Executive Summary

This handbook is intended to provide guidelines for improving current levels of structural geologic data collection and evaluations by experienced exploration and mining geologists, as well as mine and rock engineers, familiar with standard procedures of mine development and underground mining application. It is aimed towards assisting these personnel to better work together to understand and interpret rock mass conditions associated with faulting and fault slip type seismicity or rockbursting and the impact which they have on underground mine sequencing and development planning.

The intention is that the guidelines outlined within this handbook be applied particularly in two key areas:

a. for known structurally complex, high stress, seismic event and rockburst-prone mine settings; and

b. for active and/or planned mines where rockbursting or seismic events are not currently known but which, because of geologic environment and/or mining depth, could eventually experience potentially dangerous energy release conditions.

The following is a review of the essential content of each of the chapters in this document:

CHAPTER 1 – INTRODUCTION

The first chapter includes some discussion related to the differences between early exploration needs and subsequent operational structural geology needs and also those of the underground rock mechanics specialist examining rock masses and incipient structure from the viewpoint of mine design.

Geological influences on mining methods are lightly explored in early chapters as these can be identified as significant from a mine design viewpoint. Important interactions and mine sequence-related influence issues are discussed to aid identification of problem situations that can range from major (where structural faults affect everyday mining) to trivial where faults are healed to such an extent as to not be reactivated by any subsequent mining processes.

Key to establishing the propensity for structural failure leading to complications during subsequent mining is understanding stress influence (both in situ and induced) that may affect structures. Stress analyses and evaluation of its implications on major geological discontinuities is critical to achieving a mine design which, when possible, includes flexibility and thereby minimizes the risk of geological structural feature complications. Addressing these issues has been a key focus of this handbook.

CHAPTER 2 – FAULT ARCHITECTURE

The second chapter introduces the concept of Anderson style faulting. The three classic fault types — normal reverse and strike-slip — are first discussed with respect to stress states under which each was generated. Appropriate methodologies for assessing fault origin are examined as are mechanisms for fault reactivation by subsequent geological processes or by mining-induced stress changes. The importance of stress state on remobilization propensity is emphasized because the orientation of induced shear may force fault movement in a different direction from that which occurred on the fault at the time it was created. Further, the importance of induced stress state relative to fault forming stresses are examined, since orientation and magnitude differences between the two may also have major significance from a mining viewpoint.

The architecture of fault structures is examined and the three elements characteristically seen in any fault zone illustrated – (i) undeformed far-field host rock; (ii) near-field damage or transition zone; and (iii) fault core. Illustrations of the rock fabric adjacent to fault zones are explored as such fabrics provide evidence for defining the characteristics and deformation processes that caused the fault creation.

Two main sections have been created within Chapter 2. The first examines geometrical characterization, while the second looks at faults and fault systems. These are explored from the viewpoint of architecture and morphology. Basic fault morphology and terminology are explained in the initial part of the chapter whereas the second part of the chapter examines damage zones around faults. Three types of damage are identified: tip damage zones; wall damage zones; and linking damage zones.

Although faults can be simple when initially created, they often become much more complex when reactivated. In such situations, they may exist as a network of anastomosing or crosscutting structures (Figure 1). The geometry of faults is discussed from the perspective of describing faults and assessing their competence from a mining reactivation perspective. It is explained that faults should not be thought of as single planar continuous structures but rather as an association of shear bands that have various common features, including associated wall damage zones as shown in Figure 1. In fact, faults almost never occur as single planar structures but rather develop as suites of related structures, often without a constant dip or strike, except as a composite shear band.

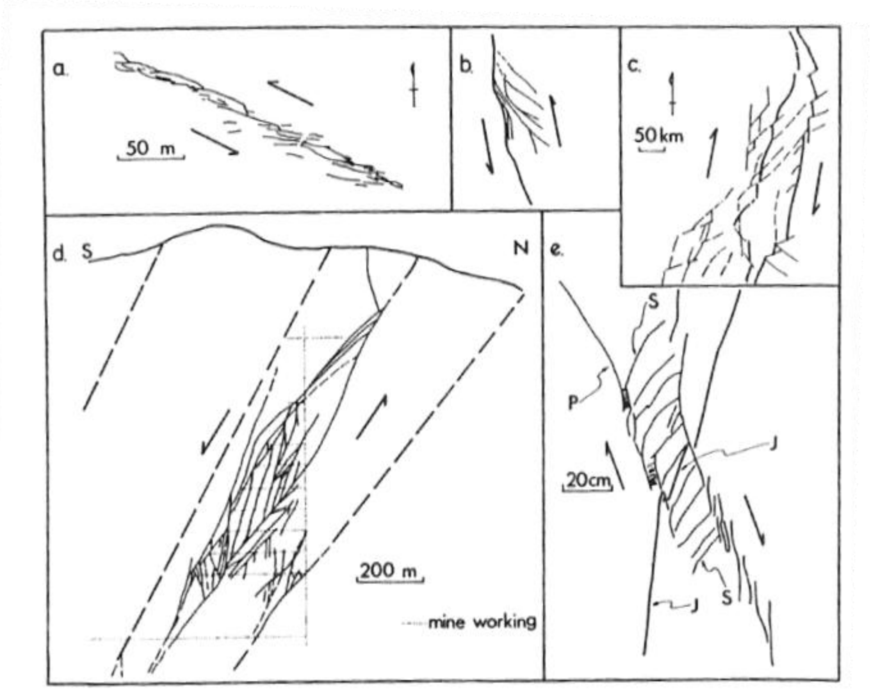

Figure 1: Some typical fault geometries: a) Dasht-e-Bayaz, Iran; b) Ales, France; and c) Taranaki graben, New Zealand – a) – c) are map views from Naylor et al. (1986). d) cross-section through a fault array in the Coeur d'Alene mine, Idaho (thin dotted lines are mine workings, from Wallace & Morris, (1986). e) Fresh fracture in a deep gold mine, South Africa (from McGarr et al., 1976). J is a pre-existing joint that has been offset, and P and S are primary and secondary fractures, according to the interpretation of McGarr et al. (1979).

Fault morphology and shear state are examined in the context of mode of origin, noting that fault structure geometry varies dependent on depth, width and shear offset, which in turn are related to the initial stress state. The division of structures between brittle and ductile modes are then explored. Generally, it is noted that brittle structures are more common at shallow depths within the Earth's crust, transitioning to more ductile structures with greater depth (>15 km typically); however, there are exceptions to this rule, particularly associated with complex nappe structures and/or with decollement zones where both brittle and ductile mechanisms can be identified. This suggests that both fabrics can exist side-by-side, created exactly at the same time geologically (Figure 2).

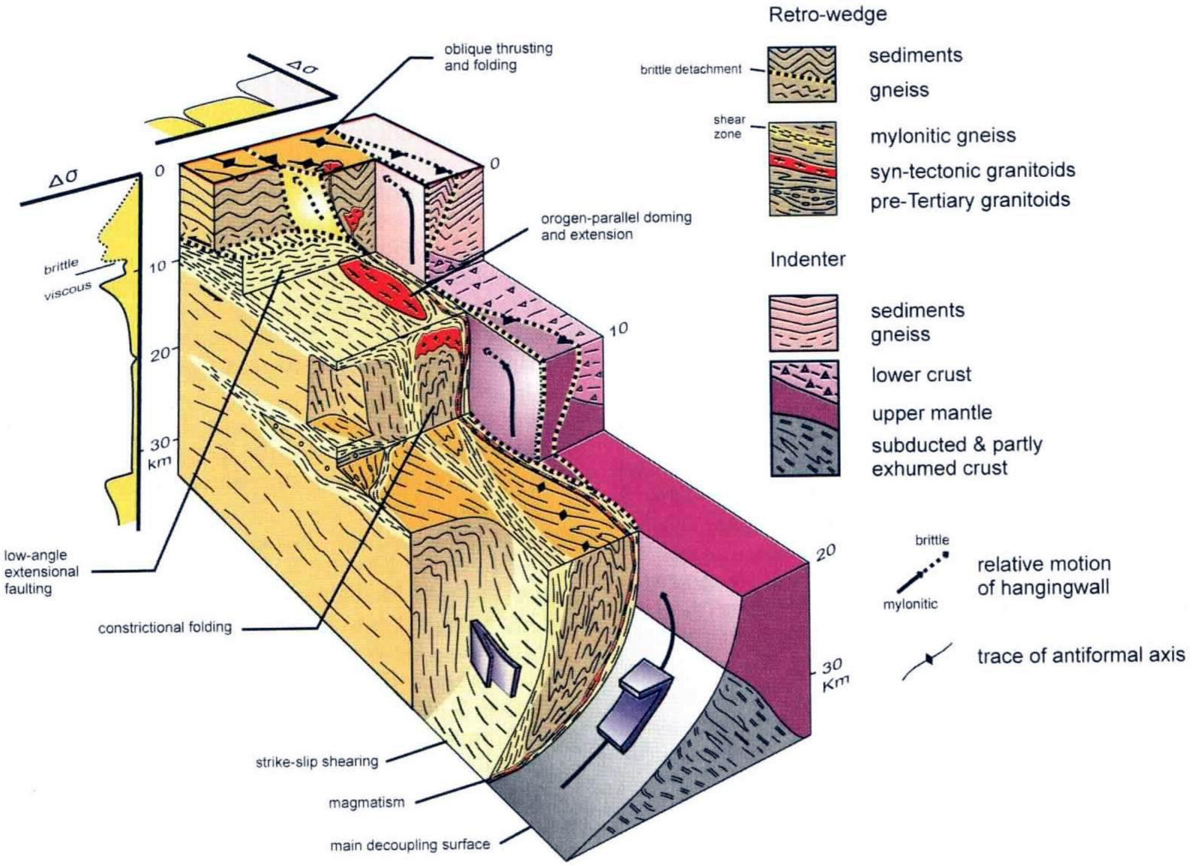

Figure 2: Generic model of decoupling zones related to strain partitioning along the Major Adriatic fault system. The significance of this figure is that both brittle and ductile processes are occurring simultaneously (Handy et al., 2005).

The geometry of faults with respect to a mining block are examined towards the end of the chapter and it is noted that depending on the geological mode of origin and subsequent history, different parts of the same mine and/or different mines in the same mining camp may well be in different structural geological domains. An example is White Pine mine where the mine has been divided into geologically controlled (low stress) and stress controlled (high stress) mining zones due to geologic conditions. Some guidelines are then provided to assist with identifying major differences between fault types as an aid to forecasting fault slip behaviour in response to adjacent mining.

Diagrams are introduced throughout the chapter showing the key elements for description of fault morphology and hence definition of a fault type, noting that dip, dip direction and striae geometry need to be recorded as basic data for each and every fault so that some assessment can be achieved of potential relative movement (in absence of visible offset that shows such relative movement directly). Slip direction is identified as a key indicator which needs to be defined, not just on the basis of attitude but with respect to movement direction; otherwise, it becomes impossible to differentiate between a reverse (thrust) fault and a normal and/or a strike-slip example. If striae or slickensides are present, the pitch and direction are useful further indicators and should also be noted, as should any vertical and/or horizontal offset. These features are discussed in more detail in Chapter 4 because kinematic indicators present on fault surfaces permit ready back-analysis of palaeostress conditions under which the fault may have formed.

The concluding sections of Chapter 2 introduce some of the concepts of plotting and compositing fault data on a stereonet in order to allow different fault type morphologies and hierarchies to be identified. This, in turn, allows reconstruction of possible changes in the stress field responsible for creation of the faults as it may have evolved through time. The concept of scale independence is also introduced, noting that in both plan and section, fractures tend to have the same geometric pattern and spatial distribution regardless of scale – a self similar power law (fractal) relationship is suggested. Some discussion is included relating to possible shear direction indicators based on displacement offsets, noting that decreased offsets are frequently observed towards fault tips and also outwards from the central segment of maximum displacement on a given fault trace.

CHAPTER 3 – FAULT BEHAVIOUR

The third chapter addresses fault behaviour. In the first part of the chapter, models of natural fault behaviour are presented as a guide to evaluating fault related seismicity in a mining environment. Behaviour differences relating to magnitude and orientation of stresses acting on faults and fracture surfaces are explored with respect to the degree of interlocking that is possible and which is largely controlled by fault geometry (Figure 3). Where interlocking is thought or known to exist, such faults have been found to pose the most direct threat to mining because of their propensity to store energy.

The physical properties of faults control their behaviour, with stress state and, in some cases, gravity controlling slip direction. The chapter discusses differences in local, regional and mining-induced stress state and notes that the prevailing local stress state acting on a fault or fracture surface in a mine might be influenced not only by the mining conditions, but also by those conditions which gave rise to the faults as well as those which prevailed throughout geological history. Some introduction to criteria for defining local rock mass damage as well as lithologic and structural variability are given as these also exert a control on fault behaviour.

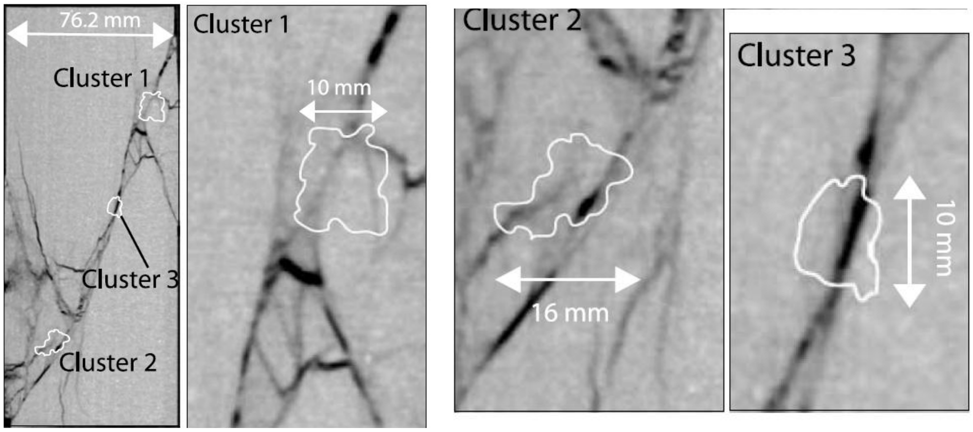

Figure 3: Acoustic Emission (AE) clusters from pre-slip AE source location data along a laboratory induced fault, prior to a stick-slip event. The clusters are geometrically controlled and related to areas along the fault with the least damage and structural irregularity (from Thompson et al., 2009).

The influence of mining on fault movement is discussed, with the point noted that the most serious fault slip events often do not occur in the immediate area of mining itself. Evidence of reactivation of embryonic fracture systems is of significant concern in such situations. Fault maturity, length and aperture (distance between footwall and hanging wall) characteristics are noted as being closely linked as are asperity, scale, and geometry. Collectively, these directly influence fault stability and behaviour and thus fault system stiffness.

A segment of Chapter 3 discusses the role of friction on fault stability and slip magnitude. It is noted that friction essentially controls rupture nucleation and propagation such as illustrated in Figure 3. Some discussion is included on frictional restraint as this is also identified as being important in healing slip plane motion during periods of subsequent geological stability. Friction is also related to arrest of rupture during sliding.

Relationships between slip length and fault width related to fault lengths are presented in discussion of scale being important, but not diagnostic in defining fault behaviour. Additionally, the significance of fault scale and its relevance to understanding the potential for a given fault to influence rock mass behaviour in response to mining is discussed as is the problem of defining the scale of a fault system when mining is actually occurring within the fault. Each is considered in relation to understanding overall system behaviour, an important control on ground response to mining.

Seismicity is examined with respect to fault behaviour, noting that levels of seismicity tend to be higher near excavation boundaries in mines where mining induced stress perturbations have occurred as a result of changes created in excavation geometry due to mine sequencing. Example mines are cited with a history of burst problems and from these cases it is clearly evident that mines which create highly stressed structures such as pillars and abutments tend to be more prone to experiencing mining-induced seismicity. Cases of stress-related fault slip induced rockbursts are cited, noting that the current geometry of a fault may not just be indicative of its likely origins, but reflect also its post origin deformation history. Developing an understanding of this history is also explored as it provides clues as to a fault’s potential future behaviour during mining since, depending on character and geometry, some faults may exert more significant influence on mine-wide rather than stope-scale rock mass response to mining.

The interaction of faults is noted as being of particular importance from the viewpoint of controlling excavation stability within a mine and also energy transfer. It is noted that fault behaviour can vary with depth, with confinement pressure playing an important role in energy release. It is noted that magnitudes of seismicity on most fault systems follow classic Gutenberg-Richter relationships between the logarithm of magnitude and the cumulative frequency of microseismic events occurring related to the fault system, irrespective of whether naturally occurring or mining induced.

The effect of water on fault induced seismicity is discussed, noting that pore pressure can reduce the effective normal stress acting across a fault and thereby induce instability, with associated initiation of shear displacement. Because any excavation damaged zones around either mining openings and/or around faults act as conduits for water, there is potential to enhance or reduce pore pressure effects if groundwater is already playing a major part in the control of movements of a fault system. Phenomena such as triggering, off-fault damage, stress shadowing and coalescence of fault segments play an important role in controlling fault behaviour, with pre-existing discontinuities and their orientation also controlling many properties.

Chapter 3 also discusses theoretical fault behaviour models for brittle faults within the upper crust, indicating that the most widely used behaviour model is based on the Mohr-Coulomb failure criterion. This suggests that a fracture initiates and spreads on the plane of interest when the shear stress exceeds a specific value depending on principal stress magnitudes, cohesion, pore fluid pressure and the coefficient of friction on the failure plane. It is noted that almost all current behaviour models being utilized for mining analysis relate only to brittle fault behaviour. Such models are considered representative for most mining situations, but may not be appropriate for back-analyzing stress states on old geological faults which were generated often under a plastic-ductile stress regime. The importance, in a mining context, of the relative stiffness of material within a discontinuity (fault system) is stressed as, when compared with the surrounding rock material, this stiffness contrast can influence local stress states and thereby influence and control fault behaviour.

Some discussion is included on current state-of-the-art discrete fracture modelling approaches and it is noted that these can be used to examine fault behaviour modes and thereby help define the magnitude of seismicity (and hence severity of associated damage) that can be generated by different scales of fault rupture. It is proposed that better characterization, both scale-wise and behaviour-wise, as well as more sophisticated numerical modeling capability, is needed when dealing with faults.

CHAPTER 4 – PALAEOSTRESS & FAULT SLIP EVALUATION

The fourth chapter brings together the descriptive aspects of Chapter 2 with the behavioural understanding from Chapter 3 as a basis for back-analysing potential fault movement behaviour. The important observation is made that structural evaluation of a mining block needs to look at regional scale features as well as drift scale fabric so that realistic fault geometry configurations can be built in 3 dimensions.

In introducing palaeostress back-analysis methods, the importance of gaining a thorough understanding of a potential mining block's past geological tectonic history is stressed. It is noted that this past history is key to defining controlling fabric hierarchy and realistically estimating changes in stress state. The benefits of undertaking comprehensive palaeostress back-analysis, which can be used to provide useful and generally reliable input into rock mechanics modelling assessments of, for example, proposed mine sequencing scenarios; far outweigh any limitations of the back-analysis techniques themselves. The techniques also have merit for evaluating a planned mining extension from an existing deposit.

Data limitations for fault slip back-analysis are discussed in the light of credible mechanics for fault development. As well, the issues surrounding acquisition of reliable lineation and rake angle data are reviewed noting that back analysis of stress states can only be as accurate and reliable as the basic lineation data collected from field observations. A significant part of the chapter steps through the various methods of palaeostress inversion analysis including: direct graphical methods, ternary diagram summary approaches, analytical Mohr circle solutions, 'beach ball' diagrams and focal plane solutions. Each is described and explained, with the respective advantages and limitations highlighted.

The concluding part of the chapter addresses slip tendency, excess shear stress and other computational methods that can be used in parallel and/or as part of a forward numerical modelling exercise for mine sequencing evaluation. An explanation is given for each of the techniques while noting that all of them are directed to contouring slip tendency on a given fault plane, assuming that for a fault to slip and/or potentially fail in a brittle manner, the magnitudes of both shear and normal stress acting on the inferred fault plane must exceed some specific threshold value which depends on the inferred shear strength of the plane.

Diagrams are included illustrating the mathematics of the fault slip tendency method and also for the excess shear stress method. Some consideration of reactivation is given, noting that remobilized movement could possibly develop where post original faulting stress magnitudes, particularly deviatoric states, exceed original stress differences. The suggestion that palaeostress back-analysis methods can also be used for forecasting slip potential and possible mining induced fault reactivation likelihood is presented.

CHAPTER 5 – FAULT CHARACTERIZATION

The fifth and final chapter addresses fault characterization from the viewpoint of ensuring adequate field definition and description of controlling features sufficient for assessing fault behaviour as described in Chapter 3 or for undertaking palaeostress or other analyses as explained In Chapter 4.

It is stressed that the importance of geologic structure, and of faults in particular, to the overall stability of operating mines means that fault characterization must receive more attention during geotechnical studies as part of routine geotechnical assessment for mines than it currently does. The simple treatment of faults as linear or undulating planes with homogeneous material properties is not sufficient for the assessment of behaviour. Faults are heterogeneous and not planar (Figure 1) as evident from the photographs in Figure 4 which show locations of the same fault with markedly differing material characteristics and fault plane orientations.

Figure 4: Fault material characteristic variation, as observed at different locations along the same fault.

Based on an assessment of fault mechanics that are important for geomechanical modelling directed towards mine sequencing evaluation, Chapter 5 targets the following factors as being key to focus on for fault characterization:

a. The system in which a fault is situated, which includes host rock characteristics, fault network, discontinuity network, mine excavation network, etc.;

b. The fault's orientation relative to the stress field; and

c. The fault's characteristics (geometry and material properties).

The concept of developing a comprehensive, integrated (i.e. fused) database of information on major fault structures that may exist within a mining block is explored within the framework of a discrete fracture network model of controlling geological discontinuity fabrics pertinent for stability assessment of the mine wide geologic system. A fully fused data environment is envisaged to encompass the whole mining block and to include all individual geologic domains that are considered of importance for mine stability. Such a database is recommended to be developed early in mine life as a framework for geologic domain assessment and fault characterization within the context of the whole mine-wide geologic system.

Once created, this integrated geologic framework of interrelated data, which characterizes not only rock mass and fabric characteristics but also describes numerically and conceptually all major identifiable faults and large-scale structure, can then form the basic reference framework for mine wide stability assessment. This integrated framework, when generated in the early exploration phase, then constitutes a skeleton which can be fleshed out as mining development occurs and additional data on geologic conditions is acquired and obtained. The framework thus becomes a “living ground model” for the mine site that is not static but is continually updated on the basis of evolving relevant datasets.

At the pre-mining stage, the spacing and variability of the following elements are identified as needing to be considered and ideally, examined within the modelled 3D environment:

i. lithology and fabric variability;
ii. discontinuity characteristics;
iii. rock mass quality; and
iv. fault segment or fault structure segment system characteristics.

During the active mining stage, it is suggested that the above datasets must be complimented through access to and use of other datasets including:

i. mine wide level plans;
ii. empirical observations; and
iii. microseismicity records.

The handbook is accompanied by two supporting appendices:

- Appendix A compiles a series of cartoons of ore deposit-types and discusses these in the light of deposit-geometry control being of most significance for mine design and assessment of potential for fault slip rockbursting or stress problems.
- Appendix B provides guidelines for standardizing geomechanical core logging and rock mass classification for use in a mining exploration program.