. . . .

CHAPTER 2

Collecting and Using Geologic Structure Data for Slope Design

David E. Nicholas* and Danny B. Sims*

2.1 INTRODUCTION

It is often said that the three most important factors in evaluating residential and commercial real estate are location, location, and location. Similarly, the three most important factors in the evaluation of open-pit slope stability are structure, structure, and structure. The adverse interaction of geologic structures with the mine walls is the greatest contributing factor to slope instability in open-pit mines, and the success of slope-stability analysis depends upon the level of understanding of the characteristics of geologic structure throughout the deposit.

In order to maintain clarity throughout this chapter, we will first define the terminology used to describe geologic structure. For data collection purposes, the geologic structures are divided into fractures and major structures. Fractures are those geologic structures that are too small and usually too numerous to be mapped and located individually. The major structures are those geologic structures that are long enough to be individually located on a geologic map. There is a continuum between fractures and major structures, and the differentiation between the two is based on a lower-truncation limit for the length of major structures. The minimum length for a major structure is usually equal to the height of one design bench.

For purposes of structure analysis, the geologic structures are divided into rock fabric, intermediate structures, and regional structures. The rock fabric may include both fractures and major structures. The intermediate and regional structures only include the major structures.

The geologic structure terminology used in this chapter is as follows:

- *Geologic structures,* which comprise all fractures and major structures, regardless of their length.
- *Fractures and/or joints,* which are geologic structures that break the intact rock into more or less discrete blocks. They usually comprise the rock fabric and sometimes the intermediate structures. The fractures and joints are too numerous and too short to be mapped individually throughout a deposit.
- *Major structures,* which are geologic structures, such as faults, that are large enough to be mapped and located as individual structures. There is actually a continuum between fractures and major structures, but the differentiation is useful for design purposes. The lower-length truncation limit can vary, but generally it is equal to the height of a single design bench.
- *Rock fabric,* which is defined as geologic structures that are too numerous to be evaluated individually. They are therefore treated statistically in a slope-design analysis. The rock fabric may include both fractures and major structures.
- *Intermediate structures,* which are geologic structures that are too numerous to be evaluated individually. They are treated statistically in a slope-design analysis. The intermediate structures only include major structures that are longer than a given, lower-length truncation limit. The lower-length truncation limit can vary, but it generally is equal to or greater than the height of two design benches.
- *Regional structures,* which are major structures that are of a regional scale. These structures generally have a minimum length of 100 m; when these structures are faults, they are usually assigned unique names on geologic maps.
- *Structural domains,* which are zones in which the distributions of orientation, length, spacing, and shear strength are similar.

The geologic structure attributes that are most critical include orientation, length, spacing, overlaps, and shear strength. Structure length and overlap must be measured from surface exposures. It is best to measure structure orientation and spacing from surface exposures as well, but these data may also be obtained from oriented core. Shear-strength data can be obtained equally well from either surface or core samples.

Although it is best to measure most of the critical geologic structure attributes from surface exposures, there is usually a limited surface area that is exposed and accessible for surface structure data collection. It is therefore necessary to extrapolate the available data and develop an accurate structure model as a basis for the slope-stability analysis.

The rock fabric, intermediate structures, and regional structures are defined to match the pit-slope design. A pit slope has three major components: bench configuration, interramp slope, and overall slope. The bench configuration is defined by bench height, catch bench width, and bench face angle. The interramp slope is formed by a series of uninterrupted benches, and the overall slope is formed by a series of interramp slopes separated by haul roads (Figure 2.1).

The bench height is determined by the size of the mining equipment. The required bench width is based on either expected failure volumes or on relationships developed by Ritchie (1963) and the State of Washington. The bench face angle is determined by the geologic structure, given that there are good blasting and digging practices. The structures controlling the bench face angle are usually the rock fabric because of their high frequency of occurrence, but the bench face angle can also be controlled by the intermediate and regional structures.

Interramp, multiple-bench, slope-stability analysis concerns only those failures that incorporate two or more benches. Structures that affect the interramp stability must therefore be equal to

---

* Call & Nicholas, Inc., Tucson, Arizona.

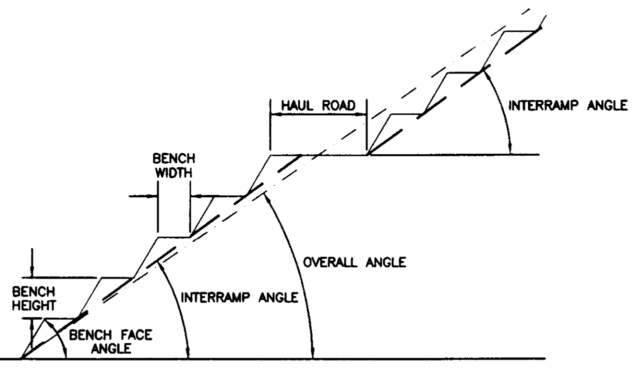


FIGURE 2.1 Typical open-pit design cross section

or greater in length than the height of two design benches. The structures that have a minimum cutoff length equal to the height of two design benches are, by definition, the intermediate structures. The intermediate structures are analyzed statistically to determine the probability of structurally controlled multiple bench failures that affect the interramp slope stability.

For both the bench face angle and the interramp slope analysis, the distribution of the geologic structure characteristics is required for statistical analysis. Collecting the data and interpreting these distributions are a challenge for the geologist and geotechnical engineer.

Overall slope stability concerns only those failures that incorporate most of, if not all, the height of the pit slope. The overall analysis can incorporate all of the geologic structure database. The regional structures are projected to future pit designs, and the interaction of the designed pit walls with each unique regional structure is analyzed. The rock fabric data and intermediate structure data are used to characterize the rock mass to determine whether there is a potential for rock-mass failure, either solely through rock fabric, intermediate structures, and intact rock or in combination with a regional structure.

The greatest challenge in overall stability analysis is probably in determining the rock-mass strength for a pit highwall. An overall weak rock mass can fail through areas that do not contain regional structures. Also, a non-daylighted regional structure may require a rock-mass buttress between the fault and the pit. In this case, the rock-mass strength must be known to determine the required buttress width. The rock-mass failures generally occur through rock-fabric-scale structures, intermediate structures, and intact rock. The rock fabric and intermediate structures that provide the weakest failure path in the rock mass generally occur in regular orientations within a structure domain; therefore, the rock-mass strength is directional dependent.

2.2 MAJOR STRUCTURES

The interramp and overall slope analysis mainly utilizes the intermediate and regional structures, both of which are part of the major-structure database. Major-structure data have a more significant impact on the slope design than that of the rock fabric, and the major-structure data are therefore the most important geologic structure data. The major-structure data are also the most difficult to collect and interpret.

2.2.1 Regional Structures

Regional structures are greater than 100 m in length, but major structures can only be mapped one bench at a time. Accurate survey, mapping, and interpretation methods are essential to determine bench-to-bench continuity and true structure length. (Mapping techniques are discussed in more detail later in this chapter.) Another problem in mapping regional structures is that it is difficult to determine the continuity of flat major structures, dipping 30° to 60°; yet these structures are the most critical to slope design. Therefore, it is important for the geologist to look for these flatter structures and, if uncertain, put them on the map and let the geotechnical engineer justify the drilling to determine the structural continuity. The regional structures have to be correctly projected on to each future pit plan, and, if possible, a structure contour has to be developed of that regional structure for future planning.

The shear strength of the structure should be determined from direct-shear test of the material that defines the fault zone. Fault zones are variable; the strength that usually controls the behavior of the fault is the strength of the material that is the weakest and comprises at least 20% of the fault zone.

2.2.2 Intermediate Structures

The intermediate and regional structure data are collected by the same major structure-mapping technique. Those structure types are differentiated in the interpretation of the data. The intermediate structures are those that have interpreted lengths that are greater than the height of two design benches and are less than 100 m.

Intermediate structures are mapped individually as major structures; however, in the stability analysis, they may be used as either unique structures or as part of a database for statistical analysis. The characteristics required are orientation, spacing, length, and shear strength. Similar to the collection of regional structure data, it is important that the geology staff follow rigorous surveying, mapping, and interpretation methods to ensure that structure lengths are properly represented on maps and in the database.

2.2.3 Mapping Techniques

Several methods are commonly used to map major structure in open pits: (1) face method, (2) mid-bench method, and (3) Anaconda (touch point) method. Call & Nicholas, Inc. (CNI) recommend the face method. The relative advantages and disadvantages of each method are presented in the following discussion.

The discussion of each method is aided by a hypothetical, plan-view geologic map, which would be produced with each different method for the same geology. An oblique view of a hypothetical pit wall is presented in Figure 2.2.

Two rock types are present, and they are cut by faults and single joints. The 3,715-level bench face has a wedge failure, and the 3,710-level bench face has a plane shear on the lithologic contact. Survey marks are represented on each bench.

A plan-view base map for the oblique view map is presented in Figure 2.3. It is important that a toe-crest base map be used regardless of the mapping method. A toe-crest map accurately represents areas that are horizontal benches and areas where the topography is sloping.

Face Method. The face method (Peters 1978) differs from the Anaconda and mid-bench methods in that the face method does not utilize a horizontal datum plane. The face method is a surface trace method that is similar to common techniques used for most surface mapping.

The face method is conducted by first surveying the bench area to be mapped. Survey marks are made in bright paint on the middle of the bench at 5- to 10-m intervals. If mapping an existing highwall, the mapping should begin at the lowest level and progress upward. Following this method, the survey marks on the bench below can be easily used to locate where structures reached the crest on the bench below, even though these structures cannot be seen by looking over the crest from above. The ability to know exactly where a structure reaches the crest is important because the mapper can stand at that crest point and look in the direction of strike across the horizontal bench to see whether the structure continues to the next level.

The survey data are recorded on the same opaque paper on which the toe and crest map is plotted. A gridded Mylar sheet is overlain for collection of the structure data. The mapper

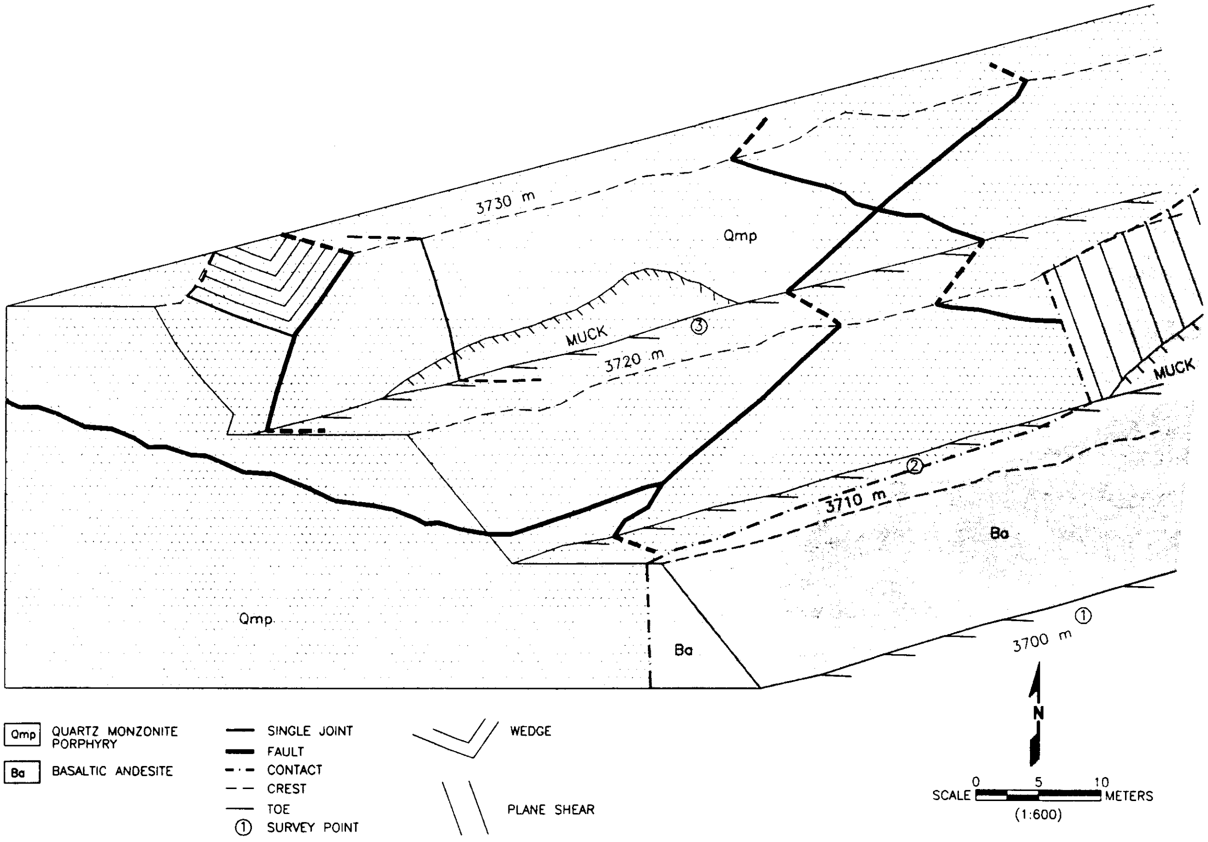


FIGURE 2.2 Oblique view pit geology

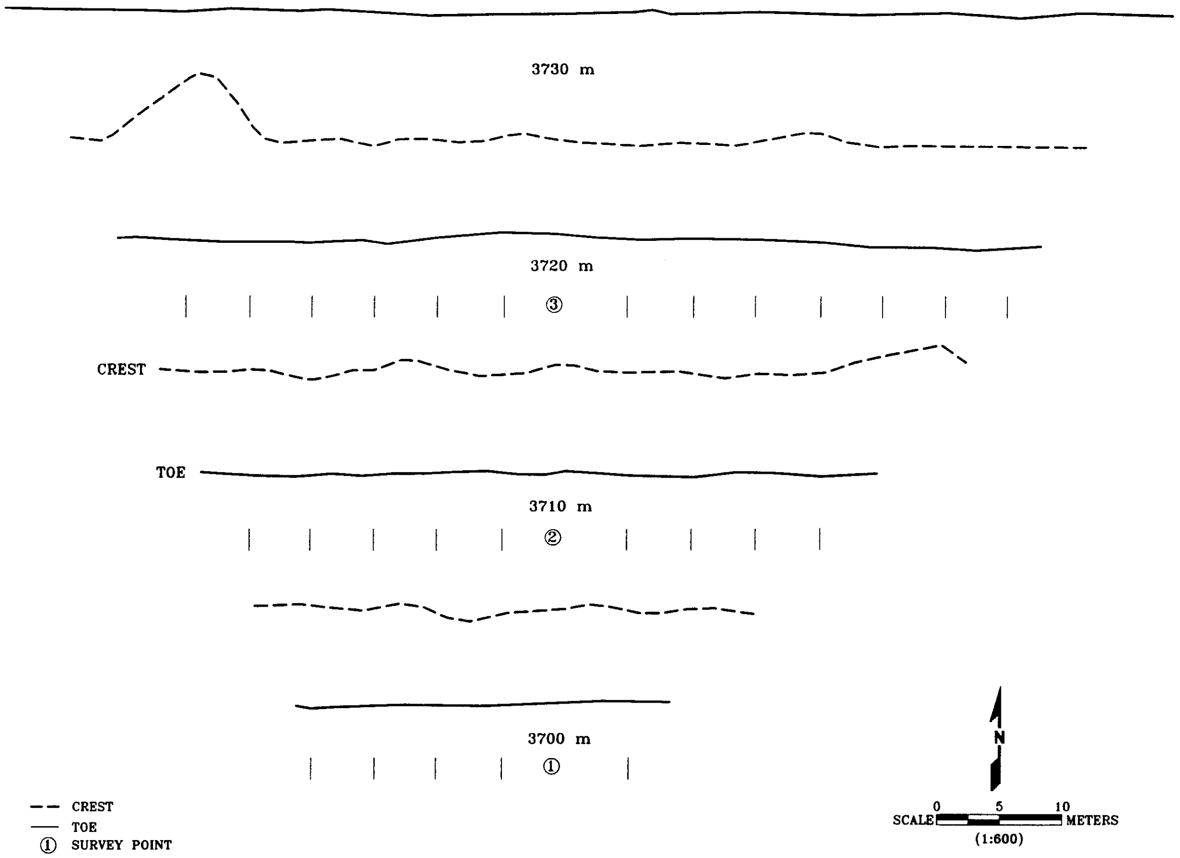


FIGURE 2.3 Plan view toe-crest pit topography map

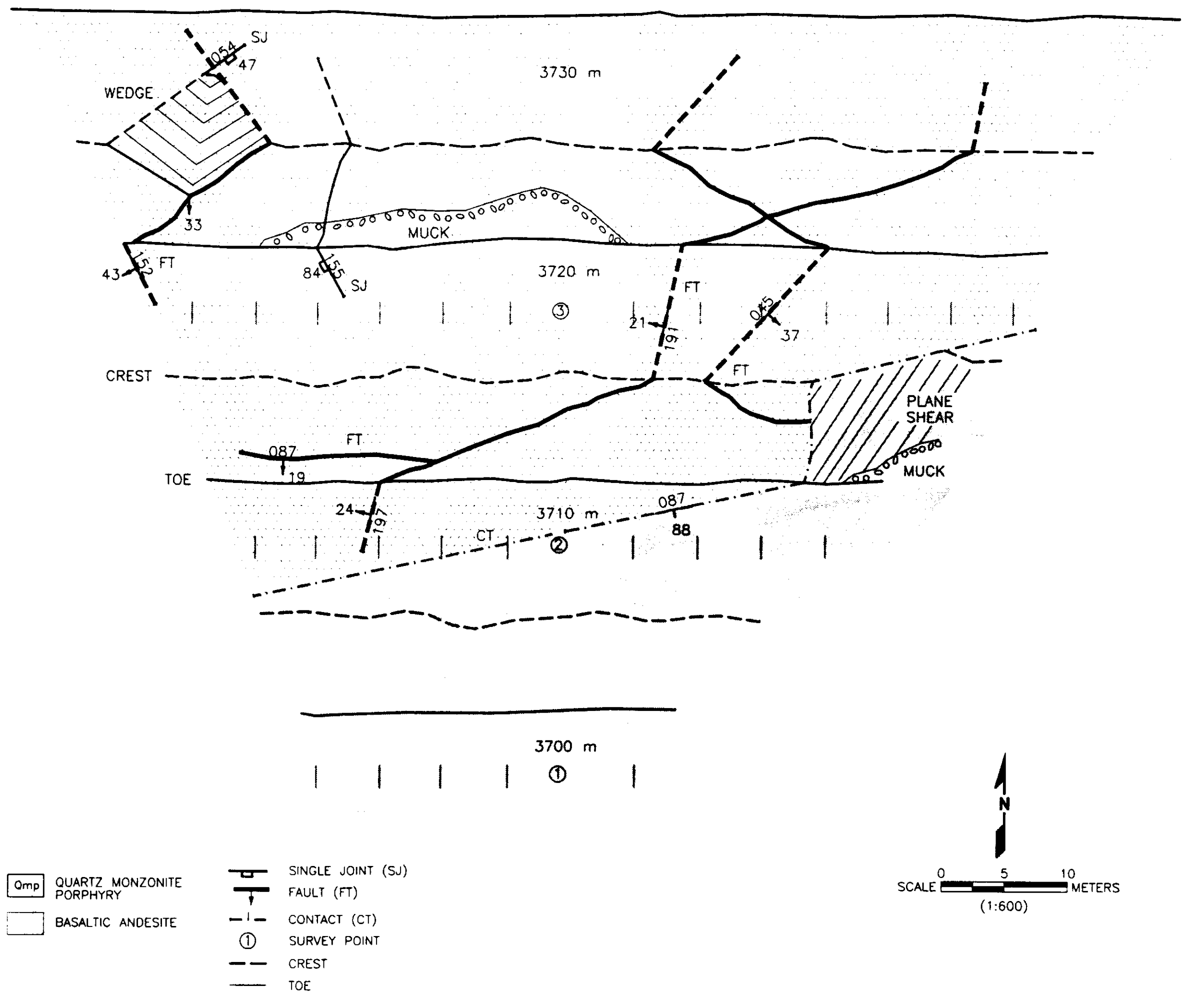


FIGURE 2.4 Face method structure map for geology shown on Figure 2.2

traverses the bench and identifies those structures that are continuous for a length equal to or greater than a single bench height. The structure is traced on the map exactly as it appears on the face. The exact locations of the crest or toe intersections are critical for determining bench-to-bench continuity. The strike and dip of the structure are measured with a compass, and the structure is dashed on the bench above and below in the strike direction. The dip is plotted with conventional dip-direction symbols for different structure types. The structure type, strike, and dip are noted next to the structure for ease in building a structure database from the map. Important features, such as plane shears, wedges, muck piles, tension cracks, and water seeps, should also be drawn onto the structure map.

The structure data should be posted to a master map at the end of each day. The new data should be interpreted in the context of previous data so that structure continuity and potential structure domain boundaries can be detected. This also gives the mapper direction when mapping future bench faces as mine development progresses.

A face-type major-structure map (Figure 2.4) was generated for the geology shown on Figure 2.2. All structures can be represented on the map because there is no horizontal datum plane to which the structures are projected. The relationship of structure to physical condition of the face can be clearly demonstrated.

Advantages to the face method include the following:

- Structures are plotted as surface traces at their actual locations, and actual structure lengths are drawn directly on the map.
- It is possible to accurately represent the relationship of structure to physical conditions of pit walls.
- Notation of the exact location of structure intersections with the toe and crest makes it possible to accurately determine bench-to-bench continuity of structures. This is especially true for the low-angle structures.

Mid-Bench Method. The mid-bench method uses a horizontal datum plane located at the mid-bench elevation of the face. A mid-bench major-structure map (Figure 2.5) was generated for the geology shown on Figure 2.2. Structures are only represented by a strike-and-dip symbol at the point where the structure crosses the mid elevation of the face. One potentially important low-angle major structure does not cross the mid elevation of the face and therefore is not represented on the map.

The advantage of the mid-bench method over the Anaconda method is that structures are less likely to be covered by muck at the mid-bench elevation than they are at waist height. Overall disadvantages to using this method include the following:

- Difficulties arise in plotting structures that do not cross the mid-bench elevation datum plane in the face.
- It is difficult to accurately represent the relationship of structures to the physical conditions of pit walls.

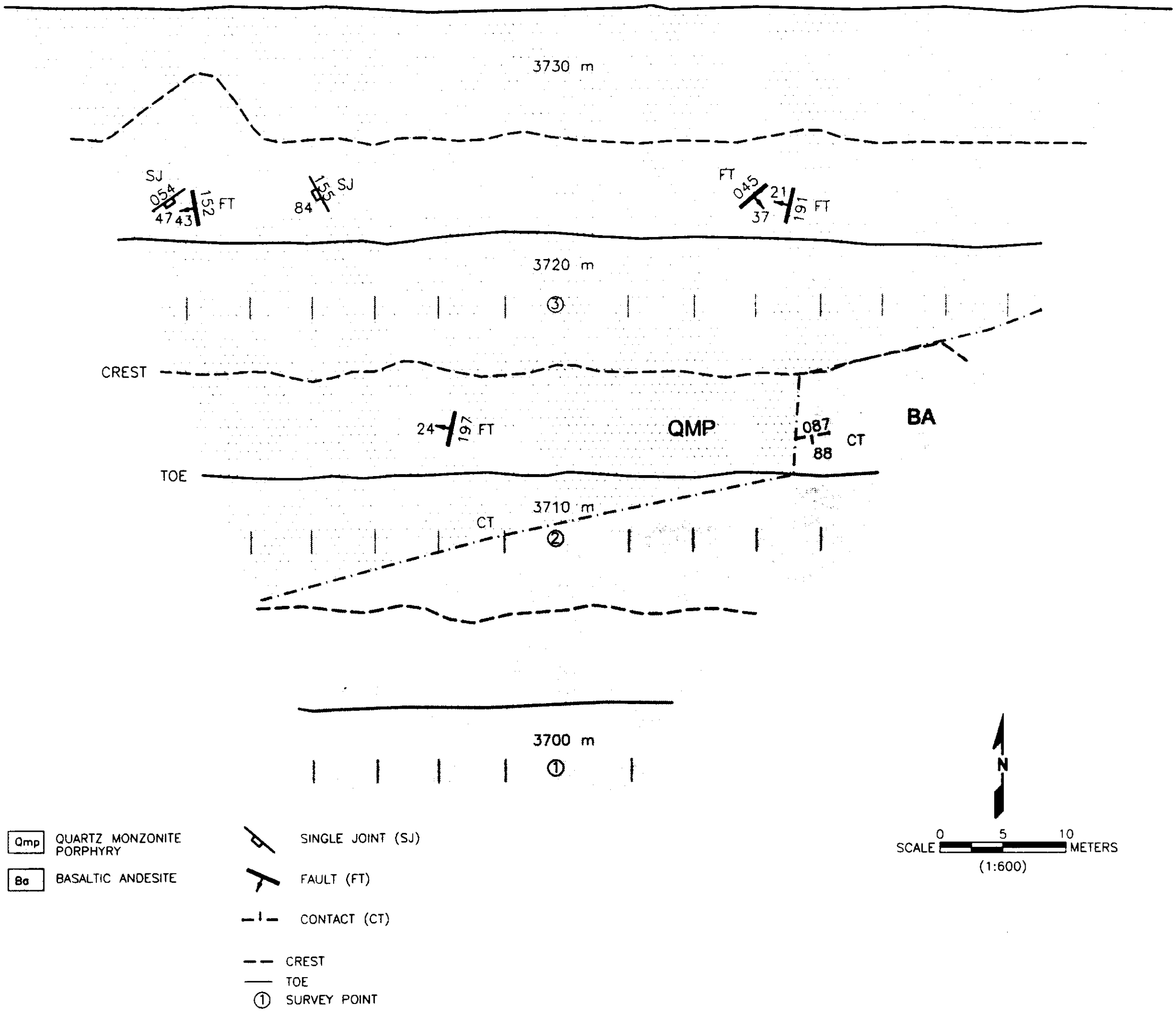


FIGURE 2.5 Mid-bench structure maps for geology shown on Figure 2.2

- It is difficult to determine bench-to-bench continuity of structures because the intersection of a structure with the toe and crest is not specifically noted. This is especially true for the highly important low-angle major structures.

Anaconda Method. The Anaconda method was developed for underground mapping, and it is probably the best method for that situation. The method is essentially the same as the mid-bench method, except the Anaconda method uses a waist-high or shoulder-high datum line to which all structures are projected. It is therefore primarily a method for producing level maps.

In an open pit, a measuring tape is laid out on the flat bench for survey reference. Structures are plotted at the face where they intersect the datum line. A strike-and-dip symbol is placed on the map at the intersection of the structure projection with the tape. The greatest operational difficulty with this method is that the waist-high or shoulder-high datum is often covered with muck.

An Anaconda-type major-structure map (Figure 2.6) was generated for the geology shown in Figure 2.2. Notice that structures are only represented by a strike-and-dip symbol at the point where the strike of the structure crosses the survey line on the bench face. Structure surface traces are not shown because the map is a two-dimensional level map. Two structures do not cross the survey line, and they cannot be displayed on the map. In an underground mapping situation, these structures would be projected to the intersection of the structure plane with the horizontal datum plane. However, on an open-pit topography map, this line of intersection would either be behind the current pit wall or in open air.

The following are disadvantages to using this method in an open pit:

- Low-angle structures that are striking parallel to the face will be projected either into air within the pit or into rock far behind the exposed face that is being mapped.
- It is difficult to represent the relationship of structure to physical conditions of pit walls. For example, the relationship of individual structures to wedge and plane-shear failures is not easily represented.
- It is difficult to determine bench-to-bench continuity of structures.

2.2.4 Major-Structure Data Management

Major-structure data should be compiled graphically on current pit maps and on level maps. Regional structures should also be graphically projected to future pit designs and cross sections. An example of a current pit, face method, major-structure map for a limestone mine in North America is presented as Figure 2.7.

Level maps should be constructed for structure data interpretation. Level maps can be constructed from face method maps at any elevation, including the toe elevation, crest elevation, or at the mid-bench elevation, because the actual surface traces are mapped over topography with this method. The toe elevation is

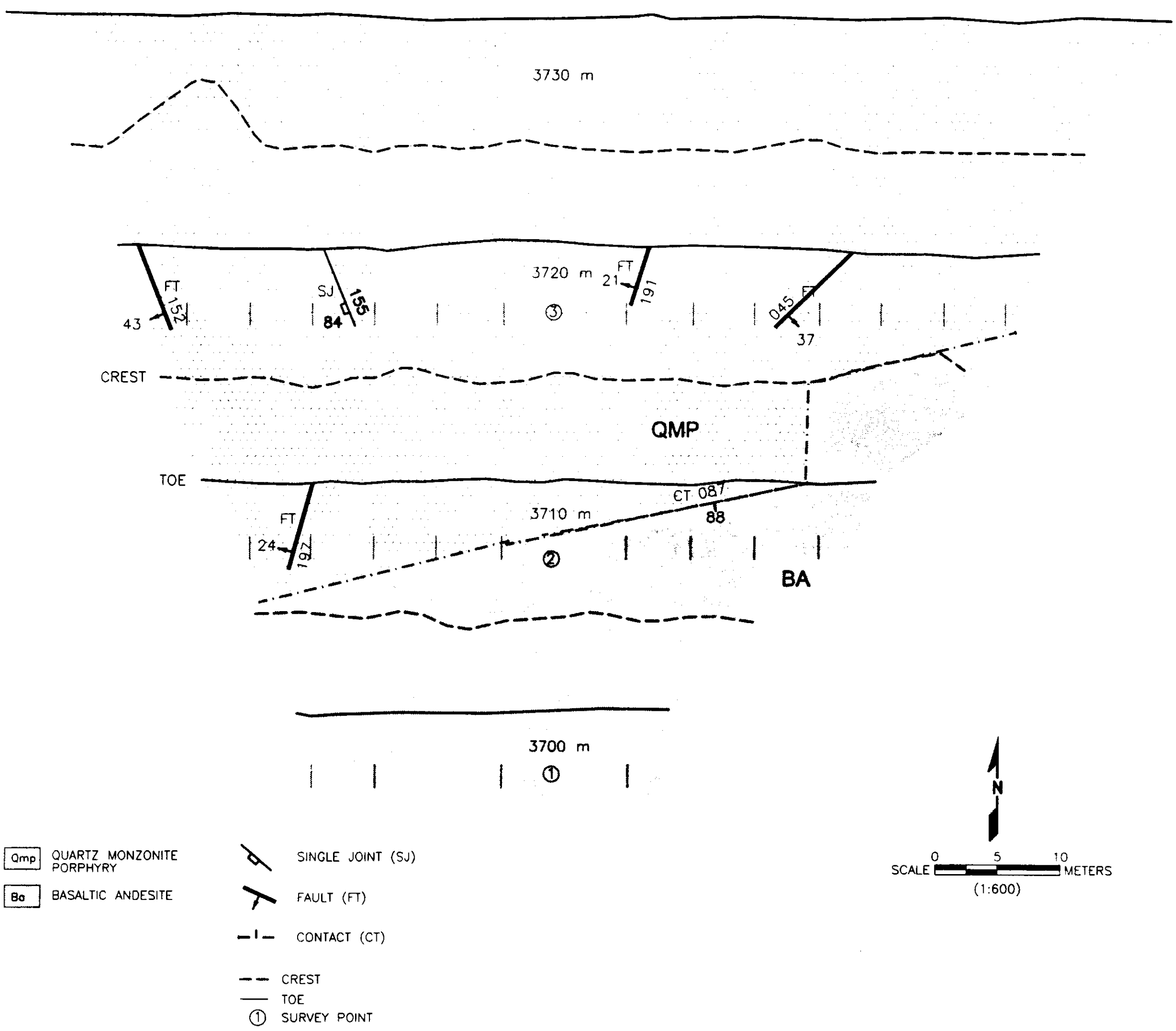


FIGURE 2.6 Anaconda method structure map for geology shown on Figure 2.2

most commonly used for level maps that are constructed from face maps.

Major-structure data should also be entered into a database for stability analysis. The data for each structure should include an ID number, northing, easting, elevation of the structure midpoint, rock type, structure type, dip direction, dip, length, thickness, and filling materials. Other data may be pertinent at different properties. With a spreadsheet, it is possible to sort structures by any variable for analytical purposes.

Any mine employee can identify a major slope failure after it has occurred. It is the job of the geologist and the geotechnical engineer to anticipate and avoid potential problems. To accomplish this, regional structures and rock types should be projected to future pit plans so that potential failure geometries can be recognized. Plan maps and cross sections should be produced for all annual pit plans through the final design. If the potential failure geometries are recognized early, the mine design might be altered to either avoid or control interramp and overall failures.

2.3 FRACTURES

The rock fabric is used in the bench design and in the determination of the rock-mass strengths. Fractures are too numerous to be analyzed as unique geologic structures, and the fracture data are generally analyzed by statistical methods. The fracture data are collected by mapping methods that provide the appropriate input parameters. Most of the fractures that are measured usually have lengths that are less than the bench height, and the minimum cutoff length is usually 0.3 to 1 m. Fracture spacing is usually less than 5 m.

2.3.1 Mapping Techniques

The fracture data are most commonly collected by using the fracture-set mapping method, scan-line method, cell-mapping method, and oriented-core method.

The various fracture data collection methods were summarized by Call (1992) as follows:

- *Fracture-Set Mapping.* Fracture sets are visually identified during the course of regular geologic mapping, and the fracture set orientation, length, and spacing are recorded.
- *Scan-Line Mapping* (also commonly called Detail-Line). The scan-line method is a systematic spot sampling method in which a measuring tape is stretched along the bench face or outcrop to be measured. For all the fractures along the tape, the point of intersection with the tape, orientation, length, roughness, filling type, and thickness are recorded.
- *Cell Mapping.* The bench face or outcrop is divided into cells. Normally, the width of the cell is equal to one to two times the height of the cell. Within each cell, the fracture sets are visually identified, and the orientation, length, and spacing characteristics are recorded along a line that is oriented in any direction.

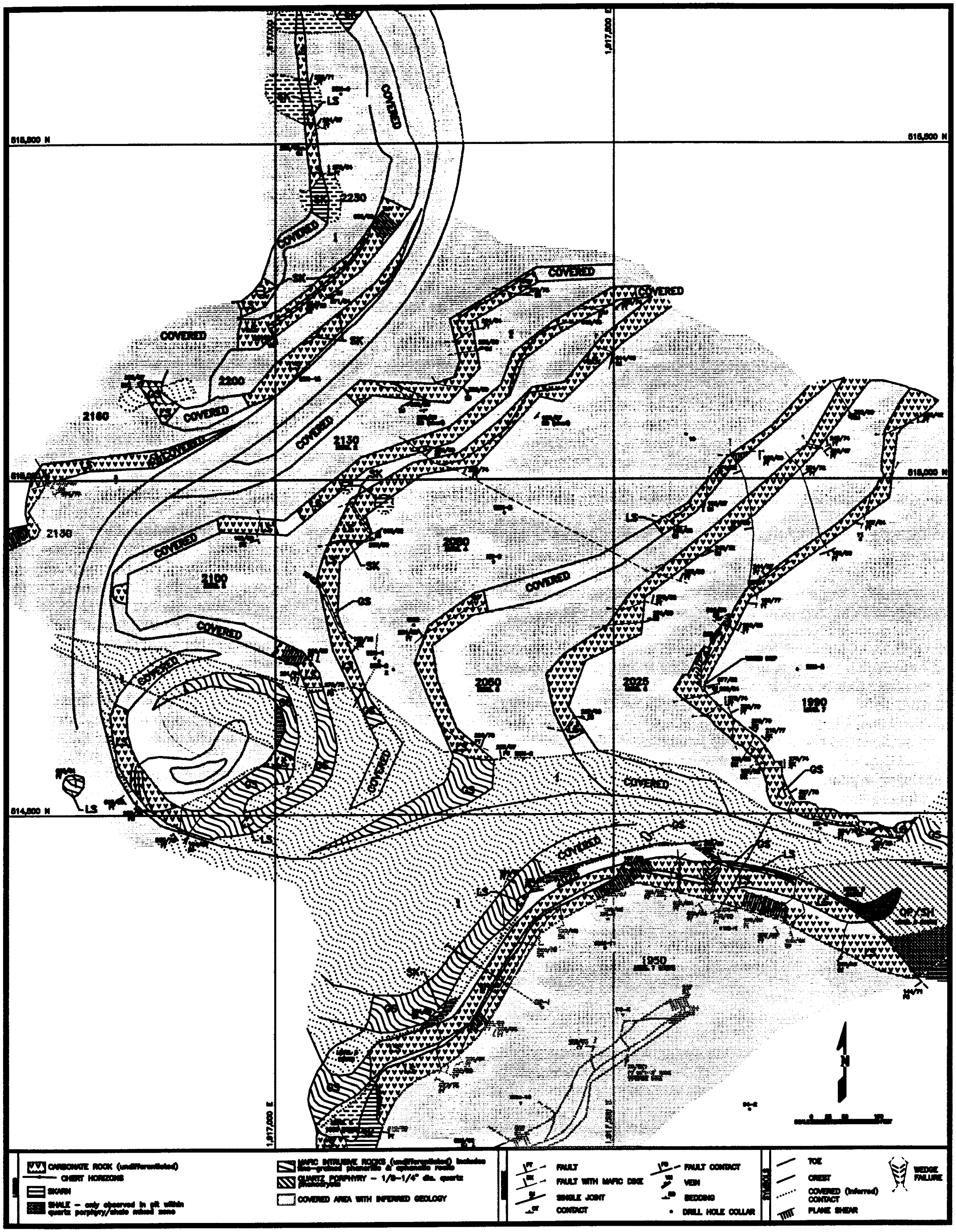


FIGURE 2.7 Face method major structure map for a current pit topography

- *Oriented Core.* Oriented core provides fracture orientation and spacing data, but length data cannot be determined with this technique. The oriented core is similar to the scan-line mapping method. Oriented coring is used when the rock types of interest are not exposed. It is also used to determine whether the geologic structural domains, which were mapped on the surface, extend back behind the pit walls.

The fracture-set mapping method is a general mapping method, and to the authors' knowledge, has not been described in detail in the literature. The scan-line method has been described in detail by numerous authors (Call, Savely, and Nicholas 1976; LaPointe and Hudson 1985; Warburton 1980). The reader is referred to these and other papers for further discussion of the scan-line mapping method. While the cell-mapping method has been summarized in previous literature (Call, Savely, and Nicholas 1976; Call 1992), it has never been described in detail. A detailed explanation for the cell-mapping method is presented in Appendix A. There are a number of oriented-core techniques, including Clay imprint (Call, Savely, and Pakalins 1982), Craelius (Rostrom 1961), and the Scribe method.

All three of the surface mapping methods will provide the basic data on orientation, spacing, and length. Cell mapping and fracture-set mapping are preferred because more data can be collected over a larger area to better define (1) the limits of structural domains and (2) the variability of the joint characteristics with the structural domain. The choice of the technique depends on type and amount of staffing available. The scan-line method requires little to no judgment in the data collection; cell mapping and fracture-set mapping require geologic judgments to be made. The scan line represents detailed information at one location equivalent to one or two cells. It would take three to seven times longer to map enough scan lines to cover the same area using the cell or fracture-set methods. The normal scan line is horizontal and has the inherent problem of mapping those joint sets that do not intersect that horizontal line, such as flat-dipping joint sets or sets that strike parallel to the wall orientation. The only way to map those sets is to map a vertical scan line or a face perpendicular to the wall. Fracture-set and cell mapping permit mapping all sets in all directions. The scan-line method can be used when confirming the distribution of the structures and also when individuals collecting the data lack geologic training.

Oriented coring is used either to collect data where surface data are limited or to determine whether the structural domains mapped at the surface extend behind the pit walls. Oriented core does not provide length data. Additionally, the oriented data is more scattered than is the surface mapping data because the oriented core represents only 7- to 15-cm^3 of the fracture plane. Consequently, it does not represent an average orientation. Also, the oriented core has a definite blind zone, which must be considered when analyzing the data.

2.3.2 Fracture-Data Processing

Fracture data are very amenable to computer processing. The process is to (1) develop Schmidt plots to define zones of similar structure orientations and structure domains (which are discussed in the next section) and then (2) define the distributions of the geologic or design sets. Design sets are those structures that define a certain potential failure mechanism, whereas a geologic set is defined because of a geologic condition. In general, a geologic set has less dispersion in its orientation. For slope analysis, we generally use the design set, except when the geologic set is defined by bedding or foliation that have length or spacing characteristics significantly different than those of the other joints mapped (Figure 2.8).

For each of the design sets, the defined distributions are the dip direction, dip, minimum dip, spacing, length, and overlap. In general, the dip direction and dip have a normal distribution, where the mean and standard deviation describe the distribution. The length and spacing generally are a Weibull function of which the negative exponential is a unique form.

Weibull Equation.

$$Y = 100 \times e^{-aXb} \qquad \textbf{EQ. 2.1}$$

Where:

Y = probability that X is greater than or equal to X
X = characteristic being defined, such as spacing or length
b = constant
a = constant; if $b = 1$, then $a = 1/(\text{mean of the characteristic})$

Figure 2.9 shows the impact of using a negative exponential versus the Weibull for fault data from a porphyry copper deposit. The length distribution is a minimum length distribution because we cannot always measure the total length of the structure. Also, we do not always measure the extreme short lengths because of difficulty in observation; statistical techniques are applied to truncated distributions to provide an estimate of the "true" distribution. There are also statistical techniques for extrapolating measured lengths given the available window size, but the extrapolation becomes unrealistic when the measured length of the structure approaches the size of the mapping window.

Overlap cannot be measured using the cell-mapping and fracture-set methods. When using the detail-line or scan-line methods, the amount of structure above or below the line can be measured. In our experience, the overlap is uniformly distributed for many fracture sets. This distribution is not applicable in bedded or foliated deposits where many of the fractures are terminated against the bedding or foliation. It is important not to focus on which distribution is most common but rather to focus on using the best distribution that fits either the data or the observations. In the probabilistic analysis, the resulting answer is dependent on the distribution used.

Shear strengths from fractures are determined from direct-shear test of natural fractures or fault gouge material. It is important to measure the range of shear strengths so that the distribution of strengths can be defined. For each structural domain, we measure at least three samples; six samples per rock type are preferred. If one joint set is more pervasive than another joint set, the shear strength of this set should be measured as an individual group.

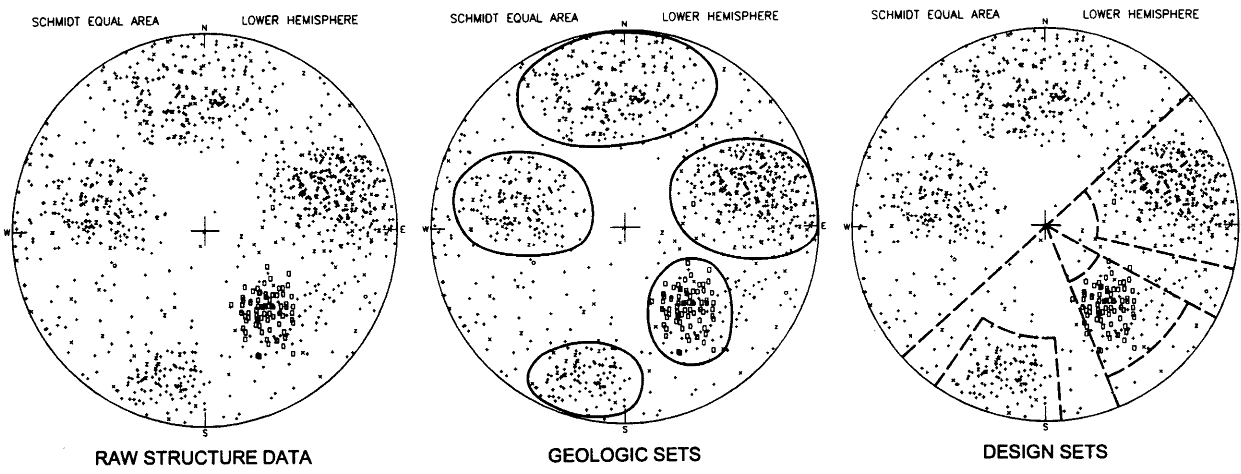
2.4 STRUCTURE DOMAINS

The structure model comprises any number of individual structure domains. Each structure domain contains geologic structure characteristics that are different from the geologic structure characteristics within neighboring domains. Boundaries that often define structure domains are engineering rock-type contacts and major structures, such as regional faults and fold axes.

The first level of structure-domain division is to separate the deposit into regions with different engineering rock types based on rock shear strength and fracture shear-strength properties. Rocks with similar strength values, regardless of petrogenesis, are considered to be unique engineering rock types, and the engineering rock-type boundaries act as the primary structure domain boundaries. Usually, the rock strength is related to the primary lithology or to secondary alteration; therefore, engineering rock types can be directly related to either lithology or alteration.

The second level of division for structure domains is regional structures. Fracture and intermediate structure orientations may vary significantly on either side of a regional fault. Fold axes are almost always structure domain boundaries because they define a boundary between areas where bedding and bedding-related fractures change in orientation.

Geologic structure orientation, length, and spacing may either be consistent across engineering rock-type boundaries and



Call & Nicholas, Inc.	PLOT LEGEND		
FILES USED: Sediments Date: Jul 24 1997	NUMBER OF POINTS: 2199 LEVEL ROCK TYPE CELLS STR. TYPE all all all all	SET DATA: + = JOINT SET = = BEDDING SET O = BEDDING JOINT SET X = FAULT SET	INDIVIDUAL STRUCTURES: z = SINGLE JOINT o = BEDDING JOINT x = FAULT % = BEDDING FAULT * = FAULT CONTACT @ = BROKEN ZONE

FIGURE 2.8 Geologic sets versus design sets

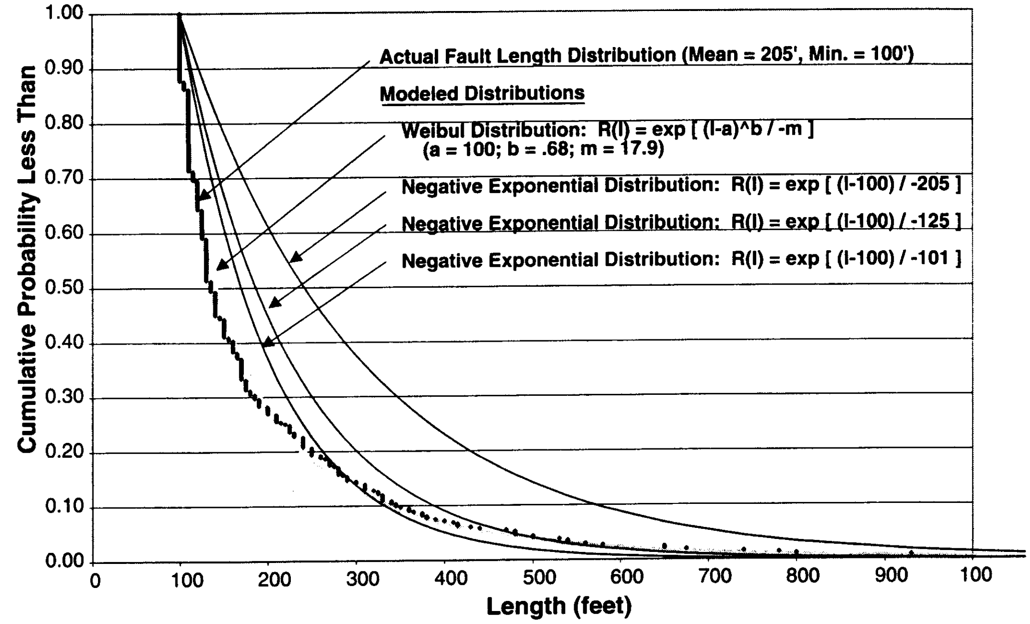


FIGURE 2.9 Structure length distributions

regional structures or they may vary between the engineering rock types and regional structures. The structure orientations are usually the best indicators of the similarities or differences among structure characteristics. Structure orientations are the easiest and most reliable structure characteristic to measure, because structure orientations can be measured at the surface from mapping and at depth from oriented core. Orientation analysis is relatively simple because variations in orientation can be easily detected on stereonets. Once the basic structure domains have been interpreted, they should be subdivided into regions both by elevation and plan. If the Schmidt plots are similar, one structure domain exists; if they are not similar, subdividing may be required. The engineer or geologist has to determine which feature is causing the need to subdivide the structure domain.

2.5 ENGINEERING ROCK TYPES

Engineering rock types are defined by intact rock and fracture shear strength; these are both critical characteristics that are used in a structural analysis. Geologic rock types with similar strength parameters are grouped into engineering rock types.

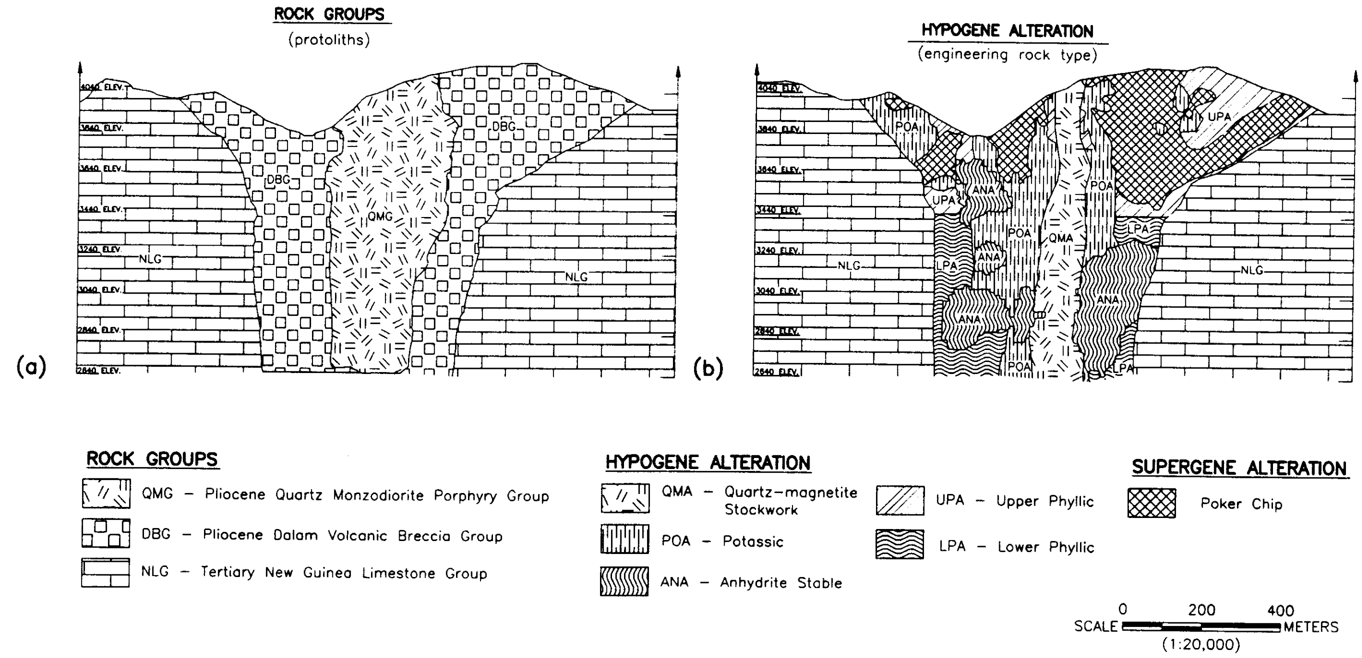


FIGURE 2.10 Grasberg deposit cross section for (a) protoliths and (b) engineering rock types

Strength test results may require dividing engineering rock types on the basis of protolith (irrespective of alteration), alteration type (irrespective of protolith), or a combination of both. Strength parameters for a given geologic rock type may also vary with depth or with geographic location within the deposit, requiring the division of one geologic rock type into two or more engineering rock types.

The engineering rock-type model for the Grasberg Igneous Complex (GIC) is presented as an example of the relationship between protolith, alteration, rock-quality designation (RQD), relative depth, and rock strength. The GIC is a diatreme, hosted within limestone. Many individual igneous phases have been identified within the GIC, and the igneous rocks can be broadly divided into the intrusive rocks and the relatively older volcanic rocks (MacDonald and Arnold 1994). Figure 2.10a demonstrates the relationship of the protoliths in cross section.

Rock-strength testing was conducted for all protoliths and alteration types, and the results were compared against all of the variables that were recorded for each test sample. The other variables included location, protolith, alteration type, and RQD. Protolith, alteration type, RQD, and relative depth ultimately differentiated the engineering rock types.

All of the igneous protoliths have been hydrothermally altered; the alteration types include quartz-magnetite stockwork, potassic, phyllic, and anhydrite stable alteration. Some of the hydrothermal alteration types overlapped so that there is some subjectivity in attributing a particular alteration type to a given rock sample.

Alteration anhydrite was leached in the near-surface environment to depths of 600 m. The leached rock is referred to as *pokerchip*. The pokerchip is characterized in core by a measured RQD of 5% or less in continuous runs. The anhydrite stable rock is best distinguished in core as rock with continuous measured RQD values of 95% or greater. The interface between pokerchip and anhydrite stable rock is often only a few meters thick.

Limestone was consistent in rock-strength properties, and all limestone was assigned as the limestone engineering rock type. Igneous rocks with an RQD of 5% or less, regardless of protolith or hypogene alteration, had similar rock-strength characteristics and were assigned to the pokerchip engineering rock type. All igneous rocks with an RQD of 95% or greater had similar rock-strength characteristics, regardless of protolith (intrusive phase or volcanic rock type in this case), and were assigned to the anhydrite stable engineering rock type. All quartz-magnetite-altered rocks, regardless of intrusive phase or volcanic rock type, had similar strength values and were assigned to the quartz-magnetite engineering rock type. All potassic-altered rocks, regardless of intrusive phase or volcanic rock type, had similar rock-strength values and were assigned to the potassic engineering rock type. Rock-strength properties for phyllic-altered rocks showed variability with depth; the phyllic-altered rocks were divided into the lower phyllic and upper phyllic engineering rock types to reflect this difference. The resulting engineering rock type model is presented in Figure 2.10b.

2.6 ROCK-MASS STRENGTH

The purpose of this chapter is not to review all classification techniques and all methods to estimate rock-mass strength; however, they must be discussed as part of the geologic structure data analysis. Chapters 3 and 4 discuss the use of these data in the catch bench, interramp, and overall slope analyses.

2.6.1 Rock-Mass Classification

All drill holes and bench faces should be mapped using one of the rock-mass classification techniques. Two of the more popular systems used today are Bieniawski's rock-mass rating (Bieniawski 1974) or Barton's rock quality (Barton, Lien, and Lunde 1974). Although these classification systems have empirical data to correlate ground behavior, such as slope angles, the empirical data should only be used if structure data are not available.

There are techniques to estimate the rock-mass strength from these rock-mass classifications (Hoek and Brown 1992; Laubscher 1977), and using a classification to estimate the rock-mass strength is both appropriate and prudent. However, the user must be aware that there is a directional condition to the rock-mass strength. For example, a rock mass with a low RQD or with a high fracture frequency will have the same classification whether the joint set is dipping back into the pit wall or dipping into the pit. Although the classification techniques allow adjustments to their values for directional considerations, they still do not provide good

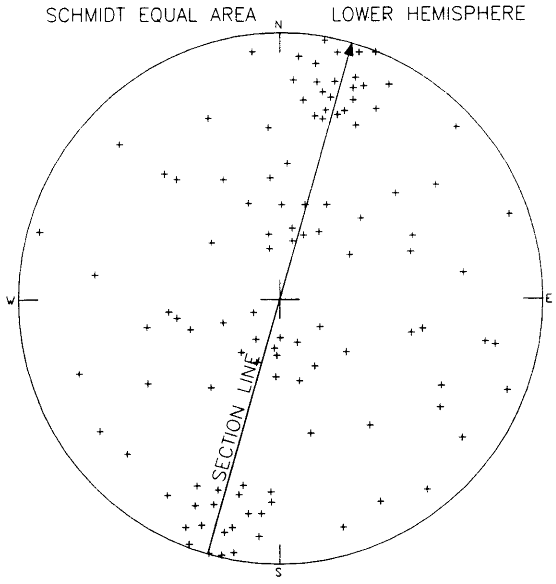


FIGURE 2.11 Schmidt plot of data used in scratch fracture model

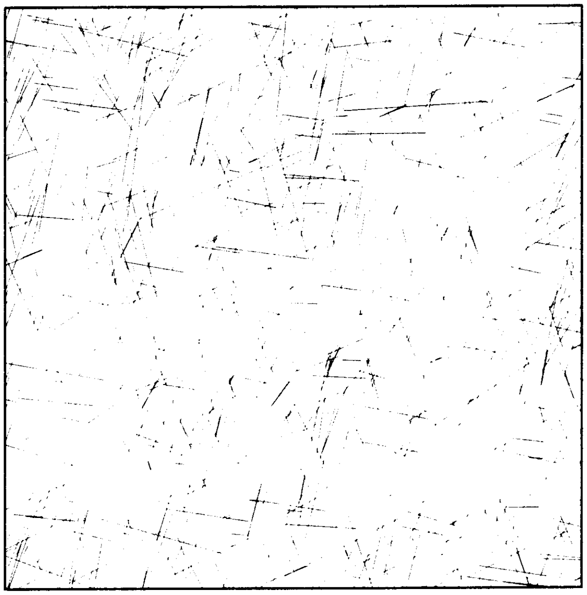


FIGURE 2.12 Scratch fracture model for three joint sets

estimates of directional strengths. If possible, the geologic structure data should be used to modify those strengths.

2.6.2 Fracture Models

Because the fabric of the rock mass is comprised of several intersecting joint systems, the strength of the rock mass will be anisotropic. This directional rock-mass strength can be estimated using fracture-modeling techniques. A step-path model (Call and Nicholas 1978) was one of the early efforts to quantify this variability. At the time, available computer memory was a serious constraint, and the analysis was limited to the evaluation of only the flattest step-path angle, which was not necessarily either the path at the critical angle or the path with the lowest percentage of intact rock. Because the failure path of interest is problem specific, Call & Nicholas, Inc. has developed a fracture simulation-modeling program that enables the engineer to visually evaluate the potential for the formation of step-path failure geometries. Initially, the fracture simulations were used to predict block sizes in a cave and, subsequently, were used for the evaluation of failure geometries in underground (Nicholas and Miller 1984) and surface excavations. A similar program, FracMan, has been used by Golder Associates to model geologic structures in either two or three dimensions. The remainder of this discussion refers to the fracture-modeling program used by Call & Nicholas, Inc.

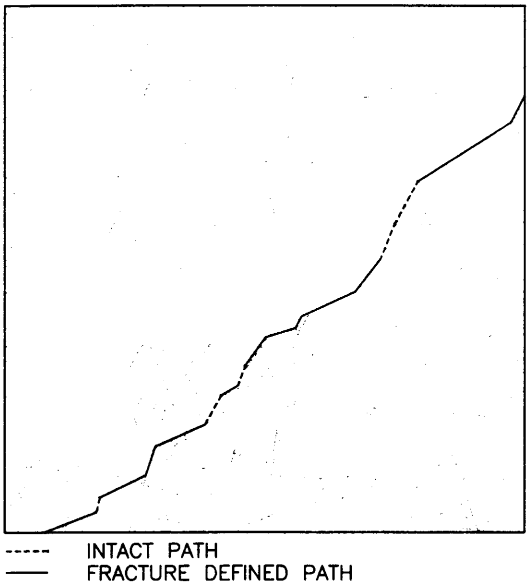


FIGURE 2.13 Path with least percent intact rock

The input to the model includes the orientation of the section of interest and the statistical distributions of the dip, dip direction, spacing, length, and overlap for the fracture sets of interest. Structures sampled from these distributions that do not meet the minimum length requirements specified by the user are suppressed in the rendering of the simulation. Geologic sets selected for the analysis usually have a dip direction that is within ±40° from the bearing of the section. The orientation sampling that is conducted is based on the distribution statistics for the geologic set being modeled. However, the minimum and maximum range of sampled values is constrained by the limits of the observed population, as shown on the Schmidt plot (Figure 2.11).

Individual structures are sampled in window strips, the narrow dimension of which is a function of the mean length of the set. The sampling windows are oriented horizontally for structures with dips (45° and vertically for structures with dips <45°). Once a simulation has been generated for the section (Figure 2.12), a separate module is used to verify that the structure overlap from the window sampling routine has produced the correct apparent spacing for each set.

After the section has been generated (Figure 2.12) and verified, potential step-path failure geometries are identified and traced on the section. The critical path may be the one with the flattest possible inclination, the one with a predefined inclination, or the one with the least intact rock (Figure 2.13). Plots of percent intact rock versus step-path angle or plots of other parameters of interest can then be produced for any step-path geometries identified.

To estimate the rock-mass strength along the section analyzed, the intact and fracture shear strengths are weighted based on the percentage of the failure path that must pass through intact rock. This modeling technique has worked well in cases where the strength of the rock mass in front of a non-daylighted major structure, such as a fault, must be determined to see whether the remaining buttress is strong enough to support the rock above it (Figure 2.14).

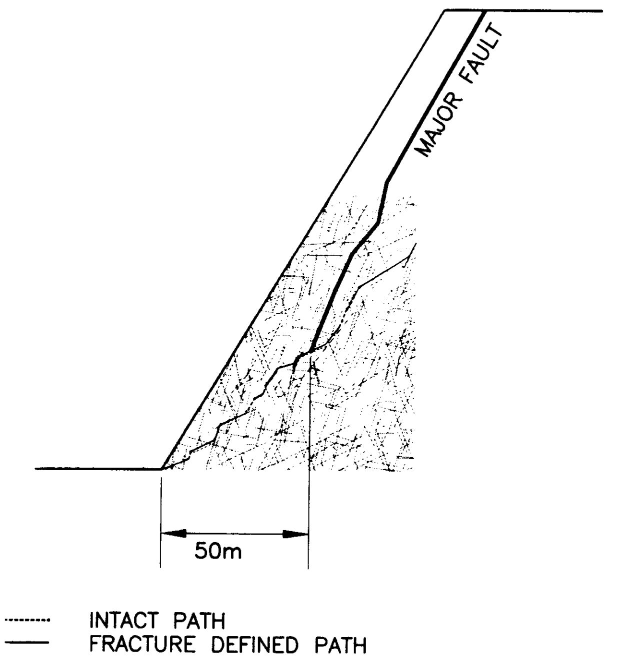


FIGURE 2.14 Failure path to evaluate non-daylighted major structure

2.7 CONCLUSIONS

The geologic structure characteristics and the orientation of the pit wall relative to the structure orientations usually determine the attainable slope angle in rock. The delineation of structural domains and the definition of the structure characteristics within each domain are essential to ensure that the structure characteristics are applied only to those areas of the current and future pits where they will actually exist.

Major-structure data are the most important and the most difficult structure data to collect and interpret. Structure length is the most difficult major-structure characteristic to measure, because the exposure in a pit requires conducting mapping on a bench-by-bench sequence, either on an existing highwall or on pushbacks of consecutive phases. Appropriate survey, mapping, and interpretation techniques are necessary to accurately measure the major-structure lengths. We strongly recommend mapping structure data for geotechnical analysis using the face-mapping method.

The major-structure data should be plotted on current pit topography maps, and the data also should be compiled on level maps and in a database. Level maps can be used to determine vertical and lateral continuity of major structures as the mine development expands. Regional structures should be extended along strike to the limits of the level maps so that they can be easily plotted on all future pit plans. The database can be used for statistical analysis for the intermediate structures.

Relatively short structures that comprise the rock fabric are too numerous to map and analyze individually, so they must be mapped with techniques that provide the appropriate input parameters for statistical analysis. There are several techniques for collecting the rock fabric data, and each has its own advantages and disadvantages. We recommend the cell-mapping method, which is described in detail in Appendix A.

Rock-mass strength is one of the most difficult parameters to quantify in slope analysis because, given the large size of the rock mass, there are no practical means to directly measure the rock-mass strength. Determination of rock-mass strength with common rock classification systems can be useful, but the classification systems usually do not account for the directional dependence of the rock-mass strength imposed by the rock fabric. A fracture model is required so that the directional aspect of the rock-mass strength can be quantitative.

2.8 ACKNOWLEDGMENTS

The *Chicken Scratch Fracture Model* was developed with the help of many people. Major contributors include David Nicholas, Dan White, John Marek, Richard Call, and Paul Pryor. We thank Chuck Brannon and George MacDonald of Freeport McMoRan Copper and Gold Company for granting permission to present and review the Grasberg rock-type data.

2.9 REFERENCES

Barton, N., R. Lien, and J. Lunde. 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, 6:4:189–236. Originally published in 1974 as Analysis of rock mass quality and support practice in tunneling. *Norwegian Geotechnical Inst.*, Report No. 54206.

Bieniawski, Z.T. 1974. Geomechanics classification of rock masses and its application in tunneling. *Proceedings Third International Congress on Rock Mechanics*, vol. 11A, 27–32. Denver, Colorado:ISRM.

Call, R.D. 1992. Slope stability. In *SME Mining Engineering Handbook* 2nd ed. vol. 1. ed. H.L. Hartman. Littleton, Colorado:SME.

Call, R.D., J.P. Savely, and D.E. Nicholas. 1976. Estimation of joint set characteristics from surface mapping data. *Proceedings 17th US Symposium on Rock Mechanics.* Utah Engineering Experiment Station, University of Utah, Salt Lake City, pp. 2B2-1 to 2B2-9.

Call, R.D., and D.E. Nicholas. 1978. Prediction of step path failure geometry for slope stability analysis. *Proceedings 19th Rock Mechanics Symposium.*

Call, R.D., J.P. Savely, and R. Pakalins. 1982. A simple core orientation technique. *Stability in Surface Mining.* vol. 3. ed. C.O. Brawner. AIME.

Deere, D.U. 1963. Technical description of rock cores for engineering purposes. *Felmechanik und Ingenieurgeologie.* 1:16.

Hoek, E., and E.T. Brown. 1988. The Hoek-Brown failure criterion–1988 update. In *Rock engineering for underground excavations, Proceedings 15th Canadian Rock Mech. Symp.*, ed J.C. Curran. 31–38. Toronto, Ontario:Dept. Civil Engineering, University of Toronto.

La Pointe, P.R., and J.A. Hudson. 1985. Characterization and interpretation of rock mass joint patterns. *Geological Society of America Special Paper 199.* Boulder, Colorado:SA.

Laubscher, D.H. 1977. Geomechanics classification of jointed rock masses–mining applications. *Trans. Instn. Min. Metall.* 86, A1–8.

MacDonald, G.D., and L.C. Arnold. 1994. Geologic and geochemical zoning of the Grasberg Igneous Complex, Irian Jaya, Indonesia. *Journal of Geochemical Exploration*, vol. 50, p. 143–178.

Nicholas, D.E., and S.M. Miller. 1984. Geotechnical considerations. In *Northwest Mining Association Short Course Mine Feasibility–Concept to Completion,* ed. G.E. McKelvey.

Peters, P.C. 1987. *Exploration and Mining Geology.* 2nd ed. New York:John Wiley & Sons.

Rostrom, E. 1961. Craelius automatic core orientator. *Canadian Mining Journal.* pp. 60–61.

Warburton, P.M. 1980. A stereological interpretation of joint trace data. *Intl. Jour. Rock Mech. Min. Sci. & Geomech. Abstr.* 17:181.

Appendix
Cell-Mapping Procedure

2.10 INTRODUCTION

The cell-mapping procedure involves dividing the bench faces into zones of equal length, called *cells*. The area from which structure data is recorded is referred to as the *cell window*. Cell dimensions are usually square (i.e., the width of each cell is equal to the bench height). Bench faces that are not obscured by overbank or blasted material are subdivided into cells, and the geologic structure present in each cell is then mapped. Cell mapping can also be conducted along irregular outcrops or road cuts; because of the physical constraints of the rock exposures, these cells may be rectangular in shape.

In an open-pit environment where multiple benches are developed, cell mapping is generally conducted using two different approaches. First, if personnel, budget, or time are not limiting factors, entire benches are mapped with contiguous cells. This type of mapping campaign allows for a complete sampling of the geologic setting in the study area, including jointing and major faults and all other structures. A second approach may be used if resources are limited or if there are time constraints; this involves mapping strings of contiguous cells, from 2 or 3 contiguous cells to as many as 10 or more, located in different parts of the study area. With this approach, individual strings of cells are selected to spot-check for potential changes in structure characteristics across the study area. A sufficient number of cell strings have to be mapped to identify structural domain boundaries across the study area.

When mapping road cuts or isolated outcrops, an attempt should be made to map strings of at least two to three contiguous cells.

A standard data sheet is used to record the following information for each cell (Figure 2.A.1). (Note: The letter C in Column 1 of the data sheet denotes information pertaining to the entire cell; the letter S denotes data pertaining to geologic structures.)

2.11 C LINE DATA ENTRY—MAPPING CELL INFORMATION

Level. The elevation of the bench, outcrop, or road cut being mapped is indicated. If surveying of cell locations is not possible, the elevation should be estimated, for example, from a topographic map.

Cell Number. The cells within a string are numbered consecutively where mine benches are developed, including those covered by muck. A break in the cell numbering sequence should be used when starting a new string of cells that is not contiguous with the previous string.

Cell Width and Height. The recorded width and height should not include obscured or nonmappable areas of the cell. For example, if the lower 3 m of a 15-m bench are covered by muck, a cell height of only 12 m is recorded.

When mapping in outcrops or partially covered road cuts, estimates of the *average* width and height of the exposure is made.

Rock Type. The two or three dominant rock types in the cell are listed in descending order of percent occurrence.

Ideally, an individual detail cell *should not cross* major (relative to pit-scale) lithologic contacts or major faults, since fracture characteristics and orientations may differ in large bodies composed of distinct rock types or fault-bound blocks.

On the other hand, if mapping is being conducted along fairly closely spaced, alternating lithologic units, for example, in a sedimentary sequence, rock types should be listed according to descending order of percent occurrence.

Face Strike and Dip. The strike of the bench face comprising the cell (using the right-hand convention) and the bench face angle are measured. Face strike is an *average* strike along the observed cell and *should always be recorded in such a way that the strike plus 90° represents the dip direction of the bench face (right-hand rule).* The average strike of a *muck cell* must be recorded if it is located within a string of cells where structural information has been collected. This is necessary to allow for the calculation of coordinates of the remaining cells in the string.

The face-dip or bench face angle should represent not the average dip but rather the dip of the flattest plane observed along the cell. For example, if the back of a wedge failure located along the crest represents the farthest back break in the cell, a plane should be projected from that point to the actual (or implied) toe of the bench.

The average bench face angle is also often collected, although not specifically required in the computer programs used to process the data and analyze back break. If the average bench face angle is recorded, it should be in addition to, not instead of, the minimum bench face angle.

If intact rock within muck cells is obscured because of raveling of the bench face following mine bench cleanup, the minimum bench face angle (and optionally the average bench face angle) should be recorded. However, if the material comprising the "muck cell" *is obviously* shot muck that has not yet been mined, only the strike should be recorded. In the latter case, the average dip is not valid since no attempt has been made to clean up blasted material.

When mapping an outcrop, the *face dip* may be difficult to determine because of the irregular nature of the exposure. In this case, the face dip is less relevant since it does not represent a mined face but rather a long-term erosional surface. Discretion should be used when comparing outcrop face dips to existing or predicted mine bench face angles.

Control. When strings of contiguous cells are mapped, survey coordinates should be taken every 5 to 10 cells; these control points are later used to determine the midpoint coordinates of each individual cell. If a cell is to be used for survey control, the level and cell number should be recorded in the control field on the data sheet. When the survey data becomes available, the coordinates should be listed in the remarks column of the field data form for bookkeeping purposes. Ideally, the first and last cell in every string should be surveyed.

When mapping individual cells, such as outcrops, each cell should be surveyed if possible.

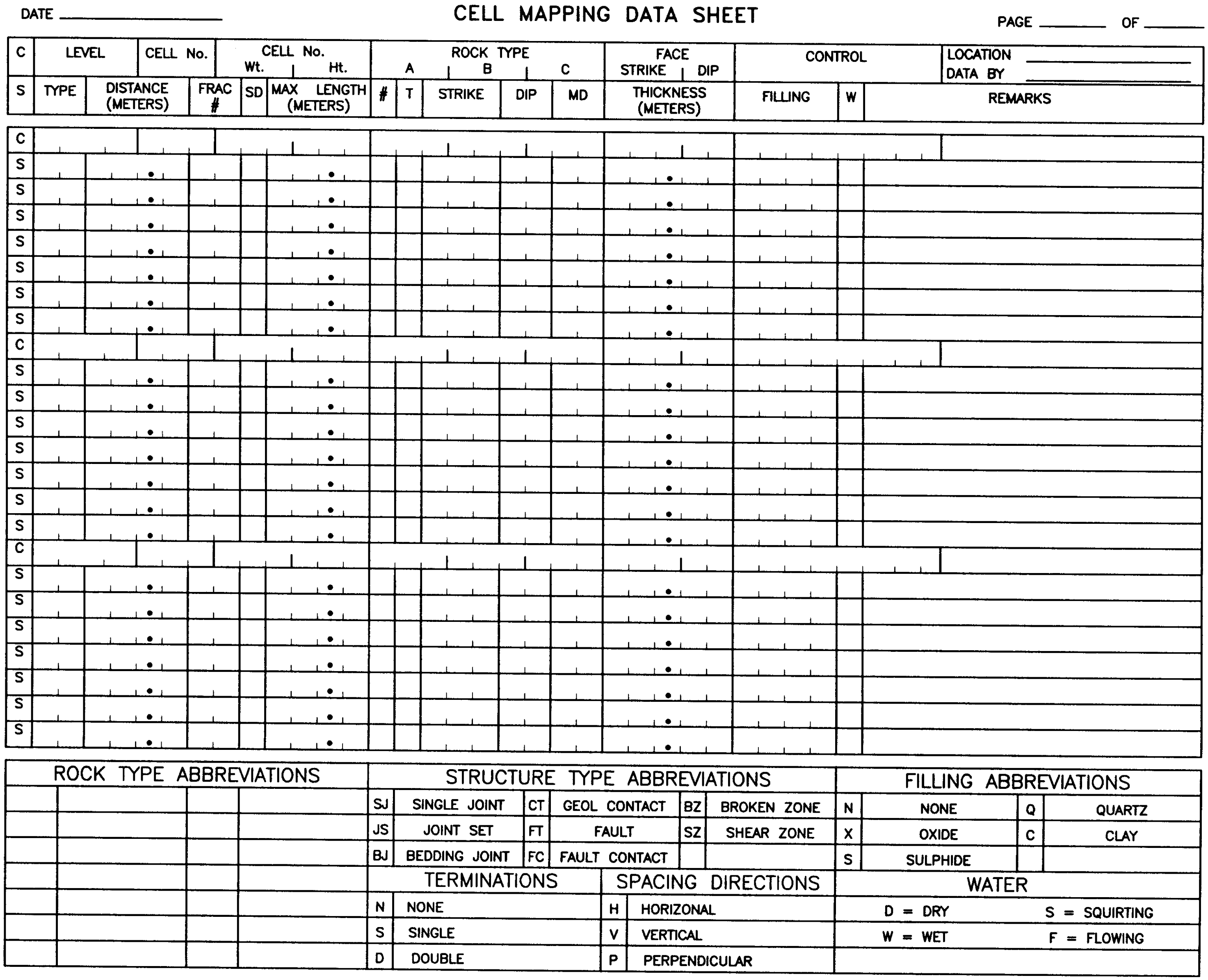
Remarks. The "Remarks" column is used to describe pertinent features of the cell; the back of the field form can also be used. Additional comments might include specific potential failure geometries (i.e., plane shear or wedge) or actual failures that have occurred along the mapped faces. Information should include a sketch, direction and angle of discrete wedge-geometry plunge intersections, and the orientation of structure(s) involved. Remarks on nature of groundwater seepage (i.e., amount of water, structure control, etc.) would also be important information. If mapping underground, the support being used could be described.

2.12 S LINE DATA ENTRY—STRUCTURE (SET) INFORMATION

For each cell, the following structure information is recorded:

Type. The geologic structure (e.g., joint set, bedding set, foliation, a single joint, etc.) is recorded using a two-character code. Major structures (e.g., fault, shear zone, etc.) are identified in the same manner.

The structure types indicated at the bottom of the cell-mapping forms are not absolute. If some site-specific structure



DATE ________ CELL MAPPING DATA SHEET PAGE ______ OF ______

C	LEVEL		CELL No.		CELL No. Wt. | Ht.		ROCK TYPE A | B | C				FACE STRIKE | DIP	CONTROL		LOCATION ______ DATA BY ______		
S	TYPE	DISTANCE (METERS)	FRAC #	SD	MAX LENGTH (METERS)	#	T	STRIKE	DIP	MD	THICKNESS (METERS)	FILLING	W	REMARKS		
C																
S																
S																
S																
S																
S																
S																
S																
C																
S																
S																
S																
S																
S																
S																
S																
S																
C																
S																
S																
S																
S																
S																
S																
S																

ROCK TYPE ABBREVIATIONS

STRUCTURE TYPE ABBREVIATIONS

SJ	SINGLE JOINT	CT	GEOL CONTACT	BZ	BROKEN ZONE
JS	JOINT SET	FT	FAULT	SZ	SHEAR ZONE
BJ	BEDDING JOINT	FC	FAULT CONTACT		

FILLING ABBREVIATIONS

N	NONE	Q	QUARTZ
X	OXIDE	C	CLAY
S	SULPHIDE		

TERMINATIONS

N	NONE
S	SINGLE
D	DOUBLE

SPACING DIRECTIONS

H	HORIZONAL
V	VERTICAL
P	PERPENDICULAR

WATER

D = DRY S = SQUIRTING
W = WET F = FLOWING

FIGURE A.1 Cell mapping data sheet

type is not covered on the form, add to it. However, be consistent during mapping and provide an explicit definition of the new structure type.

The designation "MC" should be recorded in the first "S" line whenever a muck cell is laid out and traversed in a string of cells. The software program used later to process this data recognizes the cell as one having no structures mapped.

2.12.1 Individual Structures Versus Structure Sets

When *individual* structures, such as a discrete fault, a vein, or a single joint, are recorded, only the strike, dip, minimum dip, length (the maximum length equals the length in this case), thickness, and filling type(s) should be recorded.

When structural trends are visibly indicated, but open fractures are not present, only the strike and dip of these features are recorded. A good example is massive bedding in sedimentary rocks where the bedding attitude can be estimated because of the banded nature of that rock. (Note: The recorded symbol for this type of bedding attitude should be different from the symbol used for a bedding *fracture* or *fracture set.*)

Conversely, for any structure *set* (e.g., three or more individual structures with apparent similar attitudes) all parameters in the following discussion must be recorded:

Distance. This is the distance over which the number of fractures in a structure set is counted (used later to determine average spacing of the structure set within the cell). The *distance* recorded is the length of an arbitrary counting line visibly projected across the cell window being mapped. The actual placement of the counting line for each set usually depends on site-specific physical conditions, such as the development of the structure sets across the bench face being mapped or portions of the cell that are covered or displaced.

The distance over which the number of individual fractures are counted within a set should generally be the same as the cell dimensions. For example, if the count is made horizontally for a 15-m-wide cell (SD = "H"), the distance recorded would be 15 m. Similarly, for a 12-m-high cell for which the counting direction is vertical (SD = "V"), the distance would usually be 12 m.

There are several exceptions to this rule. One case, as indicated above, would be if part of the cell is obscured by muck. The effective distance recorded would be that portion of the cell where the mapper can clearly view the structures within that set.

A second exception to the rule would occur when rock is very strongly fractured (i.e., > 50 fractures/set/cell). It is acceptable, under these conditions, to take a count of at least *30* structures in a set and then to record that distance over which the 30 fractures were observed. A count of at least 30 structures within a geologic set is considered to provide adequate information to calculate the required statistical data. In this case, the counting line should be positioned to cross the longest fracture in the set, if possible.

A third exception would be when measuring structures that are parallel to the face, using either a perpendicular or a true spacing direction, in which case the counting distance is very limited.

Fractures. The number of fractures counted in the set is recorded. A fracture is a continuous open planar feature that has some minimum designated length. We commonly use either a 0.3-m or 1-m cutoff length. Thus, only those structural features (with an open fracture) having a length of the cutoff value or greater would be included in the count. The minimum cutoff used *should always be recorded* on the field sheets, either at the top of the form or under the "Remarks" column.

It is very important that only those fractures that intersect the counting line be counted.

Spacing Direction (SD). This is the direction, in a physical sense, in which the fracture count or spacing of the fractures is measured.

V = vertical spacing (counting line projected vertically, perpendicular to the strike of the bench face), usually implemented for flat-lying structures.

H = horizontal spacing (counting line projected horizontally, parallel to the strike of the bench face), usually implemented for steeper structures oriented oblique to perpendicular to bench face.

P = perpendicular spacing (counting line projected into bench face horizontally, perpendicular to the strike of the face), implemented on structure sets that strike subparallel to parallel to bench face. This count is more difficult since accurate structure count and distance parameters rely on sufficient offset in bench face (in the third dimension perpendicular to the face) to identify individual joints.

T = true spacing (counting line in the true spacing direction, perpendicular to the plane of the structure); in this case, an attempt is made to project the counting line normal to the strike of individual sets. The true spacing can be determined directly by dividing the total number of structures by the counting distance, without the need to correct for a difference in angle between the counting direction and the true spacing direction.

In summary, the SD refers to the direction, relative to the bench face (or structure set in the case of true SD), in which the structure count (to calculate true spacing) is made. The procedure involves projecting a counting line across the cell face in the most effective orientation or direction to count the total number of structures within any given geologic set. For sets parallel to the face, neither horizontal nor vertical count will work. In which case, the counting line should be oriented either perpendicular to the bench face (SD = perpendicular) or perpendicular to the structure set (SD = true). Usually, the face is irregular enough to obtain a count of structures parallel to the face.

Maximum Length. The length of the longest fracture in a joint set or the maximum length of a major structure is measured. This is the greatest observed *trace* length and does not have to be measured at any orientation or inclination along the plane. Those structures that cross more than one cell are measured only once, with the data recorded in the first cell in which the structure is encountered. To reiterate, long structures that can be traced for more than one cell should only be recorded *once*.

Number at Maximum Length (#). The number of fractures in the cell that are at the maximum length are recorded. Quite often, there may be only one structure at the maximum length, but in the case of nonterminated fractures or fractures that are terminating against another set, more than one structure equal to the maximum length can occur in the cell.

Termination (T). The type of termination of the longest fracture.

D = doubly terminated, i.e., termination of the fracture can be identified at both ends. Fractures commonly terminate against other fractures. Fractures are also observed to *die out* within the rock mass itself.

S = singly terminated, i.e., only one termination of the longest fracture can be identified, while the other end exits the bench (cell) at the crest or in the muck pile at the toe of the bench.

N = no termination, i.e., one end of the joint extends to the bench crest while the other end exits at the toe or in muck.

Strike. The strike is measured using a conventional 0° to 360° azimuth compass, with the strike or azimuth reading 90° counterclockwise from the direction of dip of the fracture or fracture set.

The following is another way of describing the "right-hand" convention: when looking in the strike direction (with the front of the compass pointing in that direction), the structure(s) will always be dipping to your right. The average strike of the structure or set should be recorded.

Dip. The dip of a major structure or the average dip of a joint set is measured.

Minimum Dip. A dip on the flattest observable portion of the fracture surface or major structure should be recorded to compare with the average dip. This deviation in dip is a quantitative measure of the roughness of the fracture surface.

Thickness. Average thickness should be recorded for both individual structures and structure sets mapped. *Joint* surfaces commonly have an average thickness of less than 0.16 cm. The software used to process the cell data allows for three decimal places for structure thickness. Therefore, the thickness of even the very narrow joint structures should be estimated.

Fracture Filling. Filling material between fractures is recorded with a single letter abbreviation. More than one filling type should be present. Filling type designations may be site specific; however, all unique filling types have to be defined at the bottom of one or more of the cell-mapping field sheets.

Water (W). This field is used to indicate the presence of water along the joint or structure surface. The following categories are typically used:

D = dry

W = wet

S = squirting

F = flowing

When water is not present, this field is often replaced with a field for other pertinent information, such as measures of joint roughness or condition. Rock hardness can also be substituted but is typically placed on the cell (C) line rather than the structure (S) line because the hardness value would typically represent the average rock hardness within the cell and would not be associated with a specific structure.

Remarks. The "Remarks" column is used to describe pertinent features of the structure or structure set. Additional comments might include specific potential failure geometries with which the structure is associated (e.g., plane shear structure or left side of wedge geometry) or actual failures that have occurred along the mapped faces. As with the remarks on the cell line, sketches are very useful. Remarks on nature of groundwater seepage associated with the structure or set would also be important information.

For cells in which the ground is altered and jointing is either lacking or too intense to measure, the cell data should be recorded and the character of the face described in the "Remarks" column.

2.13 CELL-MAPPING GUIDELINES

1. Cell mapping should be conducted by two-person crews, not only because of safety considerations but to increase productivity and accuracy. Once a line of cells is laid out, the most efficient cell-mapping procedure is to have one mapper work near the bench face on the muck pile and the second mapper on the bench level. For both flat-lying structure sets and sets that are subparallel to parallel to the bench face, it is very difficult to determine the orientation without approaching the bench face and measuring one or more individual fractures.

   For the steeper structures oriented oblique to perpendicular to the face, it is easier to record information from the bench. The number of structures in a flat-lying set is generally more easily counted from the bench level. In other words, both members may provide statistical information for the same set. The team can periodically switch mapping positions.

   The determination of an average structure set orientation to be recorded on the field sheet should involve checking the strike and dip of the set at several locations along the cell.

   Identifying the longest structure length for sets is best done from the bench floor. The key to identifying all structure sets is to be mobile and scan the cell from all possible orientations, e.g., completing a 180° arc along the bench.
2. Cell mapping should *not* be conducted along benches that appear to have been displaced or rotated. This would include zones of blasted muck that have not been cleaned up or areas that have failed.
3. As previously indicated, emphasis should be placed on identifying as many distinct structure sets as possible when cell mapping. Structure sets observed in the field should be considered *distinct* if a difference of more than 20° for the average bearing and/or dip is indicated between individual candidates. Data can be later combined in the office, if desired, but should be recorded as distinct sets in the field.
4. In addition to the recording of parameters for individual or sets of open fractures, the orientation of stratification features, such as bedding in sedimentary rocks, lamination features such as foliation in metamorphic rocks, or flow-banding in volcanic rocks, should be routinely recorded during mapping. The orientation of lineation features, such as alignment of clasts in sedimentary rocks or alignment of the long dimensions of minerals, should also be collected.
5. It may be impossible to define specific rock types while mapping. However, descriptive criteria for identifying unique rock types should be established in the field and recorded on the field sheets. This criteria would then be used in future mapping for identifying the same rock types at other locations.