Quantification of the intact geological strength index for rock masses in hypogene environment

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Abstract

The Geological Strength Index (GSI) was introduced as an empirical tool to scale the intact rock properties, from samples to a jointed rock mass scale. Since his first conception, GSI was estimated in an empirical way, according to the proposed chart and according to a visual estimation of degree of fracturing and joint condition. Along the years, GSI has been modified for a better rock mass characterization, as for example including a massive rock mass category or presenting a special chart to characterize flysch sediments. Because many geotechnical users pointed out the necessity to quantify GSI, several Authors proposed different methodology to quantify it, based on joint spacing, rock block volume or RQD and joint condition. It is important to note that all the proposed methodologies are based on the characterization of a jointed rock mass, only recently, some Authors proposed a method to estimate GSI in weathered and hypogene rock mass. At present time, mine operations are facing the challenge to mine ore deposits at deeper conditions, with higher stress and to assess a rock mass characterized by cemented and sealed veins, that means a challenge regarding how to characterize a primary rock mass, formed by cemented joints, has occurred in many ore deposits in deeper condition. Los Sulfatos Ore Body, owned by Anglo American Sur, represents a porphyry copper deposit in hypogene environment and is characterized by a stockwork of cemented veins. The geotechnical assessment of the different Geotechnical Units, according to the traditional classification systems, shows a very uniform quality between them, so, arose the need of a better characterization of the primary rock mass. Because of that, the Authors developed a new method to quantify the GSI, based on the spacing of weaker cemented veins and on the weighted average hardness of the mineral infill. This methodology pointed out differences in terms of geotechnical quality better than the traditional classification systems.

1 Introduction

The geotechnical characterization of rock masses is a very important task in rock mechanics. Several empirical classification systems have been developed by different Authors to estimate the geotechnical quality of a rock mass based on the characterization of basic geotechnical parameters. Among these systems, a very important one is the Geological Strength Index (GSI) that was proposed for the first time by Hoek (1994) as an empirical tool to scale from intact rock properties to rock mass scale. GSI, along the years, has been modified several times and quantification methods have been proposed by different Authors. Anyway, all proposed GSI updates and quantification methods are based on the characterization of a rock mass with open joints, so all these methods work well close to the surface. In the mining industry, geotechnical geologists found good results using GSI in a supergene environment. Once the mining activity get deeper, geologists faced the challenge to characterize a hypogene rock mass, characterized by welded joints with infills having different strengths, using the empirical tools made for a supergene environment. The use of these systems does not show many differences between different Geotechnical Units, in spite of the distinct geotechnical behaviour observed during the mining activity. This lack of capacity to differentiate geotechnical quality of traditional systems is because they were designed for rock masses characterized by open joints with different degree of weathering, whereas, in deeper mines, rock masses are characterized by strong rocks intersected by hard welded veins that, when characterized according to traditional systems, fit in the upper part of the classification systems and are not able to differentiate between Geotechnical Units.

The aim of this paper is to propose a quantification method to estimate GSI in a hypogene environment, based on the spacing of welded veins and the hardness of their infill. The proposed method has been developed during geotechnical core logging of the exploration drilling campaign for the Los Sulfatos Ore Body and has been developed to be used only for a hypogene environment and cannot be used in a weathered and jointed rock mass.

2 Geology and mineral resources of Los Sulfatos orebody

The "Los Sulfatos" porphyry copper and the associated breccia complex (Figure 1), of approximately 4 km of length and 1 km width and located 5 km southeast of Los Bronces Mine, is contemporaneous and closely associated to the mineralisation at Los Bronces and the adjacent Rio Blanco deposit and is part of a district that is developing into one of the largest known concentrations of copper mineralisation in the world.

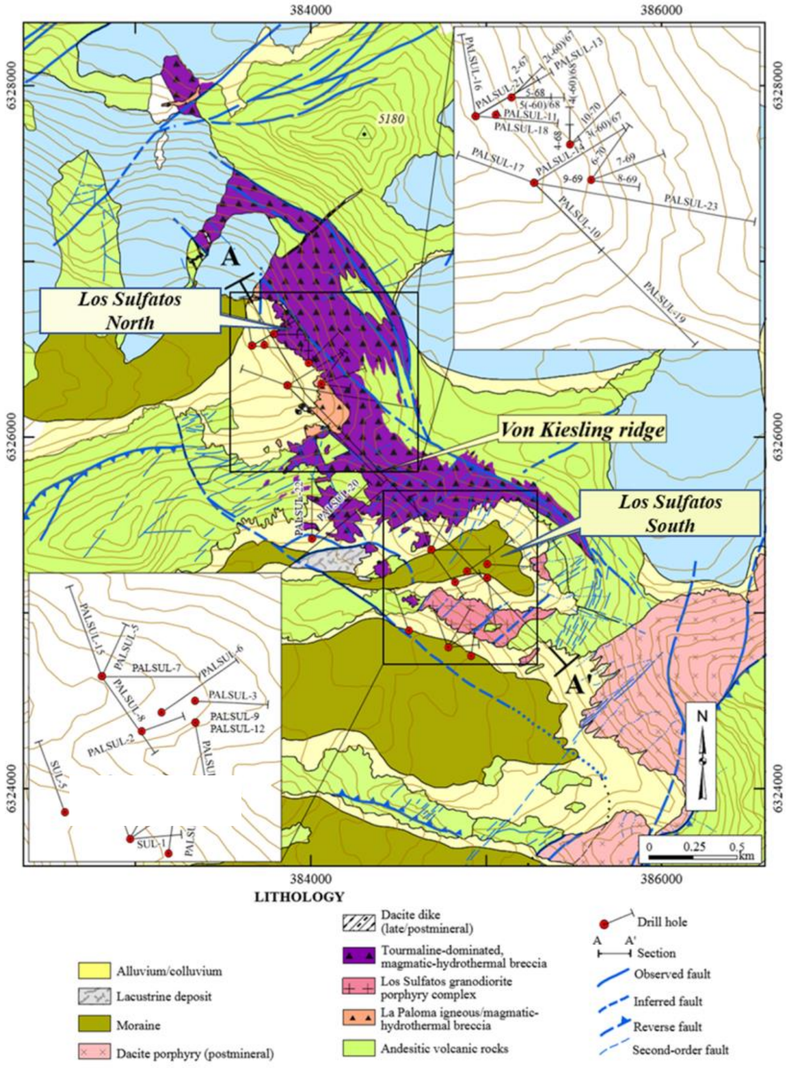


Figure 1 Geological map of Los Sulfatos Breccia Complex (Modified after Irarrazabal et al. 2012)

An updated estimation of the mineral resources of the Los Sulfatos Ore Body shows a total of 3.9 Bton of 1.14 % T Cu, mostly Inferred, (45.2 Mton of fine contained) and 0.020% Mo.

Copper sulphide mineralisation is hosted in a multi-phase porphyry stock and breccia complex. To the north, the mineralisation style is dominated by high grade geometrically complex magmatic-hydrothermal breccia bodies with chalcopyrite-pyrite mineralisation, interrupted by low-grade late stage porphyry intrusions. The central and south areas are dominated by tourmaline and rock flour breccias with pyrite-chalcopyrite mineralisation near surface, giving way in depth to disseminated hypogene bornite-chalcopyrite-molybdenite mineralisation, hosted in magmatic breccias, porphyry intrusives and strongly altered andesite volcanics (Figure 2).

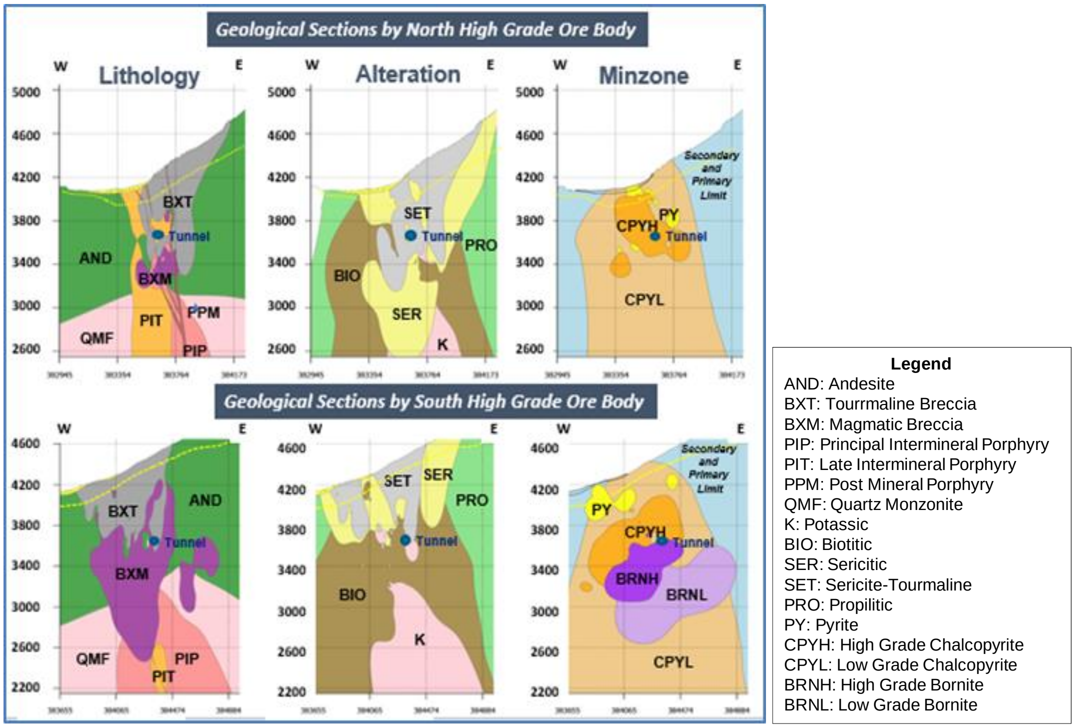


Figure 2 Geological sections of Los Sulfatos Deposit (Modified after Pablo et al. 2019)

The volcanic sequence corresponds to porphyry and aphanitic andesite with scarce tuff intercalations that can be assigned to the Farellones Formation of Middle Miocene age, presenting a strong NNE and NE structural pattern. In the southwestern margin of the prospect, these rocks show chlorite-epidote alteration with little sericite associated to D type veinlet halos. In the eastern margin, the andesites are affected by strong biotitization and A / EB veinlets, in a strip defined by the contact with the Los Sullfatos stock. To the northeastern end of the prospect, the rocks show clay-sericitic alteration in the surroundings of the tourmaline/rock flour hydrothermal breccia bodies.

In the central area of Los Sulfatos, a porphyries complex outcrops presenting at least four phases of intrusion affected by potassic alteration superimposed by sericitization associated to halos of type D veinlets.

In the central portion of Los Sulfatos Ore Body, a porphyry complex of granodioritic to quartz-monzonitic composition has been identified, composed by at least three phases of intrusion characterized by prominent quartz phenocrysts.

In the northern portion of Los Sulfatos, underneath the Filo von Kiesling, a granodioritic porphyry has been recognized that forms decametric dikes with a disseminated and in veinlets mineralization. The porphyry presents selective alteration of variable intensity associated to D veinlets halos, with calcite phenocrysts and scarce patches of potassic alteration. In the northwest portion of Ore Body, it outcrops as barren dikes, with less than 3 m of thickness and NNW orientation. The rock presents porphyritic texture and is composed of 20% of plagioclase phenocrysts, 10% of mafic phenocrysts and up to 5% of quartz. Occasionally it is cut by D type pyrite-chalcopyrite veinlets and DL pyrite – chalcopyrite - specularite iron carbonate veinlets.

The Tourmaline and Rock Flour Breccias correspond to a large extension body outcropping at the Filo von Kiesling. It presents a characteristic medium gray color due to the presence of rock flour and fine tourmaline. It is intersected by some D type veins with pyrite and little chalcopyrite and molybdenite - chalcopyrite veinlets associated with post brecciation. Finely disseminated chalcopyrite- pyrite mineralization is recognized in the matrix. The clasts are sub-rounded and very altered to sericite, corresponding to andesite and porphyry.

The intrusions of different porphyry systems were allowed by the formation of discrete igneous breccia bodies. These include granodioritic and dacitic porphyry clasts and, in less proportion, very altered sub-angular andesite clasts. In the deeper zones and the Northern part of Los Sulfatos, hydrothermal breccia bodies cemented with biotite are recognized. The clasts (andesites and porphyries) have diffuse boundaries and are included in a fine-grained matrix consisting of hydrothermal biotite, magnetite, chalcopyrite, bornite, and anhydrite.

At Los Sulfatos area, the typical hydrothermal events of a copper porphyry system have been identified. The Granodioritic Los Sulfatos Porphyry (PLS) shows a strong potassic alteration characterized by biotite and potassium feldspar, associated with intense A type veinlets (bornite – chalcopyrite). Intense biotitization is also observed in the andesites located at the contact with the PLS, in an approximately 50 m wide zone along the contact. The central portion with potassic alteration contains the core of high grade recognized so far in the deposit (above 0.8% T Cu), with intense A type veinlets containing bornite-chalcopyrite- digenite that also occur disseminated. Scarce B type veinlets contribute molybdenum mineralization in this central portion. Neither lateral nor changes at depth have been observed in the sulphide types in the potassic core or in the bornite/chalcopyrite rates. Dating using the Ar/Ar method by steps of two biotite samples from drillholes in the Sulfatos area obtained ages of 7.31 and 7.02 Ma.

A sericitic (sericite – clorite) alteration event is super-imposed to the potassic center, apparently controlled by high permeability given by the pre-existing intense A type veinlets. The sericitic alteration shows as bands of halos of D type veinlets (chalcopyrite – pyrite) and DL (chalcopyrite – pyrite – specularite). To the boundaries of the PLS, where the intensity of A veinlets decreases considerably, only narrow D veinlets are observed.

In the portions where the sericitic super-imposition is pervasive and more intense, the bornite – chalcopyrite mineralization gives place to chalcopyrite – pyrite, with decreasing Cu grades. During this sericitic event, the introduction of significant molybdenite mineralization is produced, in mono- mineral more than B type veinlets. Ar/Ar ages in sericite gave values of 6.71 and 6.94 Ma. In summary, it can be concluded that the system has the following ages:

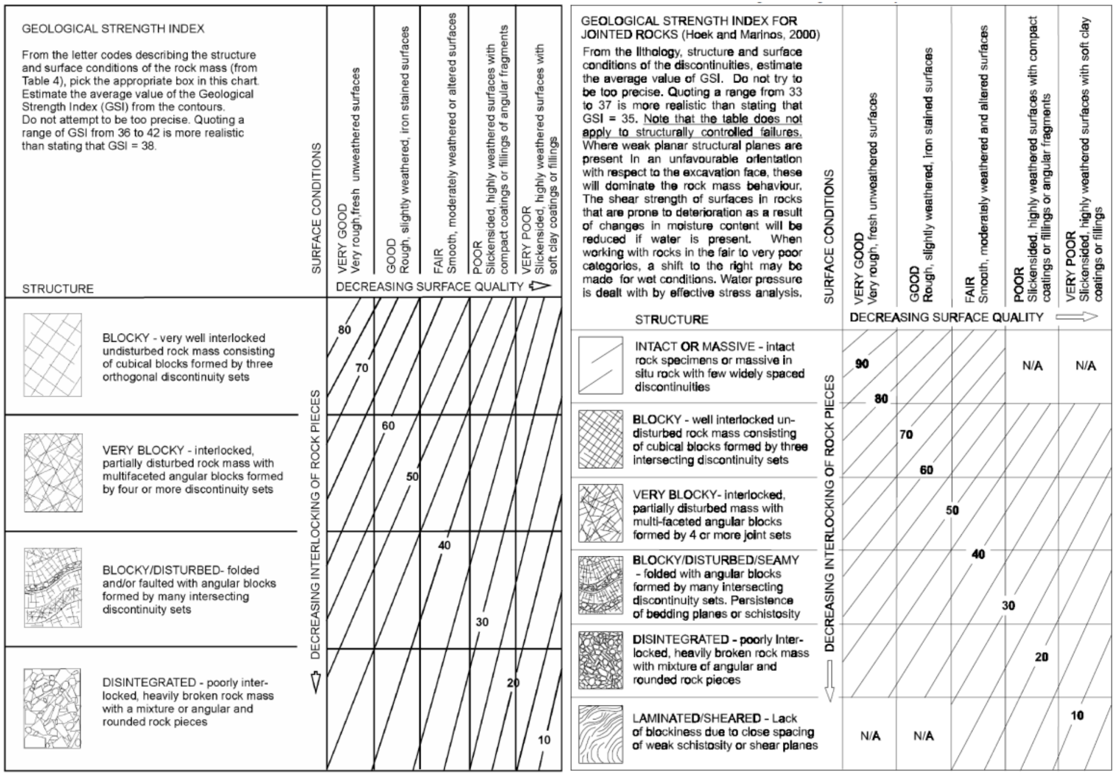
- Los Sulfatos South: **7.45 - 6.71 Ma**
  Re-Os = 7.45 - 7.42 Ma
  Sericite: Ar-Ar = 6.94 - 6.71 Ma
- Los Sulfatos North: **6.56 – 6.26 Ma**
  Re – Os = 6.56 - 6.26 Ma

The mineralization alteration system shows a marked vertical zonation in the Los Sulfatos North area, from a shallow sericitic zone in the tourmaline breccias (sericite-chlorite-anhydrite-specularite) to a deep potassic zone in biotite breccias, intrusion breccias, and andesites. However, a conspicuous biotitization zone in the andesites outcrops in the contact of these with the porphyries that intrude it. The limit of the potassic zone, beyond which the propylitic alteration develops, has not been recognized by the drillholes at the Los Sulfatos North area. Cu sulphide mineralization is strongly zoned. At depth, in the biotitic zone, chalcopyrite > pyrite grading to bornite is observed in the deepest drilled zones.

3 Quantification of GSI, Previous Studies

The Geological Strength Index was proposed by Hoek (1994) and Hoek et al. (1995) as an empirical tool to scale the intact rock properties to rock mass scale, based on the visual observation of the degree of fracturing of the rock mass and the joint condition. The proposed chart to estimate GSI considered a degree of fracturing up to Blocky, corresponding to a rock mass with three joint sets (Figure 3). Marinos & Hoek (2000) modified the GSI chart introducing a new category corresponding to Intact or Massive corresponding to a rock mass with few widely spaced discontinuities (Figure 3).

It is important to mention that previous the implementation of the empirical chart, GSI was estimated directly from Bieniawski RMR. Correlations between RMR and GSI systems were discussed in Hoek & Karzulovic (2000). The Authors suggested that for rock masses of poor quality and better $(RMR > 25)$, the GSI value can be estimated directly from the 1976 version of the Bieniawski RMR system, considering a dry rock mass (the water rating set to 10) and the adjustment for joint orientation set to 0 (very favorable). They also suggested that if the 1989 version of the RMR system is used, then the Geological Strength Index should be considered as $GSI = RMR_{89} - 5$, with the groundwater rating (in the RMR system) set to 15 and the adjustment for joint orientation set to 0. Hoek & Karzulovic (2000) also noted that for very poor quality rock masses $(RMR < 25)$, the above-mentioned correlations have proved to be unreliable and should never be used. In those cases, GSI values should be estimated directly from the GSI charts.



From the letter codes describing the structure and surface conditions of the rock mass (from Table 4), pick the appropriate box in this chart. Estimate the average value of the Geological Strength Index (GSI) from the contours. Do not attempt to be too precise. Quoting a range of GSI from 36 to 42 is more realistic than stating that GSI = 38.

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

Figure 3 GSI chart proposed by Hoek (1994) and Hoek et al. (1995) considering a degree of fracturing of the rock mass up to Blocky (on the left side) and GSI chart proposed by Marinos & Hoek (2000) considering a rock mass up to Intact or Massive (on the right side)

Hoek (2006) mentioned that, in general, geologists and engineering geologists are comfortable with the qualitative estimation from GSI charts, whereas, many engineers feel the need for a more quantitative estimation of GSI. Accordingly, different methodologies to estimate GSI values in a more quantitative way have been published in the literature in the past.

For example, Sonmez & Ulusay (1999) proposed a quantification of the entry 'Block Size' in the GSI chart by introducing the Structure Rating (SR) coefficient, which can be computed based on the Volumetric Joints (J_v) coefficient as follows:

$$SR = -17.5 \times \log J_v + 79.8 \tag{1}$$

Sonmez & Ulusay (1999) also proposed a quantification of the entry 'Joint Condition' in the GSI chart by introducing the Surface Condition Rating (SCR), using the following equation:

$$SCR = R_r + R_w + R_f \tag{2}$$

In Equation 2, R_r is the Roughness Rating, R_w is the Weathering Rating, and R_f is the Infill Rating of the discontinuities (the total rating is calculated as the average of individual ratings for each joint set).

Cai et al. (2004) proposed a quantification of the entry 'Block Size' using a different GSI chart (Figure 4) by considering the spacing and block volume associated with a set of joints. The 'block volume' coefficient V_b is calculated according to the following equation:

$$V_b = \frac{S_1 S_2 S_3}{\sin(y_1)\sin(y_2)\sin(y_3)} \tag{3}$$

In Equation 3, S_i and y_i are the joint spacing and the angle between joint sets, respectively (Figure 5).

Cai et al. (2004) also proposed a quantification of the entry 'Joint Condition' in the GSI chart by introducing the Joint Condition Factor (Jc), which is computed with the following equation:

$$J_C = \frac{J_W J_S}{J_a} \tag{4}$$

Where, in Equation 4, J_w and J_s are the ratings for waviness and the smoothness, and J_a is the joint alteration rating (for details, see Grimstad & Barton (1993) and Cai et al. (2004)).

Hoek et al. (2013) proposed different methods to quantify GSI, based on the Rock Quality Designation (RQD) and the 'Joint Condition' entry in either Bieniawski or Barton systems, according to the following relationships:

$$GSI = 2JCond_{76} + RQD/2 \tag{5}$$

$$GSI = 1.5JCond_{89} + RQD/2 \tag{6}$$

$$GSI = \frac{52J_r/J_a}{1+J_r/J_a} + RQD/2 \tag{7}$$

In Equations 5 and 6, $JCond_{76}$ and $JCond_{89}$ are 'Joint Condition' entries from the original Bieniawski (1976) system, and from the updated Bieniawski (1989) system, respectively. In Equation 7, J_r and J_a are the 'joint roughness' and the 'joint alteration' entries, respectively, from the Q System (Grimstad & Barton 1993). In Equations 5 through 7, RQD is the Rock Quality Designation (Deere & Deere 1988).

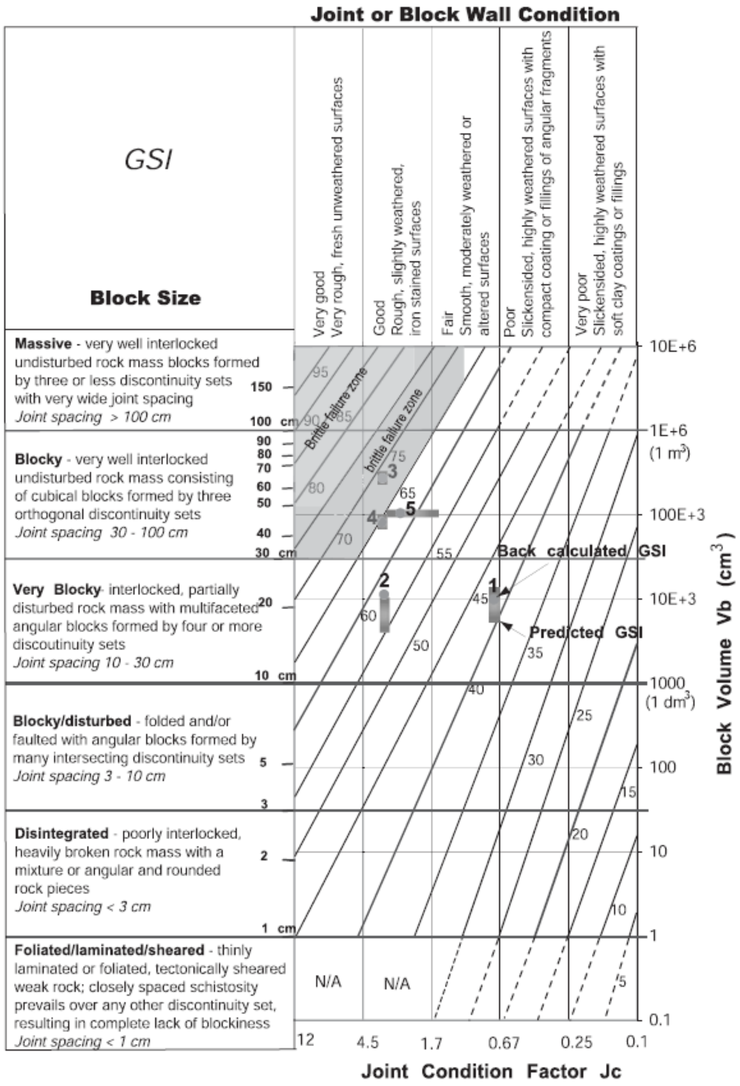


Figure 4 Quantification of GSI according to Cai et al. (2004)

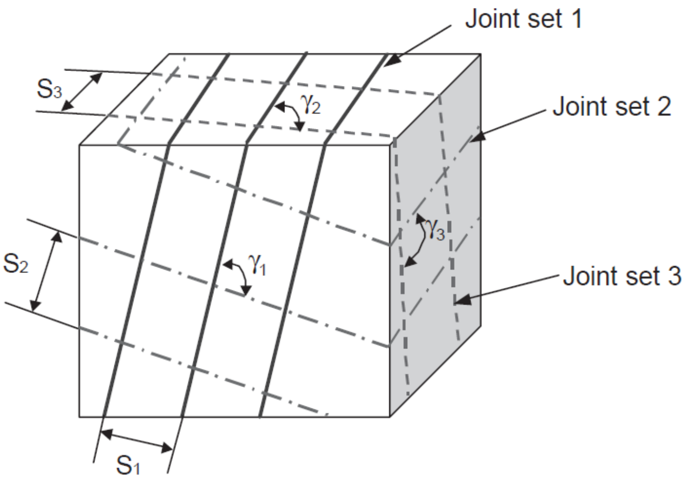


Figure 5 Rock mass with three joint sets –after Palmstrom (2005)

Recently, Day et al. (2016) proposed a Composite Geological Strength Index (CGSI) to reflect the rock mass strengthening potential due to intrablock structure. According to that, a new column was added to describe the Joint Condition of welded and strong veins and previous columns have been complemented with the description of welded structures but with less strength. In this way, the CGSI is calculated taking in account the contribution of open joints and cemented veins. Later, Day et al. (2019) introduced the “Massive” category to incorporate rock masses with widely spaced structures giving GSI values ranging between 85 and 100.

The CGSI is calculated according to the following equations:

$$CGSI = A^* + B^* \tag{8}$$

Where

$$A^* = (A_1/B_1 + A_2/B_2 + .. + A_n/B_n)/(1/B_1 + 1/B_2 + .. + 1/B_n) \tag{9}$$

$$B^* = 20 \log_{10}\left(\left(10^{-B_1/20} + 10^{-B_2/20} + .. + 10^{-B_n/20}\right) - 1\right) \tag{10}$$

$$A_n = 1.5\ x\ JCond_{89}$$

$$B_n = 20/3\ \ x\ \log_{10}(Block\ Volume\ in\ cm^3)$$

It is important to note that Joint Condition is a modified version of the Bieniawski system to consider the strengthening effect of the intrablock stuctures (for more details see Day et al. 2016).

Figure 6 shows the proposed CGSI chart to estimate GSI. Scale B, related to blockiness, has a rating up to 40 corresponding to a Blocky condition characterized by three joint sets. Scale A, related to Joint Condition, has a rating up to 55 corresponding to welded intrablock structures.

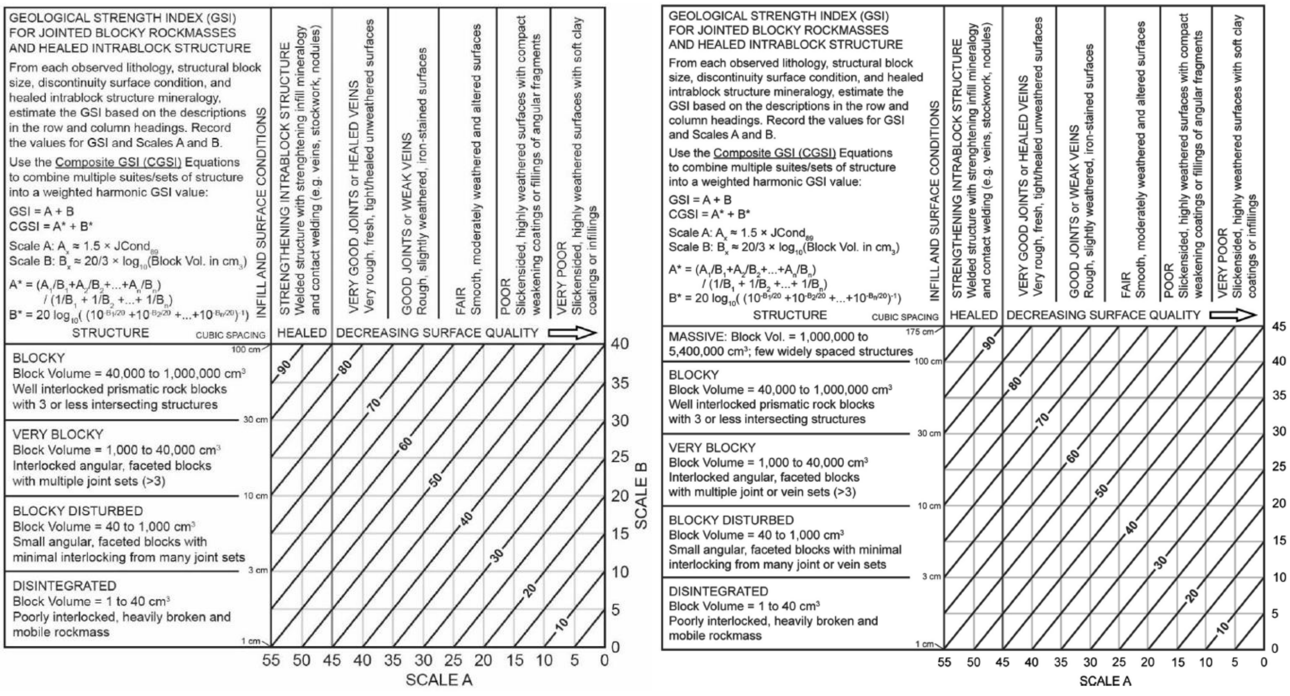


Figure 6 **Chart to estimate Composite Geological Strength Index (CGSI), after Day et al. (2016), on the left side and after Day et al. (2019), on the right side, introducing massive rock masses.**

4 Quantification of Proposed Intact Geological Strength Index

As mentioned before, the Los Sulfatos orebody is a porphyry copper deposit characterized by a primary rock mass, with a high strength intact rock that contains a stockwork of welded veins and veinlets. The exploration drilling campaign consists of almost 88,000 m of drill cores, drilled for geological, geotechnical, and hydrogeological purposes. All available drill cores were geotechnically logged to characterize the rock mass according to the main classification systems, such as: RMR (Bieniawski 1989), MRMR (Laubscher 1990), IRMR (Laubscher & Jakubec 2001), Q System (Grimstad & Barton 1993), and GSI (Hoek et al. 2013). Table 1 summarizes the geotechnical quality of the main Geotechnical Units. As can be observed from Table 1, Los Sulfatos is characterized by a low fractured and a good to very good rock mass and by a lack of variability, in terms of GSI rating, among the different Geotechnical Units.

This homogeneity can be interpreted because GSI, and the other classification systems, with the exception of IRMR, have been developed for rock masses characterized by open and more or less weathered joints. Therefore, a fresh, tight and strong rock mass, as Los Sulfatos, will fit in the upper part of these classification systems such that they will be not able to easily differentiate the geotechnical quality among different Geotechnical Units, even if characterized by very different alteration types such as potassic and sericitic.

Table 1 Rock mass geotechnical quality of the 4 main Geotechnical Units of Los Sulfatos orebody

Geotechnical Unit	Number of Intervals	FF/m	RQD	RMR_{B89}	RMR_{L90}	$IRMR_{LJ01}$	GSI_{2013}	Q'93
Andesite	5,867	2.4	96	76	59	61	77	49
		Moderate spacing	Excellent	Fair to Good				Very Good
Potassic Magmatic Breccia	5,922	2.2	97	78	62	63	77	54
		Moderate spacing	Excellent	Good				Very Good
Sericitic Magmatic Breccia	5,424	2.1	97	77	60	63	77	56
		Moderate spacing	Excellent	Fair to Good				Very Good
Tourmaline Breccia	11,982	1.4	98	81	66	71	78	103
		Wide spacing	Excellent	Good to Very Good				Extremely Good

In addition, the abovementioned main Geotechnical Units were characterized by a large laboratory testing campaign in order to estimate the intact and rock mass properties. The laboratory campaign considered the typical rock tests, such as: density, porosity, seismic wave velocity, tensile strength, unconfined compressive strength, static elastic moduli measurement and triaxial tests (Table 2). Tests results confirmed the good geotechnical quality and the high strength observed during the core logging for all Units of Los Sulfatos deposit (Table 3).

Table 2 Type and amount of laboratory tests per each geotechnical unit.

Geotechnical Unit	Density γ	Porosity η	Wave velocity V_p V_s	Tensile strength Ti_{50}	UCS UCS_{50}	Static elastic moduli E_i ν_i	Triaxial tests Tx
Andesite	72	52	36	44	59	59	134
Potassic Magmatic Breccia	66	66	27	27	88	88	136
Sericitic Magmatic Breccia	41	41	31	33	42	42	109
Tourmaline Breccia	94	94	50	57	123	118	259

Table 3 Type and amount of laboratory tests per each geotechnical unit.

Geotechnical Unit	γ (g/cm^3)	η (%)	V_p (m/s)	V_s (m/s)	Ti_{50} (MPa)	UCS_{50} (MPa)	E_i (GPa)	ν_i (–)	σ_{ci} (MPa)	m_i (-)
Andesite	2.76	0.99	4820	2803	13	132	54	0.25	130	12.5
Potassic Magmatic Breccia	2.68	1.85	4892	2798	13	152	51	0.26	152	17.9
Sericitic Magmatic Breccia	2.75	1.69	4990	2830	11	131	49	0.27	131	15.9
Tourmaline Breccia	2.73	4.07	4874	2751	12	139	50	0.27	140	12.0

As mentioned before, Los Sulfatos rock mass is characterized by a fresh high strength intact rock (Figure 7) with a stockwork of cemented veins characterized by different type of mineral infill associations, such as anhydrite, anhydrite-chalcopyrite, anhydrite-bornite, gypsum, and others. All of these veins are sealed inside the rock mass and only some of them, the weaker ones, can be open during drilling process or the mining activity (Figure 8). Based on these results and the geotechnical characteristics of the Los Sulfatos rock mass, the requirement arose to estimate GSI in a different way, that considers a rock mass with a stockwork of cemented veins with a mineral infill showing different strength behaviour. This challenge was faced by modifying the GSI chart as shown in Figure 9.

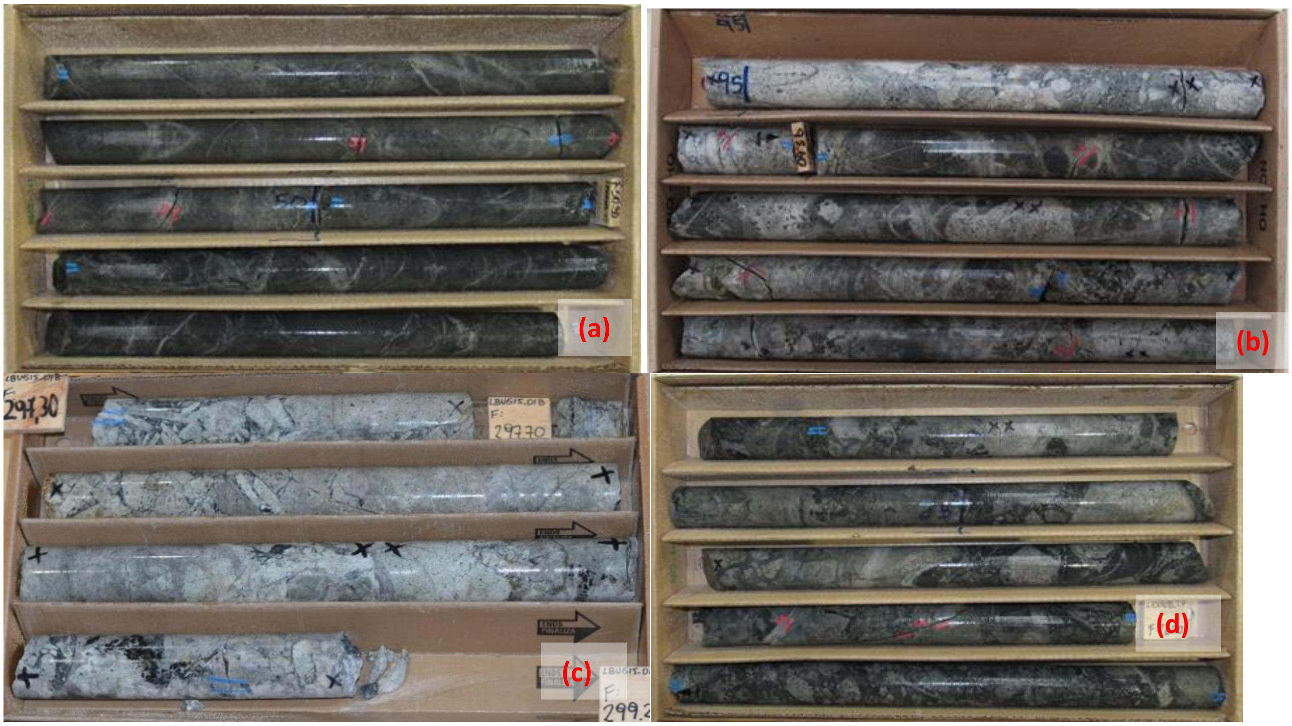
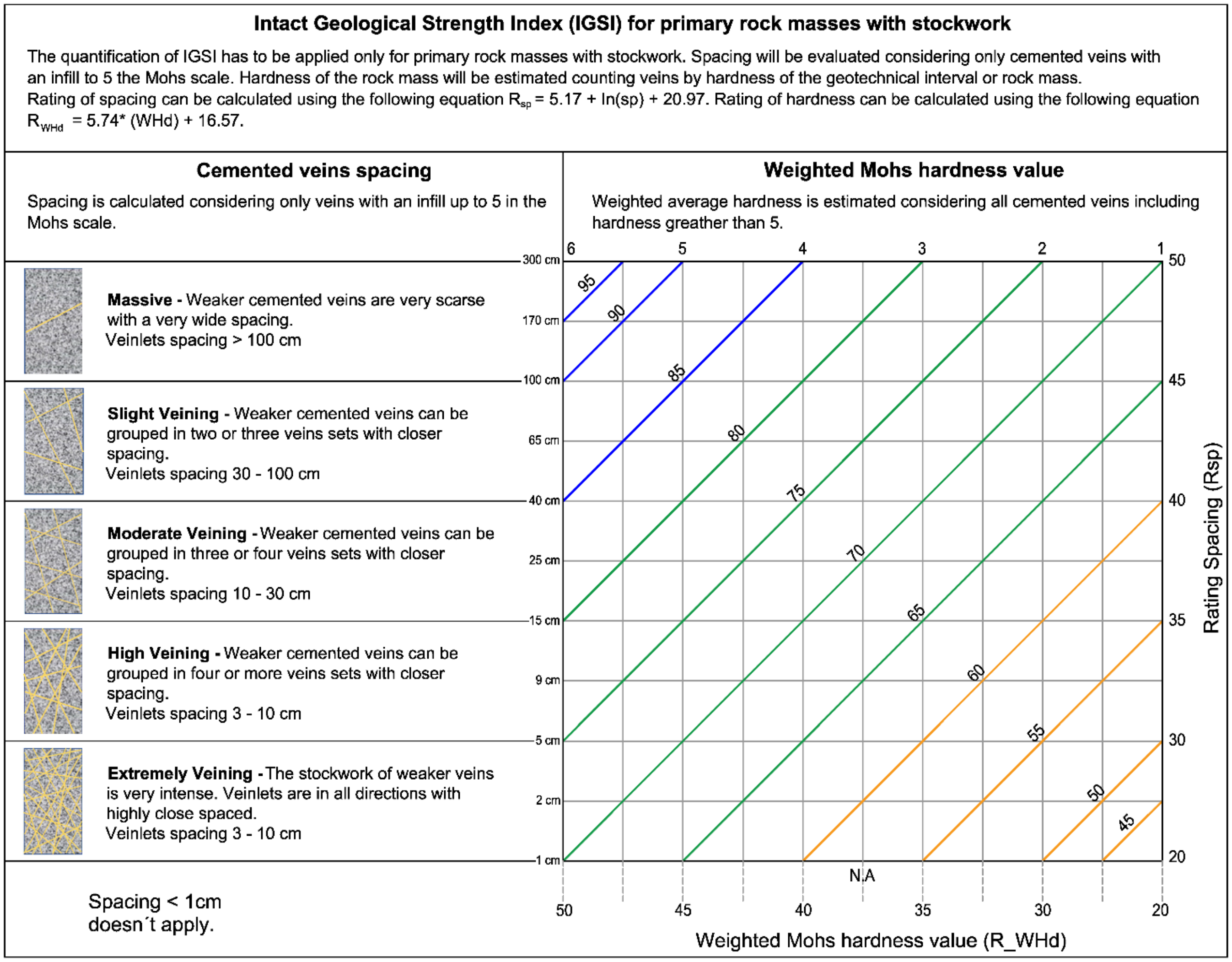


Figure 7 Examples of primary rock masses at Los Sulfatos orebody. (a) Andesite, (b) Potassic magmatic breccia, (c) Sericitic magmatic breccia, (d) Tourmaline Breccia.

Figure 8 Examples of cemented and open cemented veins at Los Sulfatos orebody. Mineral infills: (a) Bornite-anhydrite-chalcopyrite, (b) Pyrite-anhydrite, (c) Chalcopyrite, (d) Anhydrite.



Intact Geological Strength Index (IGSI) for primary rock masses with stockwork

The quantification of IGSI has to be applied only for primary rock masses with stockwork. Spacing will be evaluated considering only cemented veins with an infill to 5 the Mohs scale. Hardness of the rock mass will be estimated counting veins by hardness of the geotechnical interval or rock mass.
Rating of spacing can be calculated using the following equation $R_{sp} = 5.17 + \ln(sp) + 20.97$. Rating of hardness can be calculated using the following equation $R_{WHd} = 5.74^* (WHd) + 16.57$.

Cemented veins spacing

Spacing is calculated considering only veins with an infill up to 5 in the Mohs scale.

Massive - Weaker cemented veins are very scarse with a very wide spacing.
Veinlets spacing > 100 cm

Slight Veining - Weaker cemented veins can be grouped in two or three veins sets with closer spacing.
Veinlets spacing 30 - 100 cm

Moderate Veining - Weaker cemented veins can be grouped in three or four veins sets with closer spacing.
Veinlets spacing 10 - 30 cm

High Veining - Weaker cemented veins can be grouped in four or more veins sets with closer spacing.
Veinlets spacing 3 - 10 cm

Extremely Veining - The stockwork of weaker veins is very intense. Veinlets are in all directions with highly close spaced.
Veinlets spacing 3 - 10 cm

Spacing < 1cm
doesn´t apply.

Weighted Mohs hardness value

Weighted average hardness is estimated considering all cemented veins including hardness greather than 5.

Figure 9 Proposed chart for quantification of Intact Geological Strength Index (IGSI) for primary rock masses with stockwork.

The proposed IGSI is quantified based on the spacing between cemented veins and the Mohs hardness of the mineral infill.

The potential degree of fracturing of the rock mass when disturbed is evaluated according to the spacing between cemented veins that have a Mohs hardness up to 5, representing the weaker mineral infill that could be open during drilling or mining activities, such as blasting, induced stresses, caving, etc. The range of spacing defining different categories of rock mass is similar to the proposed by Cai et al. (2004) and the rating is assigned according to spacing as shown in the Chart of Figure 9.

Cemented veins, in a geotechnical interval, are counted according to the mineral association and the Mohs hardness scale. The number of veins with a Mohs hardness of 2, then 3, etc. up to >5 is counted and then a representative Mohs hardness of the geotechnical interval is calculated by a weighted average as a function of the vein spacing. Once the spacing and the Mohs hardness are calculated it is possible to assign their ratings and calculate the final IGSI.

It is important to note that IGSI ranges between 40 and 100 instead of 0-100 range as for the conventional GSI. The different range can be explained because conventional GSI was conceived to characterize secondary rock masses and then was added the massive condition to include the higher quality of primary rock masses, instead, the aim of IGSI is to characterize primary rock masses that in general terms show at least a very blocky degree of fracturing and a fair joint condition, according to that, we can assume that IGSI should start from a minimum IGSI rating of 40 up to 100.

This method to quantify the proposed IGSI has been tested characterizing almost 1,000 geotechnical intervals from several drill cores of the exploration campaign. The calculated IGSI has been compared with the conventional GSI quantified according Hoek et al. (2013) and with the CGSI quantified according Day et al. (2019). The CGSI was estimated considering the presence of only one suite of discontinuities formed by cemented veins due to the absence of open joints. In addition, the comparison included the abovementioned classification systems. Table 4 shows the IGSI estimated average values for each Geotechnical Unit, compared with other GSI methods and classification systems.

Table 4 Quantification of IGSI compared with other GSI methods and with traditional classification systems for Los Sulfatos orebody

Geotechnical Unit	IGSI	CGSI	GSI_{2013}	RMR_{B89}	$IRMR_{L90}$	$IRMR_{LJ01}$	Q'_{93}
Tourmaline Breccia	83	86	78	81	64	68	101
Sericitic Magmatic Breccia	82	83	76	75	58	61	46
Potassic Magmatic Breccia	85	86	76	77	62	64	64
Andesite	84	83	78	77	60	61	55
Post Mineral Porphyry	70	79	75	75	60	56	42
Principal Intermineral Porphyry	86	88	78	78	62	67	66
Late Intermineral Porphyry	79	88	78	80	66	68	101

From Table 4 it is possible to note that GSI, estimated according to Hoek et al. (2013), ranges from 75 to 78 indicating a very homogeneous rock mass, whereas, IGSI ranges from a minimum value of 70 up to a maximum of 86. This bigger variation can be explained with the different characteristics of the typical mineral infills observed in the different Geotechnical Units; i.e., the lowest value associated to Post Mineral Porphyry is related to the predominance of gypsum as mineral infill of the cemented veins and a higher vein frequency. The lowest rating of the Post Mineral Porphyry is confirmed by an IRMR rating of 56, being the only classification system that include the effect of the cemented veins and microdefects. Slightly differences between potassic and sericitic alterations are marked IGSI instead of traditional GSI.

The Andesite and Breccias geotechnical units show IGSI ratings very similar to CGSI indicating a good correlation for primary rock masses characterized by veining cemented by stronger mineral infill, whereas, if the cemented veins are characterized by weaker mineral infill, IGSI shows lower ratings than CGSI.

The proposed quantification method allows practitioners to distinguish different geotechnical quality based on the strength of the mineral infill and its frequency. It has been observed in several underground mines in Chile, in primary rock masses, that traditional classification systems are not able to point out different geotechnical behaviour between Geotechnical Units, whereas, the mining experience shows different geotechnical qualities among them.

5 Conclusions

Traditional classification systems have been developed for jointed rock masses, characterized by open, or partially open and weathered joints. These systems have been applied successfully in this type of rock mass in mining operations around the world. With the increase of depth of the mining operations, mining industry faced the challenge to mine orebodies at greater depth that are characterized by high strength rock masses with a stockwork of cemented veins in a higher stress. In these hypogene environments, it was difficult for traditional systems to characterize and point out different geotechnical qualities among different Geotechnical Units. Attempts to improve classification systems for primary rock have been done by Laubscher & Jakubec (2001) and Day et al. (2016) to improve MRMR and GSI, respectively.

The aim of this work is to present a new method to quantify GSI, called Intact GSI (IGSI), for a porphyry copper deposit in an hypogene environment. The proposed IGSI is quantified based on the rating assigned to the spacing between cemented veins and the rating of the average of the Mohs hardness of the mineral infill.

This method has been tested at Los Sulfatos Ore Body, a porphyry copper deposit in hypogene environment. Results pointed out a better geotechnical quality differentiation among Geotechnical Units, due to the different mineralogical infill strength and different alteration types, compared with the geotechnical assessment using traditional systems.

The proposed method has been developed for primary rock masses and should not be used in a jointed rock mass characterized by open and weathered joints.

At present time, Los Sulfatos Ore Body has only an isolated exploration tunnel, developed with TBM method, and is still not developing mining activities, because of that, it was not possible to do a back analysis to calibrate and validate the quantified IGSI. When an future project will start the construction stage it will be possible verify the quantified values.

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References

Bieniawski, ZT 1976, ‘Rock Mass Classification in Rock Engineering’, Proc. Symp. Exploration Rock Engineering, Johannesburg, 97-106.

Bieniawski, ZT 1989, Engineering Rock Mass Classifications. A Complete Manual for Engineers and Geologists in Mining, Civil and petroleum Engineers. Wiley, New York.

Cai, M, Kaiser, PK, Uno, H, Tasaka, Y & Minami, M 2004, ‘Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system’. International Journal of Rock Mechanics & Mining Sciences, 41, 3–19.

Day, JJ, Diederichs, MS & Hutchinson, DJ 2016, ‘Validation of Composite Geological Strength Index for healed rockmass structure in deep mine access and production tunnels’. Tunneling Association of Canada. 2016 Annual Conference. Capitalizing on Underground Infraestructure. October 16-18, 2016, Ottawa, Ontario, Canada.

Day, JJ, Diederichs, MS & Hutchinson, DJ 2019, ‘Composite Geological Strength Index Approch with Application to Hydrothermal Vein Networks and Other Intrablock Structures in Complex Rockmasses’. Geotech. Geol. Eng., Vol.37, pp. 5285-5314.

Deere, DU & Deere, DW 1988, The Rock Quality Designation (RQD) Index in Practice’. Rock Classification Systems for Engineering Purposes, ASTM STP 984, Louis Kirkaldie, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 91-101.

Grimstad, E & Barton, N 1993, ‘Updating of the Q-System for NMT’, International Symposium on Sprayed Condrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support, Fagernes.

Hoek, E 1994, ‘Strength of rock and rock masses’. ISRM News Journal 1994;2(2):4-16.

Hoek, E, Kaiser, PK & Bawden, WF 1995, ‘Support of underground excavations in hard rock’. Rotterdam: Balkema.

Hoek, E 2006, ‘Practical rock engineering’, www.rockscience.com

Hoek, E & Karzulovic, A 2000, ‘Rock mass properties for surface mines’, *Slope Stability in Surface Mining*, Society for Mining, Metallurgical and Exploration, Littleton, Colorado, 59-70.

Hoek, E & Marinos, PG 2000, ‘Predicting tunnel squeezing problems in weak heterogeneous rock masses’. Tunnels and Tunnelling International;132(11):45-51.

Hoek, E, Carter, TG & Diederichs, MS 2013, ‘Quantification of the Geological Strength Index chart’, ARMA 13-672, 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, June 23-26.

Irarrazabal,V, Sillitoe,RH, Wilson,AJ, Toro,JC, Robles,W, Lyall,G,2010, 'Discovery History of a Giant, High Grade, Hypogene Porphyry Copper-Molybdenum Deposit at Los Sulfatos, Los Bronces-Río Blanco District, Central Chile'. In Economic Geology, Special Publication #15, Chapter 14, 253-269p.

Laubscher, DH 1990, 'A geomechanics classification system for the rating of rock mass in mine design', J. S. Afr. Inst. Min. Metall. 90-10, 257-273.

Laubscher, DH & Jakubec, J 2001, 'The MRMR Rock Mass Classification for Jointed Rock Masses'. In Eds.: Hustrulid, W.A. & Bulock, R.L., Underground Mining Methods: Engineering Fundamentals and International Case Studies. SME: Littleton, Colorado. Pag. 475-481.

Pablo, M 2019, 'Actualización del Modelo Geológico de Los Sulfatos. Enero 2019: Litología, Alteración y Zona Mineral' (AngloAmerican Internal Report).36p.

Palmstrom, A 2005, 'Measurements of and Correlations between Block Size and Rock Quality Designation (RQD)', Tunnels and Underground Space Technology, 20, 362-377.

Sonmez, H & Ulusay, R 1999, 'Modifications to the geological strength index GSI and their applicability to stability of slopes'. Int. J. Rock. Mech. Min. Sci., 36, 743-60.