In Situ Stress Measurements at the Stillwater Mine, Nye, Montana

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ABSTRACT

The magnitudes and directions of in situ stresses affect the stability of mine openings, as well as the type and amount of ground support needed to maintain a safe working environment for miners. Using hollow inclusion stress cells, researchers from the Spokane Research Laboratory of the National Institute for Occupational Safety and Health obtained two in situ stress measurements from the face of two footwall lateral drifts at the Stillwater Mine near Nye, MT. The first measurement, obtained in 1997, was collected under the valley beneath the Stillwater River. The second measurement was obtained in 2002 under the main frontal massif of the Beartooth Mountains in the western sector of the mine. Although few data are available, the major principal stress under the valley has been recorded as nearly horizontal in a north-south direction perpendicular to the ore body, while beneath the mountains, stress runs east-west parallel to the ore body. This paper documents the measurements, describes the in situ stress state, and discusses a finite-difference analysis of the biaxial test.

1. INTRODUCTION

Because ground falls continue to be a major contributor to underground injuries and fatalities in the mining industry, researchers at the Spokane Research Laboratory of the National Institute of Occupational Safety and Health and associates are studying the conditions that control ground falls. One condition that influences excavation stability is in situ stress. To obtain measurements of in situ stress, hollow inclusion cells (HI-Cells) developed by Australia's Council for Scientific Investigation and Research Organization (CSIRO) were installed at two locations at the Stillwater Mine.

The Stillwater Mine, the largest primary producer of palladium and platinum in the Western hemisphere, is situated in the Stillwater igneous complex in south-central Montana, USA. The Stillwater Complex is a 42-km- (26-mile-) long, layered, stratiform, mafic-to-ultramafic igneous intrusion approximately 2.7 billion years old that hosts a palladium- and platinum-rich layer known as the J-M Reef. Currently, production is primarily accomplished using variations on horizontal cut-and-fill mining, but longhole stoping practices are playing an increasingly important role.

Originally deposited almost horizontally, the complex was tilted to the north during the Eocene Laramide Orogeny. This event resulted in the strike of the J-M Reef being approximately 290° with a dip from 45° to 70° north. The predominant orientation of the faults is parallel with strike. A large reverse fault lies from 0 to 91 m (300 ft) stratigraphically above the hanging wall of the J-M Reef and is known as the South Prairie fault. Two other large thrust faults (the Lake and the Horseman) have the same strike but opposing dip angles to the ore zone. The Lake fault lies about 915 m (3,000 ft) below the J-M Reef while the Horseman fault lies approximately 1,040 m (3,400 ft) above it. Doleritic or diabasic mafic dikes cut the Reef and typically strike northwest and dip about 35° to 70° southeast. Several strike-slip faults lie perpendicular to the Reef and dip steeply east or west (Page and Zientek, 1985). Figure 1 is a plan view of the J-M Reef, the faults, and the Stillwater River, as well as the two in situ stress measurement sites. Figure 2 shows the location of the two sites in vertical section. The first overcore was done on September 11, 1997, under the valley 515 m (1,700 ft) beneath the Stillwater River (Johnson et al., 1999). At the second site, located under the plateau of the Beartooth Mountains and west of the western wall of the Stillwater valley, two successive overcores were taken on April 5 and 6, 2002, at a depth of approximately 850 m (2,800 ft) below the surface.

2. IN SITU STRESS MODELS

Before the measurements are described, it is useful to predict in situ stress using overburden pressures and the Sheorey equation.

Hoek et al. (1998) review the current models used to estimate in situ stress. Hoek reports that although there is significant amount of scatter in vertical stress measurements taken around the world, vertical stress can be estimated using overburden stress. Overburden stress is the product of the depth and the unit weight of the rock. At the

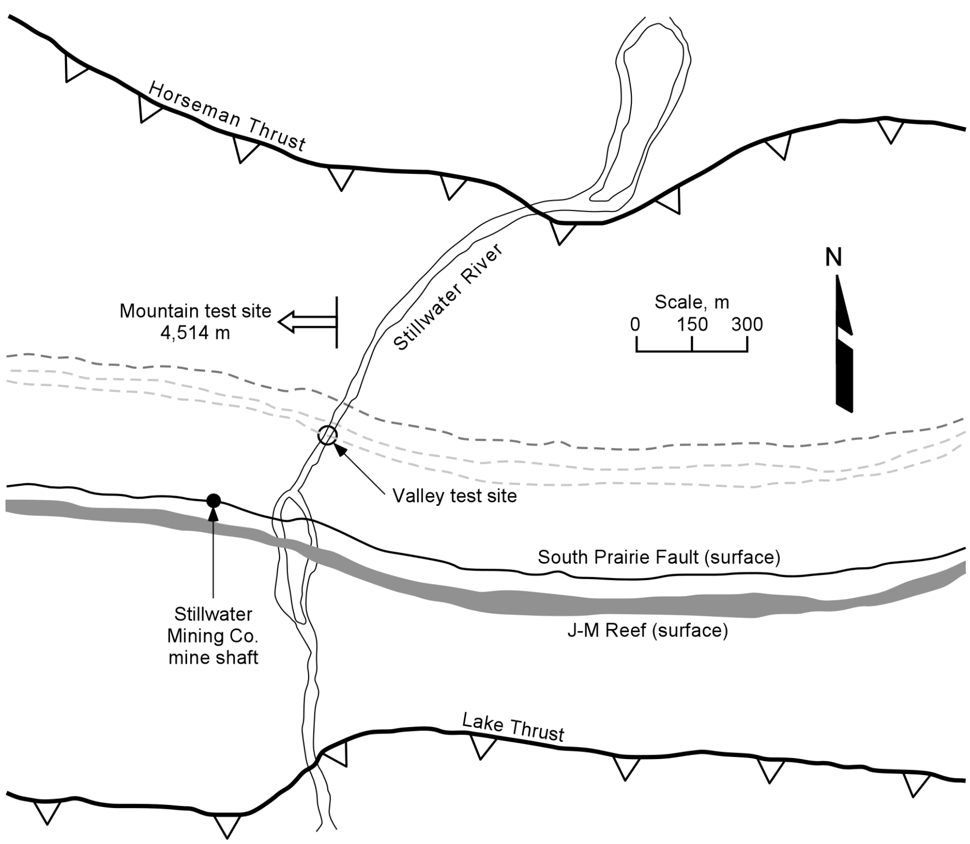

Figure 1—Plan view of surface structures at the Stillwater Mine and location of stress measurement sites. Dashed lines show J-M Reef and South Prairie fault projected underground.

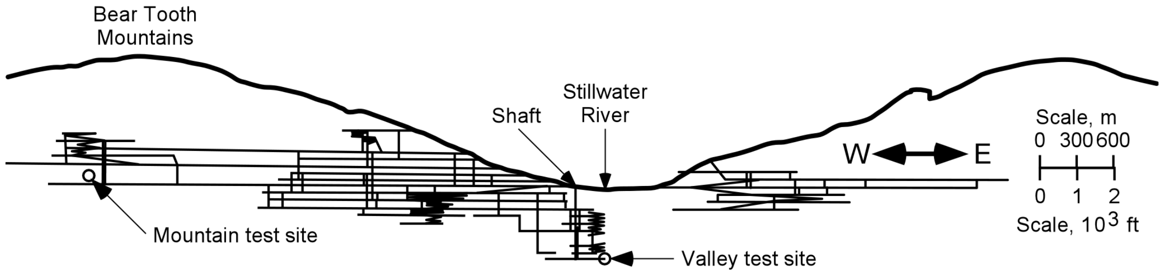

Figure 2.—Vertical section of Stillwater Mine showing location of stress measurement sites.

Stillwater Mine, the specific gravity of the rock is about 2.8, giving a density of about 2,800 kg/m^3 (175 lb/ft^3) and producing a vertical stress gradient of about 0.03 MPa/m (1.2 psi/ft). An estimate of vertical stress at a depth of 518 m (1,700 ft) under the valley is 14.4 MPa (2,090 psi). Under the mountain, at a depth of 850 m (2,800 ft), overburden vertical stress is 23.8 MPa (3,450 psi).

Models for horizontal stress are usually expressed as a ratio of average horizontal to vertical stress, denoted as "k." Hoek et al. (1998) present the Sheorey equation for computing k as—

$$k = 0.25 + 7E(0.001 + 1/z)$$

where E = elastic field modulus, GPa,
and z = depth, m.

Johnson et al. (1999) report an elastic modulus of the rock of 55 GPa (8 million psi). k then equals 1.3, giving an average horizontal stress under the valley of 18.7 MPa (2,700 psi). The computed Sheorey value under the mountain is 1.1, giving an average horizontal stress of 26.2 MPa (3,800 psi).

3. TEST DATA

Azimuth and dip, as well as position in a coordinate system, are required to orient the direction of the stresses. At the Stillwater Mine, a mine grid coordinate system is used that takes advantage of the general east-west trend of the ore body by defining east and west as being parallel to the ore body and equal to the Montana state plane azimuth minus 20° (State of Montana, 2001). The mine grid coordinate system is thus aligned with the J-M Reef, allowing stresses to be presented orthogonally to the reef. The mine grid azimuths for the valley and mountain sites are 100° and 90°, respectively, as measured as a positive angle east of north. Dip is defined as a positive angle measured downward from the horizontal. The borehole dip angle at both sites was -5° to allow for water drainage.

The standard procedure for installing HI-Cells was followed (Geokon, 1976). Overcoring strain changes were determined by taking the difference between initial and final measurements. The initial strains are approximately zero. Picking final strains is a bit of an art. The manual indicates that for a normal overcore, the final strain readings should become stable or flat and show little change in strain with additional overcoring distance. Figure 3*A*, 3*C*, and 3*E* show overcoring strains as a function of distance for each HI-Cell. Generally, each HI-Cell plot shows a peak strain followed by a fairly flat portion that deceases toward the end of the overcore. The reason for the decrease in strain near the end of the overcore is not known, although each HI-Cell was equipped with a 120-ohm precision resistor that showed only a small variation (about 0.1 ohm) in resistivity change during overcoring, indicating that temperature effects were not likely. The final strains for the valley and the first mountain overcore were obtained by averaging the readings in the flat portion of the curve. The final readings for the second mountain overcore were taken as the peak strains. Table 1 lists the strain changes from overcoring for the three cells at the two sites.

The elastic properties of the overcore were determined from a biaxial chamber test in which a radial pressure of 6.9 MPa (1,000 psi) was applied to the core, and the strains were recorded as listed in table 2. The biaxial test is extremely important because it uniquely determines the elastic properties of the system, including core, epoxy, and cell, that unlock in situ stress from overcoring strains. This test should be performed immediately after each overcore. Plots of strain-versus-pressure are shown in Figure 3*B*, 3*D*, and 3*F*. Each figure shows linear,

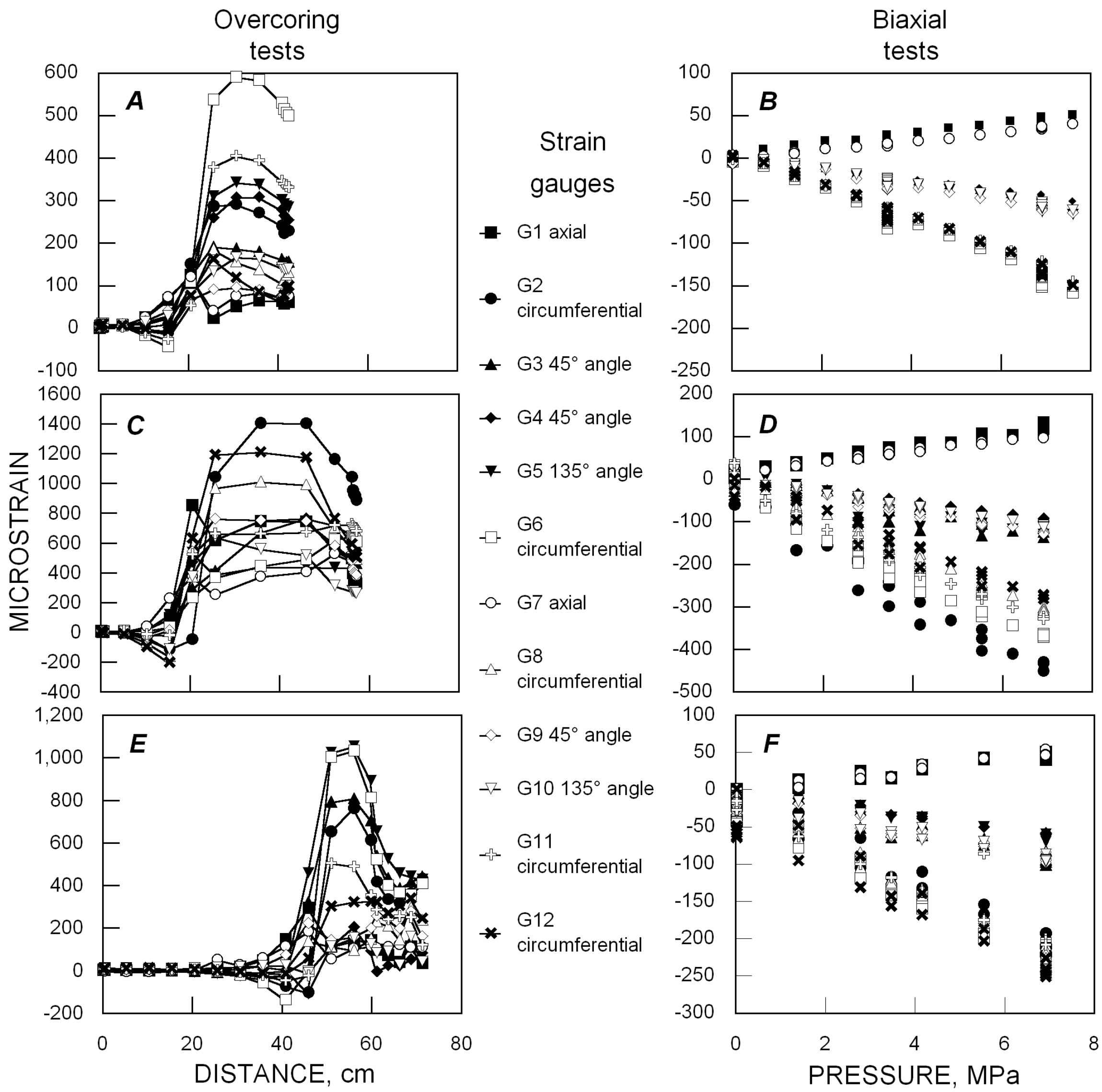

Figure 3.—Overcoring (*A, C, E*) and biaxial (*B, D, F*) strains for the valley (top row) and mountain sites 1 (middle row) and 2 (bottom row).

Table 1. Change in strain from overcoring HICell, microstrain.

ID	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
Valley .	57	275	177	304	333	580	80	142	90	159	394	96
Mtn1 . .	741	1400	712	752	433	462	389	995	746	535	661	1190
Mtn2 . .	135	760	806	202	1080	1030	100	93	155	180	486	320

Table 2. Averaged change in strain from cyclic biaxial chamber loading to 6.90, MPa.

ID	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12
Valley . .	44	-131	-49	-45	-55	-140	40	-134	-55	-55	-132	-134
Mtn 1 . .	120	-428	-100	-106	-102	-385	79	-297	-132	-109	-355	-259
Mtn 2 . .	56	-177	-71	-54	-59	-211	61	-196	-69	-37	-192	-196

Table 3. Elastic properties calculated from each biaxial test.

ID	Young's modulus	Poisson's ratio
Valley	124.8 GPa (18.1 Mpsi)	0.31
Mountain 1	48.3 GPa (7.0 Mpsi)	0.29
Mountain 2	86.2 GPa (12.5 Mpsi)	0.30

isotropic behavior. The program, STRESS91 (RST Instruments, 1991), was used to calculate material properties from the averaged circumferential and axial strains at 6.9 MPa (1,000 psi) for each overcore (table 3). Although each biaxial test was linear and repeatable, an extremely large variation can be seen in the elastic modulus of the overcores. As a check on the elastic modulus of the rock, a standard compression specimen was prepared from the EX core from the mountain site and mounted with strain gages and tested. The results of the compression test gave an elastic modulus of 96.6 GPa (14.0 Mpsi).

Because the J-M Reef is composed of similar rock, it was very surprising to see such a wide variation in elastic moduli. Researchers considered whether the epoxy might have been the source of such variation and investigated this possibility with a numerical model. Thus, as an independent check of the elastic parameters calculated from the biaxial test strains using the STRESS91 program, a finite-difference analysis was done using Itasca's FLAC software (Itasca, 2002). The model was a simple two-dimensional axisymmetric geometry of the biaxial test consisting of an EX hole, HI-Cell, epoxy, and rock. The elastic properties of the HI-Cell are a Young's modulus of 2.6 GPa (377,000 psi) and a Poisson's ratio of 0.4 (RST Instruments, 2000). The Poisson's ratio of the rock and the epoxy is 0.3. The Young's modulus of the rock (E_{rock}) was varied between the values of 125 GPa (18.1 million psi) from valley biaxial test, 96.6 GPa (14 million psi) from an unconfined EX specimen compression test, 86.2 GPa (12.5 million psi) from the second mountain biaxial test, and 50 GPa (145,000 psi) from the first mountain biaxial test. The shear moduli of the epoxy (G_{epoxy}) were varied between 1 MPa and 1 GPa (145 and 145,000 psi) (Biehl, 2000). Young's modulus of the epoxy was calculated by FLAC from the shear moduli.

The results of the analyses are shown in Figure 4. The data points connected by lines depict the strains calculated using FLAC for the different values of E_{rock} and G_{epoxy} chosen for the models. The separate data points on the right side of the graph are the actual measured axial and circumferential strains recorded from the biaxial tests in the field. The results showed very little sensitivity to G_{epoxy} and E_{epoxy} over three orders of magnitude and generally good agreement between the model results and the measured data.

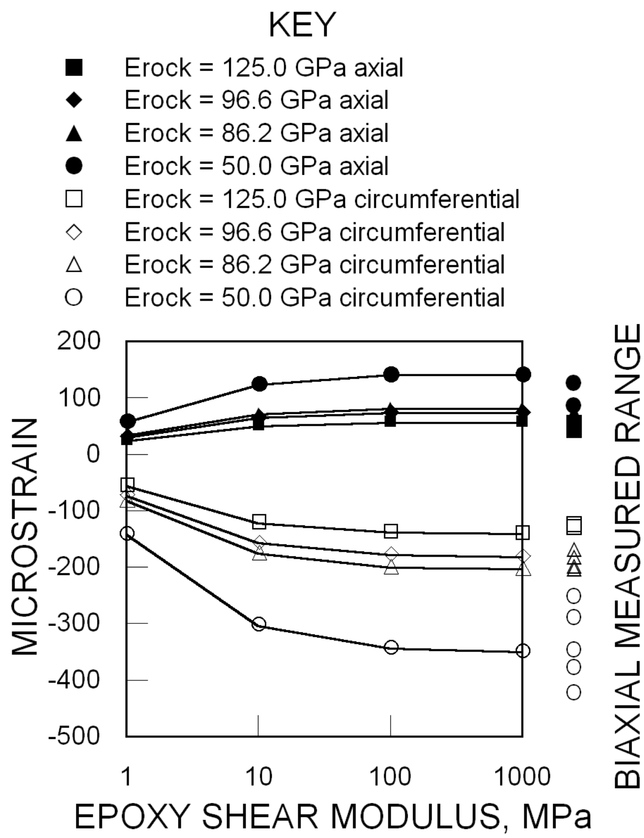

Figure 4.—Calculated strains from finite-difference analysis using measured elastic rock moduli from the biaxial tests and varying epoxy elastic moduli by three orders of magnitude.

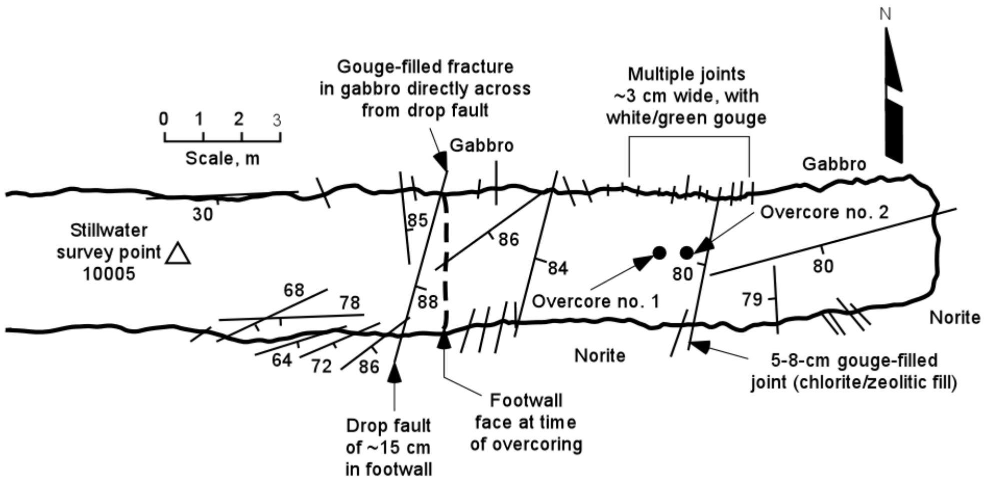

Figure 5.—Plan view of mountain stress site showing location of overcores and structural geology.

4. RESULTS

With the known stress orientation, elastic properties calculated from biaxial chamber tests, and strain changes obtained from overcoring, the in situ stress field can be calculated. It is interesting that such a large difference in the magnitude of Young's modulus between the two overcores under the mountain did not produce a large difference in calculated in situ stress. Table 4 lists the mine grid components of stress from each overcore. All the in situ stresses reported in this paper used all 12 strain gages of the HI-Cell to compute the standard error, which is defined as the standard deviation of the computed stress about the regression line.

The two mountain overcores do not show reproducibility. Since the overcore measurements were taken, the footwall drift was extended an additional 12 m (40 ft), allowing detailed mapping of the faults and joints in the drift (Figure 5). According to the map, the overcores were close to a 5- to 8-cm- (2- to 3-in) wide, gouge-filled fault. The higher shear stress and odd overcoring plot of the second overcore in the mountains appears to be affected by this fault, but the effect has a limited range of influence since the overcores were separated by only 0.6 m (2 ft).

A useful way to examine the two stress sites is to normalize the stress. This is a common practice since most in situ stress theories express horizontal stress in terms of vertical stress. Table 5 lists the mine grid stress ratios. If the second overcore at the mountain site is excluded because of the influence of the fault, then from the valley to the mountains, the east-west horizontal stress ratio is nearly constant at 1.5 times vertical stress, but varies from 1.9 to 0.8 for the north-south stress.

At the valley site, the measured vertical stress of 14.7 MPa (2,130 psi) is 2% higher than the calculated overburden stress of 14.4 MPa (2,090 psi). Under the mountains, the average measured vertical stress of 25.3 MPa (3,700 psi) is 6% higher than the calculated overburden stress of 23.8 Pa (3,450 psi). The ratio of measured average horizontal stress at site 1 gives a value of k of 1.7. The computed k, assuming an elastic modulus of the rock of 55 GPa (8 million psi), gives a k value of 1.3, which is about 25% less than the measured average horizontal stress ratios. At the second site, the computed k value is 1.1, and the average measured ratio 1.2.

The principal in situ stresses were also calculated by the program, and the results are shown in Table 6.

Orientation of the major principal stress under the valley is almost due north-south, or perpendicular to the ore body, the intermediate principal stress is east-west, and the minor principal stress is ver-

Table 4. Mine grid in situ stress and standard error in parenthesis, MPa.

ID	Sns	Sew	Svert	Sns/ew	Sew/vert	Svert/ns
Valley	28.0 (0.3)	21.4 (0.8)	14.7 (0.3)	1.1 (0.3)	-0.8 (0.3)	2.3 (0.2)
Mountain 1 .	20.4 (2.4)	38.5 (6.2)	28.4 (2.4)	2.1 (2.5)	-2.7 (2.8)	0.7 (1.4)
Mountain 2 .	35.4 (0.8)	26.8 (2.1)	22.2 (0.8)	-11.4 (0.8)	-5.2 (0.9)	8.7 (0.5)

Table 5. Stress ratios of mine grid components of stress.

Location	East-west:north-south	East-west:vertical	North-south:vertical
Valley	0.8	1.5	1.9
Mountain 1	1.9	1.4	0.7
Mountain 2	0.8	1.0	1.3

Table 6. Principal stress from each overcore, MPa.

ID	S1 (azimuth, dip)	S2 (azimuth, dip)	S3 (azimuth, dip)
Valley	28.5 (8, 9)	21.4 (276, 9)	14.2 (323, -78)
Mountain 1	39.4 (264, 14)	27.9 (235, -75)	20.0 (353, -7)
Mountain 2	24.2 (146, -14)	15.2 (109, 73)	10.9 (234, 10)

tical. At the mountain site, the first overcore shows the orientation of the major principal stress as east-west or parallel to the ore body. However, both measurements under the mountain show that intermediate principal stress is ±15° from vertical. The dip angle of the ore body is about 60° under the valley and about 45° under the mountains and does not appear to influence the direction of the principal stresses.

5. CONCLUSIONS

The orientation of the principal stresses seems to be controlled by the general east-west structure of the mine. Vertical stress is well approximated by the overburden stress gradient of 0.03 MPa/m (1.2 psi/ft). The east-west horizontal stress parallel to the strike of the ore body appears to be a constant value about 1.5 times vertical stress. The north-south horizontal stress perpendicular to the ore body appears to be a variable value about 1.9 times vertical stress under the valley and 0.7 under the mountain.

It is recommended that in situ stress measurements be continued in the Stillwater Mine to establish a database on the distribution of stresses in the mine. Future stress measurements should be made to determine the effect of depth and topography on north-south stress.

Large variations in the elastic modulus obtained from the biaxial tests do not seem to affect the magnitudes of in situ stresses. A finite-difference model of a biaxial test showed little sensitivity to the elastic modulus of the epoxy and consequently indicated that the HI-Cell is a relatively robust instrument for determining in situ stress.

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