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Application of Fault Stability Analysis Techniques for Design of Deep Engineering Projects

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ABSTRACT:

Because of the potentially problematic conditions created to deep mining or civil projects by adverse fault slip behaviour, assessing what geological structures are under a critical stress state is becoming an increasingly important endeavour. This paper presents common structural geology techniques that are not widely known or regularly applied either for deep civil engineering design or for deep high stress mining, but which can have merit for risk minimization for excavation development. Several techniques are explored and guidelines for using fault mapping data and applying stress inversion approaches are presented for advancing understanding of past and current stress state – both of which are key to establishing propensity for slip on geological structures.

1. INTRODUCTION

For deep engineering projects (including deep mining projects, deep geothermal projects and deep civil engineering projects), faults, if adversely oriented with respect to the insitu or induced stress state can give rise to significant problems for safe excavation.

Because of the potentially problematic conditions created for deep mining or civil projects by adverse fault slip behaviour, assessing what geological structures are under a critical stress state is becoming an increasingly important endeavour. This is of particular importance in mining as mines progress ever deeper, and in civil engineering as more deep, long transportation tunnels are implemented under the world's highest mountain chains.

Since for most regions of the world, the earth's crust is at a frictional dynamic equilibrium point (Zoback and Townend, 2001, [33]), many of the geological structures that might be traversed by large engineering projects could be problematic if oriented to the local stress state such that they are critically stressed. In these situations even relatively small changes created by mining or by large scale underground construction can drive these structures to failure, potentially inducing adverse seismicity, fault slip and/or even in extreme situations, severe rock bursts.

Several structural geology techniques that are not widely known or even commonly applied either for deep civil engineering or for deep, high stress mining, are explored in this paper as they can have merit for aiding risk minimization during design stages for deep excavation development. Application of two of the most promising techniques are examined and some helpful presentation methods are illustrated to show where application of these methods can lead to better understanding and hence forewarning of potential problem conditions.

2. RATIONALE

For deep mining situations, or for deep civil tunnels, particularly under major mountain chains, faulting often creates significant excavation risks. In many mining situations the ore zone is itself a major fault and all development within and across it can result in its being adversely mobilized, on occasion initiating rockbursts, sometimes well away from the plane of the ore zone, (White and Whyatt 1999, [29], Bewick et al., 2009, [4]).

Almost always in deep tunnels and excavations, bad ground associated with significant faulting exerts major influence on conditions, negatively affecting progress, Carter, 2011, [9], but all too often the character of the rockmass associated with the encountered faulting is not examined with respect either to its fault geometry or to its originating stress regime, so often the severity of potential problems are not fully appreciated prior to them being encountered, so little is done in advance to mitigate potential problems. In the case of the Yacambu Tunnel in Venezuela, which exhibited extreme squeezing conditions associated with very weak phyllites, (Hoek and Guevara, 2009 [17]) rockmass conditions were so adverse that it lead to the failure of the TBM's being used for tunnelling

Some inference that such problems could have been more severe than expected might have been better appreciated if, rather than considering all problems rockmass related, the criticality of the 2km wide Bocono Fault zone, one of the main plate margin faults of the Andes had been given more attention.

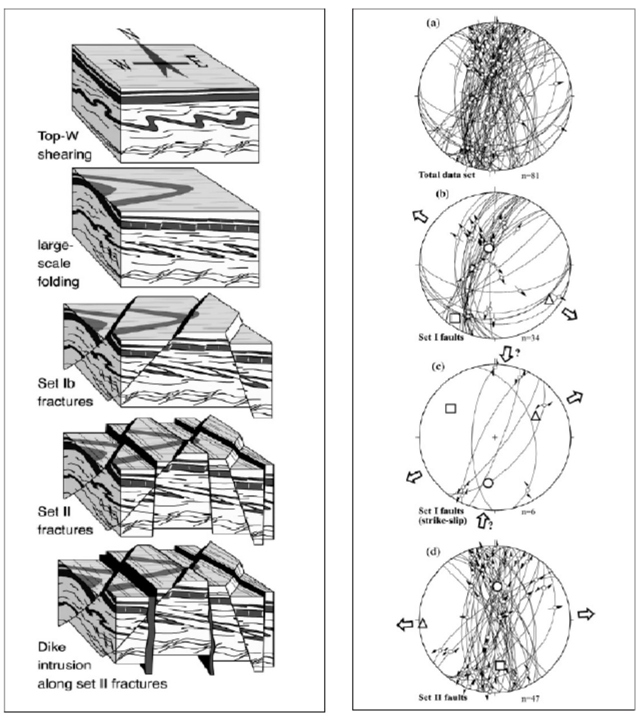

Figure 1: Block model reconstruction of geological history and associated palaeostress inversion results (after Larson, 2003[19])

Similarly, the heavy bursting which has complicated tunnelling along a several kilometre stretch of the Olmos Tunnel drive in Peru, when looked at on a plate margin scale can also be seen to be related to major tectonism of the Andes, Roby et al., 2008,[27], Lewis, 2009,[20]. Several of the faults on the Nathpa Jhakri scheme in India, including the Sungra Fault, where extremely poor ground associated with bursting and mudrush events was encountered, (Carter, 2005, 2008 [10,12]), again, when viewed on a continent-wide scale can also be seen as a major tectonic structure – in this case a recumbent sliver off the Main Central Thrust (MCT) that traverses the southern Himalayas. It is not therefore to be unexpected that stress states locally to these features, when encountered in a deep tunnel might be anomalous, with magnitudes and directions totally at variance to conditions "normal" even for such faults at that depth.

Mining may not in most cases be having to deal directly with young active crustal fault structures, but because many mines actually are exploiting ore bodies set within geologically ancient major crustal deformation zones, they may on occasion be recreating similar conditions, by remobilizing ancient geologic fault structures. This points to the need to carefully look, not just at the basic geotechnics of deep mines or deep tunnels in terms of Q/RMR/GSI and other key rock mechanics parameters, but also to look at them in much more geological detail, principally from a regional structural perspective.

In particular, *three key geological factors* need consideration over and above straightforward definition of rock mass quality, stress state and groundwater conditions – namely:

(i) structural geological regime;
(ii) current regional tectonic state, and
(iii) likely palæostress history.

In planning for tunnelling through mountain zones, or for laying out stoping sequences for a deep mine, there is merit in applying block model reconstruction techniques (such as shown in Figure 1) as a means for estimating probable palæostress history events that could exert an influence on local stress regimes. Such approaches allow the variability associated with the many different styles of geological faulting to be examined.

In a mining context, even today, much too frequently, inadequate understanding of likely mine-wide stress-structure interaction is commonplace. As will be evident from subsequent discussion, because of the often complex and frequently contorted, mining-induced stress regimes that can develop even with routine mining when major faults exist cross-cutting and/or paralleling an ore zone, quite severe stress-structure interaction problems can develop. In consequence, damaging seismicity not infrequently occurs without warning, and often before proper mitigation measures have been put into place.

Given increased geological structural understanding, it is considered that it should however be possible to alleviate some of these problems. Block model reconstruction of palæostress history, as per Figure 1, complete with stereonet synthesis of structural fabric data for each stage of faulting genesis, can yield key information on possible changes in stress configurations over geologic time. These palæo-history reconstruction approaches if applied early enough in the design process can allow estimates to be made of controlling stress orientations and ratios of principal stress magnitudes.

Insight can thus be gained way prior to being able to get underground and measure stresses.

Application of structural analysis tools holds potential also: (i) for aiding evaluation of difficulty of crossing specific faults on a planned tunnel alignment or within a planned mining extraction sequence, and (ii) for helping with definition of adverse principal stress orientations in a mature mining situation that could potentially rejuvenate old faults.

3. METHODS

Two standard structural geological techniques which have merit for evaluating relationships between stress state and faulting are: (a) palæostress determination by fault-striæ data inversion; and (b) slip tendency analyses for fault stability ranking.

For both analysis methods, two different situations must be distinguished: (i) the creation of new faults and (ii) the re-activation of existing faults or other planes of weakness. The first case is an idealized end member which almost never occurs in natural settings, but can occur as a result of fairly large scale mining, where stress states have been significantly altered. The second situation is much more commonplace, as in the vast majority of geological settings pre-existing planes of weakness exist cross-cutting any rockmass. Applying some of the proposed techniques outlined in this paper to establish stress state ahead of an excavation may help also in assessing the potential for activation of new or re-activation of ancient structural planes.

3.1. Palaeostress estimation techniques

A substantial literature exists on palæostress inversion techniques, largely based on brittle tectonic stress indicators, including several methods for evaluating fault-striæ data sets. A complete review of most older methods can be found in Ramsay and Lisle (2000, [26]) while recent review in Célérier et al. (2012,[14]) provides information on newer developments.

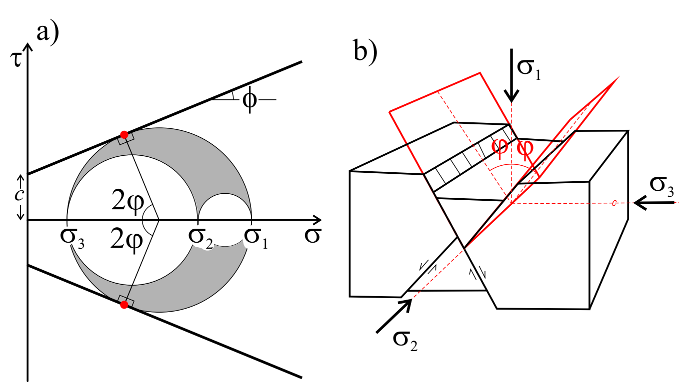

Figure 2: a) Coulomb criteria in a Mohr diagram. b) Relation between stresses and conjugate set of faults

Rock failure and formation of faults has been traditionally evaluated using Coulomb's failure theory, where strength is controlled by cohesion, *c*, and internal friction ϕ. The display of this failure criterion in a Mohr diagram (shear vs. normal stress plot, Figure 2a) shows that with this criteria two conjugate fault planes should be formed (Figure 2b).

The orientation of the stress state controlling the formation of this conjugate fault system as shown in Figure 2b can be inferred as the following: σ_2 is parallel to the intersection line of the conjugate fault planes, σ_1 is perpendicular to σ_2 and bisects the acute dihedral angle formed by the conjugate fault planes and σ_3 bisects the obtuse dihedral angle of the conjugate fault planes and is thus also perpendicular to σ_1 and σ_2.

If only one fault plane is visible but movement sense is known (e.g. indicated by a slickenline – ie., striæ on the fault surface) one can still infer the orientation of the forming stresses by making two assumptions: (i) the ideal situation of Figure 2b is valid and (ii) some internal friction angle ϕ (typically 30° – 40°, Byerlee, 1978, [7]), controls slip. Given these assumptions and noting that by definition σ_2 is in the plane of the fault, i.e., is perpendicular to the slickenline, and σ_1 and σ_3 are in a plane perpendicular to σ_2, and they make an angle φ of respectively $45° - \phi/2$ and $45° + \phi/2$ with the slickenline, controlling fault geometry type can be readily deduced.

Since most real rock masses fail on pre-existing planes of weakness and these may not necessarily be optimally oriented with the original forming stress state (as is assumed in the derivation of Figure 2) often the geometrical relation between principal stress orientations, fault plane geometry and actual slip direction is seldom as simple as presented above. The approach to constrain the stress orientation is thus based on the assumption that the slip direction and the maximum resolved shear stress on the fault plane of concern are in the same direction.

This assumption, known as the Wallace-Bott hypothesis (Angelier, 1994 [1], Ramsey and Lisle, 2000, [26]), allows a set of measurements on specific faults to be used to back-calculate the most likely principal stress orientations and stress regime.

Finding the stress state that is assumed to have created each fault is an inverse problem and hence the analytical process to undertake these analyses is called palæostress inversion. The methodology however allows not only back-calculation of the principal stress directions but also allows determination of the controlling principal stress ratio $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$, (Angelier, 1994, [1]), with the resolved shear stress direction being dependent on this ratio only (and independent of the actual stress magnitudes).

As multiple re-activations of a single fault plane or multiple re-activations of various individual fault planes by different stress regimes at different times in their geological history are common, it is critical to carefully sort field data prior to proceeding with palæostress inversion calculations and analysis.

3.2. *Fault stability and slip tendency*

While the palæostress inversion approach just considered allows one to look backwards based on existing fault characteristics as a means to estimate possible ancient controlling geologic stress states, often one also wishes to do the opposite – and identify those faults and structures that might become a problem when stress states become altered – as for example often happens in a mining situation. The slip tendency analyses approach outlined below provides this corresponding forward projection solution in contrast to the backward looking palæostress inversion approach. The methodology discussed below was originally introduced by Morris et al.,1996, [21] as a method to evaluate the relative potential for fault activity to occur given a specific stress state. It is based on the assumption that faults are cohesionless interfaces and their re-activation occurs when the resolved shear stress on the fault plane, τ, exceeds the frictional resistance to sliding, which is a function of the resolved normal stress on the fault plane σ_n. The slip tendency, Ts, is then defined as:

$$Ts = \tau/\sigma_n \qquad (1)$$

As is evident, the higher the shear stress relative to the normal stress on the fault plane, the higher the propensity for the fault to slip.

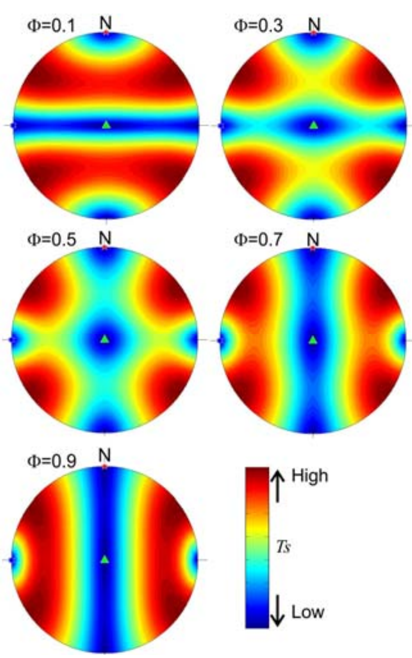

Figure 3: Slip tendency patterns on the stereonet (lower hemisphere, equal area) for various stress ratios Φ and for a strike-slip stress regime with σ_1 (red star) horizontal N-S, σ_2 (green triangle) vertical and σ_3 (blue star) horizontal E-W.

The potential slip direction and sense will in turn be driven by the direction and sense of the resolved shear stress on the fault. Contouring values of slip tendency on a stereographic projection, such as is shown in Figure 3 is one of the most useful approaches for visualizing adverse fault orientations.

In such a presentation, the pattern of slip tendency does not depend of the actual stress magnitude but only on the stress ratio, Φ and the orientation of the principal stress axes. For non extreme cases, including the case where $\Phi \approx 0.5$, the critical orientation for potential slip is well defined by a unique conjugate set of planes, but when Φ reaches the extreme limits of 0 or 1 the orientations prone to slip cover a wide range of geometries, describing a complete cone of orientations with respect to the stress directions, all with equal propensity to slip.

This is diagrammatically shown in Figure 4 alongside characteristic "beachball" diagrams for the three classic Anderson modes of faulting – normal, (right diagram), reverse/thrust (top left) and strike-slip (lower left).

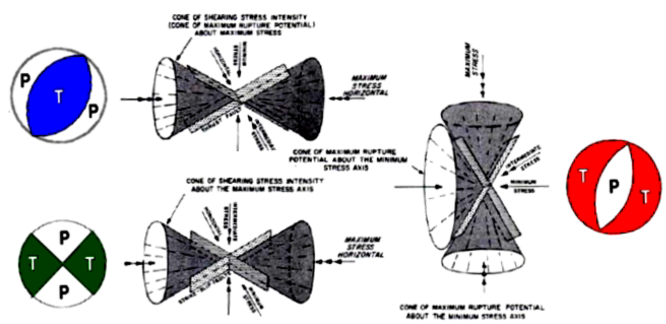

Figure 4: Characteristic cones of possible location for major principal stress with respect to shear directions and definition beachball plots (after Badgley, 1959, [11])

For any given fault of interest, in addition to the control on stress tendency orientation and stress ratio Φ, exerted by the geometry of the situation and the prevailing stress state, the actual magnitude of slip tendency depends on the mean and differential stress magnitudes. In situations where stress states are isotropic, even with relatively high mean stresses, high normal stresses are generated, thus relatively low slip tendencies result. Conversely, in areas where even moderate stress inhomogeneity exists, relatively high differential stresses develop, and thus large shear stresses will be generated and relatively high slip tendency will be computed.

Application of slip tendency analyses to engineering problems is attractive in allowing fairly rapid evaluation of a large number of potential stress ratio scenarios. Initial fault stability can be assessed (assuming only the stress ratio) and as additional constraints on the stress ratio or on stress magnitudes, are collected, these initial analyses can be readily refined.

3.3. Right dihedra and ternary plots

Irrespective of the difficulties in determining palæostress orientation from a single fault plane / striæ might be, the directions of maximum and minimum compression can nevertheless still be estimated using the right dihedra method, as for simple kinematic reasons the stress orientations must remain constrained within their respective quadrants.

As illustrated on Figure 5 the technique for constructing a dihedral plot is to draw an auxiliary plane on the sphere perpendicular to the fault plane and the striæ. The great circle for the fault plane plus this auxiliary plane then create four right dihedra or quadrants, two of them being bisected by the P-axis (the maximum compressive quadrants). Kinematically, the maximum principal stress has to lie within these two quadrants. The other two (ie., the minimum compression quadrants) are bisected by the T-axis. The line of intersection of the fault and the auxiliary plane is termed the neutral or B-axis. Taken together these three (P-, T- and B-) orthogonal directions define the kinematic axes.

Earthquake geophysicists use the same type of approach to visualize seismic events by plotting double couple focal plane inversion solutions on stereographic projections, familiarly called “beachball” plots.

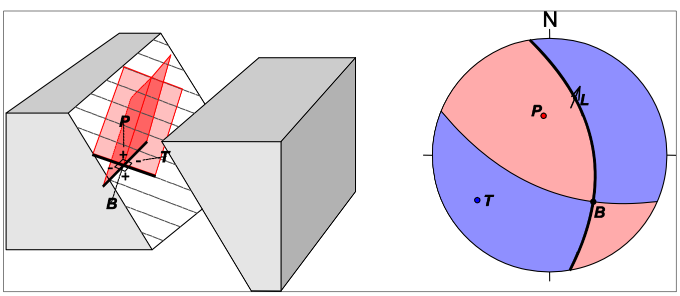

Figure 5: Right dihedra plotted in a stereographic projection (lower hemisphere, equal angle) diagram, with the maximum compression quadrants through which the P-axis passes, shown in red and the minimum compression quadrants through which the T-axis passes shown in blue. The direction of slip (as indicated by, for example, striæ on the fault) is plotted at point L, with the arrow indicating movement sense

Once one becomes familiar with what these “beachball” diagrams portray it becomes very easy to relate their geometry to any one of the classic ideal Andersonian fault models (ref. block diagrams in Figure 6). However, notwithstanding their value for visualization, importantly, it must be realized that except in the ideal situations shown in Figure 2 and Figure 6 such diagrams plotted from palæostress data rarely if ever show actual principal stress orientations.

Although the kinematic axes are usually quite close, they in fact seldom match exactly with the principal stress axes directions as real stress situations are never ideal. Despite this, in the framework that they are in fact representative of prevailing stress orientations, they nevertheless do define the ideal deformation regime implied by a given fault/striae dataset (ie., normal, reverse or strike-slip fault geometry).

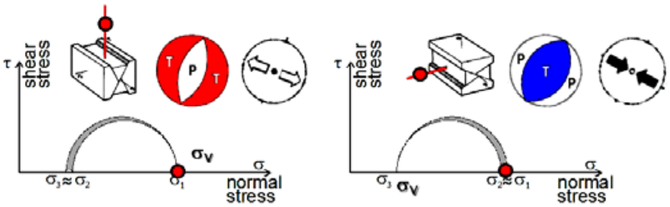

Figure 6: Classic fabrics and faulting types associated with tensional and/or compressional stress states

While individual beachball plots, such as shown in Figure 2 through Figure 6, provide good visualization of the kinematics of each specific fault fabric, plotting fabric data together on a ternary diagram, as per Figure 7 using the approach suggested by Frohlich (2001) for defining stress state geometry by reference to their kinematic axes, provides a ready means for sorting large fault solution datasets.

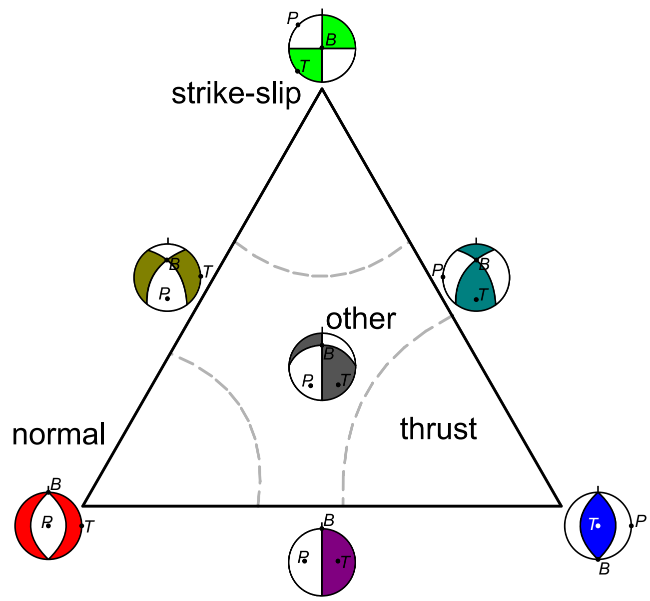

Figure 7:Ternary plot for displaying the orientation of double-couple focal mechanisms or right dihedra from fault striæ data (modified after Frohlich, 2001).

These ternary plots are cleverly simplistic in allowing fault fabric data to be sorted with respect to primary fault geometry (normal, reverse and/or strike-slip) solely by examination of the azimuth of the kinematic axis of each data point. The diagram has been constructed such that the three corners plot the end members of the spread of kinematic axes. Points plot in the left corner when the P-axis is vertical (normal regime), in the right corner when the T-axis is vertical (thrust regime) and towards the top of the triangle when the B-axis is vertical (strike-slip regime).

By convention in the diagram in Figure 7 also, rather than colouring the compressional and extensional quadrants red and blue respectively, as in Figure 5, the compressional quadrant is kept white and the tensional quadrant is colour coded with respect to fault mechanism, as defined by the kinematic axes. Red is used where the P-axis is near vertical, representing normal faults, – blue where the T-axis is near vertical, representing reverse/thrust faults, and – green where the B-axis is near vertical, as occurs where strike-slip mechanisms are dominant.

4. CASE STUDIES

To illustrate the application of these techniques, three case record data sets have been examined. These records have been selected from quite different stress regimes to illustrate the versatility of the various techniques for abstracting key data of engineering significance.

The first case record data set comes from the Himalayas from a zone of major fault disruption; the second is from a relatively stable craton where excavation at depth has not been affected by previous major mining, and the third is from a mining situation where stress changes have been of sufficient magnitude to rejuvenate existing faulting and even in a couple of cases create new faults.

Fault & Type	1-N	2-T/N	3-R	4-R	5-R	6-R
Dip	45-70°	60-70°	30-50°	40-50°	40-50°	40-50°
Strike	010-020°	010-020°	020-030°	~100°	~110°	~105°
Estimated Rake	80°	50°	80°	45°	50°	35°
Initial Intersection	Invert	Invert	Invert	Crown	Crown	Invert
Excavation Condition	Very Difficult Squeezing Conditions	Difficult with some Caving	Severe Crown Caving	Spalling & then Running Ground	Spalling & then Crown Caving	Severe Crown Caving

Table 1: Fault Type, (N=normal, T=transitional-oblique and R=reverse (thrust)), General Structural Fabric Dip Range and Summary of Excavation Behaviour during Tunnelling through several major faults along Nathpa Jhakri Headrace Tunnel (see Carter et al., 2005, [12] and 2008[10] for more details).

Excavation into and through these faults took place from four adits (as labeled on Figure 8). As a result the normal and reverse faults were tunnelled into from both sides, with somewhat different behaviour. Based on the observational data summarized in Table 1 and review of regional geology, each of Faults 3, 4, 5 and 6 were designated as thrusts with reverse shear motion, while Faults 1 and 2 appeared from available information to be normal to oblique strike-slip. As such these faults plot in different sectors of a ternary diagram (Figure 9).

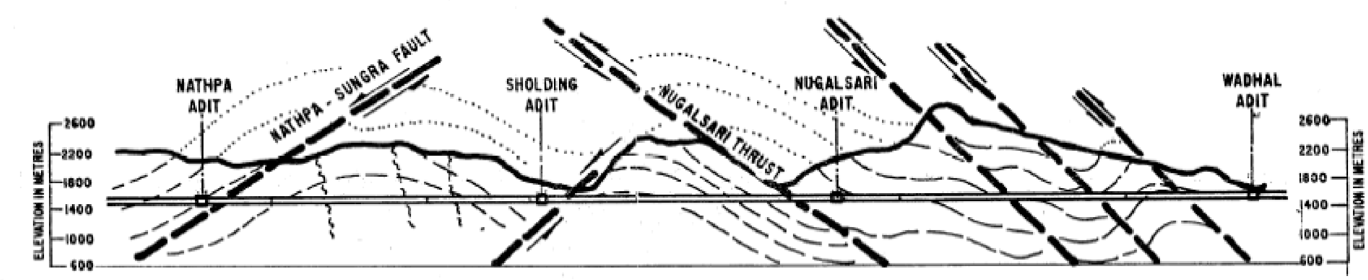

Figure 8: Schematic Interpreted Structural Section along Tunnel Alignment of part of Nathpa Jhakri Headrace Tunnel.

4.1. *Himalayan Tunnelling Examples*

Figure 8 shows a longitudinal section of part of the headrace tunnel of the Nathpa Jhakri Hydro Power scheme on the Sutlej River in Himachal Pradesh in northern India. This project involved more than 30km of tunnelling through part of the main southern boundary thrust zone of the Lesser Himalayas.

As is clear from Figure 8, six major faults were intersected within this section of the tunnel, with adverse ground conditions being encountered at each. In some cases the faulted ground was soil-like, in other cases the faults had markedly different behaviour on either side due to extreme stress contrasts. The characteristics of one of these faults is described in detail in Carter, 2008 [10] as background for analysis of its behaviour using the low-end Hoek-Brown failure extension equation.

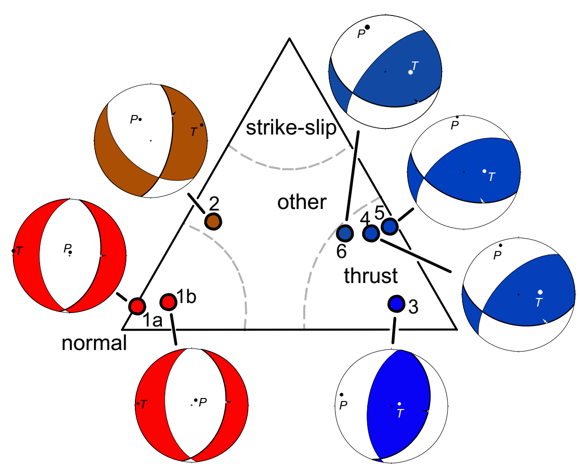

Figure 9: Ternary Diagram for Headrace Tunnel Faults (Data point numbers correspond with faults from left to right across Figure 8, as listed in Table 1). Azimuthal gnomonic projection (see Frohlich, 2001).

This type of ternary plot, being based on controlling kinematics reveals some indicators of engineering significance. First, despite the fact that the data is from multiple faults of different types (both normal and thrust), the inversion analyses (derived using the T-tecto software, Žalohar, 2010 [32]) suggest a single stress state is coherent with the kinematics (right dihedra) of all data, except Fault 3.

The palaeostress inversion suggests N-S maximum compression in an overall strike-slip stress regime (σ_2 vertical). This is consistent with current stress conditions (as compiled in the world stress map, which suggests NNE compression within a dominant thrust regime).

The field data for Fault 3 further suggests that this fault is of a completely different nature to the other faults, comprising a hundred metre wide shear structure with significant graphitic schist zones towards the fault hangingwall margin, which the other faults did not display, and also with appreciably less evidence of recent brittle activity. As such Fault 3 likely represents a more ancient tectonic feature, possibly an old plate boundary structure, thus not coherent with the stress origin of the other faults, particularly Fault 1 (which shows its maximum compression quadrant almost perfectly overlapping the minimum compression quadrant of Fault 3, confirming a quite different reactivating stress regime).

Of note also are the differences in tunnelling behaviour for these faults, suggesting that mining under faults is more adverse than mining over them, and that mining through normal mode faults seems in general to have lead to more crown caving than through the thrust faults.

4.2. Stable Craton Mining Examples

The second geologic environment case record datasets explored in this paper are derived from two mine site areas within the seismically relatively stable west central part of the US. One of the cases is from a still active mine site in Idaho – the Lucky Friday Mine. The other is from a closed down mining operation in South Dakota – the old Homestake Mine, that is currently undergoing a facelift as a new deep underground research facility.

These two sites are now in stark contrast seismically, as when both sites were operating mines both experienced significant micro-seismicity, but now only the active mine is experiencing events. The dormant mine site has become aseismic, since mining has ceased.

As such this inactive mine now provides a unique opportunity to examine deep stress states in a relatively undisturbed rockmass. Although new excavations have been constructed at depth at this site with access being provided along drifts and shafts peripheral to the old workings, these new excavations are sited in a stable part of the rockmass, more than 500 m from any influence from the original mining. As detailed data is available from underground overcore stress measurements undertaken as part of the investigations for the new facilities at SURF, formerly DUSEL, (Carter et al, 2011, [11]), the data from mapping of these new excavations, (which have been constructed for part of the newly extended Davis Campus Complex) now allow unique analysis of the affect of incipient faulting on deep rockmass stress conditions.

Mapping of these excavations, which comprise a 35 m long 15 m wide new cavern, an extension to the existing Davis Chamber and a number of drifts. identified a series of healed, ancient minor faults, as plotted in Figure 10, with beachball representations for each.

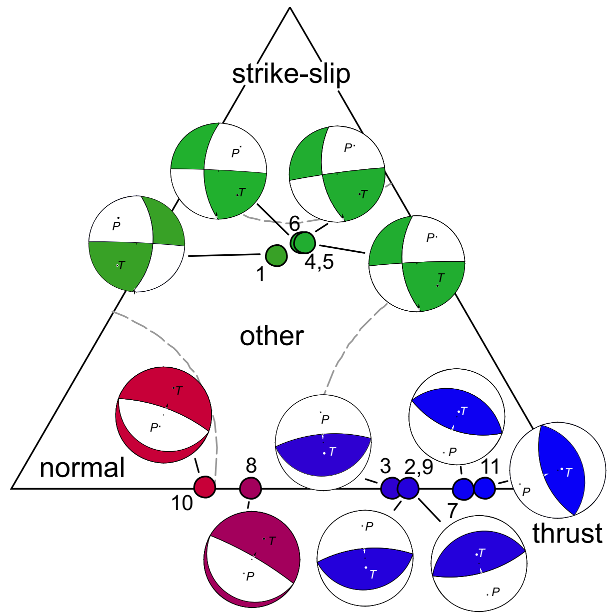

Figure 10: Ternary Diagram for the Davis Campus Complex fault data of Table 2.

	All data		Faults 8, 10 and 11 only	
Stress	Trend / Plunge	Magnitude Ratio Φ	Trend / Plunge	Magnitude Ratio Φ
σ_1	187 / 02	0	219 / 69	0.3
σ_2	078 / 84		127 / 01	
σ_3	277 / 06		036 / 25	

Table 2: Estimated Palæostresses associated with ancient mapped faulting at depth in the Davis Cavity and Transition Cavern at DUSEL (derived from Carter et al., 2011, [11])

As will be observed from the stereonets and the table all of the faults have strikes ranging from N-S to N20°W, which corresponds approximately with the orientation of local bedding/foliation and regional large-scale folding. Most observed features were also mapped with relatively steep dips (typically 50-90 degrees) with most exhibiting well developed continuity, with many observable and traceable for 20-50 m across the largest excavation spans and between adjacent excavations.

It was also noted from the mapping that offsets along the N-S trending faults indicated displacement along both strike and dip, suggesting an oblique nature. Displacements on these features were measured to range from approximately 50 to 600mm with most mapped features being well healed with quartz, calcite and occasional pyrite.

The solution of the inversion for the two sets of analyses are given in Table 2. The first set of results suggests an overall N-S maximum compression with the stress ratio $\Phi = 0$, i.e., (σ_2=σ_3) indicating a stress regime at the limit of thrust and strike-slip.

The second analyses, which was run with the three faults with distinctly different fabrics, leads to an estimate for a "normal" regime with a NE-SW extension (Figure 11b and Table 2).

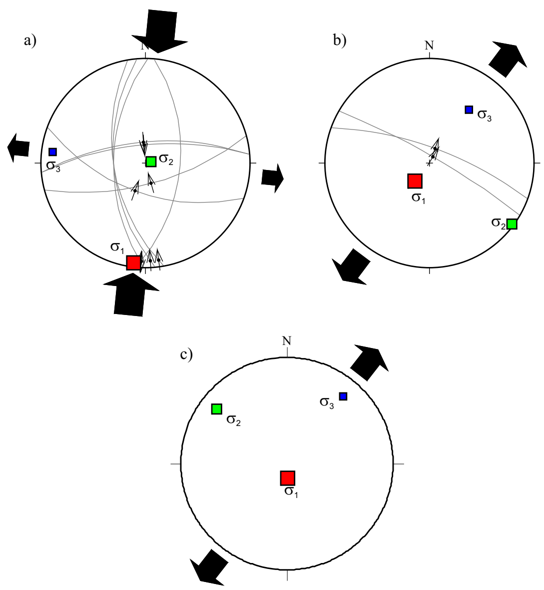

Figure 11: Stress inversion of fault data, plus current stress information. a) Inversion of all data except Faults 8, 10 & 11. b) Inversion of Faults 8 and 10. (In this case, Fault 11 is excluded). c) Current Stress Orientation, from overcore data as listed in Table 3 (from Carter et al, 2011, [11])

Stress	Magnitude [MPa]	Trend / Plunge	Magnitude Ratio Φ
σ_1	44	175 / 75	0.26
σ_2	30	308 / 10	
σ_3	25	040 / 11	

Table 3: Principal Stresses and Orientations at the 4850 Level (from Carter et al., 2011, [11])

These palæostress inversion results are quite revealing in that the results of the first inversion are quite different from the current stress state, but the results of the second inversion are very comparable with the overcore data, both in orientation and stress ratio. This suggests a polyphase stress history with a past compressive to strike-slip stress regime evolving more recently to an extensional regime.

This now stable case is instructive in that the second set of palæostress assessment yields a stress state very similar to that inferred from insitu stress measurements. The same situation is not the case for the still active mine site at Lucky Friday in Idaho.

By contrast, here high levels of micro-seismicity, some resulting in rock bursts continue to be experienced (Whyatt et al, 2002, [30]). The data from examination of the burst sites suggests that much of this seismicity has occurred in close proximity to the stoping areas along the main galena-silver vein. A few, remarkable others have occurred way off vein.

White and Wyatt (1999, [25]) report that some events have occurred on faults while others have been identified to involve "normal" geometry slip on inclined bedding dipping at about 50° to the sub-vertical stopes. Other events have been found to have occurred associated with formation of new thrust structures. Yet others have been identified from focal plane solutions to be predominantly strike-slip occurring within the boundary zones to the stoping, in an orientation parallel with bounding (control) faults. White and Whyatt [25] suggest that there is no clear mechanistic control, but Board, 1994 [6] suggested that because most of the mining stress re-adjustment is concentrating stress through remnant sills and around abutments, there was a preferred increase occurring to the major principal stress, which is oriented more or less perpendicular to the vein, favouring the generation of thrust fault structures.

Several methods of palæostress determination have been tried over the years at Lucky Friday and other Coeur d'Alene mines as approaches for determining the prevailing stress state. According to Whyatt et al., 1995 [31] the variable results from these palæostress assessments compared with insitu stress data from measurement, suggest a multi-phased stress history, with difficulty of applying the data to current conditions.

Although there is conflicting evidence in some of the papers, Whyatt et al, 2001 [30] seem convinced that the largest seismic events have all occurred out in the walls on faults, primarily in the hangingwall and they particularly note that some of the most devastating bursts in the Coeur d'Alene district have occurred when the vein becomes a seismically active fault.

One such burst case is illustrated in Figure 12. Back-analysis of this burst situation as shown in the stereonets in Figure 13 below suggests transpressional to pure thrust as the controlling mechanism.

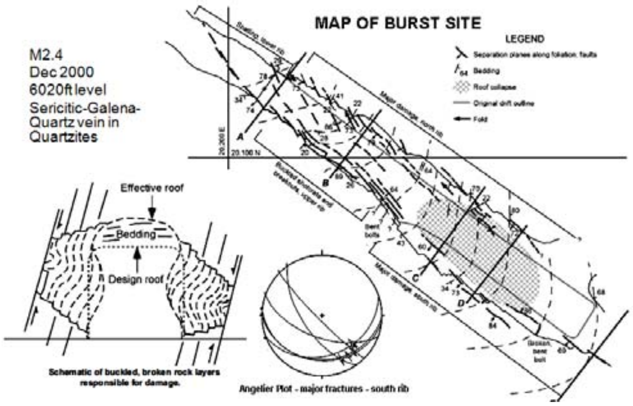

Figure 12: Map of geological structure associated with a rock burst at Lucky Friday Mine from Blake & Hedley, 2003,[5]

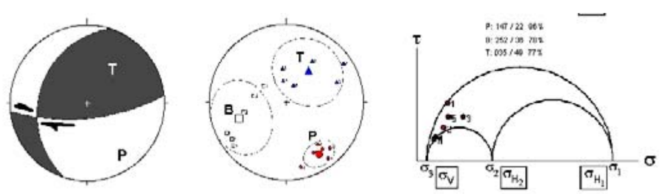

Figure 13: P-T "beachball" diagram and stress plots from Fault Slip information illustrated in Figure 12 (based on mining-induced slip data assuming Coeur d'Alene geological lineation and fault data from Venkatakrishnan, 1984 [28] and Bennett & Venkatakrishnan, 1982 [3])

Based on their evaluations Whyatt et al, 2002 [30] give guidance that mining drifts should always penetrate faults at a high-angle rather than more strike parallel, as this limits exposure to slip-bursts, noting that such bursts cause the greatest damage close to the intersection of the fault with the mine openings. The corollary to this, which is of importance to back-calculation of the point of any fault's remobilization is that such bursts seem to preferentially occur when stresses have become rotated sufficiently that they have rejuvenated the fault's original creation era stress field.

When overall mine geometry becomes large enough and stresses become re-adjusted over a sufficiently wide block of ground, faults can become rejuvenated, often triggering large seismic events, which wouldn't have been expected based on minor changes being brought about by day-to-day mining.

This situation is clearly seen in the third area case records from South Africa outlined below.

4.3. *Deep Mining Case Examples*

Conditions in the deep South African gold mines at significant depths (in some parts in excess of 4,000m) leads to extremely high stress levels and, as a result significant stress-driven fault-reactivation problems have occurred over the years. In some instances new faults have been created by the scale of mining-induced stress changes involved in initiating slip, Ortlepp, 1997 [24] .

Ortlepp, 2001 [25] reports one particular case where a very large mining-induced seismic event M_L=4.7 shook the town of Welkom in January 1989. Subsequent investigation indicated that this mining-induced event had mobilized an approximately 2km strike extent of a major fault that had been intersected in several places by the mine workings. Underground inspection of one drift excavated through and almost perpendicular to the fault strike, but way away from the zones of major mining, showed ~400mm of co-seismic dip-slip displacement across the fault trace.

Although mining induced seismicity of the magnitude of this event, which occurred on the Brand Fault, are rare, three other similar scale events have been recorded since the 1970's on the Dagbreek fault, also in the Welkom area. Given that the known stress regime in this mining district is consistent with normal faulting, with maximum compressive stress approximately vertical and equivalent to overburden, and with the minimum stress sub-horizontal and roughly one half of the vertical stress, Figure 14 shows computed slip tendency for this latter fault for the 1999 Matjhabeng mining-induced quake (M_L=4.6) which is attributed to have occurred at a depth of 1500m.

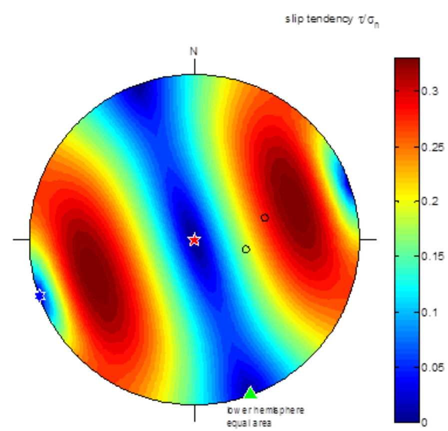

Figure 14: Slip Tendency Plot for Dagbreek Fault for M_L=4.6 mining induced quake in 1999 showing maximum potential for mid dip range eastwards slip

As will be evident from the slip tendency diagram the maximum predicted shear occurs at mid dip range, at slightly different predominant dip to the actual fault plane geometry, although close, which, given the fact that the Dagbreek fault is much shallower than the Brand Fault with dip direction/dip angles of 253°/37° to 280°/26° (Dor et al., 2002, [15]) mobilization of this fault could be expected to require less mining-induced rock mass disturbance.

Other than earthquake-induced re-activation of faulting, such major fault rejuvenation is unique to deep mining, as it's only with substantial mining activity that changes of stress of sufficient magnitude can be generated to completely remobilize a major block of ground, many kilometres wide.

Ortlepp, 2001 [22] draws the conclusion, based on the simplified classification of seismic event types listed in Table 4, that compared to seismic events and fault slip potential that exists with deep mining, the prime cause of seismic events occurring in civil tunnels in highly stressed hard rock is limited by influence volume. He suggests that only events belonging to the first two categories exist for civil cases, with most falling in the first category and only a very few in the second. The more problematic mining event cases, such as reported by Ortlepp, 2001 [22], Castro et al, 2009 [13] and Bewick et al., [4] have however occurred in mine drifts remote from stoping, so tend to be more unexpected, and as such they are of major concern to the mining industry from a planning and safety hazard reduction perspective (Carter and Bewick, 2011 [8]).

Seismic Event	Typical Characteristics	Richter Mag.(M_L)
Strain Burst	Superficial Spalling with violent ejection of fragments	**-0.2 - 0**
Buckling	Outward expulsion of large slabs parallel to opening	**0 – 1.5**
Shear Rupture	Violent propagation of shear fractures through intact rockmass (may include crushing - face/pillar bursts)	**1.0 – 3.5**
Fault Slip	Sudden renewed movement on existing fault or dyke	**2.5 -5.0**

Table 4: - Simplified classification of seismic event types (modified from Ortlepp and Stacey, 1994, [23])

In most of cases where tunnels and drifts cross a major fault that has been remobilized, generally, based on South African and deep Canadian and US experience, subsequent movement tends to be extensional, related to rockmass relaxation of the loaded abutments of the mined out block, rather than being compressional, but several fault driven rock burst cases from the Lucky Friday Mine in Idaho and elsewhere have a shear origin.

Most of the deep South African mining-induced fault movements of large scale (several kilometres strike length) are recorded as normal mode (or in some cases trans-tensional strike-slip). Accordingly, the planes of observed shear movement (Ortlepp, 2001,[22], McGarr, 2004, [22]) are characteristically steep, (typically close to $45° + \phi/2$), consistent with a sub-vertical maximum principal stress.

Some of the smaller scale displacements seen around pillars or at mining block width scale can be of reverse type, though, due to local stress redistribution with mobilization of generally lower angle dislocation planes closer to $45° - \phi/2$, suggesting a sub-horizontal major principal stress state. The data presented by Ledwaba et al., (2012) [18] describing one such shear movement at Impala Platinum Mine for example shows remobilization along a 34° dipping structure.

Contrary to natural earthquake induced fault movements, that are primarily driven by shear stress accumulation (particularly for subduction related events), mining-induced seismicity and associated fault movements are generally driven by relaxation and unclamping processes (reduction of normal stress).. As the major principal stress typically in the South African gold fields is vertical, Ortlepp and Stacey 1994 [23], any small perturbations in σ_3, due to mining relaxation, tend to enhance that vertical stress state, obviously in the case of the Welkom seismic events, sufficiently to remobilize some of the faults.

5. CONCLUSIONS

Several methods of palæostress determination have been developed over the years that can generally allow the stress regime history of an area to be well established. Fairly robust determination of stress state can be accomplished if palæostress techniques are applied to carefully collected data (which are then sorted by inferred deformation phase), with the most recent deformation phase being potentially in agreement with the current stress state obtained from in-situ testing.

In many cases, there will be agreement, but oftentimes geological palæostress back-calculation will differ significantly from in-situ stress data. This should not be taken as reason for condemning the techniques. Rather it should be seen as a means for gaining insight into previous stress regimes and geological history.

Applying these methods provides useful insight for developing an awareness of the local fault fabric and the potential for re-activation with respect to the current stress field. The techniques also allow forward thinking in a mine planning situation whereby it becomes possible to evaluate any mining-induced stress alteration (rotations and ratio changes) and see if any faults or structure becomes adversely oriented with respect to the mining created stress field.

Rather than discarding palæostress techniques as non-reliable for defining in-situ stress conditions, as seems to have been the case over the last 30 or so years, mining and tunnelling engineers should be using them to provide guidance on "what ifs" – related to potential adverse re-activation.

It should be appreciated that palæostress evaluation techniques are most useful not for defining current stress state but for developing a consistent deformation history from which it may be feasible to identify key structures that could potentially be re-activated either in the current stress field or with mining.

The information from the mining case records suggests however that fault remobilization really occurs only when stresses have become rotated sufficiently that they have rejuvenated the fault's original creation era stress field. This seems to occur only for large mining extraction when overall mine geometry becomes large enough and stresses become re-adjusted over a sufficiently wide block of ground to generate new faults or affect pre-existing faults on a fairly large scale. This scale dependency may be stress magnitude dependent, but this is far from proven.

Nevertheless it is clear from the case records that use of some of the palæostress techniques outlined in this paper might yield better understanding of overall geologic controls. It is to be hoped that use of these techniques can also become more widespread and perhaps with insight may help prevent or forewarn of conditions that might promote devastating fault slip bursting such as described, perhaps even allowing such problems of adverse stress reorientation to be engineered out by selective mine sequencing as a control on stress rotation.

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Application of the techniques discussed in this paper had fallen into disuse in parts of the mining industry partly due to changes in approach to mine planning through more focus on computer based statistical ore reserve estimation, rather than on detailed structural geological mapping and analysis of ore structure and mining extraction implications.

Several recent rockbursts in the Canadian mines rejuvenated an interest in application of these methods to help better understand fault slip. The Centre for Excellence in Mining Innovation (CEMI) in particular Dr. Peter Kaiser, Mr. Damien Duff and Mr Rob Bewick plus a number of mines are acknowledged for their contribution to this initiative. Permission for use of data from Nathpa Jhakri through Mr. Don Brophy of AECON and from DUSEL/SURF through Mr. David Vardiman are also duly acknowledged.

REFERENCES

1. Angelier, J., 1994, Fault Slip Analysis and Palæostress Reconstruction. *In: Hancock, P.L., (Ed) Continental Deformation*, Pergamon Press, Oxford, pp. 53-100.
2. Badgely, P.C., 1959. *Structural Methods for the Exploration Geologist*. Harper, New York 280pp.
3. Bennett, E.H. and Venkatakarishnan, R., 1982. A Palinspastic Reconstruction of the Coeur d'Alene Mining District based on Ore Deposits and Structural Data. *Economic Geology*, Vol. 77, pp.1851-1866.
4. Bewick, R.P., Valley, B., Runnalls, S., Whitney, J. and Krynicki, Y., 2009. Global Approach to Managing Deep Mining Hazards. *Proc. of the 3rd Canada-US & 20th Can. Rock Mech. Symp*. Toronto, 10pp
5. Blake, W. and Hedley, D.G.F., 2003. *Rockbursts: Case Studies from North American Hard-Rock Mines*. SME.
6. Board, M.,. 1994. *Numerical Examination of Mining-Induced Seismicity*. PhD Thesis submitted to the University of Minnesota. (Summary 29pp)
7. Byerlee, J., 1978. Friction of rocks. *Pure and Applied Geophysics* 116 (4), 615-626.
8. Carter T.G and Bewick R.P., 2011 *Manual: Structural Geological Guidelines for Aiding Characterization of Deep Mining Fault Behaviour*; published by Centre of Excellence in Mining Innovation, Sudbury 204pp & 2 Appendices ISBN 978-0-9879308-0-4
9. Carter T.G., 2011 Himalayan Ground Conditions challenge innovation for successful TBM Tunnelling. Invited paper in *Proc. Hydrovision India 2011 Conf*, Delhi. SESSION 5c: (Risk Management in Tunnelling), 20pp; article from 2011 paper published in *HydroWorld Magazine*, Jul-Aug 2011 Issue pp26-33 as “Successful Tunnelling in Challenging Mountainous Conditions”.
10. Carter, T.G., Diederichs, M.S. and Carvalho, J.L., 2008. Application of modified Hoek-Brown transition relationships for assessing strength and post yield behaviour at both ends of the rock competence scale. *Journal of the Southern African Institute of Mining and Metallurgy*, Vol. 108: pp 325-338.
11. Carter, T.G., Otto, S.A,. Carvalho, J.L, Popielak, R., Vardiman, D. and Hladysz, Z., 2011. Preliminary Design of the 4850-Level Excavations at DUSEL, Part 1 – Geological Engineering Evaluation of Rock Mass Conditions. *Paper ARMA 11-482 in Proc. 45th US Rock Mechanics/Geomechanics Symposium*, San Francisco,
12. Carter, T.G., Steels, D., Dhillon H.S., & Brophy D., 2005. Difficulties of Tunnelling under High Cover in Mountainous Regions, *Int'l. AFTES Cong., Tunnelling for a Sustainable Europe,* Chambery, pp. 349–358.
13. Castro, L.M.C., Carter, T.G., and Lightfoot, N., 2009 Investigating Factors Influencing Fault-Slip in Seismically Active Structures. *Proceedings of the 3rd CANUS Rock Mechanics Symposium ROCKENG09*, Toronto, 10pp. (Ed: M.Diederichs and G. Grasselli)
14. Célérier, B., Etchecopar, A., Bergerat, F., Vergely, P., Arthaud, F., Laurent, P., 2012. Inferring stress from faulting: From early concepts to inverse methods. *Tectonophysics* 581, 206-219.
15. Dor, O., Reches, Z. and van Aswegen, G., 2002. Fault Zones Associated with Matjhabeng Earthquake, 1999, Eland Shaft, Welkom. Nelsam project. (http://earthquakes.ou.edu/eland_trip_2002.pdf).
16. Frohlich, C., 2001. Display and quantitative assessment of distributions of earthquake focal mechanisms. *Geophysical Journal International* 144 (2), 300-308.

17. Hoek, E and Guevara, R., 2009. Overcoming squeezing in the Yacambú-Quibor tunnel, Venezuela. *Rock Mech, and Rock Engineering*, Vol. 42, No. 2, 389 - 418.

18. Ledwaba, L. S., Scheepers, J., Durrheim, R. J. and Spottiswoode S. M., 2012. Rockburst damage mechanism at Impala platinium. in: Proceedings of Southern Hemisphere International Rock Mechanics Symposium SHIRMS 2012. The Southern African Institute of Mining and Metallurgy.

19. Larsen, Ø., Fossen, H., Langeland, K. & Pedersen, R.B., 2003, Kinematics and timing of polyphase post-Caledonian deformation in the Bergen area, SW Norway. *Norwegian Journal of Geology*, vol. 83, pp.149-165. ISSN 029-196X

20. Lewis, W. 2009. Construccion de Tuneles Transandinos en la Cordillera de Los Andes. *Proc. Taller Internacional de Tuneles y Obras Subterranes*, Bogota.

21. Morris, A., Ferrill, D. A., Henderson, D. B., 1996. Slip-tendency analysis and fault reactivation. *Geology* 24 (3), 275-278.

22. Ortlepp W.D., 2001 The behaviour of tunnels at great depth under large static and dynamic pressures *Tunnelling & Underground Space Technology* pp 41-48

23. Ortlepp, W.D. and Stacey, T.R., 1994. Rockburst mechanisms in tunnels and shafts. *Tunnelling Underground Space Technol.* 9 (1) pp59-65.

24. Ortlepp, W.D., 1978. The Mechanism of a Rockburst, in *Proc. of the 19th US Rock Mechanics Symp*., U.of Nevada, Reno: 476-483.

25. Ortlepp, W.D., 2000. Observation of Mining-Induced Faults in an Intact Rock Mass at Depth. *Int. J. R.Mech. Min. Sci.*, 37: No. 1-2: 423-436.

26. Ramsay, J. G., and Lisle, R. J., 2000. Fault slip analysis and Stress Tensor Calculation (session 32). in *The Techniques of Modern Structural Geology: Applications of Continuum Mechanics in Structural Geology*, Vol 3. Academic Press, London, pp. 785-810.

27. Roby J., Willis, D., Carollo, B.S., and Askilsrud, O.G. 2008, Coping with difficult ground and 2000 m of cover in Peru. *Proc. WTC 2008*, Agra, India.

28. Venkatakrishnan, R., 1984. New Concepts on the Structural Control of Coeur D'Alene Ore Deposits, Idaho. Talk Presented in *Geology of Precious Metals Symposium*. 6pp.

29. White B. G. & Whyatt J. K. 1999 Role of Fault Slip on Mechanisms of Rock Burst Damage, Lucky Friday Mine. *Proc. 2nd Southern African Rock Engineering Symposium. Implementing Rock Engineering* Knowledge, ed. by T. O. Hagan (Johannesburg, Sept. 13-15, 1999). Johannesburg: Intern. Soc. Rock Mech., pp. 169-178.

30. Whyatt J.K., Blake W., Williams T.J, White B., 2002. *60 years of rockbursting in the Coeur d'Alene District of northern Idaho*, USA: lessons learned and remaining issues. SME Preprint 02–164. Society for Mining, Metallurgy, and Exploration, Inc.

31. Whyatt, J.K, Williams, T.J. and Blake W., 1995 In Situ Stress at the Lucky Friday Mine, Part 4. Characterization of Mine In Situ Stress Field. *U.S. Bur. Mines Invest. Rep., ri9582*, 27pp.,

32. Žalohar, J, 2010 *T-Tecto Program* and Software Manual

33. Zoback, M. D., Townend, J., 2001. Implications of hydrostatic pore pressures and high crustal strength for the deformation of intraplate lithosphere. Tectonophysics 336 (1-4), 19-30.