A Method for Modeling Variation of In Situ Stress Related to Lithology

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ABSTRACT: Assuring ground control safety in many mining and tunneling projects depends, at least in part, on an understanding of in situ stress conditions that will be encountered. Yet it is rarely practical to conduct more than a very limited number of stress measurements. Stresses along the route of a proposed excavation are typically interpolated from available measurements, often assuming a linear variation of stress with depth (or elevation). However, projects where multiple stress measurements are conducted often report more complex variations of in situ stress, usually in apparent relationship to geologic structures. These structures often include lithologies of contrasting elastic properties. A method is proposed for estimating stresses in these cases by first back-calculating regional loads from available stress measurements and then modeling the distribution of stress throughout the rock mass. The method has been successfully applied to a set of in situ stress measurements from the Coeur d'Alene Mining District of northern Idaho, USA. Results provided new insights into district stress conditions and the distribution of rockburst hazards along mine drifts and between various mines. This success should transfer readily to suitable deep tunneling projects.

1. INTRODUCTION

The safety of miners is too often compromised by failures of ground through any of a number of mechanisms, most of which are influenced by the state of in situ stress. Thus, a better understanding of how in situ stress varies and how these variations control the location and severity of hazards was sought as part of a research program conducted by the Office for Mine Safety and Health of the National Institute for Occupational Safety and Health (NIOSH). The proposed method for modeling in situ stress variation described in this paper is one product of this program.

More specifically, the proposed method was developed to explore the hypothesis that in situ stress variations have had a significant effect on the spatial distribution of rockburst hazards encountered during driving of development openings in the Coeur d'Alene Mining District of northern Idaho. This hypothesis was suggested by diverse results from stress measurements conducted in the district (Whyatt et al., 1995). It was supported by a 3-year study of ramp development where rockburst hazards were found to be concentrated in a number of "pockets" that constituted a small portion of the ramp system (Whyatt & White, 1998) and a case study of a rockburst fatality (Whyatt et al., 2000).

The proposed in situ stress modeling method is predicated on two assumptions. The first assumption is that stress variations within a region of interest arise primarily out of contrasts in rock mass properties (particularly elastic properties). Stiff portions of the rock mass are characterized as isolated inclusions within a softer rock mass, a characterization that could be extended to stratigraphic geometries. The second assumption is that the load path, however complex, does not vary by location within the region of interest. Since the method does not require definition of a load path, it is particularly well-suited for regions with complex tectonic histories. Other methods might be preferred where the load path is simple (e.g. Martin, 1990; Konietzky & Marschall, 1996; Homand & Souley, 1997) and where discontinuities play an important role.

The paper begins by providing a roadmap to the method and applying it to the simple case of an elliptical elastic inclusion in an initially unstressed body. The following sections extend the method for application to a rock mass, beginning with refined definitions of the relationship between various types of load sources and in situ stresses. These definitions assure unambiguous modeling of stress distributions induced by regional loads. The paper then presents a method for generating residual stress fields by relaxation of initial internal stresses, which is used to linearize generation of residual stress field estimates. These concepts are then incorporated into a fitting procedure that seeks to define a set of uniform regional loads. These loads are used to estimate stress conditions throughout the rock mass. Experience gained in applying this method to stress conditions in the Coeur d'Alene district is reviewed. Finally, factors affecting the potential usefulness of the method for mining and tunneling projects are discussed.

2. METHOD OVERVIEW AND APPLICATION TO AN ELLIPTICAL INCLUSION

The method proposed for projecting stress along the course of an excavation in a naturally variable stress field can be illustrated in the simple problem of a tunnel passing through an elliptical inclusion, perhaps an intrusive stock (Figure 1*A*). In this example, it is assumed that horizontal stress is primarily a function of regional loading and there is no residual stress. To further simplify the problem, it is assumed that regional loads are aligned with ellipse axes.

Clearly, the in situ stress field in the vicinity of the inclusion will be nonuniform and will depend on the the geometry and relative stiffness of the inclusion. The relationship between regional loads applied along ellipse axes and induced stresses, illustrated in Figure 2, has been solved exactly (Donnell, 1941). Superposing solutions for each direction of loading provides the biaxial solution. This relationship can be used to first back-calculate regional loads from the measured stresses (Figure 1*B*), and then carry out the forward calculation to determine stresses along the tunnel route (Figure 1*C*).

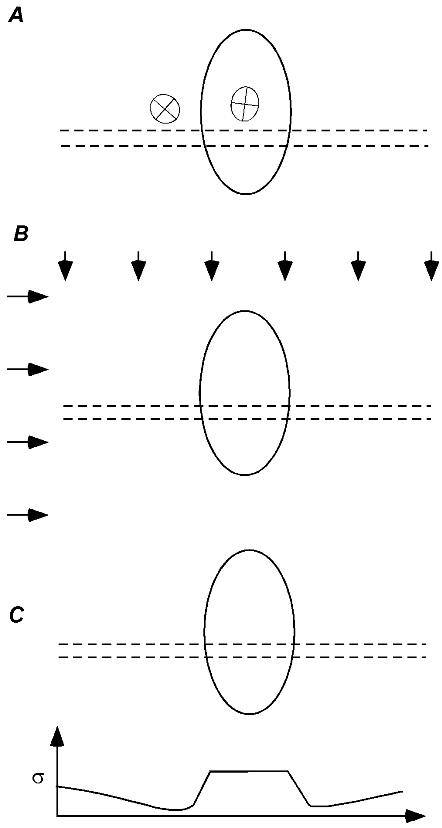

Figure 1.—Outline of modeling method. Stress measurements (*A*) are an-alyzed in light of lithologic inclusions to find regional loads (*B*), Loads are thus applied to the model to determine stresses in the region of interest, in this case, the course of a planned tunnel or mine drift (*C*).

The robustness, or insensitivity to error, of this example benefits from some characteristics of the elliptical inclusion solution. For instance, it is sometimes difficult to know the exact elongation of a buried inclusion. However, the degree of stress concentration in the inclusion increases asymptotically as the ellipse is elongated (Figure 2). Thus, errors in estimating the degree of elongation become insignificant with elongation. Also, the elliptical problem solution (and its geometric limits) has the unique property that stress is constant throughout the inclusion (Sendeckyj, 1970). Thus, the degree of stress concentration at a measurement site within the inclusion is sensitive to location error. This is particularly convenient in cases where measurements are located within the hardest available rock. This is the case with many overcore measurements, which are best suited for locations with good core recovery and linear rock deformation. Of course, real geologic structures depart from an ideal ellipse. However, these convenient properties should persist to the extent that real geologic structures approximate an elliptical geometry (and its geometric limits).

3. SOURCES OF LOAD

Real geologic settings are more complicated than the previous example in both geometry and load path. Definition of a precise and direct link between particular load sources and stresses induced within and around an inclusion is desirable for unambiguous modeling. To this end, the following definitions were developed. These definitions are extended and revised versions of definitions proposed by Hyett et al. (1986).

Residual stress: State of stress within an isolated rock mass at a uniform temperature of 25° C (77° F) that is free from all external tractions, body forces, and other load sources (i.e. gravitational, tectonic, thermal, and physico-chemical loads).

Gravitational stress: Reversible change in the state of stress caused by gravitational body forces throughout the rock mass while rock mass boundaries are maintained as lines of symmetry. A uniaxial strain model of gravitational loading is assumed [$\sigma_h=(1/1-\upsilon_v)\ \sigma_v$].

Tectonic stress: Reversible change in the stress state caused by application of tractions to rock mass

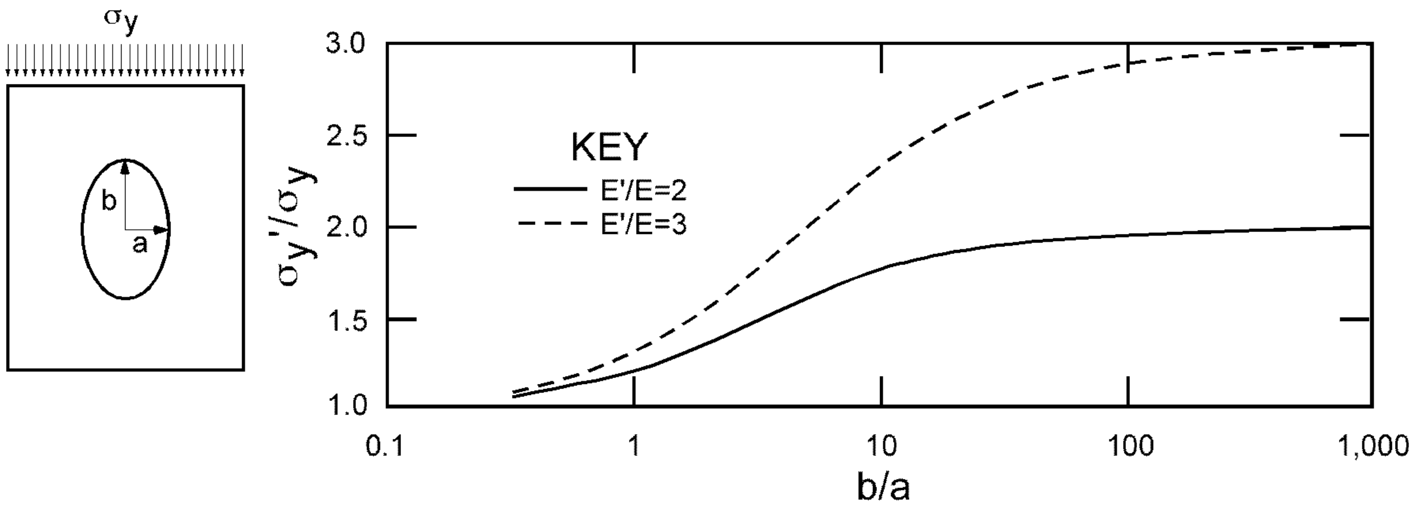

Figure 2.—Stress-concentrating effect of elliptical inclusion (plane stress).

boundaries. Does not include tractions induced byrestraint of boundary movement in reaction to application of other active load sources. Does include tractions induced by restraint of boundary movement in reaction to irreversible consequences of loading.

Physico-chemical stress: Reversible change in the stress state caused by chemical and/or physical changes in the rock (e.g. recrystallization, absorption of water, and fluctuation of groundwater levels) while rock mass boundaries are maintained as lines of symmetry.

Thermal stress: Reversible change in the state of stress caused by variation of rock temperature from a uniform temperature of 25° C (77° F) while rock mass boundaries are maintained as lines of symmetry.

In developing these definitions, a uniaxial strain model of gravitational loading was specified. However, it is not uncommon for regions relatively untouched by tectonic activity to develop horizontal stresses in excess of this model. This might occur for one of two reasons. First, it may be that an alternative model of reversible generation of horizontal stress, such as a global model of gravitational loading (e.g. Sheorey, 1994), is simply superior to the uniaxial strain model. In this case, it might be useful to apply that specific model.

Second, any tendency toward viscous deformation in such a rock mass will tend to increase the value of horizontal stress (i.e. the apparent Poisson's ratio in the uniaxial strain model). Such deformations are driven by a reduction in the total potential energy of the rock mass. This reduction results from the combination of an increase in stored strain energy due to increased horizontal stress with a greater loss in gravitational potential energy (i.e. the rock mass slumps or settles during this viscous deformation). In a rock mass with little or no long-term shear strength, the stress state will trend toward a lithostatic distribution (horizontal stress equal to the vertical gravitational stress in a homogeneous rock mass) over time.

However, by the definitions introduced here, gravitational stresses are only those that will disappear when gravitational loading is removed. Thus, the apparent increase in Poisson's ratio is just that–apparent–and the change in stress must involve other load sources that become apparent after gravitational loading is removed. In this case, the remaining stress is removed in two parts. First, remaining tractions on rock mass boundaries are removed as tectonic loads. This removal is consistent with the definition of tectonic loading as tractions applied to rock mass boundaries. Second, the remaining internal stress distribution is removed as a residual stress state, leaving a null stress state.

These definitions also consider scale, since models necessarily address load sources and stress variations in the context of their interaction with an engineering project. As a practical matter, then, load sources must be defined relative to this scale and are seen as acting either as tractions on the boundaries of this rock mass, or internally as body forces. Since residual stress is defined as "what's left" within this rock mass after loads are removed, residual stress systems larger than the rock mass in question will contribute to the tectonic load component. Similarly, the influence of any kind of loading applied outside the rock mass of interest will be applied as a tectonic load.

Thus, some rules for behavior of rock mass boundaries are also required. These are—

- Boundaries are lines of symmetry for application of load sources within the rock mass. For example, heating of the rock mass will be mirrored in neighboring portions of the crust so that rock mass boundaries will not be displaced.
- Changes in boundary tractions caused by application of loads within neighboring sections of the crust

will be passed through rock mass boundaries as tectonic loads. For example, heating of a neighboring portion of the crust by intrusion of a batholith will exert tractions on the rock mass that are functionally equivalent to tectonic boundary tractions.

- Changes in boundary tractions caused by irreversible processes (i.e. that are not removed with removal of load sources) are, in essence, part of a residual stress system that is larger than the rock mass of interest. They are treated as tectonic loads.

These rules broaden the definition of tectonic loading and the tectonic stress field that results. The broadening arises from the fact that the exact source of boundary loads is not material to understanding the state of stress in the subject rock mass.

4. REFERENCE STATE GENERATION OF A RESIDUAL STRESS FIELD

The definitions developed for various load sources provide direct and linear methods for applying all but residual stress. All the nonlinearity associated with evolution of the in situ stress field is assigned to the residual stress state. Given the complex tectonic history of many regions, it is often difficult, if not impossible, to model generation of residual stresses accurately. The obvious alternative—directly mapping the stress field—is usually impractical. However, if a residual stress field were proposed, it would be possible to determine how closely it (in combination with stresses induced by other load sources) matched measured stresses. Then, if a number of alternatives were proposed, an error measure could be used to choose which provided the best representation of the in situ stress field. This is the approach that has been taken.

This approach requires that a large number of alternative residual stress fields be generated that are relevant to the problem being considered. Furthermore, residual stress fields are much more likely to be useful if they are linked to the geometry of relevant geologic structures in a consistent and physically meaningful way. In other words, similar inclusions within a geologic setting should be associated with similar patterns of residual stress.

The analysis would be greatly simplified if a linear procedure could be developed for generating these residual stress distributions, i.e. a method whereby a limited number of residual stress states could be superposed to fit a desired distribution of residual stress. In such a case, residual stress states could be included in a fitting routine on an equal footing with gravitational and tectonic loads. Such a method can be developed by simply assigning a uniform initial stress field to the region of interest and then allowing the model to adjust elastically in the absence of load sources. This procedure is illustrated with a simple example in Figure 3.

The essential point of this example is that a unique residual stress state (Figure 3*B*) is generated by removing the boundary load, Px, from a body with a uniform and equivalent initial internal stress field. The residual stress state is revealed as the model adjusts to the absence of loads and reaches equilibrium. This residual stress state can be quite complex, depending on inclusion geometry. Since the residual stress state can also be described by the original stress field that created it (Figure 3*A*), it may be more convenient to describe the residual stress state in terms of its generating initial internal stress field or "reference state." The reference state for the residual stress distribution of Figure 3*B* is the constant initial internal stress field of Figure 3*A*.

The reference state concept has a number of interesting advantages. First, a complex, complete and self-consistent residual stress field is specified by the very few parameters required to define a uniform initial stress state. Second, the linear, reversible relationship between a reference state and a related residual stress field is much easier to handle than the irreversible processes that create a residual stress field. Third, it provides a framework for studying how the

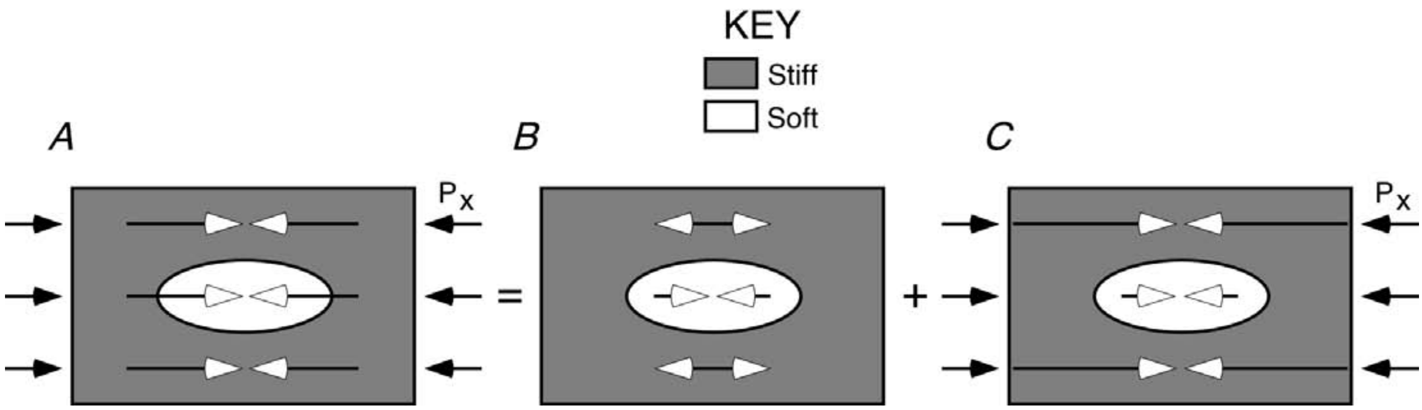

Figure 3.—Tectonic (*B*) and residual (*C*) components of a uniform stress field in an elastic model of an elliptical soft inclusion (*A*).

residual stress field relates to the lithology and geometry of geologic structures.

However, it is highly unlikely that accurate representations can be developed from reference states for all residual stress distributions that occur in nature. The hope is simply that residual stress fields can be generated that are sufficiently close to reality to be useful. When such a procedure is used in solving an inverse problem, statistical measures of the quality of fit should provide insight into whether reasonable residual stress fields are being generated. Poor approximations of significant residual stress fields will result in poor matches between model and measurement.

In exploring the potential for reference state generation of residual stress fields, it is useful to consider some characteristics of the relationship between reference state and residual stress field. These include—

Existence. All reference states will generate a particular residual stress state when load sources are removed. However, not all conceivable residual stress fields can be represented by a reference state. For example, a simple prestressed concrete beam can be imagined that contains several bars with various levels of prestress. This system will never reach a completely uniform stress state without inelastic deformation (i.e. changing the residual stress state). Residual stress states that cannot be attained exactly through relaxation of a reference state might be attainable through inelastic deformation induced by an applied load history or definition of a nonuniform initial stress state.

Uniqueness. A reference state is not necessarily a unique generator of a residual stress field in a heterogeneous rock mass. In the trivial case of a homogeneous rock mass, every uniform initial stress field is a reference state. However, the number of alternative reference states would seem to diminish greatly with the addition of geologic complexity.

Linearity. Since the reference state is defined in the context of elastic adjustment to the removal of all load sources, the relationship between reference state and residual stress field is linear. Small changes in reference state should, therefore, cause only small changes in the residual stress field.

Finally, the type of reference state that fits a given rock mass might provide some insight into how residual stresses in a rock mass were generated. For instance, if—

Low-modulus rocks are more highly stressed than high-modulus rocks, then residual stress more than nullifies the concentration of stress in high-modulus rocks that result from application of applied loads. The reference state is a higher state of stress than the applied loads. Thus, the model will expand against the applied loads, allowing high-modulus rocks to shed stress more quickly (i.e. with less deformation) than low-modulus rocks. One possible geologic interpretation of this reference state is formation of rock under high pressures followed by elastic relaxation during erosion and uplift in the absence of other sources of load.

Rocks carry the same level of in situ stress regardless of elastic modulus, then residual stress exactly counteracts structural stress induced by loading. Thus, the current state of stress is the reference state. One possible geologic interpretation is that long-term viscous processes have eliminated or greatly reduced stress contrasts between rock types. Such viscous deformation would lead toward a lithostatic stress field.

High-modulus rocks tend to be more highly stressed than low modulus rock, then residual stress incompletely counteracts or reinforces structural stress patterns. Thus, the reference state will be less than the applied loads. If residual stresses actually reinforce structural stress patterns, the reference state loads act in the opposite sense from applied loads. A tensile reference state for a rock mass, while not intuitive, is appropriate and necessary for achieving a residual stress state that amplifies structural stresses developed by compressive loading. One possible geologic interpretation is that long-term viscous processes concentrated in low-modulus rocks shift loads from soft to hard rock.

5. PROCEDURE FOR ESTIMATING LOAD SOURCES AND STRESS VARIATION

This procedure consists of (1) discovering the set of load sources currently applied to a region of interest, and then (2) projecting the state of stress caused by these loads at similar sites throughout the region. That is, the inverse problem (estimating applied loads from measured stresses) is first solved, and then the forward problem (estimating stresses from applied loads) is solved. Both steps use models of individual inclusions within the region of interest to determine relationships between local stresses and components of various regional loads (including the regional reference state).

If various inclusions are effectively isolated from each other within the region of interest, the modeling task can be broken into a number of simpler models of each inclusion. That is, if significant stress perturbations induced by the inclusions do not overlap, particularly at points of interest, there should be no difference between a regional model encompassing all inclusions and a limited number of smaller models constructed for the inclusions of interest.

These models are then loaded by unit increments of each load source component. For a three-dimensional problem with gravitational, tectonic, and residual loading, models would be run with 10 different load components. One component is the acceleration of gravity (or density of rock), which covers gravitational stress. Three traction components are pertinent, all in the horizontal plane, which may be considered to vary linearly with depth. The final six are components of the reference stress field. These components may also be considered to vary linearly with depth.

The linear relationship between unit increments of each load source component (including the reference state) and local stresses is the key to solving the inverse problem. In the forward problem, the principle of superposition can then be used to calculate the induced stress field within the model as a linear combination of stresses induced by these unit load components. In the backward problem, the load sources are fit to measured stresses. Fitting can be accomplished with any of a number of routines that reduce estimate error (e.g. a squared error measure[1]) and the solver supplied in the Excel spreadsheet program.

6. APPLICATION TO THE COEUR D'ALENE DISTRICT OF NORTHERN IDAHO

The proposed modeling method has applied with good results in an analysis of in situ stress variation in the Coeur d'Alene Mining District of northern Idaho (Whyatt, 2000). This analysis sought to reconcile widely varying measurements of in situ stress (Table 1) into a stress model that would be valid throughout the district and, hopefully, help explain observed spatial variations in the intensity of rockburst hazards. These measurements do not suggest a linear relationship with depth or elevation (e.g. Figure 4).

The regional geology of the Coeur d'Alene district is well suited to the assumptions of this method. Four mechanically significant rock types have been identified (Whyatt et al., 1996). Three of these occur in stratigraphic units while the fourth is characterized by silicification found in alteration halos emanating from quartz veins. The softest of these rock types, siltite-argillite, makes up over 80% of the accessible rock mass. Harder rock types (sericitic, vitreous, and silicified vitreous quartzite) are two to three times stiffer than siltite-argillite and are associated with economic portions of veins. In addition, these rock types typically provide better core recovery and are more isotropic than siltite-argillite rock. As such, they have been preferred host rocks for in situ stress measurements.

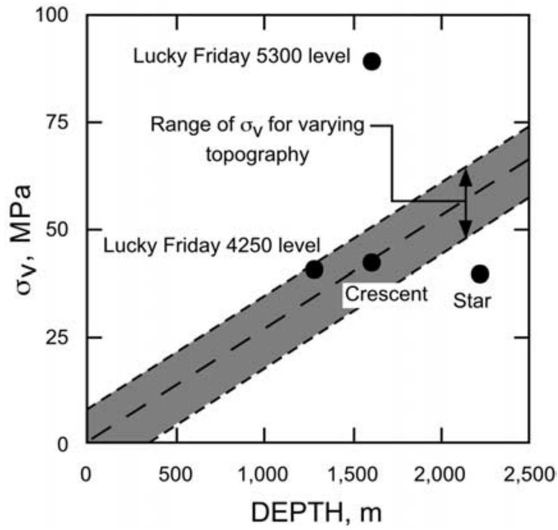

Figure 4.—Observed magnitude of vertical stress from four in situ stress measurements at various depths. Variability that can be attributed to topography is indicated by the shaded region.

Table 1.—Summary of in situ stress measurements, Coeur d'Alene Mining District, USA, megapascals

	Crescent	Star	Lucky Friday		Sunshine Mine breakouts	
	3300 level	7300 level	4250 level	5300 level	12 shaft	10 shaft
Stress σ_{h1}	54.0	66.7	89.0	113.4		
Bearing	N 20° W	N 21° W	N 38° W	S 80° W	N 80° W	N 65° W
Stress σ_{h2}	43.3	49.8	49.0	73.1		
*Measured/estimated σ_v	1.0	0.7	1.2	1.8		

*Measured vertical stress divided by an estimate of vertical stress based on depth of overburden.

[1]Defined as the sum of squares of normal stress component error plus twice the sum of squares of shear component error. Double weighting preserves invariance with respect to coordinate system.

Over the tectonic history of the district, which can be summarized as two periods of intense folding followed by three periods of intense faulting, harder rock strata have been deformed and faulted to form isolated inclusions of various shapes and sizes. The contemporary stress field is assumed to be controlled primarily by gravitational and tectonic loads, along clay-rich rock should behave over geologic time. Moreover, the method provided the best fit when intense residual stress fields were allowed to develop only at well-silicified sites. with a residual stress field.

Application of this method to these stress measurements provided a much improved stress model. For example, the squared error measurement for load sources in the horizontal plane of the measurements was more than an order of magnitude less than linear models while successfully anticipating stress orientations at the two breakout sites (which were not used in the fitting procedure). The set of loads developed in this analysis (Table 2) generated a weakly biaxial in situ stress state, close to lithostatic, in the siltite-argillite rock mass far from inclusions (Table 3). This result is well in line with how this

Table 2.—Inferred regional loads at a depth of 1500 m

Tectonic strain:
ϵ_{h1} = 1654 microstrain
Bearing = N 41° W
ϵ_{h2} = 1239 microstrain
Reference state in silicified rock:
σ_{h1} = 152 MPa (tension)
Bearing = N 67° W
σ_{h2} = 49.6 MPa (tension)

Table 3.—Estimated stress field in siltite-argillite rock far from quartzitic inclusions at a depth of 1500 m

σ_{h1} = 33.2 MPa
Bearing = N 41° W
σ_{h2} = 40.7 MPa
σ_v = 40.7 MPa

The tensile reference state for residual stress reflects the fact that silicified rocks are more highly stressed (according to both measurements and rockburst experience) than their elastic modulus would imply. This result suggests that the observed increase in rockburst hazard at these sites is due to heightened stress levels as well as to the impressive strength and brittleness of this rock type. Moreover, it suggests that the silicification process and/or resulting alteration of rock properties is associated with development of the residual stress field. As such, these silicified zones may provide interesting sites for further exploration of residual stresses.

Finally, this analysis shows that criteria for locating future stress measurement sites in the district must consider the potential for improving stress model accuracy as well as the potential for an accurate measurement.

7. CONCLUSIONS AND DISCUSSION

A method has been proposed for back-calculating regional load sources from a variety of stress measurements within a naturally varying in situ stress field. The method assumes that stress variation arises primarily from contrasts in rock properties, particularly elastic modulus, and that unusually soft or hard portions of the rock mass exist in isolated inclusions. In formulating this method, a number of definitions and boundary condition rules are proposed that clarify links between load sources and resulting reversible stresses while lumping all irreversible effects into the residual stress field. These definitions, and an approximate method of generating a residual stress field by relaxation of an initial uniform stress state (the reference state), allow back-calculation of loads with modest computational resources.

The method has been applied to an analysis of stress variation in the Coeur d'Alene Mining District of northern Idaho. It successfully found a set of regional loading conditions consistent with a diverse set of stress measurements. These loads provided reasonable estimates of stress characteristics at other points. While this model is based on a sparse data set and is far from perfect, it does provide significant advantages over linear models of stress variation with depth and elevation. Most importantly, it provides new insight into the spatial distribution of rockburst hazards.

On a more general level, these results suggest that the scatter evident in stresses measured in many regions is likely a real variation that is associated with geologic structures. Thus, consistency should be sought in load sources rather than in measured stresses. That is, stress estimates based on regional loads will often reflect stress variations that will be overlooked by direct extrapolation from available measurements. Proper investigation of load sources and modeling of associated stress variation should prove beneficial to most underground engineering projects sensitive to in situ stress conditions, but will be particularly well suited to tunnels and mine drifts extending through diverse geologic conditions.

These results also suggest that the number and spatial distribution of stress measurements may often be more important than the absolute accuracy of the measurements.

8. ACKNOWLEDGMENTS

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