UPDATE ON GROUND STRESSES IN THE CANADIAN SHIELD

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UPDATE ON GROUND STRESSES IN THE CANADIAN SHIELD

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ABSTRACT

A compilation of 165 ground stress tensor determinations by overcoring shows the following trends for the Canadian Shield according to regression:

Linear increase of principal stresses with depth:

	σ_1	σ_2	σ_3
Intercept (MPa):	12.1	6.4	1.4
Gradient (MPa/m):	0.0403	0.0293	0.0225
Correlation Coefficient:	0.84	0.77	0.75
(Dip direction/Dip):	248°/10°	300°-340°/00°	vertical

Change of principal stress/vertical stress ratio as an inverse with depth:

	σ_1/σ_v	σ_2/σ_v	σ_3/σ_v
Intercept:	1.7	1.2	0.9
Gradient (1/m):	272	141	30
Correlation coeffficient:	0.93	0.87	0.56

RÉSUMÉ

Une compilation de 165 mesures de tenseur de contraintes par surcarrotage démontre les tendances suivantes, obtenues par régression, pour le Bouclier Canadien

Augmentation linéaire en profondeur des contraintes principales:

	σ_1	σ_2	σ_3
Intercept (MPa):	12.1	6.4	1.4
Gradient (MPa/m):	0.0403	0.0293	0.0225
Coefficient de Corrélation:	0.84	0.77	0.75
(Azimut de pendage/pendage):	248°/10°	300°- 340°/00°	vertical

Changement en profondeur du rapport (inversé) contrainte principale/contrainte vertical

	σ_1/σ_v	σ_2/σ_v	σ_3/σ_v
Intercept:	1.7	1.2	0.9
Gradient (1/m):	272	141	30
Coefficient de Corrélation:	0.93	0.87	0.56

1. INTRODUCTION

At the Mining Research Laboratories of CANMET, EMR, 165 ground stress tensors are on file which have been obtained by overcoring methods. As ground stress determinations provide a significant input into numerical modelling for mine stability predictions, the above sample of ground stress tensors is analyzed in regard to trends in orientation and magnitude.

2. MEASUREMENT LOCATION AND PROCEDURES

Figure 1 presents a general geological map with the locations where ground stress determinations were carried out. Arrows show the direction of the maximum horizontal stresses. All measurements were obtained in Precambrian Strata.

Results from the stress determination program at the AECL Underground Research Laboratory (URL), Pinawa, Manitoba are part of the sample of stress tensors analyzed. However, to avoid drowning the relatively small sample of stress tensors obtained over a large area of the Canadian Shield in the URL data base, only 8 tensors per domain were admitted to the pool. This added 32 tensors to the 133 tensors from other areas of the Canadian Shield.

The sample of ground stress tensors compiled in this report has been obtained by strain recovery measurements during overcoring. Typical transducers used are USBM meter, South African and Australian strain cells. Theoretically these methods are all capable of identical results if a sufficient number of measurements are carried out in a relatively small volume of rock. However, non ideal rock properties, lack of full strain transfer from rock to sensor and distortion of stress fields due to geological differences introduce rather large variations. Details of methods and quality control of measurements are described elsewhere (Herget 1988).

3. ANALYSIS OF GROUND STRESS TENSORS

The ground stress tensors are listed in Table 1 with information on rock types, location and references. During the statistical analysis the following properties of the stress tensors were analyzed: orientation of principal stresses, change of first stress invariant with depth, change of principal stress magnitude with depth, increase of vertical stress with depth, change of principal stress/vertical stress magnitude with depth. Table 2 presents the results from regression analysis.

3.1 Orientation of Principal Stresses

All principal stress directions were plotted in the lower hemisphere of an equal area net. Figures 2, 3 and 4 show the orientation of trend and plunge of principal stress directions. Concentrations are expressed as % per 1 percent area:

Sigma 1:	248°/10°	highest concentration: 5%
Sigma 2:	300°-340°/00°	highest concentration: 5%
Sigma 3:	vertical	highest concentration: 8%

The most uniform plot is that of σ_3. The σ_1 direction correlates well with a recent compilation of fault plane solutions, borehole breakouts and hydraulic fracturing data. For Canada they show a relatively uniform stress field with the maximum principal compressive stress horizontal in a NE to ENE direction (Adams, 1987).

3.2 Increase of Sum of Principal Stresses with Depth

The sum of principal stresses is invariant and therefore was used as the property to check the sample of 165 tensors for homogeneity. The sum of principal stresses with depth was subjected to regression analysis and a correlation of better than 0.8 was obtained, (Figure 5, Table 2). Some of the invariants placed outside twice the standardized residual limit. Removing these values temporarily from the sample population improved the correlation factor and other statistics marginally. However, as the improvements were limited, the sample of 165 tensors was left intact.

3.3 Increase of Principal Stresses with Depth

Statistics in Table 2 show that there is a continuous increase of stress components with depth. Scatter plots of Figs. 6, 7 & 8 indicate a slight curvature of the distribution of principal stress points with depth. Splitting the distribution into a group of tensors obtained above 1000m and below 1000m did not show any significant improvement of statistical parameters. A single straight line regression of principal stresses with depth gave the following results:

	Sigma 1	Sigma 2	Sigma 3
Intercept (MPa):	12.1	6.4	1.4
Gradient (MPa/m):	0.0403±0.0020	0.0293±0.0019	0.0225±0.015
Correlation coefficient:	0.84	0.77	0.75

A straight line relationship will overly simplify actual site conditions if changes in lithology, faults and other discontinuities exist. Thus the pooling of data from many sites will result in a large scatter. A comparison with the URL, AECL data base (32 tensors) with the total sample of 165 tensors shows the regression equations to be very different. The correlation coefficient for the AECL sample is higher but the difference in magnitude for the mean depth of 211 m at URL is only 48.6 MPa - 39.5 MPa = 23% based on the 165 tensor sample. Comparing regression statistics of the original 133 tensor sample with those of the 165 tensor sample shows a marginal improvement for the larger sample (Table 2).

3.4 Increase of Vertical Stress

Many investigators have observed that the vertical stress component (σ_v) increases linearly with depth and that the increase is related to overburden weight. The density for rocks rich in quartz and feldspar is about 2650 kg/m^3 and for basic and ultrabasic rocks 3300 kg/m^3. This results in a vertical stress gradient of 0.0260 to 0.0324 MPa/m depending on the density of the rock formation involved.

The analysis of minimum principal compressive stress orientations in Figure 4 shows that only about 8% of the minimum stress components are oriented exactly vertical. An analysis of the minimum principal compressive stress magnitude with depth indicates a gradient of 0.0225 MPa/m with an intercept of 1.4 MPa. This indicates that the vertical stress component is higher than the average minimum principal compressive stress. The vertical stress component calculated from the 165 stress tensors is 0.0285 MPa/m (Figure 9).

From observations of seismic activity around large hydro dams and isostatic adjustments due to melting of ice sheets, it appears that the earth's crust is maintaining a delicate balance in the vertical direction and will adjust to changes in vertical loading of 0.5 to 1.0 MPa over large areas [Artyushkov 1971].

3.5 Change of Principal Stress/Vertical Stress Ratios with Depth

Principal stress/vertical stress ratios were calculated with the average vertical stress gradient and subjected to a regression in relation to the inverse of depth. The following statistics were obtained:

	σ_1/σ_v	σ_2/σ_v	σ_3/σ_v
Constant:	1.7	1.2	0.9
Regression coefficient:	272±8	141±6	30±4
Correlation coefficient:	0.93	0.87	0.56

3.6 The Friction Model

Ground stresses in the earth crust are very likely at the limit of strength that the earth's crust can support on a long-term basis [Hast 1979]. A criterion based on shear failure is readily quantified by the ratio of σ_1/σ_3:

$$(\sigma_1 - Po) \;/\; (\sigma_3 - Po) = [(\mu^2 + 1)^{1/2} + \mu]^2 \qquad (3)$$

where Po = pore pressure, e.g. hydrostatic pressure and μ = coefficient of friction.

This shear failure criterion can be rewritten to define the friction angle:

$$\mu = [R/4 - \tfrac{1}{2} + 1/(4R)]^{1/2}, \qquad (4)$$

where $R = \sigma_1 / \sigma_3$ ratio

Equating $\sigma_v = \sigma_3$ provides the following friction values based on the previously calculated σ_1/σ_v ratios:

Depth (m)	Ratio (σ_1/σ_3)	Coefficient of Friction	Angle of Friction
300m (Po = 0)	3.09	0.59	30.7°
300m (Po = hydrostatic)	3.51	0.67	33.8°
300m (Po = 0)	1.95	0.12	18.8°
300m (Po = hydrostatic)	2.93	0.56	29.4°

These obtained angles of friction are well within the range of laboratory determined shear stress/normal stress values for rock surfaces subjected to relatively high normal stresses. Jaeger (1959) quotes values for shear stress/normal stress ratios for joint surfaces tested under laboratory conditions to fall into the rather narrow range of 0.5 to 0.8.

4. CONCLUSIONS

1. Ground stress determinations by overcoring in the Canadian Shield show that the minimum compressive stress is vertical.

2. The maximum principal compressive stress has a prefered direction of NE to E horizontal and the magnitude indicates that the earthcrust is stressed to the limits of its capacity.

3. The anisotropy of stresses in the horizontal plane suggests a shortening of the North American plate in the direction of the maximum principal compressive stress by tectonic forces. A derivation of high horizontal stresses from ablation and erosion is less likely.

5. ACKNOWLEDGEMENTS

The authors are grateful that many companies and agencies made available results of ground stress determinations for this study.

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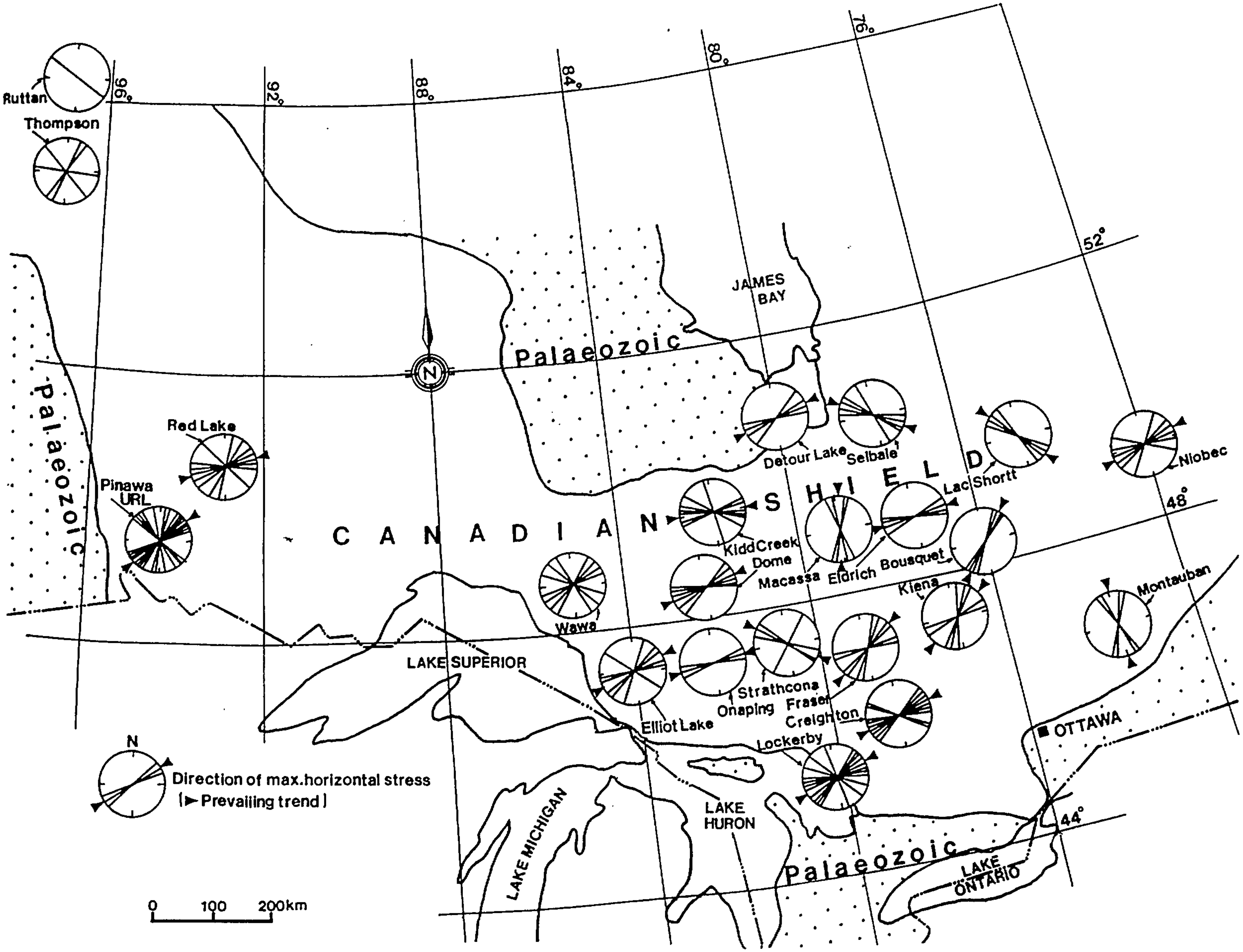

Figure 1. Location of Ground Stress Determinations

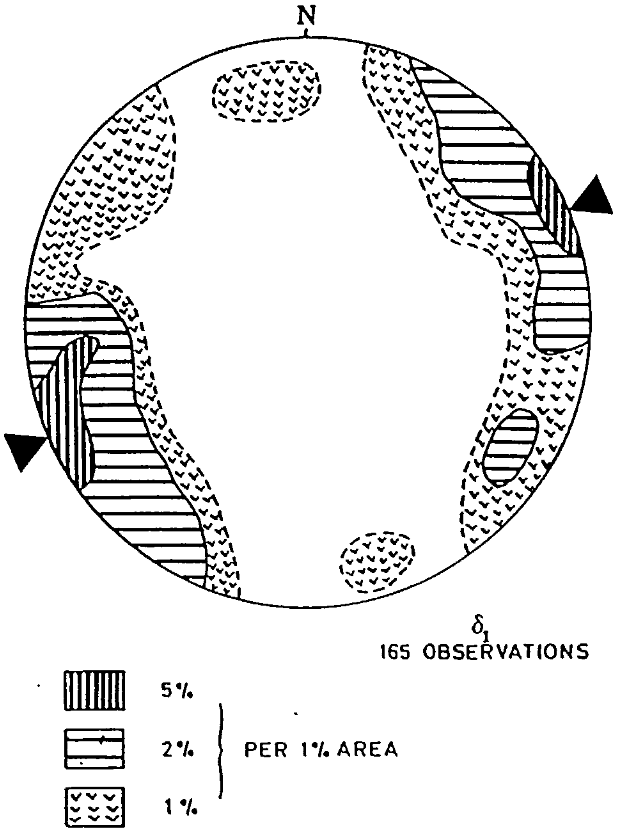

Figure 2. Equal Area Plot of Maximum Principal Compressive Stress Orientation (lower hemisphere)

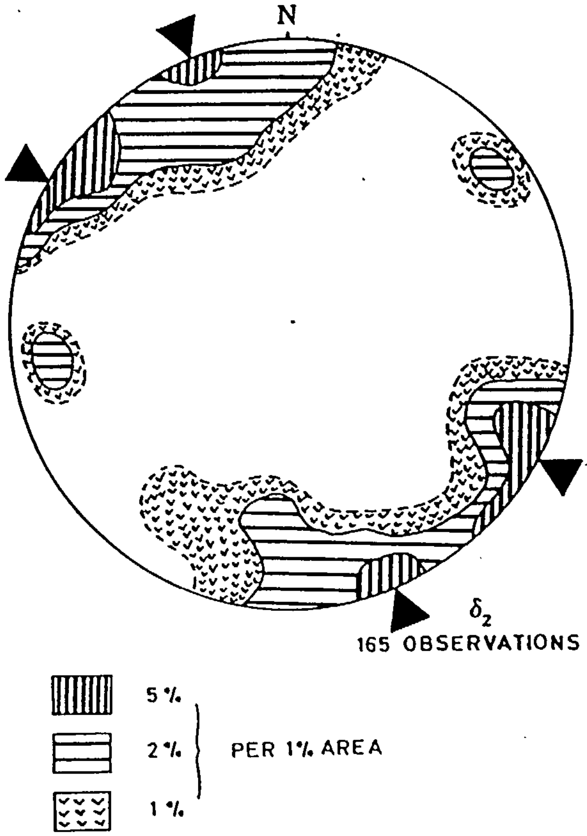

Figure 3. Equal Area Plot of Intermediate Principal Compressive Stress Orientation (lower hemisphere)

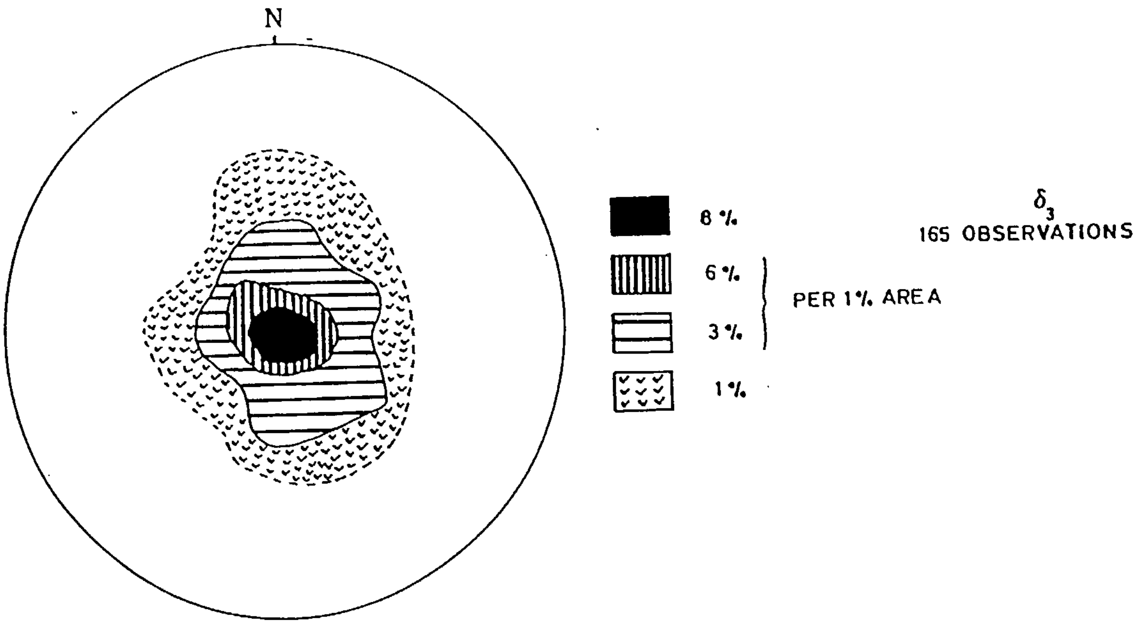

Figure 4. Equal Area Plot of Minimum Principal Compressive Stress Orientation (lower hemisphere)

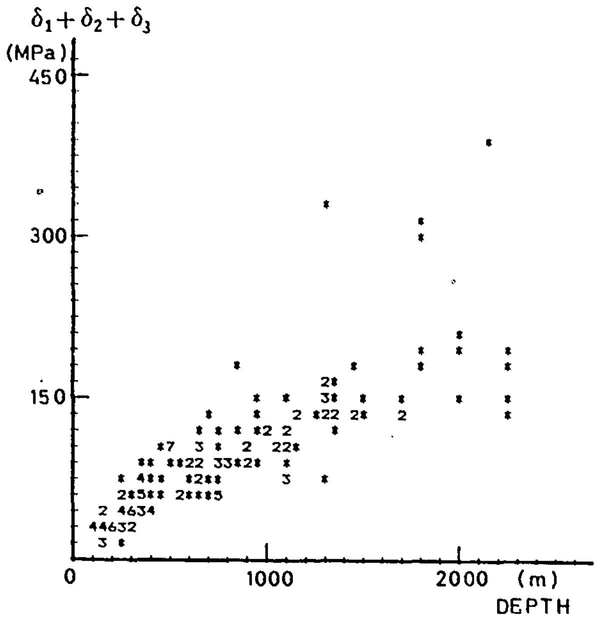

Figure 5. Increase of Sum of Principal Stresses with Depth

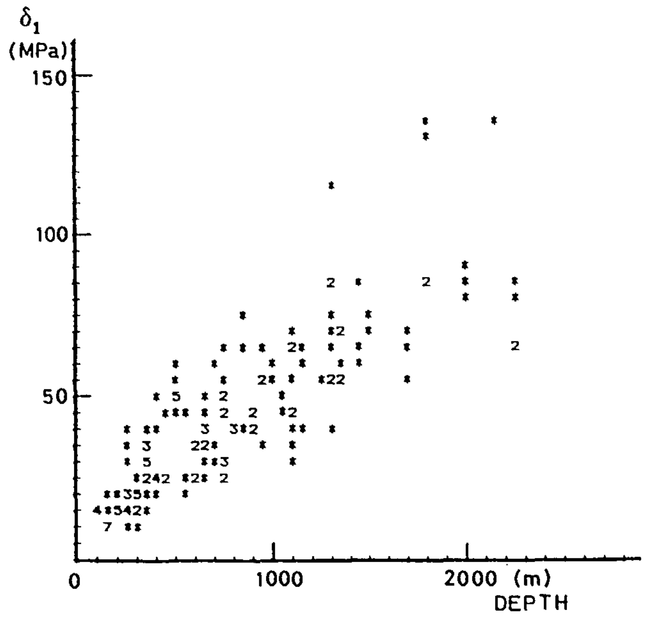

Figure 6. Increase of Maximum Principal Compressive Stresses With Depth

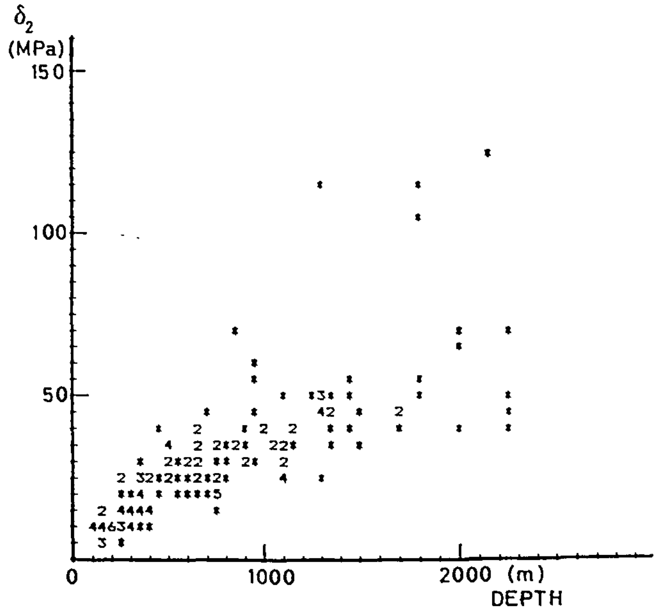

Figure 7. Increase of Intermediate Principal Compressive Stresses With Depth

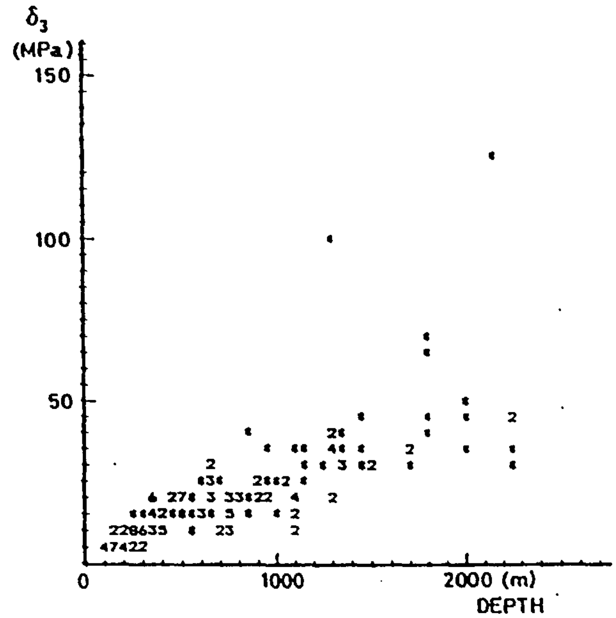

Figure 8. Increase of Minimum Principal Compressive Stress With Depth

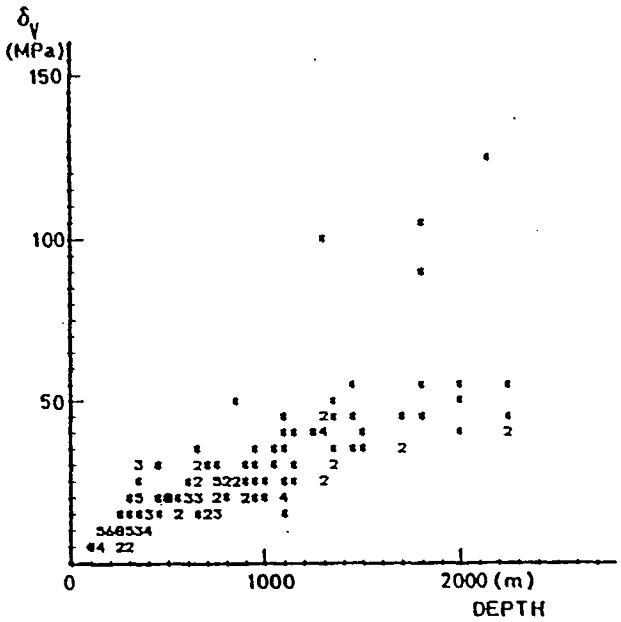

Figure 9. Increase of Vertical Stresses with Depth

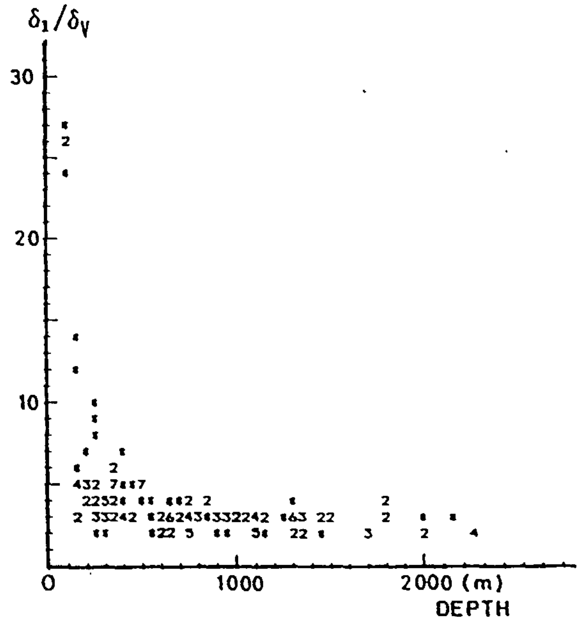

Figure 10. Change of Maximum Stress/Vertical Stress With Depth

Table 1: Ground Stress Tensors, Rock Types and Locations

	Depth (m)	σ_1 (MPa)	Dip direction/ dip	σ_2 (MPa)	Dip direction/ dip	σ_3 (MPa)	Dip direction/ dip	σ_v (MPa)	Method[1)]	Rock Type
1	335	20.7	090/00	17.2	000/00	10.3	000/90	10.3	M1,M2	Feldspathic qtz sandstone
2	305	36.5	045/00	20.0	135/00	11.0	000/90	11.0	M1	Feldspathic qtz sandstone
3	701	36.5	090/00	22.0	000/00	17.2	000/90	17.2	M1	Feldspathic qtz sandstone
4	366	21.4	118/12	20.1	027/12	16.1	230/78	16.3	M1	Siderite
5	479	30.0	251/11	27.7	343/08	18.7	110/76	19.4	M1	Metadiorite
6	570	47.2	222/17	34.1	315/09	26.7	070/70	28.8	M1	Chert
7	366	42.5	133/33	34.3	229/09	15.1	332/56	23.5	M2	Tuff
8	570.	31.6	162/11	27.9	070/12	21.5	295/74	22.1	M1	Tuff
9	570	38.3	356/22	29.5	090/11	21.4	206.66	23.9	M1	Tuff
10	570	19.9	224/04	16.6	315/06	14.6	100/83	14.7	M1	Tuff
11	1707	128.7	249/10	100.7	350/52	62.3	152/37	87.6	M1	Meta-gabbro
12	2134	61.4	265/08	37.1	142/74	26.8	358/13	49.9	M3	Qtz biotite schist
13	701	37.4	309/32	28.8	205/21	14.1	086/76	22.0	M3	Qtz biotite gabbro
14	701	38.0	300/25	27.0	032/05	16.4	128/66	18.8	M3	Qtz biotite gabbro
15	1219	60.3	250/13	45.7	348/35	34.3	144/52	38.5	M3	Meta-gabbro
16	1219	34.5	092/12	20.5	348/47	13.3	194/40	18.2	M3	Meta-gabbro
17	1219	80.7	243/06	40.0	358/76	36.6	150/22	40.1	M1	Meta-gabbro
18	2073	133.6	091/18	124.8	194/34	123.1	337/49	124.7	M1	Qtz biot.schist/granitic schist
19	488	33.1	094/06	26.8	186/23	10.7	350/60	13.4	M1	Fine grained andesite
20	732	72.6	258/19	64.7	358/25	34.4	135/58	43.9	M1	Diorite
21	853	53.3	250/10	51.9	342/09	19.1	112/77	20.9	M1	Diorite
22	853	53.7	077/12	39.9	170/18	16.3	318/70	23.6	M3	Diorite
23	610	58.5	323/11	40.5	61/32	18.3	214/54	26.8	M1	Biotite-gneiss
24	1219	113.4	207/03	112.7	115/12	96.6	305/77	97.3	M1	Granitic-gneiss
25	457	42.5	017/6	23.9	108/17	16.9	267/72	17.8	M1	Biotite schist
26	838	31.7	289/14	26.8	22/6	15.0	139/75	16.1	M1	Biotite schist
27	1707	131.7	068/00	112.2	339/61	68.9	158/28	102.2	M3	Fine grained gabbroic schist
28	1707	84.1	248/07	53.9	133/73	40.5	340/15	53.6	M3	Fine grained gabbroic schist
29	2134	63.9	266/22	39.2	159/35	28.8	022/46	37.1	M3	Qtz biotite schist
30	2134	82.7	267/20	48.2	175/28	41.9	000/61	37.4	M3	Qtz biotite schist
31	2134	78.6	274/22	65.9	017/26	39.2	149/54	43.4	M1	Meta-gabbro
32	1227	67.0	268/20	39.8	015/32	32.8	151/51	38.9	M3	Norite
33	1227	59.0	264/22	33.4	002/18	28.2	127/61	33.1	M3	Norite
34	1227	67.5	260/26	44.6	023/48	37.1	154/30	47.1	M3	Norite
35	1148	52.2	049/26	44.1	328/17	28.0	267/59	34.1	M2	Talcschist

	E (GPa)	Poisson's Ratio	Location	References
1	75.8	0.16	Nordic Mine, Elliot Lake, Ontario	6th Cdn. RM Symp., 1970, p.91-101
2	75.8	0.14	Denison Mine, Elliot Lake, Ontario	6th Cdn. RM Symp., 1970, p.91-101
3	75.8	0.14	Denison Mine, Elliot Lake, Ontario	6th Cdn. RM Symp., 1970, p.91-101
4	114.5	0.32	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
5	77.2	0.31	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
6	95.1	0.22	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
7	74.5	0.25	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
8	61.4	0.26	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
9	71.7	0.28	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
10	63.4	0.24	G.W. Macleod Mine, Wawa, Ontario	24th I Geol. Congress, 1972, Section 13, p.241-245
11	84.1	0.30	Creighton Mine, Sudbury, Ontario	10th Cdn. RM Symp, 1975, 281-307
12	55.1	0.28	Creighton Mine, Sudbury, Ontario	MRP/MRL 77/81
13	69.6	0.19	Creighton Mine, Sudbury, Ontario	MRP/MRL 78/53
14	69.6	0.19	Creighton Mine, Sudbury, Ontario	MRP/MRL 78/53
15	98.6	0.23	Creighton Mine, Sudbury, Ontario	10th Cdn. RM Symp, 1975, 281-307
16	98.6	0.23	Creighton Mine, Sudbury, Ontario	10th Cdn. RM Symp, 1975, 281-307
17	98.6	0.23	Creighton Mine, Sudbury, Ontario	10th Cdn. RM Symp, 1975, 281-307
18	66.9	0.34	Creighton Mine, Sudbury, Ontario	MRP/MRL 77-81
19	95.8	0.27	Kidd Creek Mine, Timmins, Ontario	MRP/MRL 76-148
20	79.9	0.27	Kidd Creek Mine, Timmins, Ontario	MRP/MRL 76-148
21	95.8	0.27	Kidd Creek Mine, Timmins, Ontario	MRP/MRL 76-148
22	77.9	0.27	Kidd Creek Mine, Timmins, Ontario	MRP/MRL 77-2
23	57.3	0.23	Thompson Mine, Thompson, Manitoba	MRP/MRL 79-66
24	51.9	0.26	Thompson Mine, Thompson, Manitoba	MRP/MRL 78-66
25	69.4	0.20	Birchtree Mine, Thompson, Manitoba	MRP/MRL 79-66
26	43.0	0.20	Birchtree Mine, Thompson, Manitoba	MRP/MRL 79-66
27	80.7	0.27	Creighton Mine, Sudbury, Ontario	MRP/MRL 77-81
28	68.9	0.35	Creighton Mine, Sudbury, Ontario	MRP/MRL 77-81
29	49.6	0.28	Creighton Mine, Sudbury, Ontario	MRP/MRL 77-81
30	51.7	0.27	Creighton Mine, Sudbury, Ontario	MRP/MRL 77-81
31	86.8	0.27	Creighton Mine, Sudbury, Ontario	10th Cdn. RM Symp., 1975, 281-307
32	48.3	0.2	Onaping Mine, Onaping, Ontario	Falconbridge Nickel Mines, 1980
33	56.8	0.17	Onaping Mine, Onaping, Ontario	Falconbridge Nickel Mines, 1980
34	52.8	0.19	Onaping Mine, Onaping, Ontario	Falconbridge Nickel Mines, 1980
35	84.1	0.06	Madsen Mine, Red Lake, Manitoba	BSc Thesis, Queen's Univ., 1971

Table 1: Ground Stress Tensors, Rock Types and Locations (Cont'd)

	Depth (m)	σ_1 (MPa)	Dip direction/ dip	σ_2 (MPa)	Dip/direction dip	σ_3 (MPa)	Dip direction/ dip	σ_v (MPa)	Method[1)]	Rock Type
36	1372	84.5	240/09	50.3	334/12	40.7	122/72	41.1		
37	1676	81.4	223/09	48.3	320/27	35.5	115/62	39.6		Norite
38	661	45.0	346/17	21.0	248/26	14.0	106/59	18.2	M4	Altered volcanics
39	533	38.6	128/21	34.5	031/18	16.6	264/62	16.6	M4	Norite
40	838	60.0	314/01	55.8	044/04	31.0	206/86	31.0	M4	Granite
41	665	47.4	047/00	32.9	137/00	17.8	000/90	17.9	M4	-
42	290	48.3	130/07	20.7	225/34	10.6	029/55	10.6	M4	-
43	132	29.4	120/12	16.2	215/21	5.7	001/66	5.7	M4	-
44	132	27.3	117/21	19.8	212/14	5.5	333/65	5.5	M4	-
45	132	34.0	100/14	18.8	192/08	10.5	312/74	10.5	M4	-
46	170	4.7	207/10	1.4	302/24	1.3	095/64	1.3	M4	Ore breccia
47	170	8.1	032/01	3.5	302/11	2.7	122/79	2.7	M4	Ore breccia
48	170	7.9	195/03	4.4	105/03	2.6	325/85	2.6	M4	Ore breccia
49	170	9.9	254/13	6.2	344/04	2.4	092/77	2.4	M4	Ore breccia
50	273	13.1	059/05	8.0	151/20	4.9	316/69	5.3	M4	-
51	39	15.0	321/03	11.2	052/13	3.6	218/77	3.6	M4	-
52	39	12.8	322/03	8.1	053/09	5.2	214/81	5.2	M4	-
53	60	4.0	257/32	2.0	348/02	0.6	082/58	1.5	M1	Basalt
54	70	3.4	165/10	1.4	015/68	0.5	258/10	1.6	M4	Dacite
55	180	6.9	312/10	3.3	034/01	1.8	128/80	2.0	M4	Dacite
56	180	11.7	304/04	4.3	214/03	2.0	090/85	2.1	M4	Dacite
57	180	11.7	132/03	6.8	227/56	6.6	040/34	6.6	M4	Dacite
58	290	14.7	312/12	6.9	213/35	5.6	238/52	6.4	M4	Dacite
59	81	10.0	015/28	3.4	124/31	1.8	252/46	4.0	M3	Gneiss
60	81	14.1	032/18	2.6	223/72	0.8	123/03	3.7	M3	Gneiss
61	81	9.6	157/17	5.2	255/25	1.2	037/59	2.6	M3	Gneiss
62	124	12.6	174/21	7.0	083/01	3.0	352/69	4.2	M3	Gneiss
63	190	14.6	034/06	7.0	303/12	4.8	152/76	5.0	M3	Tuff
64	190	19.1	035/00	14.4	125/11	7.2	303/79	7.4	M3	Tuff
65	900	57.2	044/21	36.8	138/11	10.5	256/66	17.7	M3	Tuff
66	900	51.8	046/00	35.8	136/03	19.0	300/86	19.1	M3	Tuff
67	115	12.3	079/18	6.3	340/26	1.2	200/58	3.1	M3	Tonalite
68	115	9.4	294/06	6.1	025/15	3.3	184/74	3.5	M3	Tonalite
69	276	22.2	275/18	9.0	009/11	5.7	129/69	7.4	M3	Tonalite
70	276	19.6	062/08	11.1	326/35	2.7	164/54	5.8	M3	Tonalite

	E (GPa)	Poisson's Ratio	Location	Reference
36	-	-	Onaping Mine, Onaping, Ontario	Falconbridge Nickel Mines, 1980
37	-	-	Onaping Mine, Onaping, Ontario	Falconbridge Nickel Mines, 1980
38	70.	0.18	Ruttan Mine, Sherrit Gordon Mines Ltd.,	CIM Bull. Dec. 1985, 47-52
39	-	-	Strathcona Mine, Ontario	Falconbridge Nickel Mines, 1981
40	-	-	Strathcona Mine, Ontario	Falconbridge Nickel Mines, 1981
41	84.8	0.33	Corbet Mine, Lac Dufault, Quebec	Falconbridge Nickel Mines, 1981
42	60.1	0.33	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
43	85.4	0.47	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
44	54.6	0.39	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
45	93.4	0.42	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
46	45.8	0.42	Kiena Mine, Quebec	Falconbridge Nickel Mines, 1981
47	55.2	0.49	Kiena Mine, Quebec	Falconbridge Nickel Mines, 1981
48	55.8	0.50	Kiena Mine, Quebec	Falconbridge Nickel Mines, 1981
49	63.8	0.37	Kiena Mine, Quebec	Falconbridge Nickel Mines, 1981
50	63.2	0.46	Kiena Mine, Quebec	Falconbridge Nickel Mines, 1981
51	66.1	0.42	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
52	61.5	0.39	Lac Shortt Mine, Quebec	Falconbridge Nickel Mines, 1981
53	65.7	0.24	Detour Lake Mine, Ontario	MRL 85-77
54	62.8	0.21	Selbaie Mine, Jontel, Quebec	MRL 84-55
55	69.7	0.25	Selbaie Mine, Jontel, Quebec	MRL 84-55
56	69.7	0.25	Selbaie Mine, Jontel, Quebec	MRL 84-55
57	69.7	0.25	Selbaie Mine, Jontel, Quebec	MRL 84-55
58	64.9	0.29	Selbaie Mine, Jontel, Quebec	MRL 84-55
59	53.1	0.17	Montauban Mine, St. Ubalde, Quebec	MRL 88-93
60	50.7	0.25	Montauban Mine, St. Ubalde, Quebec	MRL 88-93
61	50.7	0.25	Montauban Mine, St. Ubalde, Quebec	MRL 88-93
62	25.6	0.20	Montauban Mine, St. Ubalde, Quebec	MRL 88-93
63	47.0	0.29	Bousquet Mine, Cadillac, Quebec	MRL 88-132
64	47.0	0.29	Bousquet Mine, Cadillac, Quebec	MRL 88-132
65	66.9	0.24	Bousquet Mine, Cadillac, Quebec	MRL 88-132
66	53.1	0.21	Bousquet Mine, Cadillac Quebec	MRL 88-132
67	69.0	0.23	Eldrich Mine, Evain, Quebec	MRL 88-59
68	69.0	0.23	Eldrich Mine, Evain, Quebec	MRL 88-59
69	69.0	0.23	Eldrich Mine, Evain, Quebec	MRL 88-59
70	69.0	0.23	Eldrich Mine, Evain, Quebec	MRL 88-59

Table 1: Ground Stress Tensors, Rock Types and Locations (Cont'd)

	Depth (m)	σ_1 (MPa)	Dip direction/ dip	σ_2 (MPa)	Dip direction/ dip	σ_3 (MPa)	Dip direction/ dip	σ_v (MPa)	Method[1)]	Rock Type
71	260	22.7	064/08	15.1	156/15	13.5	308/73	13.8	M3	Carbonatite
72	260	27.7	064/15	15.7	160/21	4.3	301/64	7.3	M3	Carbonatite
73	260	12.3	314/24	11.1	083/54	8.1	212/24	10.8	M3	Carbonatite
74	260	23.0	214/11	5.2	110/50	4.1	312/37	5.5	M4	Carbonatite
75	305	19.9	101/02	8.0	192/32	7.0	009/58	7.3	M3	Carbonatite
76	305	22.3	090/05	9.4	180/01	7.2	280/85	9.4	M3	Carbonatite
77	732	38.3	258/25	32.8	002/27	8.4	133/52	18.7	M3	Rhyolite
78	732	59.5	095/18	33.0	002/08	17.9	261/70	22.2	M3	Rhyolite
79	1041	54.8	353/13	36.2	263/01	33.2	170/77	34.4	M1	Andesite
80	1382	69.4	126/24	31.7	271/62	25.5	029/14	37.6	M3	Andesite
81	1382	74.1	091/16	41.8	354/24	27.2	211/61	33.0	M3	Andesite
82	438	18.0	215/32	15.1	113/18	9.2	358/52	12.3	M3	Porphyry
83	438	19.5	249/28	19.1	143/28	7.0	016/48	12.4	M3	Porphyry
84	937	42.6	063/02	28.4	157/67	20.9	332/23	27.2	M3	'Greenstone'
85	937	45.5	239/26	28.5	114/49	18.2	345/28	29.5	M3	'Greenstone'
86	1238	53.3	273/01	35.5	183/21	23.8	005/69	25.3	M3	'Greenstone'
87	1238	52.0	249/08	42.5	158/10	27.2	017/77	28.2	M3	'Greenstone'
88	1585	67.5	343/13	43.2	062/40	32.8	088/47	38.9	M4	Syenite
89	1585	62.2	304/20	41.2	395/02	27.7	131/70	31.8	M4	Syenite
90	1585	54.1	168/10	33.6	261/16	29.2	046/71	30.3	M3	Syenite
91	1890	83.2	359/16	61.8	265/13	47.5	138/70	50.8	M4	Syenite
92	1890	76.0	021/18	36.1	280/30	28.5	137/54	35.2	M4	Syenite
93	1890	88.6	012/24	67.1	280/05	40.2	178/66	48.4	M4	Syenite
94	1066	34.2	196/33	29.6	300/20	25.0	056/50	28.2	M4	Quartzite
95	1066	62.9	253/11	35.9	162/05	19.8	048/78	21.5	M4	Quartzite
96	580	26.2	078/05	16.9	344/38	2.6	174/52	8.2	M3	Andesite (altered)
97	580	30.8	074/08	18.6	340/26	5.1	179/62	8.3	M3	Andesite (altered)
98	625	23.2	195/13	9.5	086/55	7.5	293/31	9.7	M3	Andesite
99	625	22.2	074/35	15.0	183/15	9.2	300/45	14.5	M3	Andesite
100	625	23.8	067/02	15.7	336/18	10.2	162/72	10.8	M3	Andesite
101	625	40.8	217/15	17.9	042/75	9.5	307/01	19.4	M3	Andesite
102	625	24.0	141/15	16.1	046/17	9.8	270/67	11.3	M3	Andesite
103	625	24.5	056/38	17.2	258/49	3.9	155/11	19.5	M3	Andesite
104	670	62.2	317/24	30.6	058/23	16.6	185/55	26.5	M3	Andesite
105	670	49.9	278/14	21.3	042/65	2.6	183/20	20.9	M3	Andesite

	E (GPa)	Poisson's Ratio	Location	References
71	74.6	0.26	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
72	74.6	0.26	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
73	74.6	0.26	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
74	74.6	0.26	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
75	74.8	0.35	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
76	74.8	0.35	Niobec Mine, Chicoutimi, Quebec	MRL 87-15
77	65.0	0.31	Kidd Creek Mine, Timmins, Ontario	MRL 87-142
78	65.0	0.31	Kidd Creek Mine, Timmins, Ontario	MRL 87-142
79	96.5	0.29	Kidd Creek Mine, Timmins, Ontario	MRL 87-142
80	87.9	0.22	Kidd Creek Mine, Timmins, Ontario	MRL 87-142
81	87.9	0.22	Kidd Creek Mine, Timmins, Ontario	MRL 87-142
82	59.8	0.24	Dome Mine, Timmins, Ontario	MRL 88-87
83	59.8	0.24	Dome Mine, South Porcupine, Ontario	MRL 88-87
84	63.3	0.28	Dome Mine, South Porcupine, Ontario	MRL 88-87
85	63.3	0.28	Dome Mine, South Porcupine, Ontario	MRL 88-87
86	65.6	0.29	Dome Mine, South Porcupine, Ontario	MRL 88-87
87	65.6	0.29	Dome Mine, South Porcupine, Ontario	MRL 88-87
88	64.3	0.16	Macassa Mine, Kirkland Lake, Ontario	MRL 85-63
89	64.3	0.16	Macassa Mine, Kirkland Lake, Ontario	MRL 85-63
90	64.3	0.16	Macassa Mine, Kirkland Lake, Ontario	MRL 85-63
91	68.6	0.19	Macassa Mine, Kirkland Lake, Ont.	MRL 85-63
92	68.6	0.19	Macassa Mine, Kirkland Lake, Ont.	MRL 85-63
93	68.6	0.19	Macassa Mine, Kirkland Lake, Ont.	MRL 85-63
94	75.5	0.17	Stanleigh Mine, Elliot Lake, Ont.	MRL 84-119
95	75.5	0.17	Stanleigh Mine, Elliot Lake, Ont.	MRL 84-119
96	74.3	0.25	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
97	74.3	0.25	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
98	91.7	0.21	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
99	91.7	0.21	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
100	91.7	0.21	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
101	90.5	0.23	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
102	90.5	0.23	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
103	86.5	0.21	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
104	83.5	0.20	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
105	83.5	0.20	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108

Table 1: Ground Stress Tensors, Rock Types and Location (Cont'd)

	Depth (m)	σ_1 (MPa)	Dip direction/ dip	σ_2 (MPa)	Dip direction/ dip	σ_3 (MPa)	Dip direction/ dip	σ_v (MPa)	Method[1)]	Rock Type
106	670	41.7	091/09	25.0	190/44	10.0	352/44	18.1	M3	Andesite
107	990	49.8	058/17	26.2	321/23	10.9	180/61	16.5	M3	Andesite
108	990	41.6	086/10	19.0	351/26	15.3	195/62	17.5	M3	Andesite
109	990	68.6	079/20	25.5	333/37	7.2	195/47	20.9	M3	Andesite
110	1220	81.6	254/01	40.7	345/31	14.1	162/59	21.2	M3	Andesite
111	1220	67.4	246/27	39.3	341/11	30.1	092/61	37.9	M3	Andesite
112	1220	74.1	238/30	43.5	336/12	32.6	085/57	43.7	M3	Andesite
113	1190	50.6	295/16	44.0	203/08	33.0	087/72	34.5	M4	-
114	1190	53.9	218/19	47.2	184/17	30.5	056/64	34.4	M4	-
115	518	22.5	239/10	13.9	336/34	12.7	135/54	13.3	M4	-
116	518	22.7	344/31	22.2	250/07	12.8	148/58	15.5	M4	-
117	572	35.2	262/19	26.3	359/18	18.7	129/63	21.2	M4	-
118	572	39.6	237/16	29.9	328/02	24.4	063/74	25.5	M4	-
119	572	28.7	244/18	20.2	153/03	10.1	056/72	12.0	M4	-
120	572	25.2	166/19	21.5	259/09	15.9	013/70	16.9	M4	-
121	792	37.2	268/21	26.6	173/12	21.9	055/66	24.0	M4	-
122	792	39.9	322/03	37.6	052/05	15.3	204/84	15.5	M4	-
123	792	39.9	304/14	23.7	214/00	15.8	123/76	17.3	M4	-
124	792	33.6	252/03	29.3	082/01	19.5	183/87	19.6	M4	-
125	1006	42.6	021/28	30.8	188/62	15.4	288/06	33.2	M4	-
126	1006	23.3	050/22	19.4	316/09	13.3	206/66	14.8	M4	-
127	1006	32.7	046/20	20.1	311/16	7.6	185/65	11.4	M4	-
128	1006	35.8	027/18	22.1	130/35	9.0	275/50	15.6	M4	-
129	1006	62.9	113/30	44.4	219/25	29.7	342/49	40.6	M4	-
130	1006	61.3	266/26	32.2	119/60	18.0	003/14	36.9	M4	-
131	1372	55.0	250/55	45.1	105/30	27.0	005/17	50.2	M4	-
132	1372	63.1	277/02	37.4	185/36	28.5	009/54	31.6	M4	-
133	12.19	8.8	053/04	4.5	143/01	1.4	250/86	1.4	M5	Pink Granite
134	12.03	9.2	210/06	3.2	118/18	0.6	317/71	0.9	M5	Pink Granite
135	11.90	7.9	216/09	5.4	307/05	1.5	063/80	1.7	M5	Pink Granite
136	11.89	8.6	207/02	5.1	117/00	1.1	027/88	1.1	M5	Pink Granite
137	61.39	7.4	043/25	4.5	306/14	1.6	189/60	2.8	M5	Pink Granite
138	61.39	7.4	040/31	3.7	304/09	1.10	199/58	2.8	M5	Pink Granite
139	61.38	7.3	057/32	5.0	316/18	1.1	201/53	3.2	M5	Pink Granite
140	61.37	6.5	044/24	3.7	309/11	1.0	195/64	2.0	M5	Pink Granite

	E (GPa)	Poisson's Ratio	Location	References
106	83.5	0.20	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
107	85.3	0.22	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
108	85.3	0.22	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
109	85.3	0.22	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
110	84.8	0.20	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
111	84.8	0.20	Campbell Red Lake Mine, Red Lake, Ont.	MRL 87-108
112	84.8	0.20	Campbell Red Lake Mine, Red Lake Ont.	MRL 87-108
113	-	-	Strathcona Mine, Sudbury, Ontario	Falconbridge Nickel Mines
114	-	-	Strathcona Mine, Sudbury, Ontario	Falconbridge Nickel Mines
115	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
116	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
117	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
118	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
119	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
120	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
121	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
122	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
123	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
124	-	-	Lockerby Mine, Sudbury, Ontario	Falconbridge Nickel Mines
125	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
126	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
127	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
128	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
129	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
130	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
131	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
132	-	-	Frazer Mine, Sudbury, Ontario	Falconbridge Nickel Mines
133	69	0.26	URL, Pinawa, Manitoba	AECL files
134	69	0.26	URL, Pinawa, Manitoba	AECL files
135	69	0.26	URL, Pinawa, Manitoba	AECL files
136	69	0.26	URL, Pinawa, Manitoba	AECL files
137	69	0.26	URL, Pinawa, Manitoba	AECL files
138	69	0.26	URL, Pinawa, Manitoba	AECL files
139	69	0.26	URL, Pinawa, Manitoba	AECL files
140	69	0.26	URL, Pinawa, Manitoba	AECL files

Table 1: Ground Stress Tensors, Rock Types and Locations (Cont'd)

	Depth (m)	σ_1 (MPa)	Dip direction/ dip	σ_2 (MPa)	Dip direction/ dip	σ_3 (MPa)	Dip direction/ dip	σ_v (MPa)	Method[1)]	Rock Type
141	183.44	16.2	165/44	12.1	330/45	4.9	067/07	13.9	M5	Pink Granite
142	183.43	14.8	219/03	12.9	309/12	6.6	115/78	6.9	M5	Pink Granite
143	183.42	13.1	213/05	11.3	304/09	6.1	095/80	6.3	M5	Pink Granite
144	183.39	16.8	233/23	11.3	325/05	9.0	067/66	10.2	M5	Pink Granite
145	128.40	13.8	206/08	8.3	116/01	3.5	020/82	3.7	M5	Pink Granite
146	128.99	12.8	194/08	9.1	103/11	6.1	317/77	6.4	M5	Pink Granite
147	128.96	16.7	181/10	9.6	088/18	6.4	298/70	7.1	M5	Pink Granite
148	128.85	13.0	050/12	8.3	303/52	5.5	149/35	7.5	M5	Pink Granite
149	234.64	29.2	214/23	11.9	115/22	10.1	346/58	13.4	M5	Grey Granite
150	234.49	31.5	219/20	12.2	070/67	10.4	313/11	14.4	M5	Grey Granite
151	235.42	25.5	228/41	13.3	104/32	12.3	351/32	18.2	M5	Grey Granite
152	235.37	26.8	233/29	17.4	124/30	14.0	357/46	17.9	M5	Grey Granite
153	235.33	26.6	218/63	21.6	119/04	14.6	027/27	24.4	M5	Grey Granite
154	235.27	36.0	230/31	25.1	118/32	16.8	354/42	24.1	M5	Grey Granite
155	235.18	28.0	240/53	18.7	118/21	14.6	016/28	23.5	M5	Grey Granite
156	235.12	31.1	065/16	18.4	161/21	15.4	300/64	17.2	M5	Grey Granite
157	416.68	43.9	074/03	27.2	164/07	14.9	325/82	15.1	M5	Grey Granite
158	416.60	49.0	057/03	31.1	148/15	13.2	316/75	14.5	M5	Grey Granite
159	416.55	45.4	069/06	31.0	159/03	14.9	276/84	15.3	M5	Grey Granite
160	416.77	54.7	162/03	22.2	070/24	13.6	258/66	15.2	M5	Grey Granite
161	416.73	48.3	150/04	26.3	059/14	13.6	257/76	14.6	M5	Grey Granite
162	416.71	53.7	151/13	22.9	058/10	13.9	294/74	16.3	M5	Grey Granite
163	417.17	48.7	022/01	31.6	112/07	14.3	285/83	14.6	M5	Grey Granite
164	417.17	41.4	016/03	30.3	107/16	12.8	276/74	14.2	M5	Grey Granite
165	26.0	3.5	055/14	1.2	280/71	0.5	148/13	1.3	M5	Dolomite

1) Method
M1 - doorstopper M2 - USBM deformation M3 - CSIR triaxial cell M4 - CSIRO triaxial cell
M5 - CSIR triaxial modified (read during overcoring)

	E (GPa)	Poisson's Ratio	Location	References
141	69	0.26	URL, Pinawa, Manitoba	AECL files
142	69	0.26	URL, Pinawa, Manitoba	AECL files
143	69	0.26	URL, Pinawa, Manitoba	AECL files
144	69	0.26	URL, Pinawa, Manitoba	AECL files
145	69	0.26	URL, Pinawa, Manitoba	AECL files
146	69	0.26	URL, Pinawa, Manitoba	AECL files
147	69	0.26	URL, Pinawa, Manitoba	AECL files
148	69	0.26	URL, Pinawa, Manitoba	AECL files
149	55	0.3	URL, Pinawa, Manitoba	AECL files
150	55	0.3	URL, Pinawa, Manitoba	AECL files
151	55	0.3	URL, Pinawa, Manitoba	AECL files
152	55	0.3	URL, Pinawa, Manitoba	AECL files
153	55	0.3	URL, Pinawa, Manitoba	AECL files
154	55	0.3	URL, Pinawa, Manitoba	AECL files
155	55	0.3	URL, Pinawa, Manitoba	AECL files
156	55	0.3	URL, Pinawa, Manitoba	AECL files
157	55	0.3	URL, Pinawa, Manitoba	AECL files
158	55	0.3	URL, Pinawa, Manitoba	AECL files
159	55	0.3	URL, Pinawa, Manitoba	AECL files
160	55	0.3	URL, Pinawa, Manitoba	AECL files
161	55	0.3	URL, Pinawa, Manitoba	AECL files
162	55	0.3	URL, Pinawa, Manitoba	AECL files
163	55	0.3	URL, Pinawa, Manitoba	AECL files
164	55	0.3	URL, Pinawa, Manitoba	AECL files
165	43.9	0.20	Nanisivik Mines, N. Baffin Island	MRL 89-147

Table 2 Statistics of regression of stress magnitudes [MPa] with depth [m]

Type	Observations	Regression coefficient	Std. error	Constant	Std. error of estimate	Correlation coefficient	T-test	Mean depth	Mean magnitude
$\sigma 1+\sigma 2+\sigma 3$	165	0.0918	0.0050	20.1569	34.4517	0.82	18.268	676	82.2
	32	0.2049	0.0096	5.3631	7.5614	0.96	21.362	211	48.6
	133	0.0944	0.0060	15.9117	37.1153	0.80	15.631	789	90.4
$\sigma 1$	165	0.0403	0.0020	12.1013	13.8865	0.84	19.961		
$\sigma 1$	32	0.1083	0.0057	2.1307	4.4617	0.96	19.137		
$\sigma 1$	133	0.0411	0.0023	10.4445	14.4346	0.83	17.497		
$\sigma 2$	165	0.0293	0.0019	6.4022	12.7724	0.77	15.777		
$\sigma 2$	32	0.0623	0.0040	1.8221	3.1650	0.94	15.514		
$\sigma 2$	133	0.0298	0.0023	5.4663	13.9632	0.75	12.402		
$\sigma 3$	165	0.0225	0.0015	1.3894	10.5942	0.75	14.642		
$\sigma 3$	32	0.0343	0.0036	1.4104	2.8527	0.86	9.478		
$\sigma 3$	133	0.0235	0.0019	0.00927	11.6606	0.73	12.402		
$\sigma 1/\sigma v$[1)]	165	272.3166	8.2169	1.7165	1.3981	0.93	33.141		
$\sigma 2/\sigma v$	165	140.9055	6.2640	1.1837	1.0658	0.87	22.495		
$\sigma 3/\sigma v$	165	30.2982	3.5359	0.8560	0.6016	0.56	8.569		

[1)] $\sigma v = 0.0285$ MPa/m