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# Development of Geometallurgical Indices for Semi-Autogenous Grinding at Sarcheshmeh Porphyry Copper Mine

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**Abstract**

Geometallurgy tries to predict the instability the behavior of ores caused by variability in the geological settings, and to optimize the mineral value chain. Understanding the ore variability and subsequently the process response are considered to be the most important functions of an accurate geometallurgical study. In this paper, the geometallurgical index is presented as a new tool to optimize the mining activities. Geometallurgical index is described as any geological feature that makes a footprint on the process performance of ores. In a comprehensive research work at the Sarcheshmeh porphyry copper mine, the geological features that affect the main process responses including the product grade and recovery and plant's throughput are subjected to investigation. In the current report, the rock hardness variability in terms of semi-autogenous grinding power index (SPI) and its effects on the mill throughput and energy consumption are presented. Ninety samples are collected based on the geological features including lithology, hydrothermal alteration, and geological structures. The samples are mineralogically characterized using XRD, XRF, and electron and optical microscopy. The Starkey laboratory mill, commercialized by Minnovex, is used to perform the SPI comminution test. The SPI results show a wide range of hardness, varying from 12 to 473 minutes. The correlation between the SPI results and the geological features show that lithology is a key geological feature that defines the hardness variability. In addition, the hydrothermal alteration would be an effective parameter in the period that the plant is fed with a single lithology.

## 1. Introduction

Today, the mining industry faces significant challenges brought by the technical and economic issues. Modern mining requires the exploitation of lower grade and more mineralogically complex and heterogeneous orebodies in order to satisfy the growing demands of the industry [1]. In addition to the multiple processing difficulties imposed by such ores, deep mining and environmental and social issues have become the critical challenges towards a sustainable mining development.

In the mining industry, new trends have focused on increasing the efficiency along with the optimization of energy consumption. The key parts of the mining value chain are geology, mining, mineral processing, process metallurgy, and waste management [2]. In the recent years, mine-to-mill and mine-to-market paradigm have come to be the main attempts to achieve a sustainable mining activity. Geometallurgy is a selected expression for paradigm that tries 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. Moreover, it has been proposed that market requirements could be considered in such a template. The potentially key outcomes of improved geometallurgical knowledge are enhanced forecasting, increased certainty, technical risk reduction, improved economic optimization of mineral production, and sustainable mine development [3-6].

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Geometallurgy is divided into geometallurgical modeling and geometallurgical planning. Geometallurgical modeling has been presented as 3D spatial modeling [7-10], geometallurgical tests [11-13], and integrated mineralogical approaches [14-16]. On the other hand, geometallurgical planning is mostly carried out by a combination of market requirement and geometallurgical modeling tools.

The purpose of this work was to present a novel geometallurgical modeling in geometallurgical index terms for a semi-autogenous comminution process. In the mineral processing, the term 'comminution' includes the following unit operations: crushers, grinding mills (tumbling mills and stirred mills), and sizing processes [17]. Comminution is accountable for most proportions of a mineral processing plant capital and operation cost. Cohen has estimated that up to 70% of the total plant power draw is consumed by comminution [18]. Grinding, as the last stage of the comminution process, is the most energy-consumer operation in a mineral processing plant that accounts for more than 50% of the operating cost [11]. In particular, the hardness variability plays a crucial role in the performance of the mineral processing plant, especially in the semi-autogenous grinding (SAG) mill [19].

In this work, the effects of hardness 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. The semi-autogenous grinding power index (SPI) test was used to define the SAG characteristics of the samples.

**2. Orebody description**

Porphyry copper deposits are well known as the world's primary source of copper. Also, most of them contain important sources of molybdenum and gold [20, 21]. Sarcheshmeh porphyry copper deposit is occurred along with more than 50 porphyry and vein-style deposits and prospects in an elongated NW-SE trending Tertiary volcano-plutonic belt of approximately 450 km length and an average width of 80 km (Dehaj-Sarduiyeh belt) as the southern segment of the Urumieh-Dokhtar magmatic arc [22]. The deposit is well-known as a typical copper porphyry deposit with respect to the alteration type, mineralization style, ore grade and size, tectonic setting, and rock features [23-25].

The Sarcheshmeh orebody is centered on a granodiorite-quartz monzonite porphyry stock, which is locally called the Sarcheshmeh porphyry (SP). The core area of the principle stock appears to have been intruded by a fine-grained porphyritic intra-mineralization, which is called the late fine-grained porphyry (LF). A series of intra- to post-mineralization dikes (i.e. hornbland porphyry, feldspar porphyry, and biotite porphyry) with variable compositions cut the porphyries and andesitic wall rocks [26]. Hydrothermal alterations and the mineralization at Sarcheshmeh are centered on the stock and are broadly synchronous with its emplacement. The early hydrothermal alteration was dominantly potassic and propylitic, and was followed later by phyllic, silicic, and argillic alterations [24]. Figure 1 shows the main rock types and Figure 2 shows the hypogene alterations.

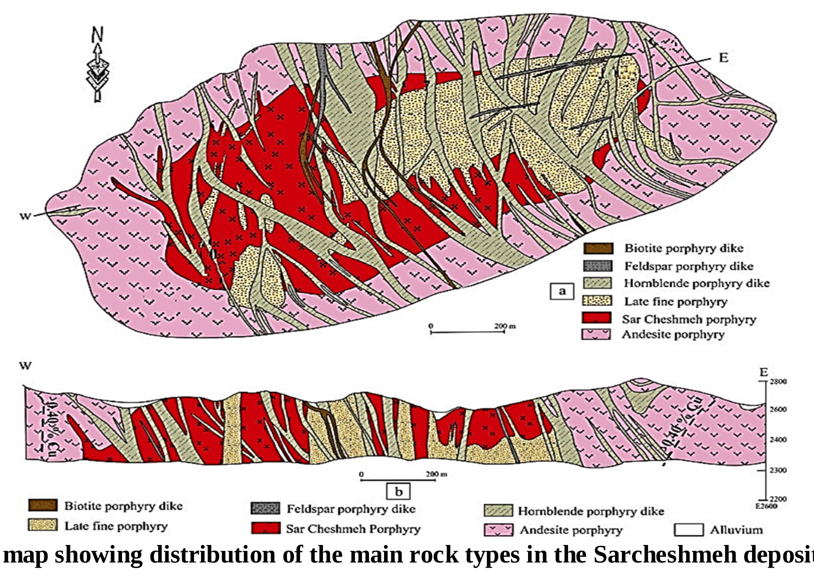


**Figure 1. (a) A map showing distribution of the main rock types in the Sarcheshmeh deposit within 0.40% Cu cutoff at 2,400 m elevation. (b) East−west cross-section of the Sarcheshmeh deposit [26, 27].**

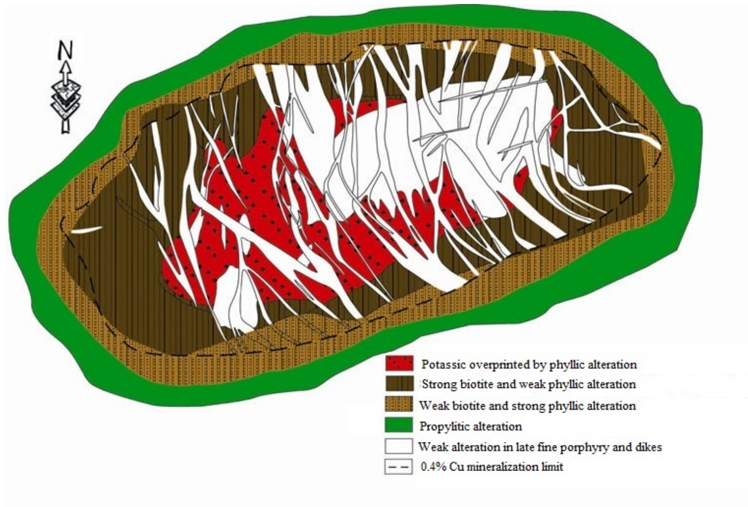


**Figure 2. Hypogene alteration pattern in the Sarcheshmeh deposit within the 0.40% Cu cutoff at 2,400 m elevation [26].**

## 3. Materials and methods

Based on a comprehensive survey [28], three different geometallurgical approaches have been identified: traditional, proxie, and mineralogical. In the traditional approach, chemical assays form the basis of the geometallurgy, so the metallurgical response is calculated from the chemical composition of the ore. The proxie approach uses the geometallurgical tests to characterize the metallurgical behavior of ore in different processing stages. Examples of the geometallurgical tests are the Davis tube [29] and Minnovex crusher index test [30]. Finally, the mineralogical approach refers to the program where a geometallurgical model (i.e. deposit and process model) is built largely based on mineralogy. Often this means that an accurate information on modal mineralogy is required for the whole orebody [31].

In the present work, a new methodology was used using a combination of the proxie and mineralogical approaches (Figure 3). In this method, after specifying the key ore forming parameters by geological surveying, the samples are taken for the geometallurgical tests (GTs). Based on the target metallurgical response, some quantitative and/or qualitative set points are defined. If the results obtained lead to a normal process response, a regular geometallurgical index will be introduced for that treated domain; otherwise, a detailed process mineralogy should be carried out. Based on the results, some geometallurgical indices are defined by one geological parameter or a combination of parameters.

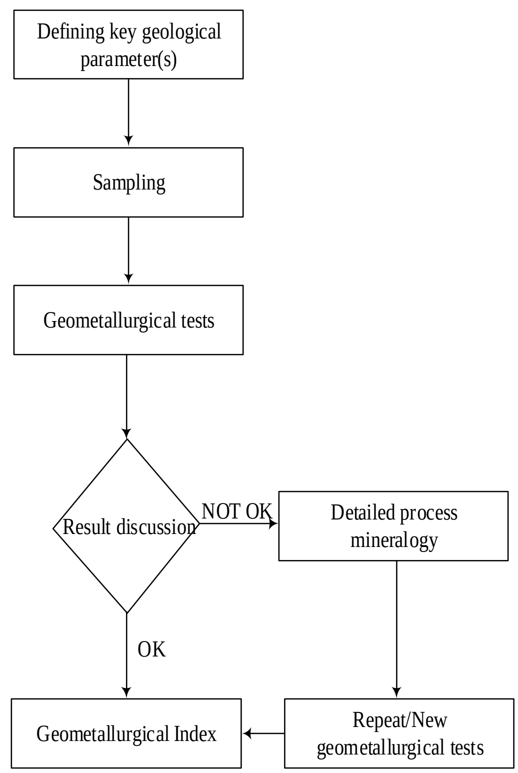


**Figure 3. Schematic pathway for implementing geometallurgy.**

In this work, sampling was performed based on the specified key geological parameters. The semi-autogenous grinding (SAG) power index (SPI) test was selected as the main metallurgical test. For the samples for which the results were out of norm, the detailed process mineralogical studies were performed. Finally, GIs were identified based on the results of the geometallurgical tests and mineralogical characterization.

### 3.1. Key ore-forming parameters at Sarcheshmeh

In order to find out the key ore-forming parameters, all the geological information containing lithology, alteration, mineralization zones, and structural control of ore mineralization were studied as the potential GIs. At a porphyry copper deposit, the mineralization zones are divided into oxidation, supergene enrichment, and hypogene. Currently, at Sarcheshmeh, extraction of the oxidation zone and most of the supergene zones have been finished, and the mining operation is in progress in the hypogene zone along with some locally remained supergene areas. In the processing viewpoint, the geological structures are limited to the texture of rocks. Therefore, it was reasonable to study the textures along with the mineralogical characterization. Therefore, lithology and alteration were selected as the key geological parameters affecting the hardness specification of the ores, and hence, the possible GIs.

### 3.2. Sampling

Sample size (number and weight) and spatial location in the mine block are three under discussion issues in geometallurgical sampling [28, 32, 33]. Time-consuming GTs are the major limitations for choosing a sampling standard that covers all the variations. In some cases, broad numbers of samples have been tried. However, most of these studies have used the reserve estimation tools instead of the metallurgical tests such as chemical assays, geological information, mineralogical studies, and Rock Quality Designation (RQD) [19]. For this reason, some modeling and simulation tools such as geostatistics and principle component analysis (PCA), as data driving approaches, have been used [34].

In this work, ninety hand-picked and drill core samples were collected at 17 different zones within the mine block. Each sample was about 20 kg for hand-picked, and up to one m of half spilt drill cores for the underground samples (Table 1). The lithologys were andesite (AN), Sarcheshmeh porphyry (SP), granodiorite (GR), late fine porphyry (LF), and dikes (DI). As well, phyllic and potassic alteration were the main alterations in the mineralized zone. Based on the degree of alteration, phyllic consists of sericite-quartz (SQ), quartz-sericite (QS), and silicified (SI); potassic alteration was divided into biotite (BI) and potassic (PO) alterations.

**Table 1. Number of samples taken in different lithologies and alterations.**

| 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 |

### 3.3. Characterization studies

The characterization studies include both the chemical and mineralogical investigations. Each sample was visually observed for texture, lithology, alteration, and rough mineralogy. In the following, XRF, XRD, petrographic microscopy, scanning electron microscopy (SEM), and mineral liberation analysis (MLA) were used for the fresh and ground samples. In the lithological studies, the modal mineralogy, texture, mineral associations, grain size, micro-structures, and hydrothermal alteration were investigated in the characterization studies. By a combination of the chemical analysis, semi-quantitative XRD, and the modal analysis technique, the major minerals which accounted for 90% to 98% of the mineralogical composition were identified. Also MLA as the newest minerals analysis instrument was used on a limited number of samples to calibrate the semi-quantitative XRD. Compared with MLA, XRD is a more available and easy analytical instrument. Petrographic microscopy and SEM were practiced to pick out the ore texture specifications including grains size, distribution of minerals, minerals association, and micro-structures.

#### 3.3.1. Geometallurgical Comminution tests

The geometallurgical tests are the conventional metallurgical ones such as the flotation, gravity, magnetic, and commination tests. They are used to quantitatively characterize the possible variation in the metallurgical properties. It should be noted that although the quantitative data is required for geometallurgical evaluation, the domains are more essential. Domaining is the operation of separating the mineralized orebody into the zones of similar characteristics. For this reason, using the alternative simplified tests are possible for the geometallurgical tests.

In the comminution studies, the resistance of ores to breakage is measured through the crushability and grindability testing. The geometallurgical comminution tests (GCTs) are used to predict the throughput of a mineral processing plant for the varying ore properties. According to [13], 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.

### 3.3.2. SAG power index (SPI)

At least six distinct small-scale testing methodologies (MacPherson, work index series, advanced media competency, drop weight test, SPI, and SAGDesign) have been used to a large extent to examine the autogenous grindability characteristics of the ores [35]. In this work, the SPI test approach was selected to investigate the semi-autogenous hardness variability. The Starkey laboratory mill, commercialized by Minnovex, was used in order to perform the test. The mill had a 304.8 mm (1 ft.) diameter by 101.6 mm (4 inches) length. It was equipped with six, one inch by one inch, charge lifters located at 60°intervals. The mill was loaded with 15% steel balls of 32 mm as the grinding media. The SPI tests were done on 2 kg samples to a specified size of 100% passing 19 mm and 80% passing 12.7 mm. The samples were repeatedly ground and removed from the Starkey SAG mill until the ore portion reached a fineness of at least 80% passing 1.7 mm. SPI, expressed in minutes, is the time required to achieve this size distribution. Finally, the curve of mass retained on 1.7 mm was plotted versus cumulative grinding time and SPI was interpolated. SPI is defined as the time necessary to reduce an ore sample from an F80 of 12.7 mm to a P80 of 1.7 mm. A higher grinding time indicates a higher resistance to grinding, thus a harder ore.

Converting SPI (minutes) into power draw (kWh/t) is done using several empirical equations. Starkey *et al*. have developed the CEET software based on a campaign of SPI test work at five Canadian SAG plants [36]. In the present work, without considering the other effective operational parameters on the power consumption of SAG, Equation [1 was applied. The equation is an empirical customized model to predict the SAG mill power consumption at the Sarcheshmeh comminution circuit [37, 38].

$$P = [0.09(SPI)^{0.9}] \quad [1]$$

## 4. Results and discussion

### 4.1. Geological and mineralogical features

Based on the geological investigation of the mineralized zone, the key ore-forming parameters of the Sarcheshmeh porphyry deposit were divided into the lithology and hydrothermal alterations. The mineralized zone at the Sarcheshmeh deposit consists of volcanic, intrude sub-volcanic, and intrusive rocks. The volcanic rocks at Sarcheshmeh are fine-grained andesite porphyries. The Sarcheshmeh porphyry (SP) is a granodiorite stock intruded into the volcanic rocks. Late fine (LF) is sub-volcanic to intrusive post-mineralization quartz-monzonite and granodiorite rock with a fine grain texture. The dikes (DI) have a wide range of volcanic and intrusive lithologies that are divided into hornblende porphyry, feldspar porphyry, and biotite porphyry. GR is the ore shell and the outer layer of the mineralized zone, where low copper mineralization has occurred.

The phyllic and potassic alterations were 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 was divided into the biotite (BI) and potassic (PO) alterations.

The predominant minerals in the samples were quartz, alkali-feldspar, plagioclase feldspar, and clay minerals (chlorite, kaolinite, illite, montmorillonite, and dickite). Disseminated chalcopyrite, pyrite, chalcocite, and minor molybdenite were the predominated sulfide minerals.

The major geological and mineralogical characteristics related to the comminution properties are shown in the Figure 4. The porphyritic texture that consisted of phenocrysts in a fine grained matrix, heterogeneous altered minerals, veinlets, and different grain size were identified as the possible factors in the comminution behavior. The phaneritic textured rocks comprising large particles in granodiorite rocks verses aphanitic and porphyritic textures with fine grains in andesitic rocks were the major primary textures (Figure 4a and 4b). The secondary textures are mostly the results of alterations, and to a lesser extent, due to the structural parameters (Figure 4c and 4d). The most remarkable texture in SP, as the softest lithology, was a combination of large phenocryst particles in a matrix of fine particles.

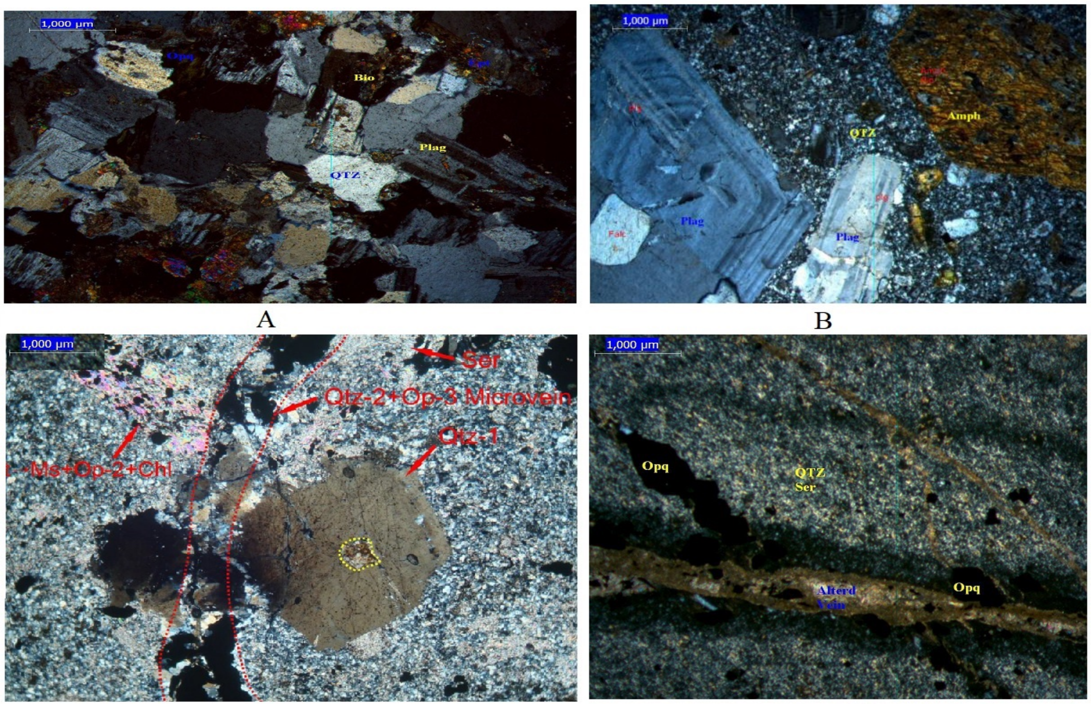


**Figure 4. Major textures in Sarcheshmeh. a and b: primary preserved texture. c and d: secondary altered texture, plagioclase altered into sericite with a fine grained quartz and filled veinlet.**

### 4.2. SPI grindability test

The calculated values of SPI are shown in Table 2 and Figure 5. The samples were ranked according to their resistance to the comminution process experienced inside a semi-autogenous mill from the weakest to the hardest. These values vary from 12 minutes to 473 minutes. Based on these values and energy conversion (Equation [1]), the samples were classified into soft (less than 80 minutes), medium (80-150 minutes), hard (150- 200 minutes), and very hard (more than 200 minutes).

**Table 2. Results of SPI tests on the samples.**

| Alteration | | Lithology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SP | | AN | | GR | | DI | | LF | |
| | | min | kWh | min | kWh | min | kWh | min | kWh | min | kWh |
| Phyllic | SQ | 67 | 3.96 | 30 | 1.92 | 150 | 8.18 | - | - | - | - |
| | QS | 80 | 4.65 | 138 | 7.59 | 190 | 10.12 | 252 | 13.04 | 283 | 14.48 |
| | SI | 111 | 6.24 | 150 | 8.17 | 230 | 14.48 | 162 | 8.77 | 176 | 9.45 |
| Potassic | BI | - | - | 114 | 6.39 | - | - | - | - | - | - |
| | PO | 100 | 5.68 | - | - | 160 | 8.67 | - | - | - | - |

#### 4.2.1. SPI variability and lithology

The results obtained show that while the minimum SPI occurs in an andesite rock, on average, SP shows a minimum resistance to semi-autogenous milling. In SP, the SPI values vary from 45 minutes to 117 minutes. At the other end, LF with the same lithology has the highest hardness. In GR, DI, and LF, the variation range is high. It can be seen that the SP rocks are the softest and the LF rocks are the hardest. The hardness increases as SP < AN < GR < DI < LF.

In spite of a wide range of SPI values in each rock type, the predominant values are limited to a bounded domain, specified in red ellipsoids in Figure 5. Also it is observable that the slope of average of SPI, blue dash, is smoothed in comparison with the slope of maximum values of each rock type, shown in black dash.

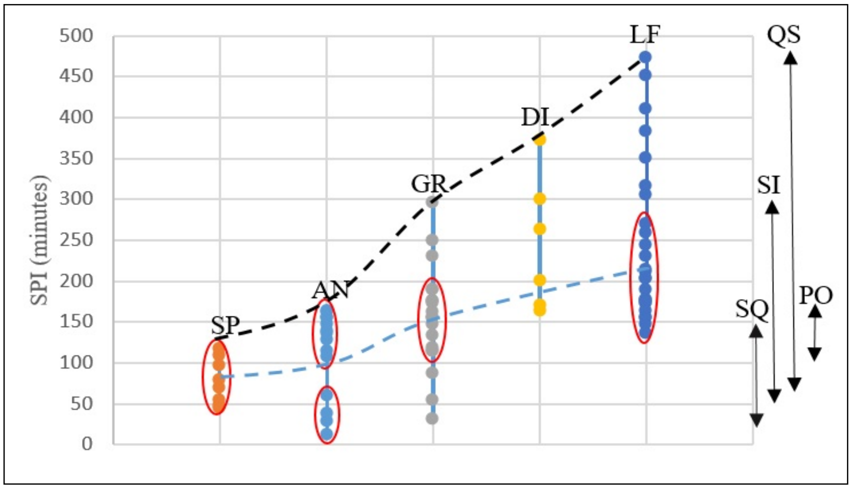


**Figure 5. SPI variability in different lithologies and alterations.**

### 4.2.2. SPI variability and alteration

The results of SPI and characterization study indicate that in the SP, AN, and GR rocks, the resistance to semi-autogenous milling increases in phyllic alteration by increasing the degree of alteration. As the process of phyllic alteration increases, the plagioclase feldspars in the original rock are replaced by alteration minerals, and the sericite and quartz contents increase relative to the original amount [21]. Sericitisation is an acidic alteration that produces white mica, mostly thin muscovite called sericite with a sericitic texture. If the hydrothermal alteration continues, then ultimately, the original minerals are completely replaced by quartz in a silicified form. Silicification was seen in the samples as quartz vein filling and stockwork. Therefore, the degree of alteration in the phyllic alteration was divided into sericite-quartz (SQ), quartz-sericite (QS), and silicification (SI). Unlike SP, AN, and GR, in LF and DI, SPI gets higher in abundance of sericite minerals.

Potassic alteration was seen in the forms of biotite (BI) and potassic (PO) alterations. In comparison to the phyllic alteration, the potassic alteration was seen in a lesser extent in the mineralized zones. The samples with potassic alteration tend to have a reverse relation with the degree of alteration. The result show that by increasing the hydrothermal alteration, the generated minerals, mostly biotite, cause a lower hardness.

### 4.2.3. SPI variability with Cu grade

The chemical assay of the target mineral and/or other minerals have been used in the traditional approaches. The correlation between SPI and the Cu grade in the ore is shown in Figure 6. The results obtained show that there is no evidence to have any relation between Cu grade and SPI. Also the probable correlation between SPI and other major and minor elements, especially Si, was studied but no specified association was observed.

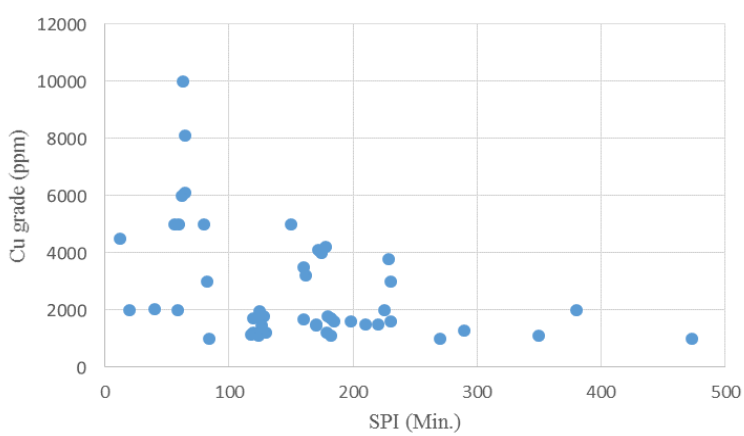


**Figure 6. SPI variability versus Cu grade.**

## 5. Conclusions

The current work has provided a new methodology to perform a geometallurgical program for the hardness variability in the semi-autogenous milling. The approach uses a combination of geological studies, mineral processing tests, and mineralogical characterizations. The most important issues and the results obtained are as follow:

- A smart sampling was used by predicting the key factors in the hardness variability. In this method, the geological settings are considered as the base for sampling standard.
- The results of geological studies of the deposit show that the key factors that make different comminution properties are lithology, alterations, geological structures, and ore texture. The last two items were considered to be a function of lithology and hydrothermal alteration. Therefore, they were not dealt as independent items.
- The SPI test results show that the resistance to semi-autogenous milling varies in different lithologies. Therefore, lithology was considered as the primary geometallurgical index.
- It can be concluded that if mineralization occurs in a single rock type, the hydrothermal alteration (type and degree of alteration) defines the hardness variability. Therefore, the hydrothermal alteration was considered as another geometallurgical index.
- It is possible to use geometallurgical indices to predict the comminution property of the ore. Also plant throughput is predictable by using GIs.
- The results obtained show that there is no systematic relation between chemical analysis and SPI.

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# توسعه شاخص‌های ژئومتالورژیکی برای خردایش نیمه‌خودشکن در معدن مس پورفیری سرچشمه

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**چکیده:**

ژئومتالورژی به فرآیند پیش‌بینی ناپایداری رفتار فرآوری مواد معدنی (نا شی از تغییرپذیری مولفه‌های زمین شنا سی) و به دنبال آن بهینه‌کردن زنجیره ارزش مواد معدنی گفته می‌شود. شناخت تغییرپذیری کانسنگ و در نتیجه پیش‌بینی پاسخ فرآوری کانسنگ به عنوان مهم‌ترین کارکردهای یک مطالعه ژئومتالورژیکی دقیق در نظر گرفته می‌شود. در این مقاله شاخص ژئومتالورژیکی به عنوان مولفه نوینی برای بهینه‌سازی فعالیت‌های معدنی ارائه شده است. شاخص ژئومتالورژیکی به هر ویژگی زمین‌شناسی که بر روی عملکرد فرآوری مواد معدنی تاثیرگذار باشد، اطلاق شده است. در یک مطالعه جامع در معدن مس پورفیری سرچشمه ویژگی‌های زمین‌شناسی موثر بر پاسخ‌های اصلی فرآوری شامل عیار و بازیابی محصول و ظرفیت کارخانه مورد بررسی قرار گرفت. در این گزارش تغییرپذیری سختی کانسنگ با استفاده از شاخص خردایش خودشکنی (SPI) و اثرات آن بر روی ظرفیت کارخانه و انرژی مصرفی ارائه شده است. تعداد نود نمونه بر اساس ویژگی‌های زمین شناسی شامل لیتولوژی (نوع سنگ)، دگرسانی گرمابی و ساختارهای زمین‌شناسی برداشت شد. خواص‌سنجی کانی‌شناسی نمونه‌ها با استفاده از XRD، XRF و میکروسکوپ نوری و الکترونی صورت گرفت. از آسیای آزمایشگاهی استارکی (تجاری‌سازی شده توسط شرکت مینووکس) برای انجام آزمایش‌های خردایش نیمه خودشکن استفاده شد. نتایج آزمایش SPI بیانگر دامنه گسترده سختی از 12 تا 473 دقیق می‌باشد. ارتباط بین نتایج آزمایش خردایش و ویژگی‌های زمین شناسی نشان می‌دهد که لیتولوژی یک ویژگی کلیدی تعیین‌کننده تغییرپذیری سختی خردایش می‌باشد. علاوه‌بر این، دگرسانی گرمابی یک مولفه موثر بر خردایش در بازه‌های زمانی که کارخانه صرفا با یک نوع لیتولوژی خاص باردهی می‌شود، خواهد بود.

**کلمات کلیدی:** ژئومتالورژی، مولفه ژئومتالورژیکی، تغییرپذیری کانسنگ، مس پورفیری، SPI.