

APPROACH TO GEOTECHNICAL CHARACTERIZATION AND SLOPE DESIGN DATA ACQUISITION PROGRAMS IN DIFFERENT DEPOSIT TYPES

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ABSTRACT

This paper will present an approach to identify critical aspects for consideration at a prefeasibility stage when characterizing parameters related to geology, structural geology, hydrogeology, and rock mass for definition of geotechnical domains for slope design. Also presented will be worked examples of three deposit types: general porphyry rock masses (i.e. alteration aspects, joint characterization), intermediate-sulphidation epithermal gold-silver deposits, and fault-controlled orogenic deposits. The intention is to discuss specific geotechnical attributes with consideration to each deposit type, and present a series of deposit-specific considerations that highlight the more important geological-related geotechnical aspects that would need to be established when evaluating these types of deposits for the expected slope performance for design purposes.

1. INTRODUCTION

Often during a project's prefeasibility study, geotechnical investigation and evaluation programs are outlined with limited consideration of the actual geotechnical context of the mineralization and the rock mass around it. In some cases, the drill holes are laid out at a predetermined spacing that is based on previous experience, excavation depth, and possible pit sizes. The drill holes are either drilled parallel to proposed pit shell geometries or back into the slope to intersect the lower parts of the slope with the intention of investigating the existence of any faults structures/weak zones that may impact the slope stability.

Slope design engineers often do not stop to assess the geological and geotechnical context of a potential deposit and that of the proposed pit that will be developed to exploit the deposit. At the investigation planning stage, there is often little consideration given to what can be gleaned from a better understanding of the geological context, with the aim of developing a far more functional slope stability evaluation program. Frequently, drilling programs are started without evaluating of the deposit's geological and geotechnical characteristics and what they imply to the slope design and the whole project itself.

There are often different silos of evaluation being undertaken during a prefeasibility study. Exploration geologists work on the definition of infill drilling program and the slope designer may try to get a structural geologist involved to investigate the deposit. Meanwhile, metallurgists are developing their own programs to obtain core so they can undertake various tests to establish crushing and process design parameters and environmental geochemist are also developing their separate programs. Additionally, geotechnical engineers and hydrogeologists may work together to combine their programs to gain the required information from a specifically developed geotechnical mapping and drilling program. This often results in uncoordinated data acquisition programs that, at a late stage, may encounter a number of critical assessment aspects that we do not have the raw data for nor time to consider. This often leads to sub optimized evaluations and costly changes of direction within the prefeasibility study.

We often find ourselves dealing with potential deposits where the explorationists are only too keen to define additional mineralization but are not eager to assess any complications to the mineral resource that may manifest because of structural geology, alteration, and geotechnical aspects. Many smaller-tier clients believe that this decreases the value of their asset before they sell to one of the larger major's or mid-tier companies. Somehow this value-add approach and process needs to be kept frugal and still be used to motivate these types of clients to consider the improved understanding of the risks and opportunities as a valuable asset.

What this paper suggests is a front-end process to a prefeasibility study that includes having a technical workshop on the actual geological, geotechnical, and possibly metallurgical and environmental geochemistry context of the deposit. This would need to be undertaken prior to establishing prefeasibility study data acquisition and evaluation programs for the various disciplines. It is suggested that when a workshop is undertaken that it includes the client's deposit geologist, a structural geologist, a mine closure geochemist, a metallurgist, a mining engineer, a hydrogeologist and the geotechnical engineer/geologist. The latter five team members would be from the teams undertaking the prefeasibility

study. On the slope design side, this workshop forms the initial part of a process flow for undertaking of the slope geotechnical data acquisition and evaluation program.

2. WORKSHOP APPROACH

For the workshop to be a success it is recommended that a presentation be prepared by the exploration geology team that covers the various aspects of the mineralization and the surrounding rock mass. The following aspects should be covered in the presentation:

- Regional structural geology interpretation
- Mine scale structural interpretation
- Mineralization context and what deposit, if any has been used as a reference analogue, including the exploration targeting model
- Generic mineralization type and expected characteristics in and around the orebody
- Controlling lithologies
- Mineralization geometry and depth

For the workshop team, the geological sections and early 3D geological models, the exploration core photographs and the exploration database would be beneficial to work through the various examples of the faults, alteration types, and lithology variances. It is suggested that the findings (e.g. pit size, dump/dam locations, environmental influences and economic drivers) of the Preliminary Economic Assessment be presented at the start of the workshop so that the mining context and the potential areas affected is well understood and debated during the workshop.

The intention is to work through information and use geological and engineering experience to anticipate likely project-relevant conditions within the mineralized area, the pit slopes, and the areas of the proposed major infrastructure. The workshop is expected to provide guidance on the establishment of conceptual models and generate questions to be answered to satisfy the prefeasibility study requirements in the multiple disciplines.

This approach is loosely based on the approach established by Fookes et al. (2001) in their paper Total Geological History: A Model Approach to the Anticipation, Observation and Understanding of Site Conditions. Their paper focused on geotechnical evaluations of civil sites and the premise of their paper was that the conditions and geotechnical characteristics of the ground are the product of the geological and geomorphological history of the site. This included past and present climatic conditions, in short, the total geological history of the site. The engineering performance of the site results from the influence of the engineering works on the total geological history.

Following this approach, a process flow has been developed to establish the geotechnical context of the studied deposit. This illustrates the various models on which the slope design geotechnical domain models are developed; the models then feed into the process flow developed by Read and Stacey (2009) in their book Guidelines for Open Pit Slope Design. This approach is shown in Figure 1 below.

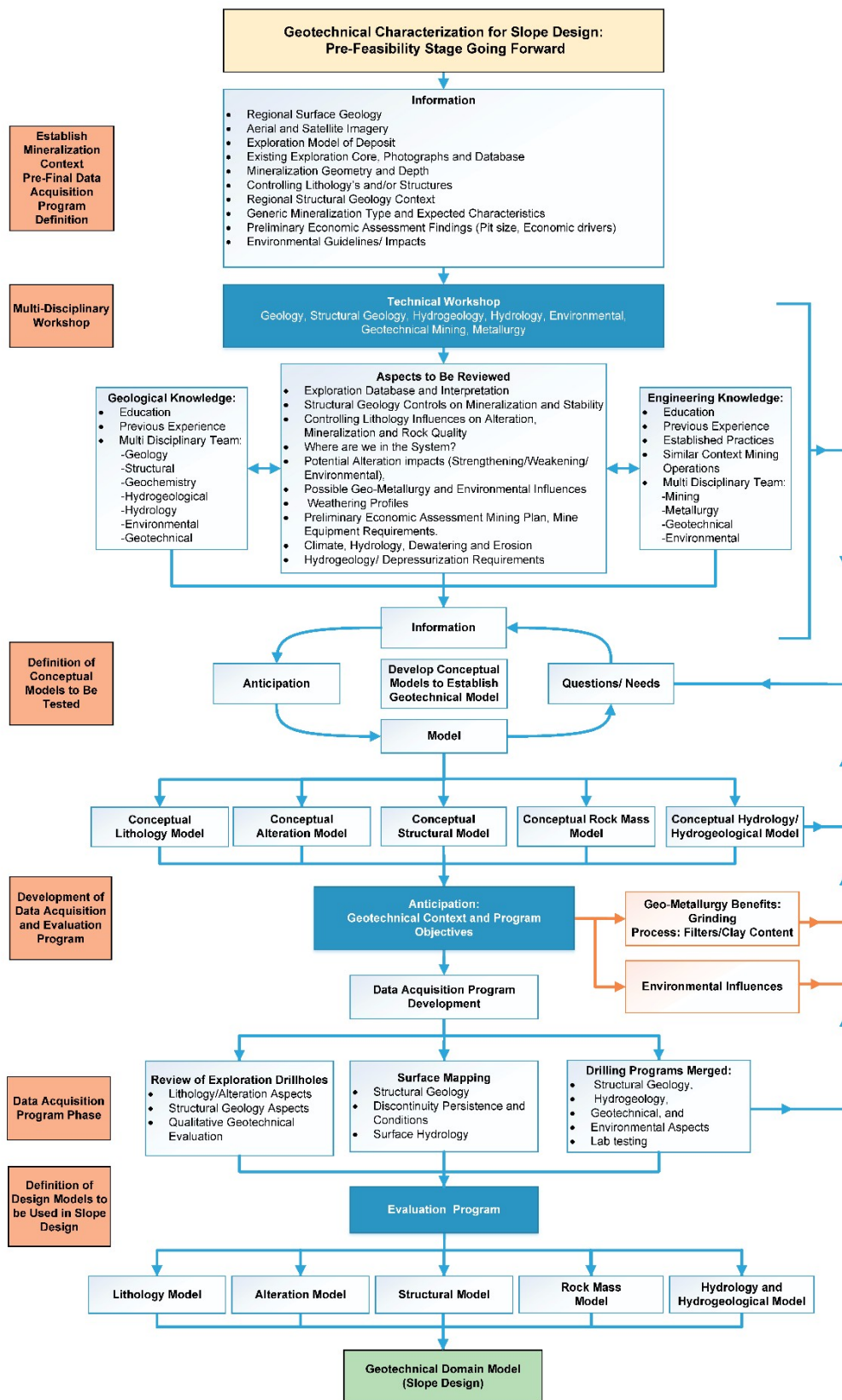


Figure 1: Process flow for the development of the various input models on which the slope design geotechnical domain models are based.

3. CONCEPTUAL MODEL EVALUATION STRATEGY

Once the workshop is completed and the context of the potential open pit mine is well understood, the intention would be to find an analogue mining operation or operations that are of similar context and research any information around the geological and mining context. If possible, a visit should be undertaken by representative team members to the operation and as much information as possible should be collected on the various geotechnical related aspects as they apply to the slope design and the mining operation. This should include the following important information where relevant:

- Alteration impacts
- Discrete structural geology features and structural fabric impacts
- Geotechnical domains
- Dewatering requirements
- Trafficability issues
- Bench geometries, inter-ramp angles, and stack heights
- Any slope performance history

This information is used to contribute to the establishment of the various conceptual models, from which to determine what model aspect has a low reliability and what needs to be tested by the prefeasibility data acquisition programs. These conceptual models would be tested during the data acquisition and early evaluation phase and then used to establish the final models that Read and Stacey (2009) have recommended to be established for the generation of geotechnical domains and the undertaking of the subsequent slope design. The following conceptual models need to be developed, as they are impacted by the mining plan:

- Lithology model
- Alteration and weathering model
- Structural and fabric model
- Rock mass model
- Hydrogeological model

Even if a site visit is not possible, the initial literature review should aim to gain information on the various characteristics listed above. The intention is to anticipate the range of geotechnical and hydrogeological conditions and generate a number of questions while developing these models need to be used as the basis for the development of the data acquisition program. It will be important to strike a balance approach as to what is actually needed for the prefeasibility study and what can be left to the feasibility study.

GEOTECHNICAL DATA ACQUISITION PROGRAM

Having considered the various established conceptual modes, the slope design relevant data acquisition programs need to be developed. As a minimum, these programs should include the following:

EXPLORATION PROGRAM REVIEW: This should include a period on site where the core observations and the details of the observations recorded in the database are discussed in detail with the site geologists. Very important will be the understanding of the logged alteration and the intensity, how these manifest in the core and how important these will be not only to the geotechnical evaluation program, but to the prefeasibility study in general. At the same time, the impact of the alteration on the rock strength can be determined. In some cases, it may be necessary to bring in an alteration specialist to log a number of the boreholes to try to interpret the alteration types and intensities for use in the alteration conceptual model.

The quantity and the nature of the fault structures intersected in the core and whether these have been used for some sectional interpretation should also be discussed. It is important to start trying to interpret what may be primary and secondary structures at this early stage and how these manifest within the core. This will be very valuable in understanding the nuances of the logging and the interpretations developed by the exploration geologists and how these would need to be adapted for use in the geotechnical evaluation program. This review logging will, in essence, develop a calibrated model for the interpretation of the full resource drilling database and interpretation.

SURFACE MAPPING PROGRAM: If there is sufficient surface outcrop or road cuttings, a structural and geotechnical mapping program can be undertaken. At the same time, weathering profiles and the nature of the potential over-

burden and thickness can be assessed. Part of the evaluation would be an assessment of the surface hydrology in the area potentially impacted by the mining plan and how it would potentially impact the hydrogeology.

DRILLING PROGRAM: A drilling program should be undertaken after establishing the various conceptual models and coming up with the various subsurface questions. The drilling program will need to take into consideration the requirements of the lithology, alteration, surface weathering, structural geology, geotechnical and the hydrogeological investigation requirements. Being able to optimize the drilling program and achieve a compromise on the number of holes will be beneficial to the client. At this stage, it would be worth discussing the program requirements with the other vested parties including: exploration geology; metallurgy and environmental geochemistry.

Using this approach is expected to generate an optimized data acquisition program to answer the main questions for the prefeasibility study and limit the costs relative to a siloed, discipline-based program. This will help avoid the late stage, critical assessment aspects that we do not have the raw data for nor time to consider. This approach will lead to an optimized evaluation and avoid costly changes of direction during the late stages of the prefeasibility study.

4. DEPOSIT TYPE: GENERAL WORKED EXAMPLES

Three deposit types are to be used as examples of how information can be obtained from available literature and how it can be applied to the project at hand. The first are porphyry deposits, the second are intermediate-sulphidation epithermal gold–silver deposits and the third is the general group of strongly structurally deformed deposits. All these deposits are associated with active tectonic accretionary margins (Figure 2), where many common types of ore deposits occur due to recycling of metals into the crust. The approach will be to highlight what more geological-related geotechnical aspects would need to be established when evaluating these types of deposits based on their more specific geological characteristics.

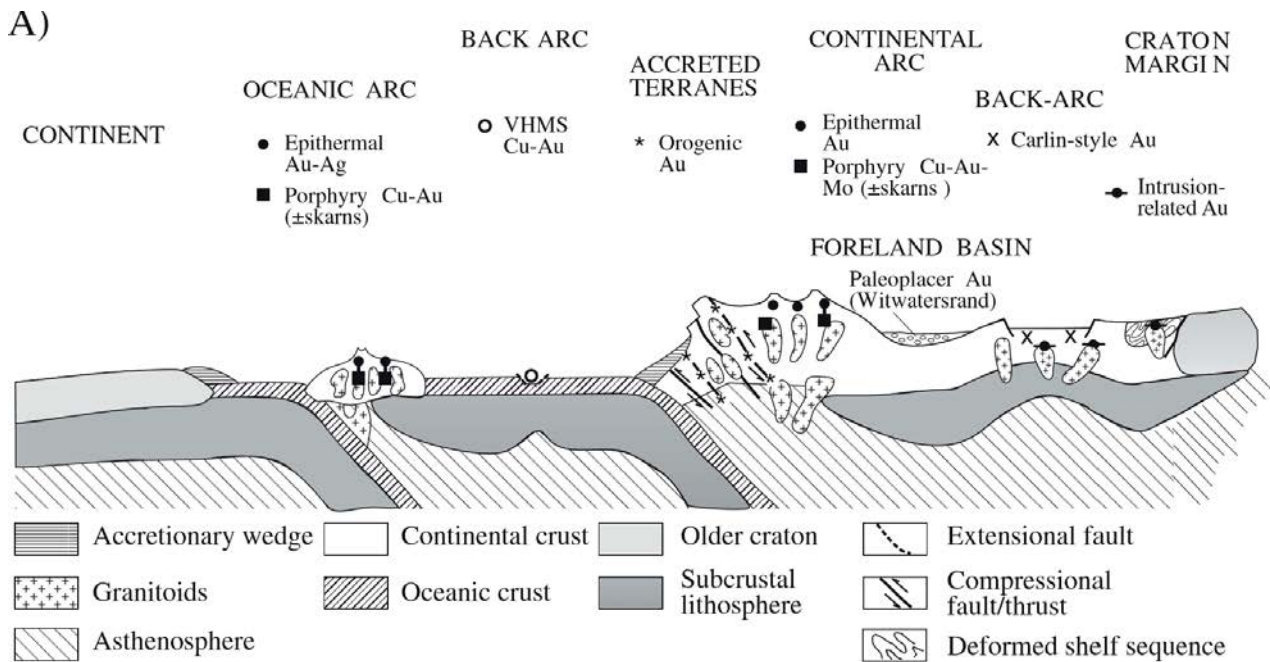


Figure 2: Schematic example of an active tectonic accretionary continental margin, illustrating the location where different types of deposits can form. From Groves et al. 2005.

PORPHYRY DEPOSITS

From a geological perspective, the general characteristics of porphyries and intermediate-sulphidation epithermal gold–silver deposits are illustrated in the comprehensive text of Sillitoe’s 2010 paper Porphyry Copper Systems. Indicated in this paper is the worldwide location and age of copper porphyry systems that can be used as references or analogues to the deposit that is being evaluated. A reasonably quick literature search of the various deposits can highlight deposits that are of a similar context to that being evaluated (Figure 3).

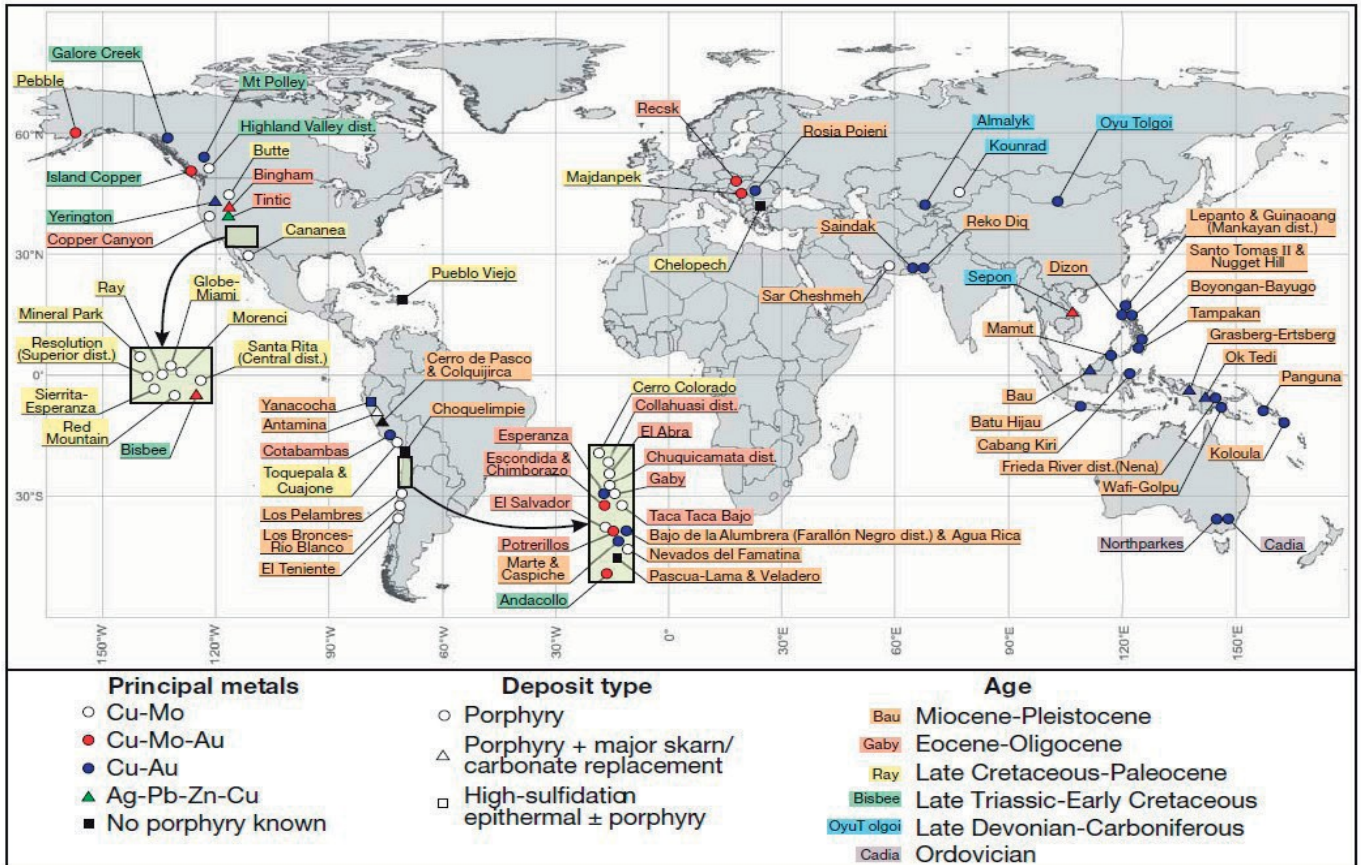


Figure 3: Worldwide locations of porphyry Cu systems cited as examples of features discussed in Sillitoe (2010). Also shown are the principal deposit type(s), contained metals, and age.

Sillitoe's (2010) paper provides generalized schematics of the anatomy of a telescoped copper porphyry system (Figure 4) as well as the generalized alteration-mineralized zoning pattern. Also provided is a schematic of the generalized alteration-mineralized zoning pattern for a non-telescopic Cu porphyry. Other papers and documents like the USGS Scientific Investigations Report 2010-5070-B Porphyry Copper Deposit Model and Seedorff et al. (2005) and reference tables in the Economic Geology's 100th Anniversary Volume are also helpful texts to be referred to when assessing these types of deposits.

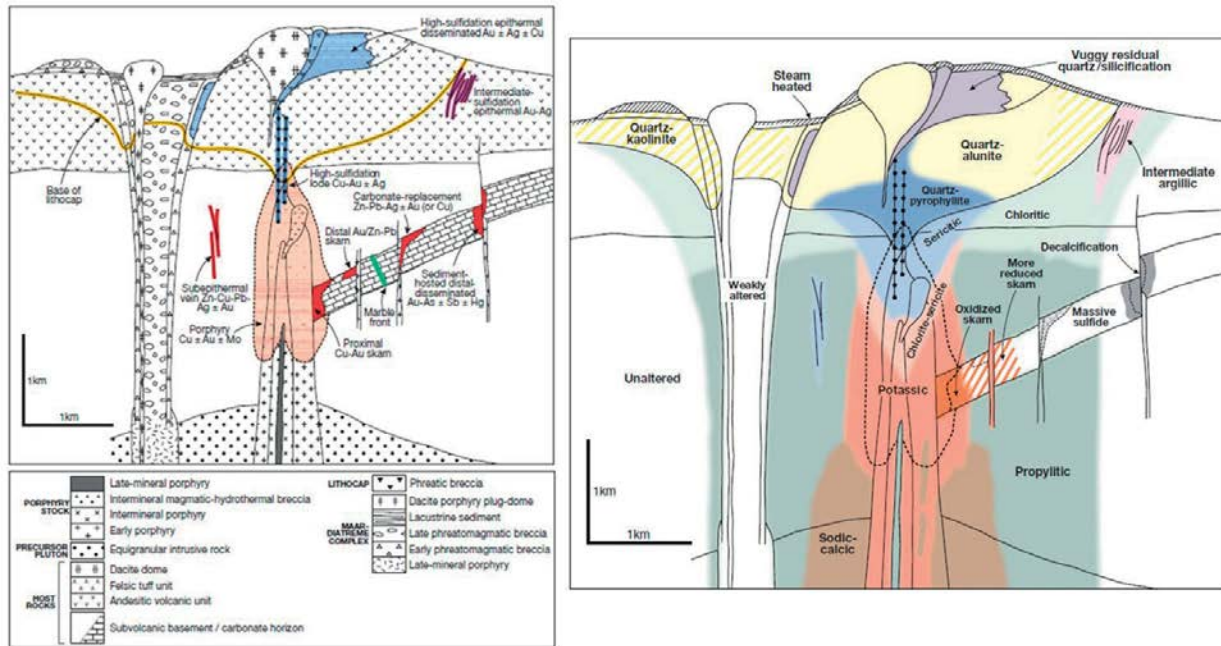


Figure 4: (a) Anatomy of a telescoped porphyry Cu system showing spatial interrelationships of a centrally located porphyry Cu ± Au ± Mo deposit in a multiphase porphyry stock and its immediate host rocks; and other proximal deposits. (b) Generalized alteration-mineralization zoning pattern for telescoped porphyry Cu deposits, based on the geologic and deposit type (from Sillitoe 2010).

Porphyry deposits are associated with multiple intrusions and dikes of diorite to quartz monzonite composition with porphyritic textures. The economic deposits of copper and/or gold, molybdenum ± silver are located in alteration zones formed from hydrothermal fluids that originate from a voluminous magma chamber up to several kilometers below the deposit itself. The thermal effects of the porphyry intrusive system also drive circulating meteoric water that can interact with the hydrothermal fluids, causing additional alteration zone types (Table I).

Porphyry geological systems can be complex, and their characteristics have direct impact on the geotechnical characteristics of the rock mass. The different types and zones of alteration (Table I) impact rock strength, clay content, rate of weathering and intensity of micro-fracturing. These impacts can vary depending on the protolith emplaced and the porphyry associated rock types also affected by the various alteration phases. Hosting faults structures and syn-emplacement stresses impact hydrothermal fluid flow patterns and associated fractures, magmatic and hydrothermal breccias, the occurrence of sills, stock work veins and other vein trends, and therefore control rock mass anisotropy patterns throughout the deposit. The geometries and strength properties of the different intrusions and host rock need to be defined. Sills often improve stability of a slope by breaking the continuity of adverse structures, but should be carefully assessed before making such assumptions. If heavily fractured or altered, they may not improve slope stability, but rather impact it adversely.

Table I. Characteristics of principal alteration-mineralization types in porphyry Cu systems.
Modified after Sillitoe (2010)

<i>Alteration type (alternative name)</i>	<i>Position in system (abundance)</i>	<i>Key minerals</i>	<i>Impact on rock mass quality – Impact very dependent on the protolith and pre-existing rock mass conditions and subsequent geological activity/overprinting</i>
Sodic-calcic	Deep, including below porphyry Cu deposits (uncommon)	Albite/oligoclase, actinolite, magnetite	An increase in the intensity of the sodic-calcic can lead to strengthening of the rock mass, but at higher intensities can result in a decrease in the rock strength.
Potassic (K-silicate)	Core zones of porphyry Cu deposits (ubiquitous)	Biotite, K-feldspar	This alteration typically has a limited impact on rock mass strength.
Propylitic	Marginal parts of systems, below lithocaps (ubiquitous)	Chlorite, epidote, albite, carbonate	An increase in the intensity of the propylitic alteration can result in a decrease in the rock mass quality, typically resulting in highly fractured rock with low RQD values and reduced joint conditions (1). However, this alteration typically adversely effects the rock mass quality less than phyllic and potassic alterations. (1)
Chlorite-sericite (sericite-clay-chlorite [SCC])	Upper parts of porphyry Cu core zones (common, particularly in Au-rich deposits)	Chlorite, sericite/illite, hematite (martite, specularite)	An increase in the intensity of the chlorite-sericite alteration results in a decrease in the rock mass quality through the increased abundance of clays and weaker joint conditions. Typically resulting in fragmented rock based with very low to no RQD. (1)
Sericitic (phyllic)	Upper parts of porphyry Cu deposits (ubiquitous, except with alkaline intrusions)	Quartz, sericite	As alteration intensity increases the rock mass strength decreases (2, 3). An exception to this is in the case of extensive anhydrite precipitation that can improve rock quality, but subsequent dissolution generates gypsum and in the process, fractures the rock (1).
Advanced argillic (secondary quartzite in Russian terminology)	Above porphyry Cu deposits, constitutes lithocaps (common)	Quartz (partly residual, vuggy), alunite,4 pyrophyllite, dickite, kaolinite	The effect of the alteration on the rock mass is dependent on the grade of the argillization which varies from 1 – trace amounts of clay minerals to 3 – complete alteration into clay. An increase in the intensity, or grade of the alteration, decreases the rock mass quality. (1)

1. Eggers, M.J. 2016. Engineering geological modelling for pit slope design in the porphyry copper-gold deposits of Southeast Asia, in PM Dight (ed.), Proceedings of the First Asia Pacific Slope Stability in Mining Conference, Australian Centre for Geomechanics, Perth.
2. Hoek, E. 2001. Rock mass properties for underground mines, published in Underground Mining Methods: Engineering Fundamentals and International Case Studies. Society for Mining, Metallurgy, and Exploration.
3. Yildirim, B.G. 2016. 'Development of a correlation between mineralogy, rock strength measures, and breakage of Copper Porphyries'. Thesis. University of Queensland, Australia.

Breccias of various types are associated with magmatic and hydrothermal systems, and in particular with porphyry systems. Breccia types are spatially associated with different parts of the system, different alteration zones, and can be of different size, composition and alteration mineralogy (Table II). Breccias have a significant impact on the rock mass strength. Informed anticipation of these well-known characteristics of porphyry systems allows the geotechnical engineer to search for specific, possibly relevant rock mass conditions, based on findings of the initial exploration drill core review, exploration database assessment and discussions with the geologists. At the same time, the approach used by the geologists to define alteration intensity can be investigated, and if required, a separate re-logging program by an alteration specialist can be obtained.

The above approach will afford the tailoring of any infill exploration drilling, or engineering study related drilling, to adapt the logging methods and the lab testing programs to assess the critical alteration types. These adjusted approaches could provide substantial benefit to the geotechnical domaining, metallurgical process influences, and the geo-chemical assessment of the waste and tailings placement requirements.

Table II. Features of principal hydrothermal breccia types in porphyry Cu systems. Modified after Sillitoe (2010)

Type	Position in system (abundance)	Form	Matrix/cement	Alteration types (Table I)
Magmatic hydrothermal	Within porphyry Cu deposits, locally around them (ubiquitous)	Irregular, pipe-like bodies (10s–100s m in diam)	Quartz-magnetite-biotite-sulfides/ quartz-muscovite- tourmaline-sulfides ± rock flour ± igneous rock (i.e., igneous breccia)	Potassic ± chlorite-sericitic ± sericitic; uncommonly
Phreatic (porphyry Cu level)	Within and around porphyry Cu deposits (relatively common)	Dikes, uncommonly sills, and irregular bodies	Muddy rock flour	Sericitic, advanced argillic, or none
Phreatic (epithermal level)	Within litho-caps; local surface manifestations as eruption breccia (relatively common)	Irregular bodies (10s–100s m in diam)	Chalcedony, quartz, alunite, barite, sulfides, native S	Advanced argillic
Phreatomagmatic	Diatremes span porphyry Cu and epithermal environments; surface manifestations as maar volcanoes (present in ~20% of systems)	Kilometer-scale, downward-narrowing conduits	Rock flour with juvenile tuff or magma blob component; early examples cut by porphyry Cu mineralization	None or advanced argillic, but early examples with any alteration type depending on exposure level

The impact of tectonic deformation on a porphyry deposit can vary. They occur in compressional arc environments, which can be dynamic, complex deformational environments. Some deposits are not strongly deformed, whereas others experience an extended history of tectonic deformation with structural reactivation syn-mineralization and post-mineralization. Defining the fault systems accurately in such deformed deposits is typically essential for assessing slope stability (see section on deformed deposits below).

Based on our experience, the following geological, structural geotechnical and geotechnical aspects should be considered when trying to anticipate the potential context of the porphyry and the potential conceptual models to be tested and evaluated:

GEOLOGY

- Geology and lithology aspects: Identify geometries and contact relationships, including breccia types (Table II), geological attributes and contact relationships.
- Alteration type and intensities: Identify the location of the deposit in the porphyry system (Figure 4) and what types of weakening and strengthening alteration can be expected based on a literature survey and previous experience (Table I). Explore the use of a site-specific system such as the Alteration Strength Index developed by Wyering (2014) for assessing alteration and lithology impacts and geothermal drilling performance and considers the quantities of primary and secondary mineral occurrences within the altered zones.
- Alteration review: Review existing exploration core in the higher weakening alteration areas to assess potential alteration impacts. Clay speciation assessment in the field using a visual-infrared spectrometer and verification and quantity assessment in the laboratory using X-ray diffraction and a scanning electron microscope analysis should be undertaken.

STRUCTURAL GEOLOGY

- Fault systems: Determine the first- and second-order fault patterns. Many porphyry deposits have intrusive and other lithological contacts that are at least partly spatially controlled or displaced by fault systems, since they form within active tectonic environments.
- Alteration patterns: Review the spatial distribution of the alteration zones in comparison with the fault system. The geometry and extent of the alteration domains can be strongly influenced by the fluid pathways provided by fault structures. Some broad fault zones are internally zoned by different alteration domains.
- Rock mass fabric/anisotropy: Determine the dominant vein trends and compare to first- and second-order fault trends. The vein and fracture systems are often oriented sub-parallel to the faults, or in Riedel fault geometries proximal to the faults. The fault system can therefore help define domains, each of which has a local rock mass strength anisotropy caused by pervasive vein systems.
- Discontinuity infill properties: Describe the infill material on faults, fractures, and veins. The nature of infill material within the faults, fractures, and veins is typically dependent on the local alteration system and proximity to the centre of the driving porphyry system. The structure infill properties can therefore help constrain the spatial extent of alteration domains, and the alteration domains can help predict the properties of the discontinuities.

GEOTECHNICAL

- Alteration type and intensities: Review the dominant alteration types (Table I) and assess the interpretation of alteration intensity by reviewing the site-established descriptions and the reference atlas of lithology types and alteration types. Specifically determine what the intensities mean in terms of joint conditions and intact rock strengths in altered rock mass areas. An alteration specialist may be required to determine the predominant alteration types and intensities to be used for the undertaking of 3D modelling. Assessments of density and porosity could help identify substantially impacted altered zones that will have reduced rock strengths.
- Exploration drill holes: Perform a qualitative review of rock mass conditions of all holes in the exploration database using a calibrated system of photos that considers drilling conditions and rock mass impacts. This would be calibrated against geotechnical drill holes in similar rock mass conditions.
- Qualitative rock mass block model: Depending on the drillhole spacing and the complexity of the deposit, develop a block model that has well-defined hard and soft domain boundaries. Rigorously test the model with data from geotechnically logged drillholes, litho-structural domains and alteration intensity domains.
- Joint counts and fracture frequency: Attempt to understand the principal joint sets joint conditions in contrast to the shorter, less continuous cooling joints.
- Micro-fracturing intensity: Characterize the intensity of micro-fracturing in different lithological, alteration, and structural domains, and try quantifying the impact of micro-fractured intact rock strength.
- Testing programs: Establish suitable strength and shear strength testing programs that reflects representative variability within the rock masses related to various alteration types and intensities.

INTERMEDIATE-SULPHIDATION EPITHERMAL GOLD-SILVER DEPOSIT

Epithermal veins systems form in near-surface (<2km) volcanic environments (White and Hedenquist, 1995). These environments are typically extensional or strike-slip during formation, in order for veins to form within dilating faults. Understanding the structural geology will inform the understanding of the vein geometries and continuity of

mineralization associated with dilation zones. The system can consist solely of veins or can include vein stockworks and breccias, and commonly include extensive alteration zones.

The hot fluids, from which the veins precipitate, are derived from a mix of meteoric groundwater and non-meteoric fluids from magmas at depths of around 5 to 10 kilometers below surface, and therefore tend to be spatially associated with porphyry systems (Sillitoe 2010). Alteration tends to be propylitic/chloritic, but can be intermediate argillic/phyllitic/sericitic, depending on the influences that include meteoric fluid interaction. Low sulphidation type epithermal systems interact with rock and meteoric groundwater more extensively, forming more neutralized alteration fluids. High sulphidation epithermal systems contain acidic fluids rapidly channeled from the hot magma, have limited groundwater interaction and dissolve the rock, leaving vuggy silica. Therefore, like porphyry systems, understanding the type of epithermal system will inform the engineer on the type of alteration to expect.

The pattern of the faults and veins creates complexities that need to be understood for the geotechnical analysis. The major ore-bearing veins commonly have sub-parallel orientation to faults and/or veins. Like in porphyry systems, defining the domain patterns of the veins and fractures enables characterization of the rock mass throughout the existing or planned open pit. These vein systems form at the same time as the controlling faults. Therefore, the vein geometries and observed cross-cutting relationships with other veins and faults greatly help define the timing relationships and continuities of the entire geological system.

GEOLOGY

- Geology and lithology aspects: Identify geometries and contact relationships. Breccia pipes can form along veins, typically at areas of structural complexity or vein intersections.
- Alteration type and intensities: Identify the location of the deposit in the potential system (high or low sulphidation) and what types of weakening and strengthening alteration can be expected based on a literature survey and previous experience.
- Alteration review: Review existing exploration core in the higher weakening alteration areas to assess potential alteration impact.

STRUCTURAL GEOLOGY

- Vein geometries: Define the geometries and kinematics of the veins. The vein geometry and shape of dilation zones are controlled by the direction of displacement along the vein during formation, which can often be confirmed by slickenside measurements.
- Structural Patterns: Map the frequency and infill properties of veins, faults, and fractures. Displacements in the veins can be matched to identified fault trends and used to define the timing relationships and continuity of faults and veins. Identify the spatial and orientation association of joints and veins to the faults systems and define domains of similar patterns and frequencies.

GEOTECHNICAL

- Alteration types and intensities: Review the dominant alteration types and assess the interpretation of alteration intensity by reviewing the site established descriptions and the reference atlas of lithology and alteration types. An alteration specialist may be required to determine the predominant alteration types and intensities to be used for the undertaking of 3D alteration modelling. Rock mass degradation over time, as a result of alteration, could also be a factor to be considered.
- Exploration drill holes: Perform a qualitative review of rock mass conditions of all holes in the exploration database using a calibrated system of photos that considers drilling conditions and rock mass impacts. This would be calibrated against geotechnical drill holes in similar rock mass conditions. Focus areas would be finding zones of intense fracturing and weakening alteration.
- Qualitative rock mass block model: Depending on the drillhole spacing and the complexity of the deposit, develop a block model that has well-defined hard and soft domain boundaries. Rigorously test the model with data from geotechnically logged drillholes, litho-structural domains, and alteration intensity domains.
- Testing programs: Establish suitable strength and shear strength testing programs that reflect all the variability within the rock masses and test the impacts of alteration on rock strengths within the same lithology domains.

DEFORMED DEPOSITS IN OROGENIC BELTS

Orogenesis is a prolonged geological process that may subject the rock to multiple phases of compressive strain, tectonic relaxation with extension, and oblique shearing along strike-slip systems. Deformed rock mass can contain complex brittle and ductile structural features that form and deform at different stages of the evolution of the orogenic belt. There are a variety of deposits that form along accretionary continental margins and ultimately are strongly deformed by orogenesis (Groves et al. 2005). Porphyry and epithermal deposits described above are examples. In addition, orogenic gold deposits (Groves et al. 1998, Goldfarb et al. 2005) and volcanic-hosted massive sulphide deposits typically form in or adjacent accretionary margins (Groves et al. 2005). Sedimentary exhalative deposits can also form near tectonic margins and are deformed during accretion (Goodfellow 2007).

Any of these deposits can be so deformed and possibly metamorphosed as to be barely recognizable in comparison to undeformed deposits. To interpolate observed lithological contact or mineralization patterns from areas of observation (mapping and boreholes) into areas lacking data, it is necessary to understand the deformation patterns and the relative timing of different structural features. We find that many clients underestimate the geological complexity of the deformation patterns on their projects. The majority of geotechnical practitioners in the industry are willing to accept these geological assumptions about the rock mass based on inexperienced structural observations, despite the risk to the geotechnical designs created by that lack of knowledge.

Common types of structural geological features that can influence stability in open pits are illustrated in Figure 5. Basement rock often contains different or older deformational features than younger cover rocks and may therefore have a different dominant structural fabric. Fold systems commonly develop an axial planar cleavage, represented as rock foliation (alignment of micaceous minerals) that has a distinct strength anisotropy. Zones of greater strain intensity and higher fold frequency, tend to have more closely spaced or penetrative foliation. Foliation development also varies significantly depending on the rock type.

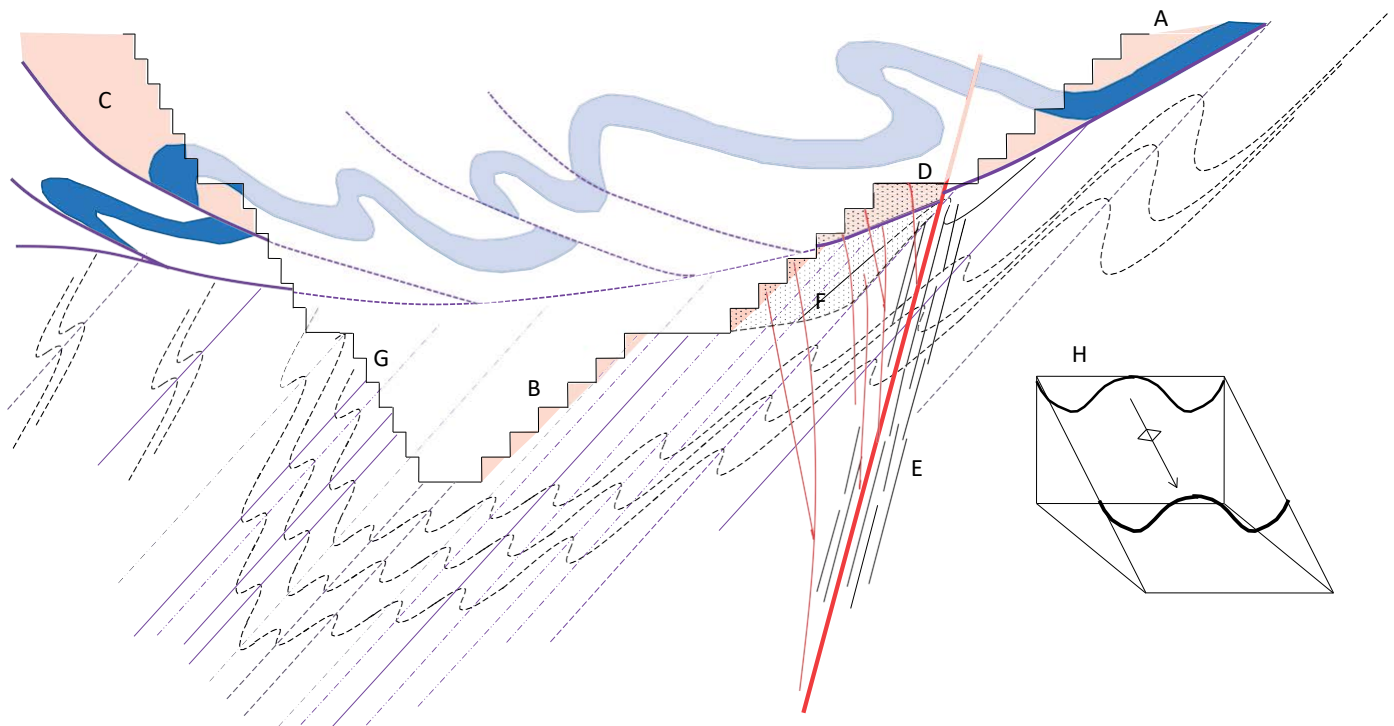


Figure 5: Schematic illustration of typical structural geology influences on open pit stability in orogenically deformed rock mass. Red shading indicates possible sliding or wedge failure. Local rock failure may be influenced by, (A) weak or sheared lithological contact, (B) weak foliation, (C) failure on basal fault surface, (D) failure on basal surface with fault tensile release plane, (E) damage zone around a fault, (F) toppling failure associated with steeply dipping fault system, (G) stable slope with favourable oriented fold folds and rock fabric, (H) 3-D perspective with unfavourable fold plunge.

Foliation strength is difficult to quantify in geotechnical models. The geologist and engineer need to consider the spacing, continuity, mineralogical properties, and orientation when investigating foliation impact on intact rock strength. A range of point-load test results oriented at different angles to the foliation can help quantify strength variations to inform stability analyses. In natural and mining slopes, foliation and geometry of the associated fold crenulations often has significant impact on the manner in which rock breaks and deforms over time (Zorzi et al. 2014, Stead and Wolter 2015).

Any fault segments in the rock represent discontinuities of significant continuity that impact rock mass behavior, at a scale dependent on the continuity of the structure, e.g. bench-scale, stack-scale or overall pit (Sullivan 2013). The geometry, infill textures, and properties of fault surfaces and fault rock influence how much faults contribute to rock mass deformation. Estimates of the fault surface clay content and fault rock brecciation can guide engineers in quantifying the frictional and cohesive properties of the fault zones as input into stability models (Wyllie and Mah 2004). Fault systems that dip out of slopes need careful investigation, as they may directly control slope failure (Stead and Wolter 2015, Figure 5). The contact zones between different rock units or packages should not be ignored, as they may be weak zones, and possibly activated by fault systems.

GEOLOGY

- Geology and lithology aspects: Identify geometries and contact relationships. Deformed deposits and host rocks can have complex contact relationships and may require more than typical drilling meterage to adequately define.
- Alteration type and intensities: Identify the location of the deposit in the potential system and what types of weakening and strengthening alteration can be expected based on a literature survey and previous experience.
- Core review: Review existing exploration core to determine the range of rock types. There are likely to be a variety of metasediments and schists that have reduced or strongly anisotropic rock strength properties. How well is the spatial distribution of these rocks understood?

STRUCTURAL GEOLOGY

- Ductile deformational fabrics: Determine the dominant, most penetrative foliation. Define the later cross-cutting foliations if present. Establish the spatial distribution in orientation of the foliation sets, particularly the penetrative foliation. What is the deformation geometry or folding pattern, and relative timing of the different deformation phases? Are the fold plunges or limb geometries unfavourable to bench stability? Interpolate the orientation of the foliation into unmapped areas. Is the orientation of foliation such that it can impact bench or stack stability (Figure 5B), or blasting damage and bench break-back angles?
- Define the deformation of the lithological contacts in terms of shear zone strain and/or folding geometries. Are deformed or sheared lithological contacts unfavourably oriented for stability (Figure 5A and D)?
- Brittle faulting: Determine the orientation and relative timing of all cross-cutting fault systems. Consider not only the primary structures, but also the orientation and frequency of second-order faults. The pattern defined by the faults should make sense in the context of the deformation history and the expected kinematics of the fault systems. Are fault geometries unfavourably oriented for stability by forming a basal sliding surface (Figure 5C) for planar or wedge failures, tensile release plane in a Prandtl wedge (Stead and Wolter 2015, Figure 5D), or for a system of steeply dipping faults that can contribute to stack-scale toppling failure (Figure 5F)?
- Joint sets: Review the spatial distribution of all joint sets in terms of their orientation and frequency relative to the fault and fold patterns. Define structural domains that describe and explain the joint patterns relative to the brittle fault and fold patterns. It is common for fault zones to contain damage zones of increased fracturing around the fault core (Figure 5E). These damage zone widths and fracture frequencies vary for each fault and should be mapped or logged.

GEOTECHNICAL

- Alteration types and intensities: Review the dominant alteration and rock types and the predicted (3D modelled) spatial distribution within the geotechnical design area. Which rock or alteration types are in key geotechnical design areas?
- Rock mass fabric/anisotropy: Use the structural understanding of the dominant foliation or fracture set to define or 3D model the expected rock mass fabric (anisotropy).

- Exploration Drill holes: Perform a qualitative review of rock mass conditions of all holes in the exploration database using a calibrated system of photos that considers drilling conditions and rock mass impacts. This would be calibrated against geotechnical drill holes in similar rock mass conditions.
- Testing programs: Establish suitable strength and shear strength testing program that reflects all the variability and anisotropy within the rock masses of the each of the rock or alteration types.
- Brittle faulting: Define the brittle fault network system in 3D and identify geometries that can be hazardous for slope stability.
- Structural domains: Use the structural domains as input into the finalization of geotechnical domains for further design.

5. CONCLUSION

An approach has been introduced which emphasises the need to identify critical aspects for consideration when defining geotechnical data acquisition and evaluation programs for slope design during prefeasibility, by means of multi-disciplinary workshops and discussions. These aspects include characterising parameters related to geology, structural geology, and rock mass. The approach is expected to help avoid unexpected problems during the later stages of study, and contribute to optimized evaluations and avoidance of project cost overruns.

Worked examples of three deposit types were presented: porphyry rock masses, intermediate-sulphidation epithermal gold–silver deposits, and strongly deformed deposits in orogenic terranes. For these deposit types, a series of deposit-specific approaches were developed based on our experiences that highlight the more important geological-related geotechnical aspects and associated characteristics that are expected to impact slope performance.

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