF, and NAF categories, the median sulfur contents change by more than an order of magnitude.

The percentile distributions of sulfur contents in the waste rock samples for each ARD category are shown in Fig. 7. Only 10% of the NAF samples contain more than 0.4% S, whereas virtually all of the PAF samples, and all of the high-PAF samples contain more than 0.4% S. It may be possible to utilize a sulfur cut-off value such as this to produce an ARD waste schedule for the project. It might also be suitable for operational identification of NAF and PAF waste types and to facilitate selective waste rock placement should this be required.

Upper Limit of Leachable Metals

A multi-element analysis of the waste materials was conducted to establish an absolute upper limit of the metals available for leaching from the samples. The contents of

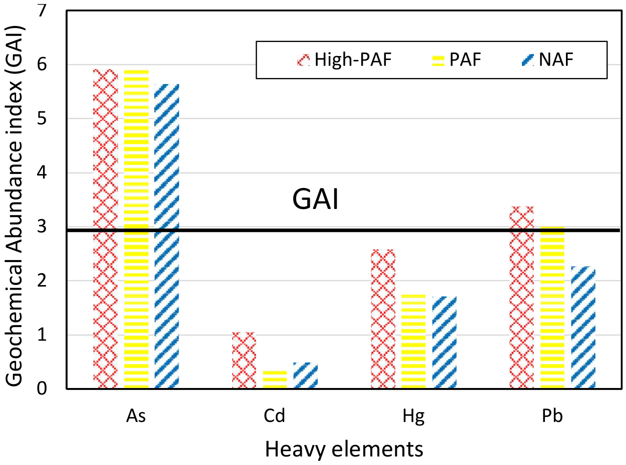

Fig. 8 Presents the GAI values for As, Cd, Hg, and Pb for 127 waste samples from the Sariguney deposit. A GAI value > 3 signifies significant enrichment

each sample were compared to average crustal abundance data to provide an indication of elements that are enriched well above typical background concentrations. The degree of enrichment was quantified using a geochemical abundance index (GAI) (GARD 2021), which compares the actual concentration of elements with their crustal abundance on a logarithmic scale (log 2) and is defined by the formula:

$$GAI = Log_2\left(C_n/\left(1.5 \times B_n\right)\right)$$

where Cn is the concentration of the potentially hazardous metals in the sample and Bn represents the average crustal abundance of the specific element of interest (n), as reported by Mason (1966).

The primary objective of the GAI is to identify elements (particularly metals and metalloids) that may occur in waste rock at concentrations markedly greater than typical background levels. This can guide further investigation to evaluate their potential environmental impact. Per the GARD protocol (GARD 2021), a GAI ≥ 3 indicates enrichment at a level that requires additional scrutiny (Table S-1).

The GAI values of As, Cd, Hg, and Pb for the 127 waste samples of Sariguney deposit are graphically illustrated in Fig. 8. This diagram delineates that arsenic in high-PAF, PAF, and NAF waste samples, and lead in high-PAF and PAF samples, have maximum enrichment levels ≥ 3.

Apart from sulfur, the two elements that stand out as enriched, and are recognized as environmentally important, are arsenic and lead. Some samples were also enriched with cadmium and lead. The main concern with respect to these enriched elements would be their potential to adversely affect surface and groundwater quality should conditions arise that promote their dissolution and subsequent mobilization. Almost all samples were also enriched with antimony at concentrations well above average crustal abundance. Whilst antimony can adversely affect aquatic ecosystems and drinking water quality, it does not generally have the same environmental importance as the other enrichments noted above.

The GAI plots (Fig. 8) indicate that the concentrations in waste rock vary widely and that overall, concentrations tend to be greater in acid-generating rock than in non-acid forming rock, but high concentrations also occur in non-acid forming rock. The data suggest that arsenic and lead enrichment is likely to be widespread across the deposit, whereas enrichment with cadmium and mercury in waste rock will be far less frequent. Cadmium enrichment was confined to ≈ 10% of the waste rock samples, the remainder containing < 1 mg/kg (which was the analytical detection limit). Mercury enrichment was confined to ≈ 20% of the waste rock samples, again with the remainder containing < 1 mg/kg.

The substantial enrichment of nearly all of the waste rock with arsenic, as well as the potential enrichment with lead, cadmium, and mercury, may present challenges for managing waste rock and mine site waters. The average arsenic concentration in the waste rock samples was 790 mg/kg, with ≈ 86% of the samples containing > 100 mg/kg of arsenic. In contrast, the typical concentration range for arsenic in uncontaminated soils is ≈ 5 to 10 mg/kg. The potential leaching of arsenic from the waste rock will be influenced by several factors, including the level of exposure of the rock to atmospheric oxygen (which affects the oxidation rate of arsenical pyrite and arsenopyrite) and the pH of the waste rock (which influences metal solubility). The persistence of high arsenic values within the weathered zone of the deposit suggests that arsenic should be relatively immobile in the oxide waste rock that is close to pH neutral. In such material, the solubility of arsenic will probably be controlled by adsorption onto hydrous iron and aluminum oxides. However, if oxidation and acidification of PAF rock occurs, then arsenic solubility in the dump overall would be expected to increase. Acidification increases the solubility of various metals, potentially causing their dissolved concentrations in dump drainage to exceed water quality guidelines.

Conclusion

The geochemical assessment results suggest that ARD poses a potential risk for the Sariguney deposit. Nearly all of the ore samples, most low-grade ore, and about half of the waste rock samples are likely to generate acid. This issue is particularly concerning for waste dumps and low-grade ore stockpiles that may be exposed to atmospheric conditions for extended periods. ARD generation also presents a risk within the pit, where high-PAF and PAF rock surfaces may remain exposed. Generally, ARD is not a major concern for run-of-mine (ROM) ore, where retention time within a ROM stockpile is typically limited to a few days. However, the lack of ANC in Sariguney ore suggests that delays in ore processing could lead to acid generation. Further specialized testing, such as column tests, is needed to quantify the potential lag time, but based on current data, acidic conditions are expected to develop within weeks to months. If low-grade ore is selectively mined and stockpiled to allow for possible future processing, measures must be taken to reduce sulfide oxidation and prevent ARD generation until processing occurs. Additionally, management strategies for controlling ARD development in waste rock dumps and stockpiles should be identified and critically assessed. The findings of this study indicate that most of the waste rock lacks sufficient ANC, greatly limiting the selective blending of PAF and NAF materials to create an in-situ buffering effect. More than two-thirds of the samples tested had ANCs < 10 kg H_2SO_4/t, which means that most rock will have the capacity to neutralize the acid potential of $< 0.3\%$ S in the form of pyrite. It is expected that most of the NAF rock, if blended with acid-generating waste, will provide little additional neutralizing capacity and will simply "dilute" the acid waste.

A small percentage of NAF waste does have moderate to high acid neutralizing capacity, but its effectiveness in controlling ARD within waste dumps depends on factors such as actual availability within the deposit, mining schedule, and the feasibility of identifying these materials within ore blocks. Such material could be used to extend the lag time of high-PAF rock to allow sufficient time for over-dumping of such material. More selective use of the higher ANC rock could involve placement in drainage lines, use as intermediate cover layers over acid-generating rock, or use as final capping for waste dumps.

The GAI plots (Fig. 8) reveal that the waste rock exhibits a wide variability in metal concentrations—with acid-generating rock generally showing higher levels than non-acid forming rock—yet high concentrations can also occur in the latter. The data indicate that arsenic and lead enrichment is widespread, with arsenic averaging 790 mg/kg and 86% of samples exceeding 100 mg/kg (compared to typical uncontaminated levels of 5–10 mg/kg), while cadmium and mercury enrichment is less common. Although blending with lower AGP materials can somewhat mitigate the leaching potential, our findings suggest that this approach will generally be insufficient. Given that factors such as oxygen exposure and pH critically influence the leaching behavior (with arsenic solubility controlled by adsorption onto hydrous iron and aluminum oxides in near-neutral conditions but increasing with oxidation and acidification), it is imperative to consider additional, more effective mitigation measures—such as lining AG wastes and collecting and treating seepage—to ensure that dissolved metal concentrations remain within acceptable water quality limits.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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