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Evaluation of the geometallurgical indices for comminution properties at Sarcheshmeh porphyry copper mine, Iran

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Abstract

Geometallurgy has become an important tool to predict the processing behaviour of ores, and to decrease the production risks associated with the variable nature of economic mineral deposits. Understanding the ore variability and subsequently the response of the ore to processing are considered to be the most important functions of an accurate geometallurgical study. In this paper geometallurgical indices for grinding properties of a copper ore are investigated. Geometallurgical index (GI) is described as any geological feature which makes a footprint on the processing performance of the ores. A comprehensive study at Sarcheshmeh porphyry copper mine was undertaken. This included the process responses of the ore such as grade, recovery and plant throughput as possible geometallurgical indices. In this paper the effects of rock breakage variability on the plant throughput and energy consumption are presented. Ninety samples were collected based on geological features including lithology, hydrothermal alteration, and geological structures. The samples were characterized using X-ray diffraction, X-ray fluorescence, electron and optical microscopy. A small scale simulated test method for Bond ball mill work index (BWI) was used to perform the comminution examinations. The results showed that BWI values vary from 5.67 kWh/t to 20.21 kWh/t. Examination of the possible correlations between BWI and the geological features showed that the key geological feature related to comminution variability is lithology. In addition, the hydrothermal alteration would be an effective parameter in the period that the plant is fed with a single lithology.

Keywords: *Geometallurgy, Geometallurgical index, Ore variability, Bond work index, Porphyry copper.*

1. Introduction

The mining industry faces significant challenges brought by technical and economic issues. Modern mining requires the exploitation of lower grade and more mineralogically complex, heterogeneous orebodies in order to satisfy the growing demands of the industry (Voigt et al. 2019). In addition to the multiple processing difficulties imposed by such ores, deep mining, environmental and social issues have become critical challenges towards a sustainable mining industry.

In mineral processing, new trends have focused on increasing the efficiency, along with the optimization of energy consumption. In recent years, one of the most important attempts toward a sustainable mining activity has been focusing on creating mine-to-mill and mine-to-market paradigms. Geometallurgy is a selected expression for the paradigm that is used to predict the process performance of an ore in the plant, and tailings in the dam through the integration of geology, mining, and processing parameters. Potential key outcomes of improved geometallurgical knowledge are enhanced forecasting, increased certainty, technical risk reduction, improved economic optimization of mineral production and sustainable mine development (Ashley and Callow 2000; Bennett and Lozano 2004; Williams and Richardson 2004; David 2007).

Geometallurgy is divided into geometallurgical modeling and geometallurgical planning. Geometallurgical modeling incorporates the geological, mineralogical and metallurgical information into a *3D spatial block model*; i.e. domaining and block models to predict the processing behaviour (Ehrig 2011; Keeney and Walters 2011; Garrido et al. 2018; Lishchuk et al. 2018), *geometallurgical tests* (Mwanga et al. 2015; Hilden and Powell 2017; Heiskari et al. 2019), and *integrated mineralogical approaches* (Kuhar et al. 2013; Koch et al. 2019; Rincon et al. 2019). On the other hand, geometallurgical planning is mostly carried out based on a combination of market requirements with the technical characteristics of a mining operation.

The purpose of this study is to present a novel geometallurgical investigation, in terms of geometallurgical index (GI) for the ball mill comminution process of the Sarcheshmeh porphyry copper mine. In mineral processing, the term ‘comminution’ includes the following unit operations: crushers, grinding mills (tumbling mills and stirred mills), and sizing processes (Napier-Munn et al. 1996). Comminution accounts for a large proportion of a mineral processing plant’s capital and operation cost. Cohen (1983) estimated that up to 70% of total plant power draw is consumed by comminution. Grinding, as the last stage of the comminution process, is the most energy-consuming operation in a mineral processing plant that

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can account for more than 50% of the operating cost (Heiskari et al. 2019). In this work, the effects of rock breakage variability on the plant throughput and energy consumption are presented. The samples were collected based on the geological features including lithology, hydrothermal alteration, and geological structures. A small scale simulated test method for Bond ball mill work index (BWI) was used to characterize the comminution properties.

2. Geology and ore body description of the Sarcheshmeh deposit

Porphyry copper deposits are well-known as the world's primary source of copper. In addition, most of these deposits contain important sources of molybdenum and gold (Sillitoe 2010; Yildirim et al. 2014). Sarcheshmeh Cu-Mo-Au mine is located 65 km southwest of Rafsanjan city, Kerman province, southeastern Iran (Fig 1). This porphyry deposit occurs along with more than 50 porphyry and vein-style deposits, in an elongated NW-SE trending tertiary volcano-plutonic belt. The belt is approximately 450 km in length and an average width of 80 km (Dehaj-Sarduiyeh belt), as a part of the southern segment of Urumieh-Dokhtar magmatic arc (Boomeri et al. 2010).

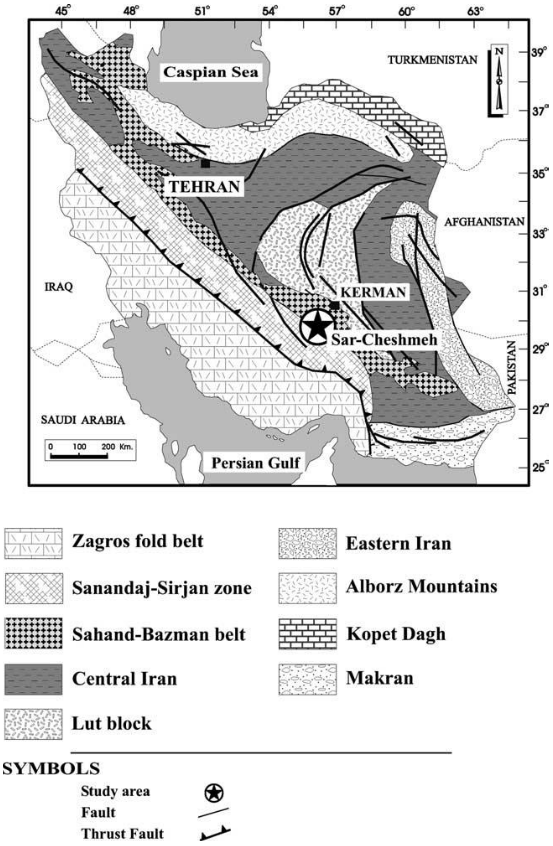

Fig 1 .Simplified map showing some major geological-structural zones of Iran and location of Sarcheshmeh porphyry copper deposit (Hezarkhani 2006).

The deposit is a typical copper porphyry with respect to the alteration types, mineralization style, ore grade and size, tectonic setting, and rock features (Waterman and Hamilton 1975; Hezarkhani 2006; Boomeri et al. 2010). Sarcheshmeh orebody is centered on a granodiorite-quartz monzonite porphyry stock, which is locally called the Sarcheshmeh porphyry (SP). The core area of the main stock appears to have been intruded by a fine-grained granodiorite intra-mineralization, which is called the late fine-grained porphyry (LF). A series of intra- to post-mineralization dikes (DI) with variable compositions cut the porphyries and andesitic wall rocks (Shafiei and Shahabpour 2012). The dikes are composed of a wide range of volcanic and intrusive lithologies. These are divided into hornblende porphyry, feldspar porphyry, and biotite porphyry. The andesite (AN) wall rock, with lower content of copper, surrounds the mineralized zone. Another granodiorite (GR) body is located at the ore shell and formed the outer layer of both andesite wall rock and the mineralized zone (Hezarkhani 2006; Boomeri et al. 2010). Figure 2 shows the main lithologies at the Sarcheshmeh deposit.

The mineralized zone at the Sarcheshmeh deposit consists of intrusive, volcanic, and sub-volcanic rocks. The Sarcheshmeh porphyry (SP) is an early mineralized granodiorite to quartz monzonite stock which is intruded into the volcanic andesitic rocks. The texture in the SP is a combination of porphyritic, which generally consists of plagioclase and quartz phenocrysts in a fine siliceous groundmass, and granular porphyry texture. The volcanic wall rock with low grade mineralization is a fine-grained suite of andesite porphyries. The late fine-grained porphyry (LF) is a sub-volcanic to intrusive post mineralization quartz-monzonite to granodiorittic rock (Waterman and Hamilton 1975; Hezarkhani 2006; Boomeri et al. 2010).

Hydrothermal alterations and the mineralization at Sarcheshmeh are centered on the main stock. Early hydrothermal alteration was dominantly potassic and propylitic, and was followed later by phyllic, silicic and argillic alterations (Hezarkhani 2006). The phyllic and potassic alterations are predominant in the mineralized zones. Fig 3 shows the hydrothermal alterations in the Sarcheshmeh deposit.

3. Materials and Methods

Based on a comprehensive review three different geometallurgical approaches have been introduced: traditional, proxies, and mineralogical (Lishchuk et al. 2015). In the *traditional approach* chemical assays form the basis of the geometallurgical programme, so the metallurgical response is calculated from the chemical composition of the ore. But in the *proxies approach* the geometallurgical tests (GTs) are used to characterize the metallurgical behaviour of the ore. Examples of geometallurgical tests are the Davis tube (Niiranen and Böhm 2012) and the Minnovex crusher index test (Kosick et al. 2002).

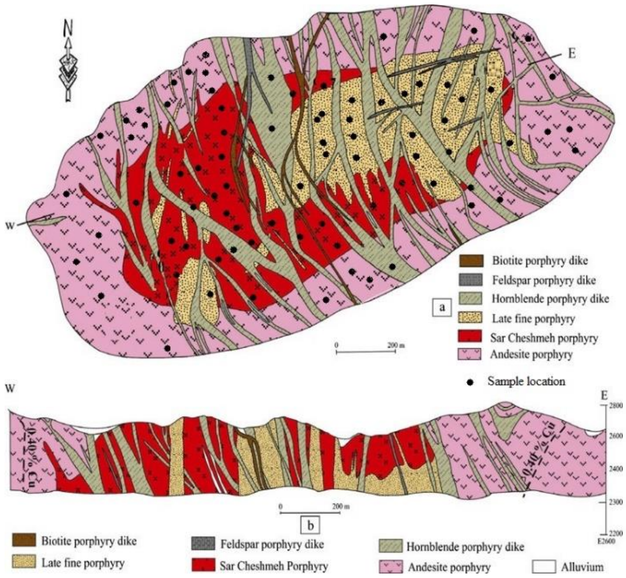

Fig. 2. (a) Map showing distribution of the main rock types in the Sarcheshmeh deposit within 0.40% Cu cutoff at 2,400 m elevation. (b) East–west cross-section of the Sarcheshmeh deposit (Etminan 1977; Shafiei and Shahabpour 2012).

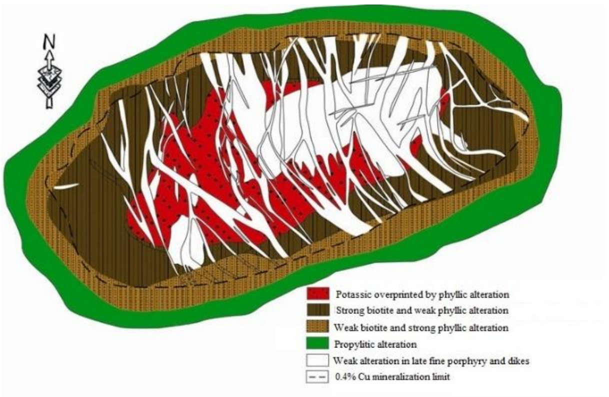

Fig 3. Hypogene alteration pattern in the Sarcheshmeh deposit within the 0.40% Cu cutoff at 2,400 m elevation(Shafiei and Shahabpour 2012).

On the other hand the *mineralogical approach* refers to a programme where the geometallurgical model is built largely based on mineralogy. Often this means that accurate information on modal mineralogy is required for the whole ore body (Lamberg et al. 2013).

In the present work a new methodology was used based on a combination of the proxies and mineralogical approaches (Fig 4). In this method, after specifying the key ore forming parameters by geological surveying, the samples are taken for the GTs. Based on the expected metallurgical behaviour, some quantitative and/or qualitative set points are defined. If the results lead to a normal process response, a regular geometallurgical index (GI) will be introduced for that treated domain; otherwise, detailed process mineralogical studies are carried out. Then, the GTs are repeated with a new condition. Based on the confirmed results some GIs are defined. A geometallurgical index may consist of one geological unit or a combination of them.

The Bond ball mill work test (BWI) was selected as the geometallurgical comminution test (GCT). For the samples in which the results were out of the norm, detailed process mineralogical studies were performed. Finally, the GIs were introduced based on the results of the GTs and mineralogical characterization.

3.1. Key ore-forming parameters at Sarcheshmeh

In order to find the key ore-forming parameters related to comminution properties at the Sarcheshmeh deposit, all the geological information including lithology, hydrothermal alteration, mineralization zones, and structural control parameters were studied.

Mineralization in a porphyry copper deposit is commonly divided into oxidation, supergene enrichment and hypogene zones. At Sarcheshmeh mine, the oxidation zone and most of the supergene zone have been mined out. Current mining focuses on the hypogene zone along with the minor remaining supergene resources. In this deposit, the structural controls, mostly the faults, are limited to displacement of the units, and to a minor extent some influences on the ore texture. So, the structural parameters were not selected as an independent ore-forming parameter. As a result, lithology and hydrothermal alteration were selected as the key geological parameters affecting the hardness specification of the ores, and hence the possible GIs.

3.2. Sampling

The number of samples, the amount of required sample, and the spatial location of samples in the mine block are three main questions in the geometallurgy (Stewart 2010; Dominy et al. 2016; Lishchuk et al. 2016). In addition to the budget restrictions in a project, time consuming GTs are the major limitation for choosing a sampling paradigm that covers all variations. In some cases, broad numbers of samples have been tried by the reserve estimation tools, such as chemical assays, geological information, RQD (Rock Quality Designation), and semi-quantitative mineralogical studies (Deutsch et al. 2016). In these cases modeling and simulation tools such as geostatistics and PCA (principle component analysis), as data driving approaches, have been used with limitations (Suriadi et al. 2018).

Given that, lithology and hydrothermal alteration were selected as the key ore-forming parameters, the samples were taken based on the paradigm that covers most of the variations, both in surface and underground mineralization. In this work ninety hand-picked and drill core samples were collected at 17 different zones within the mine block (Fig 1). Each sample was about 20 kg for hand-picked, and one half of drill cores (85 mm diameter), totaling a length of one meter for each underground sample (Table 1).

Table 1. The number of samples that were taken in different lithologies and hydrothermal alteration zones. **Lithologies** (SP: Sarcheshmeh porphyry, GR: granodiorite, LF: late fine porphyry, AN: andesite, DI: dike). **Alterations** (SQ: sericite-quartz, QS: quartz-sericite, SI: silicified, BI: biotite, PO: potassic)

Alteration		lithology				
		AN	SP	GR	LF	DI
Phyllic	SQ	3	5	3	0	0
	QS	9	11	6	8	3
	SI	6	3	4	5	2
Potassic	BI	4	0	0	0	0
	PO	0	5	4	9	0

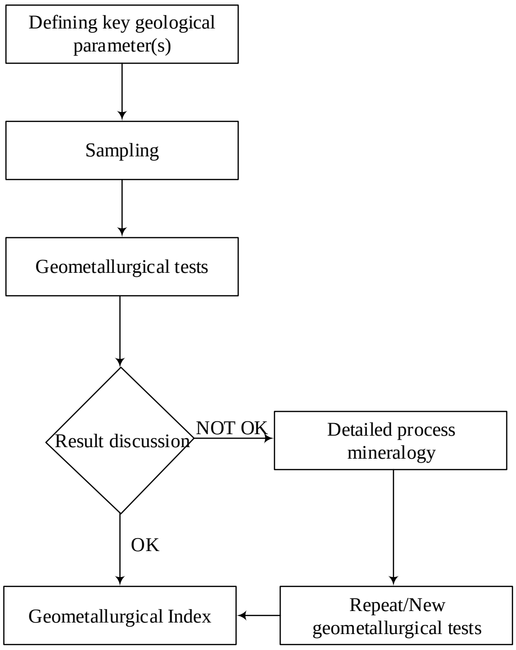

Fig 4. Schematic pathway for implementing geometallurgy

3.3. Characterization study

The characterization studies including chemical, petrographic and mineralogical investigations were carried out. Each sample was macroscopically described in terms of lithology, mineralogy, hydrothermal alteration, macro structures and texture. This was followed by XRF (X-ray fluorescence), XRD (X-ray diffraction), petrographic microscopy, SEM (scanning electron microscopy), and QAM (quantitative automated mineralogy) for fresh and ground samples.

Lithological classification, mineralogical composition, texture, mineral associations, grain size, micro-structures and hydrothermal alteration were investigated in the characterization studies. By a combination of the chemical analysis, QXRD (semi-quantitative XRD), and the modal analysis technique, major minerals which accounted for more than 90% to 98% of the mineralogical composition were identified. Also QAM was used on limited numbers of particulate samples to calibrate QXRD, in order to identifying the abundance of major minerals. Due to being readily available and easy to conduct, XRD is a more usable equipment for mineral identification. It should be noted that the minerals library for the QAM was firstly created based on XRD, then other characteristics of minerals were studied.

The QAM study was performed on a ZEISS SIGMA 300 VP SEM equipped with a BSE (back-scattered electrons) detector, at 129 eV energy resolution. The used QAM was fitted-out with the ZEISS automated quantitative mineralogy software platform. The acceleration voltage of the primary electron beam was set to 20 kV. The 120 µm aperture providing 80 µA beam current used was used to obtain a high input count rate for the EDX (energy dispersive X-ray) detectors. The carbon coated polished samples were analyzed with a grain X-ray mapping measurement mode at a magnification of 500 times. Back scattered electron (BSE) image grey level calibration was set with epoxy resin as background (BSE grey value < 25) and gold metal as upper limit (BSE grey value > 250). An example BSE and color-coded imagining of minerals by QAM for a SP sample is shown in Fig 5. Petrographic microscopy and BSE images of SEM were also used to determine the ore texture specifications, including grain size, mineral associations, distribution of minerals and micro structures.

In order to measure the degree of alteration, the normative approach was used (Piché and Jébrak 2004). In this approach, hydrothermal alteration is quantified by using normative mineral ratios for volcanogenic massive sulfide (VMS) exploration. In the current study, the approach was developed based on a combination of calculating the secondary minerals along with the alkali element depletion.

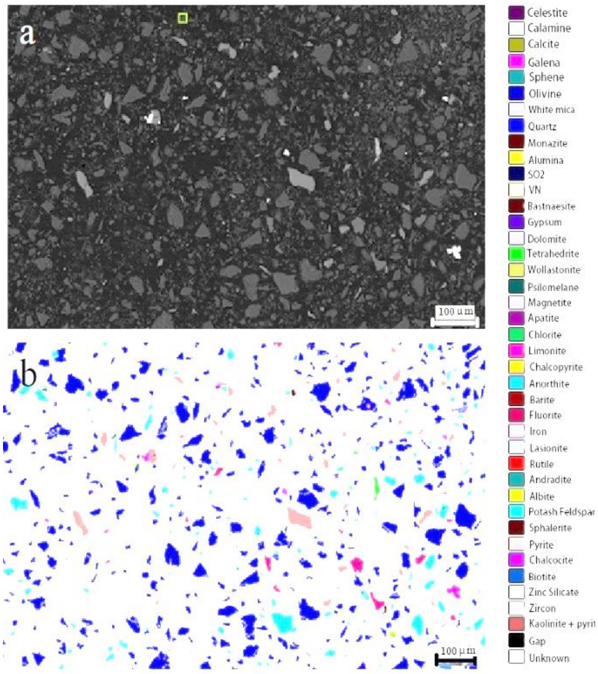

Fig. 5. Images of polished particles mount of SP using the QAM. a) BSE imagining and b) X-ray mapping with color-coded legend of minerals present in the sample.

3.4. Geometallurgical Comminution tests

The geometallurgical tests (GT) are the conventional metallurgical investigations, such as the comminution, flotation, gravity, and magnetic tests. These tests are used to characterize the possible variations in the metallurgical properties of the ores. In geometallurgy exact numbers are not as important as domains. A domain is an exclusive classification of ore by a common property or set of properties (David 2007). In such cases, using a precise test i.e. a reproducible test, is extremely important. For this reason, the use of alternative simplified tests is acceptable for the geometallurgical investigation.

In the comminution studies, the resistance of the ore to breakage is measured through crushability and grindability testing. The geometallurgical comminution tests (GCTs) are used to predict the throughput of a mineral processing plant. According to Mwanga et al. (2015), a proper GCT should fulfill the following requirements: (1) the test should be relatively simple, (2) the test should be repeatable and not person-dependent, (3) the test should be easy to conduct, (4) the test should be fast and inexpensive, (5) the required sample size should be small, (6) the test should give values for both crushability and grindability, (7) the results of the test should be used in modeling and simulation, and (8) it should be possible to extend the test by including the mineral liberation information.

3.4.1. Bond Ball Mill Work Index

Bond ball mill work index (BWI) was first established by Bond (Bond 1952; Bond 1961). This test is still the most used approach in the design and analysis of comminution circuits (Mwanga et al. 2017). The bond test applies a standardized ball mill of 305 mm, both in diameter and length. The required sample is around 10 kg with particle sizes finer than 3.35 mm. The test is conducted in a dry locked-cycle, until the circulation load reaches 250%. The test often needs 7 to 10 cycles to meet the defined criteria. The BWI [kWh/t] is then calculated by using Bond’s empirical Equation 1.

:

$$W_i = 1.1 \times \frac{4.45}{P^{0.23} G^{0.82} . \left(\frac{1}{\sqrt{p_{80}}} - \frac{1}{\sqrt{f_{80}}}\right)} \qquad \text{(Equation 1)}$$

W_i: Bond ball mill work index, (kWh/t)

P : target screen size, (µm)

G :Mass of product per number of revolutions passing P

p_{80} and f_{80}: 80% passing size of product and feed respectively, (µm)

Because of the rather time consuming and the significant sample requirements, several suggestions have been made over years to modify the Bond test. Nematollahi (1994) used a scaled down test with a coefficient of two-thirds of the standard Bond ball mill where both the diameter and length are 200 mm. The test is operated at the same critical speed as the Bond ball mill runs. The mill is charged with 85 steel balls weighing 5.9 kg, and ranging in diameter from 16 to 38 mm. The ore is packed to a volume of 207 cm^3 instead of 700 cm^3 required for the standard Bond test. The test is conducted to produce a circulating load of 250%. After reaching equilibrium, the grindability of the last three cycles are averaged. Equation2 is used to calculate the ball mill work index.

$$W_i = \frac{11.76}{P^{0.23} G^{0.75} . \left(\frac{1}{\sqrt{p_{80}}} - \frac{1}{\sqrt{f_{80}}}\right)} \qquad \text{(Equation2)}$$

Where *P, G, p_{80} and f_{80}* are the same with Equation 1**.** The results obtained by the Nematollahi method have been compared with the Bond ball mill test, and the results show a maximum relative error of 5%. Therefore, in this investigation Nematollahi’s standard ball mill was used in order to calculate the equivalent BWI.

4. Results

4.1. Petrography, hydrotermal alteration and mineralogy

The petrographic study showed that granodiorite, quartz-monzonite and andesite are the main rock types in the mineralized zone. The petrography of SP, as the principle host of the copper minerals, indicated a predominant granodiorite with a minor quartz-monzonite lithologies. The LF zone, as the closest mineralized zone to the main stock, is mostly granodiorite too. The outer units of the mineralized zone are the andesitic wall rock with lower copper content. An independent granodiorite body is located close to the andesite wall rock and consists of the lowest copper contents. The petrographic composition of dikes is variant, but mostly is andesite.

The major minerals in the all samples were quartz, potassium feldspar, plagioclase, and clay minerals including chlorite, kaolinite, illite, montmorillonite, and dickite. Disseminated chalcopyrite, pyrite, chalcocite, and minor molybdenite were the predominant sulfide minerals. The mineralogy of SP showed to be a combination of phenocrysts and fine grained groundmass. More than 40% (by volume) of the SP content is composed of phenocrysts, commonly plagioclase, potassium feldspar, quartz and biotite but the groundmass is mainly composed of fine quartz and potassium feldspar. Andesite wall rock and dikes are consist of plagioclase, potassium feldspar, quartz, and biotite. Plagioclase mainly occurred as phenocrysts, but potassium feldspar is mostly formed the groundmass of andesite. Hydrothermal alteration characterization indicates that the phyllic and potassic zones are predominant in the mineralized zones. Based on the degree of alteration, the phyllic alteration was divided into three stages including sericite-quartz (SQ), quartz-sericite (QS), and silicified (SI). Also the potassic alteration is divided into the biotite (BI) and potassic (PO) alterations. The textural properties of the mineralized units are affected by hypogene hydrothermal alteration and later supergene process. Phaneritic textured rocks comprised of large minerals in granodiorite rocks verses aphanitic and textures in andesitic rocks were the major primary textures (Fig 6a and b).

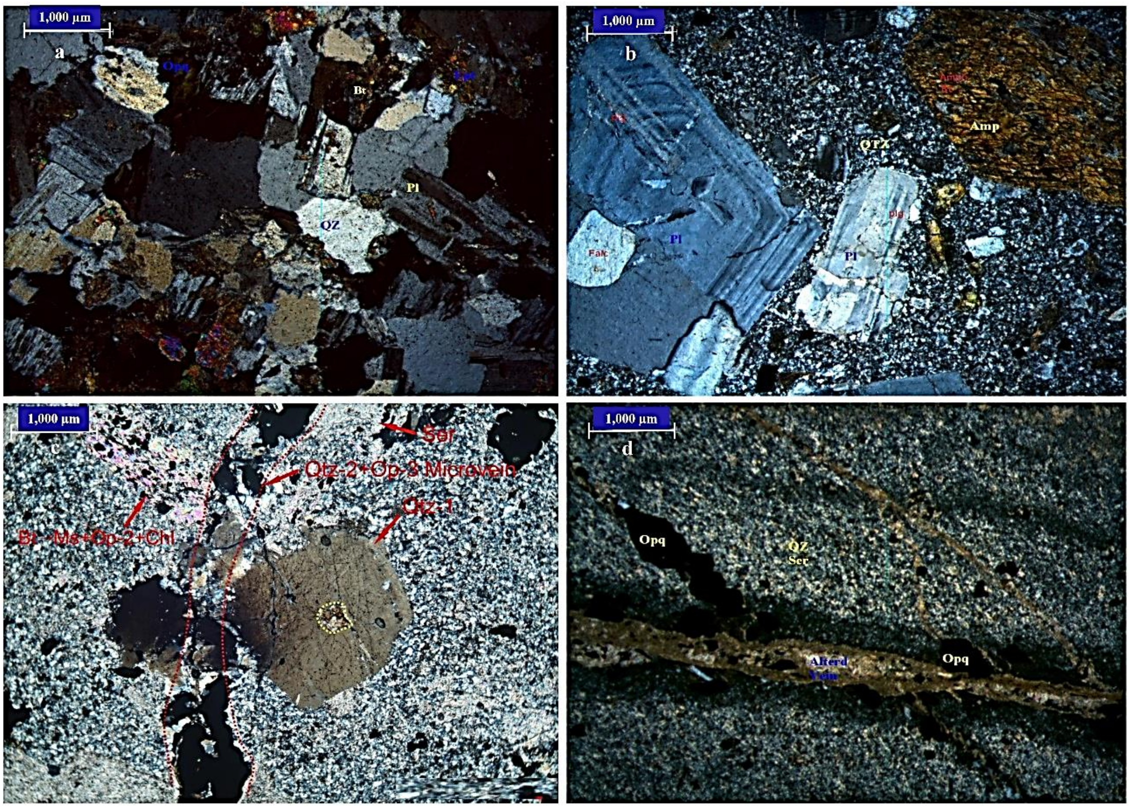

Fig 6. Major textures at Sarcheshmeh. Granodiorite (a) and andesite (b) with primary preserved texture. Andesite (**c)** and (d**)** with secondary altered textures which plagioclase altered into sericite with a fine grain quartz and filled veinlet (Qz: quartz, Pl: plagioclase, Bt: biotite, Amp: amphibole, Or: orthoclase, Ser: sericite, Ms: muscovite, Opq: opaque minerals)

Table 2. The results of BWI tests on different lithologies. *lithologys* (SP: Sarcheshmeh porphyry, GR: granodiorite, LF: late fine porphyry, AN: andesite, DI: dike). *Alterations* (SQ: sericite-quartz, QS: quartz-sericite, SI: silicified, BI: biotite, PO: potassic)

		Lithology				
		SP	AN	GR	DI	LF
BWI (kWh/t)	Min-max	5.67-9.98	8.63-16.29	11.68-17.79	11.78-20.21	13.14-16.75
	Average	8.85	12.59	14.07	14.86	15.31

Secondary textures are mostly the results of hydrothermal alterations, and to a lesser extent the effects of structural controls. The secondary textures were identified as altered fine grain minerals (lesser than 1 mm), specially sericite, biotite, and clay minerals (Fig 6c). Veinlets were also filled by secondary minerals (Fig 6d).

4.2. Ball mill work index (BWI)

The results of BWI test on the samples is shown in Table 2. These results indicate a wide range of hardness variability. The samples were ranked according to their resistance to the comminution process from the weakest to hardest. Based on the BWI values, the samples were classified into soft (less than 10 kWh/t), medium (10 -15 kWh/t), and hard (more than 15 kWh/t). The results indicated 22 percent of samples are soft, 58 percent of samples are medium, and 20 percent of samples are hard to grind in a ball mill.

As shown in table 2, the minimum value of BWI is 5.67 kWh/t, was identified in SP lithotype, and the maximum value is 20.21 kWh/t in DI lithotype. The average values of BWI for SP, AN, GR, DI, LF were 8.85, 12.59, 14.07, 14.86, and 15.31, respectively. The simple average of BWI, including all samples, was 13.06 kWh/t. The weighted average of BWI, which represents the real required power draw for a ball mill circuit, would be a function of the GI, by considering the mine's block model.

5. Discussion

Major geological characteristics related to comminution properties are shown in Fig 6. Porphyritic textures which consist of phenocrysts in a fine-grained matrix, heterogeneous altered minerals, veinlets, and different grain sizes and shapes could be the main reasons for the different comminution behaviours.

The results of GCTs indicate that despite a similar lithology, the BWI of SP, LF and GR is significantly different; consequently, the ball mill power draw and plant capacity are incomparable in these lithologies. As an example, the difference of BWI for SP and LF lithologies, which they are close to each other at the mine pit, is primarily a consequence of homogenous texture in LF, i.e. narrow range of grain sizes, but heterogeneous texture in SP, i.e. wide range of grain sizes. Also at the micro scale, LF has a fine grain and granular texture (Fig 7a). The sizes of LF particles are less than 1 mm, and mostly micron sized. At the macro scale, LF is a post mineralized stock, with less weathering and hydrothermal alteration. The number of silicic stockworks, as weak points, in the LF is fewer than the SP. The predominant alteration in the LF is phyllic alteration with the high content of fine sericite. On the other hand SP has coarser and heterogeneous particles (Fig 7b). The predominant alteration in the SP lithology is QS with high content of quartz and sericite. The number of stockworks are higher and they are filled by secondary minerals (Fig 6**Error! Reference source not found.**d). The stockworks are a reason for a low grinding resistance. The other lithologies show intermediate comminution properties. The heterogeneous texture and more altered minerals in andesite are the reasons for its low BWI.

The effect of hydrothermal alteration on the BWI was found to be different and sometimes contradictory. The lithologies with phyllic alteration have a wide range of BWI, from soft to hard, but the samples with potassic alteration have a narrow BWI that changed from medium to hard. The average of BWI in potassic alteration was 15.5 kWh/t. The integration of BWI and characterization studies indicate that the resistance to grinding increases in the phyllic alteration by increasing the degree of alteration. As the process of phyllic alteration increases, the plagioclase in the original rock are replaced by alteration minerals, in which the sericite and quartz content increase relative to the original amount (Yildirim et al. 2014). Sericitisation is an acidic alteration that produces white mica, mostly with very thin grain size, termed sericite with a sericitic texture. If the hydrothermal alteration continues then total silicification occurs, where the minerals are completely replaced by quartz. Silicification was seen at Sarcheshmeh as quartz veins and stockworks. Sericitisation and silicification increase the BWI due to the generation of fine and thin flaked particles. On the other hand, in phyllic alteration, the degree of potassic alteration had a reverse effect on the BWI. It means that in a particular lithology with potassic alteration, by increasing the degree of alteration the BWI decreases. It is a reason of more heterogeneous new texture.

Without considering other key-ore forming parameters, such as lithology and alteration, the mineralogical composition was used to investigate the correlation between mineralogical composition and BWI. The mineralogical composition is shown for 15 samples in Fig 8. The compositions accounted for major minerals which range from 90 (wt %) to 98 (wt %) of the mineralogical composition. Quartz, orthoclase, plagioclase, chalcopyrite, clay minerals, sericite, and pyrite were the major minerals in the samples. The results in Fig 8 suggest that it is not possible to use the minerals content to predict the BWI. The minimum BWI in the Fig 8 belongs to a SP sample with QS alteration. On the other hand, the highest BWI belongs to a DI sample with the same alteration.

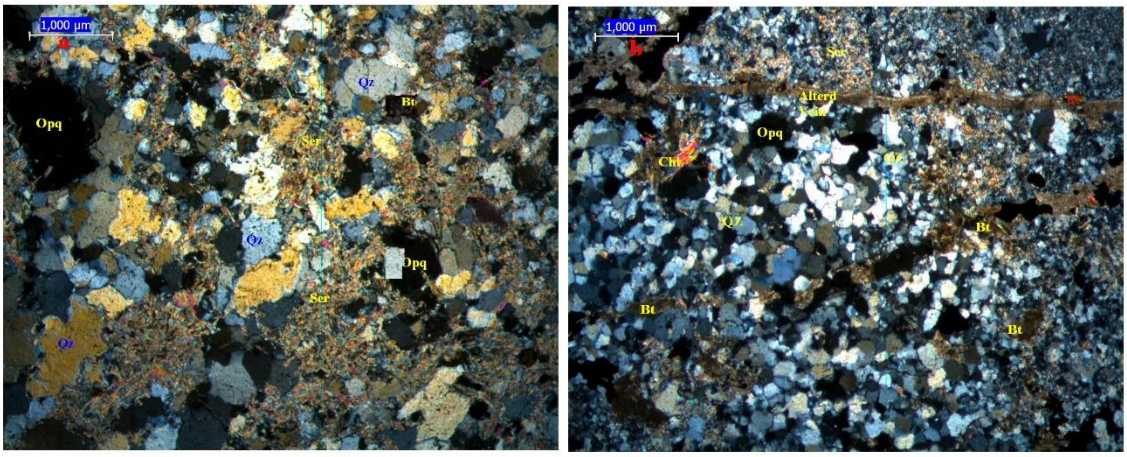

Fig 7. a) LF with fine particles and weak alteration, b) SP with coarser particle and strong alteration (Qz: quartz, Pl: plagioclase, Bt: biotite, Amp: amphibole, Or: orthoclase, Ser: sericite, Ms: muscovite, Opq: opaque minerals)

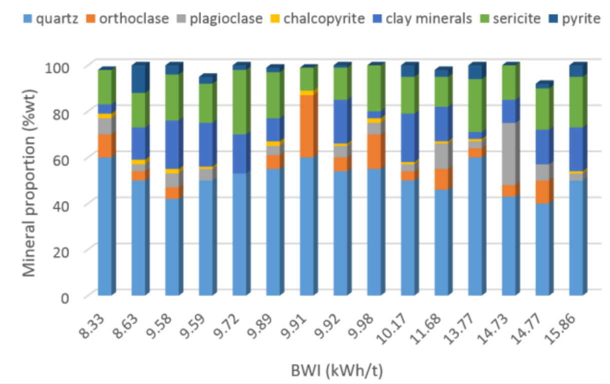

Fig 8. The correlation between modal mineralogy and BWI

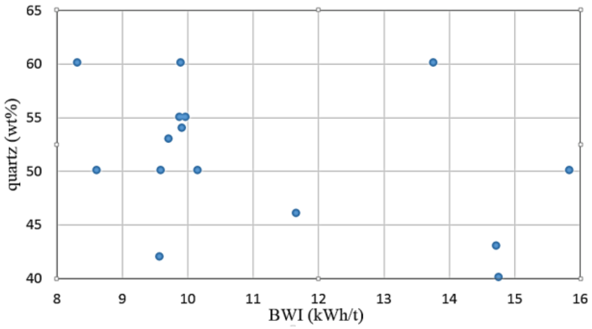

Fig 9. The correlation between quartz content and BWI

The quartz content in the samples was selected as a proxy to investigate the probable relevance with the BWI. In addition to the hardness specification of quartz, high values and broad variations of this mineral were the reasons for choosing quartz for a detailed investigation. Fig 9 shows quartz content plotted against the BWI. The content of quartz in the softest and hardest samples were 60% and 50%, respectively. It should be noted the mineralogical composition shows the actual content of quartz or any minerals, without considering the primary amount in the original rock and the secondary extent that has been generated during the alteration process. For this reason, a specified lithology could hold different amount of a mineral. Secondary minerals, such as quartz were observable in the microscopic studies as fine grain, filled veinlets, and stockworks.

Other minerals, and a combination of minerals such as clays, were also subjected to investigate the possible relations between the BWI and mineralogical abundance. The total amount of quartz, plagioclase, and orthoclase minerals (QAP), as the common constituent minerals of igneous rocks that represents the original rock composition, were used to predict the BWI. The difficulty that was imposed by alteration minerals, did not let to correlate the BWI and mentioned mixture of minerals. As mentioned, most of the plagioclase in the original rock is converted to secondary minerals. The results for the clay minerals also showed that in a specific lithotype, if increasing the degree of alteration leads to high content of clay minerals, the BWI would increase, otherwise there is no possible way to correlate clay composition with the BWI.

6. Conclusions

This paper has provided a comprehensive new methodology to perform a geometallurgical program for defining geometallurgical indices in a ball mill comminution process. The most important issues and the obtained results are:

-Smart sampling by predicting the key factors on the comminution properties.

-Geological features those selected as the key factors were rock types, alterations, geological structures and ore texture.

-In Sarcheshmeh porphyry deposit lithology was shown to be the most important key factor on the ball mill comminution process.

-It can be concluded that if the mineralization occurs in a porphyry deposit with a single rock type, the hydrothermal alteration defines the hardness variability.

-No systematic relation was observed between mineral composition and BWI.

References

Ashley K, Callow M (2000) Ore variability: Exercises in geometallurgy, *Engineering and Mining Journal* 201:24.

Bennett C, Lozano C (2004) The Architecture of the Geometallurgical Model, *Proceedings Procemin*:1-8.

Bond FCJCE (1961) Crushing and grinding calculations Brit.

Bond FCJME (1952) Third theory of comminution, 4:484.

Boomeri M, Nakashima K, Lentz DR (2010) The Sarcheshmeh porphyry copper deposit, Kerman, Iran: A mineralogical analysis of the igneous rocks and alteration zones including halogen element systematics related to Cu mineralization processes, *Ore Geology Reviews* 38:367-381.

Cohen H (1983) Energy usage in mineral processing, *Transactions of the Institution of Mining and Metallurgy* 92:160-163.

David D The importance of geometallurgical analysis in plant study, design and operational phases. In: *Proceedings Ninth Mill Operators' Conference 2007* : 241-248.

Deutsch JL, Palmer K, Deutsch CV, Szymanski J, Etsell TH (2016) Spatial modeling of geometallurgical properties: techniques and a case study, *Natural Resources Research* 25:161-181.

Dominy S, O'Connor L, Xie Y (2016) Sampling and testwork protocol development for geometallurgical characterisation of a sheeted vein gold deposit. In: *Proceedings of the International Geometallurgy Conference*, Perth, Australia: 15-16.

Ehrig K (2011) Quantitative mineral mapping, *The First AusIMM International Geometallurgy Conference*: 31.

Etminan H (1977) Le porphyre cuprifère de Sar Cheshmeh (Iran): rôle des phases fluides dans les mécanismes d'altération et de minéralisation. Fondation scientifique de la géologie et de ses applications.

Garrido M, Sepúlveda E, Ortiz JM, Navarro F, Townley B (2018) A Methodology for the Simulation of Synthetic Geometallurgical Block Models of Porphyry Ore Bodies.

Heiskari H, Kurki P, Luukkanen S, Gonzalez MS, Lehto H, Liipo J (2019) Development of a comminution test method for small ore samples, *Minerals Engineering* 130: 5-11.

Hezarkhani A (2006) Hydrothermal evolution of the Sar-Cheshmeh porphyry Cu–Mo deposit, Iran: evidence from fluid inclusions, *Journal of Asian Earth Sciences* 28: 409-422.

Hilden MM, Powell MS (2017) A geometrical texture model for multi-mineral liberation prediction, *Minerals Engineering* 111: 25-35.

Keeney L, Walters SA (2011) methodology for geometallurgical mapping and orebody modelling. In: *GeoMet 1st AusIMM International Geometallurgy Conference*. Australasian Institute of Mining and Metallurgy, pp 217-225.

Koch P-H, Lund C, Rosenkranz J (2019) Automated drill core mineralogical characterization method for texture classification and modal mineralogy estimation for geometallurgy, *Minerals Engineering* 136:99-109.

Kosick G, Bennett C, DOBBY–SGS G (2002) Managing Company Risk by Incorporating the Mine Resource Model into Design and Optimization of Mineral Processing Plants, *TECHNICAL BULLETIN* : 21.

Kuhar L, McFarlane A, Chapman N, Meakin R, Martin R, Turner N, Robinson D (2013) Calibration and testing of a geometallurgical leaching protocol for determining copper mineralogical deportment. In: *Proceedings of the 2nd AusIMM International Geometallurgy Conference*: 177-186.

Lamberg P, Rosenkranz J, Wanhainen C, Lund C, Minz F, Mwanga A, Parian M (2013) Building a geometallurgical model in iron ores using a mineralogical approach with liberation data. In: *Proceedings of the Second AusIMM International Geometallurgy Conference*, Brisbane, Australia: 317-324.

Lishchuk V, Lamberg P, Lund C (2015) Classification of geometallurgical programs based on approach and purpose. In: *SGA 2015*.

Lishchuk V, Lamberg P, Lund C (2016) Evaluation of sampling in geometallurgical programs through synthetic deposit model. In: *XXVIII International Mineral Processing Congres*s, Québec City, September: 11-15.

Lishchuk V, Lund C, Lamberg P, Miroshnikova E (2018) Simulation of a mining value chain with a synthetic ore body model: Iron ore example, *Minerals* 8:536.

Mwanga A, Rosenkranz J, Lamberg P (2015) Testing of ore comminution behavior in the geometallurgical context-A review, *Minerals* 5:276-297.

Mwanga A, Rosenkranz J, Lamberg P (2017) Development and experimental validation of the Geometallurgical Comminution Test (GCT), *Minerals Engineering* 108:109-114.

Napier-Munn TJ, Morrell S, Morrison RD, Kojovic T (1996) Mineral comminution circuits: their operation and optimisation.

Niiranen K, Böhm A (2012) A systematic characterization of the orebody for mineral processing at Kirunavaara iron ore mine operated by LKAB in Kiruna, Northern Sweden, *Impc* 1039: 3855-3864.

Piché M, Jébrak MJJoGE (2004) Normative minerals and alteration indices developed for mineral exploration, *Journal of Geochemical Exploration* 82: 59-77.

Rincon J, Gaydardzhiev S, Stamenov L (2019) Coupling comminution indices and mineralogical features as an approach to a geometallurgical characterization of a copper ore, *Minerals Engineering* 130: 57-66.

Shafiei B, Shahabpour J (2012) Geochemical aspects of molybdenum and precious metals distribution in the Sar Cheshmeh porphyry copper deposit, Iran, *Mineralium Deposita* 47: 535-543.

Sillitoe RH (2010) Porphyry copper systems, *Economic geology* 105: 3-41.

Stewart M, Coward S, Vann J (2010) Challenges of quality management in sampling and measurement of geometallurgical variables, *Sampling Conference*: 69-159.

Suriadi S, Leemans SJ, Carrasco C, Keeney L, Walters P, Burrage K, ter Hofstede AH, Wynn MT (2018) Isolating the impact of rock properties and operational settings on minerals processing performance: A data-driven approach, *Minerals Engineering* 122: 53-66.

Voigt M, Miller J, Bbosa L, Govender R, Bradshaw D, Mainza A, Becker M (2019) Developing a 3D mineral texture quantification method of drill core for geometallurgy, *Journal of the Southern African Institute of Mining and Metallurgy* 119: 347-353.

Waterman GC, Hamilton R (1975) The Sar Cheshmeh porphyry copper deposit, *Economic Geology* 70: 568-576.

Williams SR, Richardson J (2004) Geometallurgical Mapping: A new approach that reduces technical risk. In: *Proceedings 36th Annual Meeting of the Canadian Mineral Processors*: 241-268

Yildirim BG, Bradshaw D, Powell M, Evans C, Clark A (2014) Development of an effective and practical Process Alteration Index (PAI) for predicting metallurgical responses of Cu porphyries, *Minerals Engineering* 69: 91-96.