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Direct Shear Tests on Geological Fractures and Sawcut Samples from an Open Pit Mine in Northern Manitoba

by

P. Miles and G. Herget

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SUMMARY

Direct shear tests on samples of quartz-chlorite gneiss were carried out to determine the shear resistance along geological fractures and sawcuts for open pit design. Shear tests were performed at both low (10 to 36 psi) and high (150 to 1430 psi) normal stresses. It was found that the peak angle of friction varied between 30° and 63° with a mean of 44°. The peak shear stress/normal stress data was best represented by the power curve $\tau = a\sigma_n^b$. As a comparison, a straight line interpretation ($\tau = a + b\sigma_n$) is also given, which yields, however, a poorer fit of the data. The standard errors from regression were used to calculate the cumulative distributions of τ at a given normal stress of 15 psi. The large discrepancy of the standard errors has a profound effect on the cumulative distributions at low normal stresses.

A mean residual angle of friction of 29.3° was found which agreed well with the angle of friction from flat sawcuts (28.9°). A calculation of the angle of friction at zero dilatancy from measurements of horizontal and vertical displacements at peak yielded a value of 33°.

Direct Shear Tests: Geological Fractures: Sawcuts: Angles of Friction: Mohr- Coulomb: Power Curve: Dilatancy.

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CONTENTS

FIGURES

LIST OF SYMBOLS

τ - Shear stress [psi]

σ_n - Normal stress [psi]

r - Correlation coefficient

N - Number of observations

S_{τ/σ_n} - Standard error of estimate

s - Shear displacement [in.]

n - Dilatancy [in.]

i_e - Geometric component of angle of friction [degrees]

ϕ - Angle of internal friction

A - Amplitude [in.]

L - Wavelength [in.]

1. INTRODUCTION

Direct shear tests were performed on samples of quartz-chlorite gneiss to determine the shear resistance along sawcuts and geological fractures of known in-situ orientation. The samples were obtained as diamond drill core from the slopes of an open pit in Northern Manitoba.

In the following, sample descriptions, testing procedures, results and analysis are presented.

2. SAMPLE DESCRIPTION

Jointed diamond drill core (4 in. diameter) was obtained from the wall of an open pit for the purposes of direct shear testing. The orientations of the geological fractures were known and testing was to simulate failure of the pit slopes.

The samples were of a quartz-chlorite gneiss with varying amounts of biotite and garnet. Almost 80% of the shear surfaces were at least 50% slickensided and were characteristically black, shiny, striated, and soft. Many slickensided surfaces were partially coated with a thin, soft layer of calcite. Several very rough, interlocking surfaces were formed by the intersection of the gneissosity with the shear plane. The individual shear surfaces are described in more detail in Appendix A.

3. TESTING PROCEDURES

3.1 Sample Preparation and Testing Arrangement

Most fractures were marked in terms of desired shear direction. Some directions were changed so that shearing took place along the slickensides. The directions of shear movement are given in Appendix A as angles to the left or right of vertical, as shown in Figure 1. All jointed samples were sheared top down except for No. 17. Six samples were provided with sawcuts, three from sample No. 7 and three from sample No. 22, to obtain a check on the residual shear resistance.

Blocks of rock containing the fractures or sawcuts were cut so that they could be moulded into forms suitable for the direct shear testing rig. The samples were moulded in a portland cement-sand mixture of 1:3

and left to cure for at least three days.

Direct shear tests were made with a Hoek shear box. For the initial tests at low normal stresses (10 to 36 psi) the shear box was modified so that the normal load was applied by lead weights and the shear force was applied by a hand screw via a proving ring. For these tests, shear force and shear and normal displacement were plotted by an x, y, y recorder.

High normal stress tests were made with the direct shear box using hydraulic hand pumps to apply the normal and shear loads. Shear force and shear displacement were recorded by an x, y recorder.

4. RESULTS AND ANALYSIS

Objectives of the shear tests were to define the peak shear resistance and its variation at different normal stresses and to obtain a value of the residual angle of friction.

4.1 Results

To allow interpretation of the continuous records obtained by measuring shear force/shear displacement, three phases were distinguished as shown in Figure 2 and described below.

a) Peak Shear Resistance

This reflects the maximum shear resistance obtained for a given normal stress which appears shortly after onset of shear displacement.

b) Post Peak Shear Resistance

Shear resistance reduces with displacement after the peak to a relatively constant value. The lowest average value is recorded.

c) Residual Shear Resistance

This is a value of shear resistance after considerable sliding which is constant with displacement.

In most cases the third phase could not be determined with confidence. Also, in many of the high normal stress tests a peak shear resistance did not exist. This indicates that the interlocking asperities causing the peak at low normal stresses are not effective (too weak) at the higher normal stresses. The presence of small rock chips and a large amount of rock powder on the shear surfaces after testing shows the effect of continuous wear on the surfaces. Even the sawcut samples showed these effects after testing at high normal stresses.

Necessary data to quantify shear and displacement data in these phases are given in Appendix A. If phase three was obtained, it is given in the table in the post peak column and is marked with an asterisk.

4.2 Peak Shear Resistance at Various Normal Stresses

Two sets of data are presented. Figure 3 shows a peak shear stress/normal stress diagram representing only low normal pressure tests. Figure 4 represents all tests. In each case the straight line Mohr-Coulomb function and a power curve were fitted to the data. A power curve showed a better fit in both instances. The relationships for both cases are presented below.

Low normal stresses (Figure 3):

straight line:

$$\tau = a + b\,\sigma_n$$
$$\tau = (2.5 \pm 2.45) + (0.954 \pm 0.11)\,\sigma_n$$
$$r = 0.727$$
$$N = 69$$
$$S_{\tau/\sigma_n} = 7.46$$

power law:

$$\log \tau = \log a + b \log \sigma_n$$
$$\log \tau = (0.155 \pm 0.105) + (0.895 \pm 0.081) \log \sigma_n$$
$$r = 0.803$$
$$N = 69$$
$$S_{\tau/\sigma_n} = 0.129$$

Low and high normal stresses (Figure 4):

straight line:

$$\tau = a + b\,\sigma_n$$
$$\tau = (10.0 \pm 5.8) + (0.970 \pm 0.033)\,\sigma_n$$
$$r = 0.949$$
$$N = 97$$
$$S_{\tau/\sigma_n} = 47.6$$

power law: $\log \tau = \log a + b \log \sigma_n$

$$\log \tau = (0.031 \pm 0.039) + (0.998 \pm 0.023) \log \sigma_n$$
$$r = 0.975$$
$$N = 97$$
$$S_{\tau/\sigma_n} = 0.125$$

The peak angle of friction of 43.7° (arc tan 0.954) for the low normal stress cases agrees very closely with the angle 44.1° (arc tan 0.970) obtained for all tests combined. The power relationship representing all tests, which is very nearly linear, yields an angle of friction of 44.9° (arc tan 0.998).

A calculated example for a normal stress of 15 psi using the relationships for all tests gives the following results:

straight line:

$$\bar{\tau} = 10.0 + 14.55$$
$$\bar{\tau} = 24.55 \text{ psi}$$
$$S_{\tau/\sigma_n} = 47.6$$
$$\bar{\tau} = 24.55 \pm 47.6 \text{ psi}$$

power law:

$$\log \bar{\tau} = 0.031 + 1.174$$
$$\log \bar{\tau} = 1.205$$
$$S_{\tau/\sigma_n} = 0.125$$
$$\log \bar{\tau} = 1.205 \pm 0.125$$
$$\bar{\tau} = 16.02 \begin{smallmatrix} +5.34 \\ -4.01 \end{smallmatrix} \text{ psi}$$

A comparison of the mean values of τ at 15 psi normal stress and the correlation coefficients indicates some agreement between the straight line and the power curve; however, a considerable difference exists for the standard errors and indicates that the power curve provides a far superior relationship between shear resistance and normal stresses.

4.3 Shear Resistance Due to Dilatancy

Measurements of shear displacement (s) and dilatancy (n) during shearing at low normal pressures allowed determination of the geometric component affecting shear resistance. This geometric component is defined as:

$$\text{angle } i_e = \text{arc tan } (dn/ds).$$

Since the residual angle of friction could not reliably be determined, an attempt was made to obtain the angle of friction at zero dilatancy using the equation,

$$\tau = \sigma_n \tan(\phi + i_e).$$

This was obtained by running a regression analysis of arc tan (τ/σ_n) on arc tan (dn/ds) which is shown in Figure 5. The angle of friction at zero dilatancy was found to be 33°. This compares well with the mean residual angle of friction for the geological fractures of 29.3°, [arc tan (τ/σ_n) - arc tan (dn/ds)] and the mean post peak value for the sawcuts of 28.9°.

5. REFERENCES

1. Herget, G. and Miles, P., "Shear Resistance of Geological Fractures in Weathered and Fresh Rock", Mining Research Centre Divisional Report, 1974.

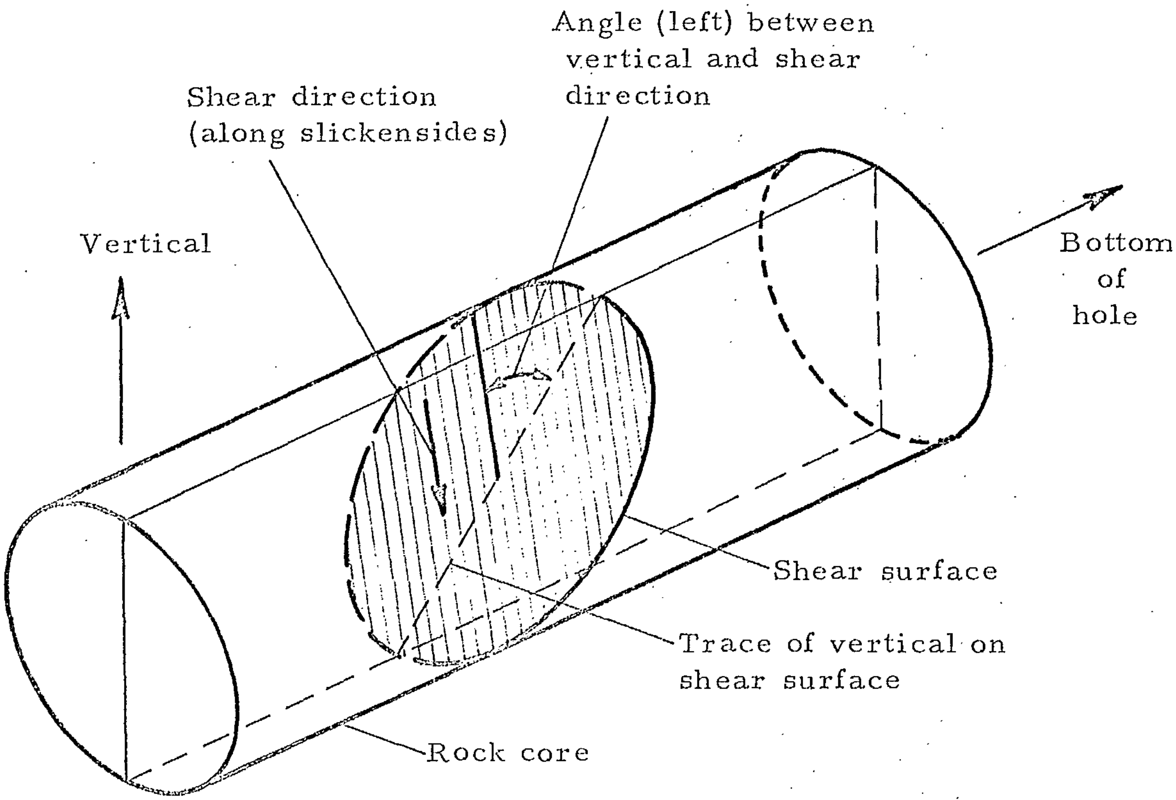

FIGURE 1: Determination of Direction of Shear Movement.

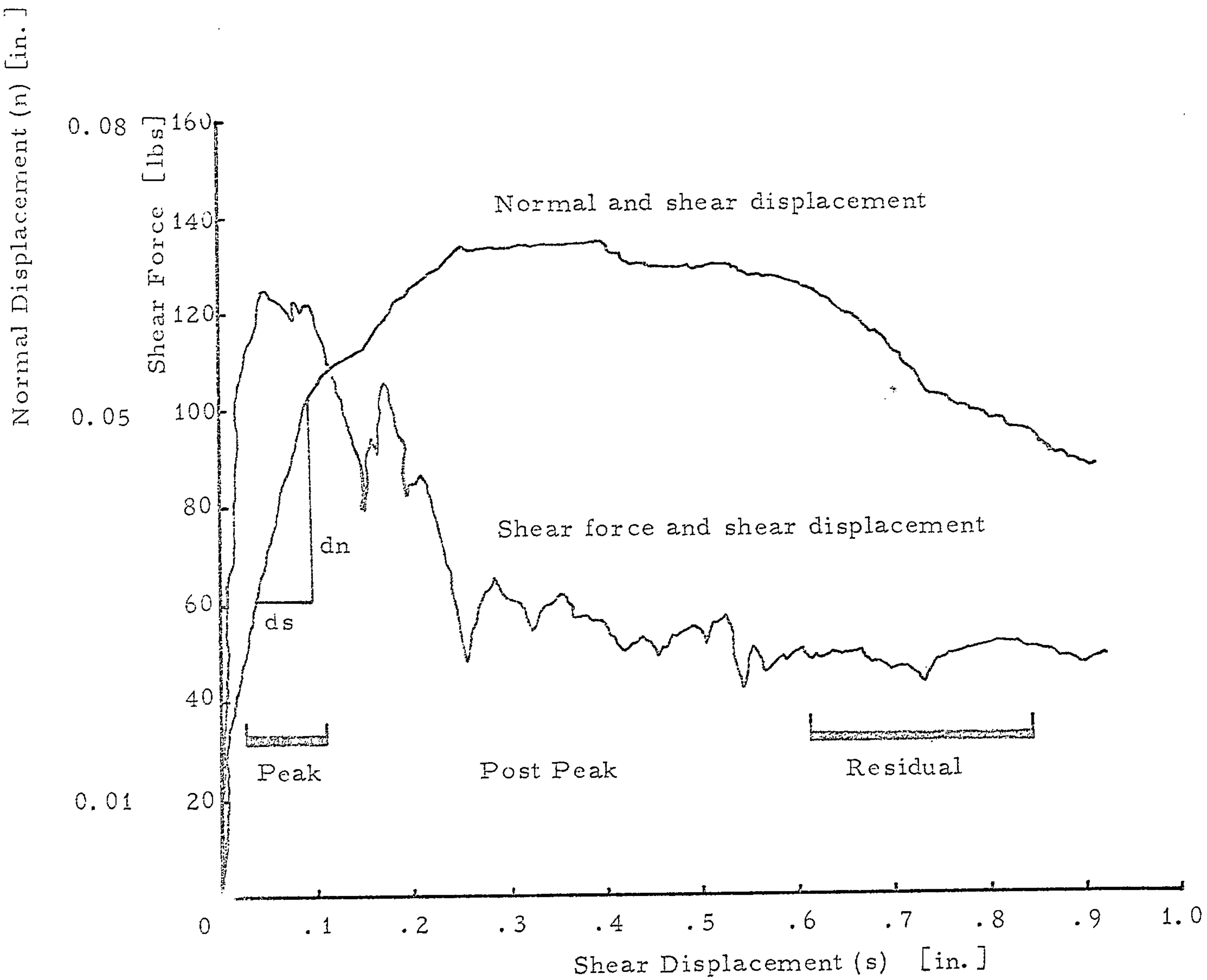

FIGURE 2: Direct Shear Test on Geological Fracture in Quartz-Chlorite Gneiss at a Normal Stress of 20 psi.

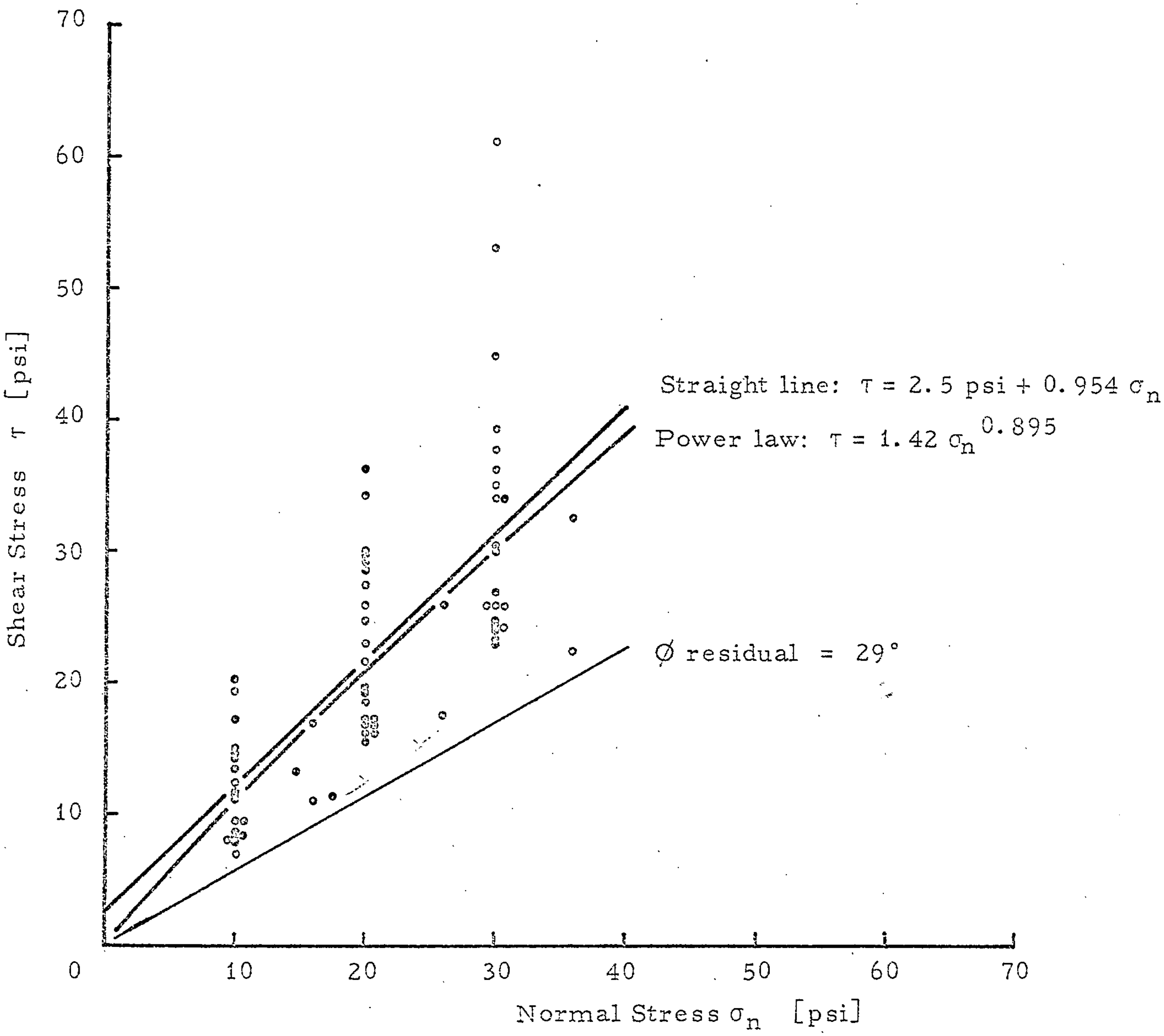

FIGURE 3: Peak Shear Resistance at Low Normal Stresses in Direct Shear Tests.

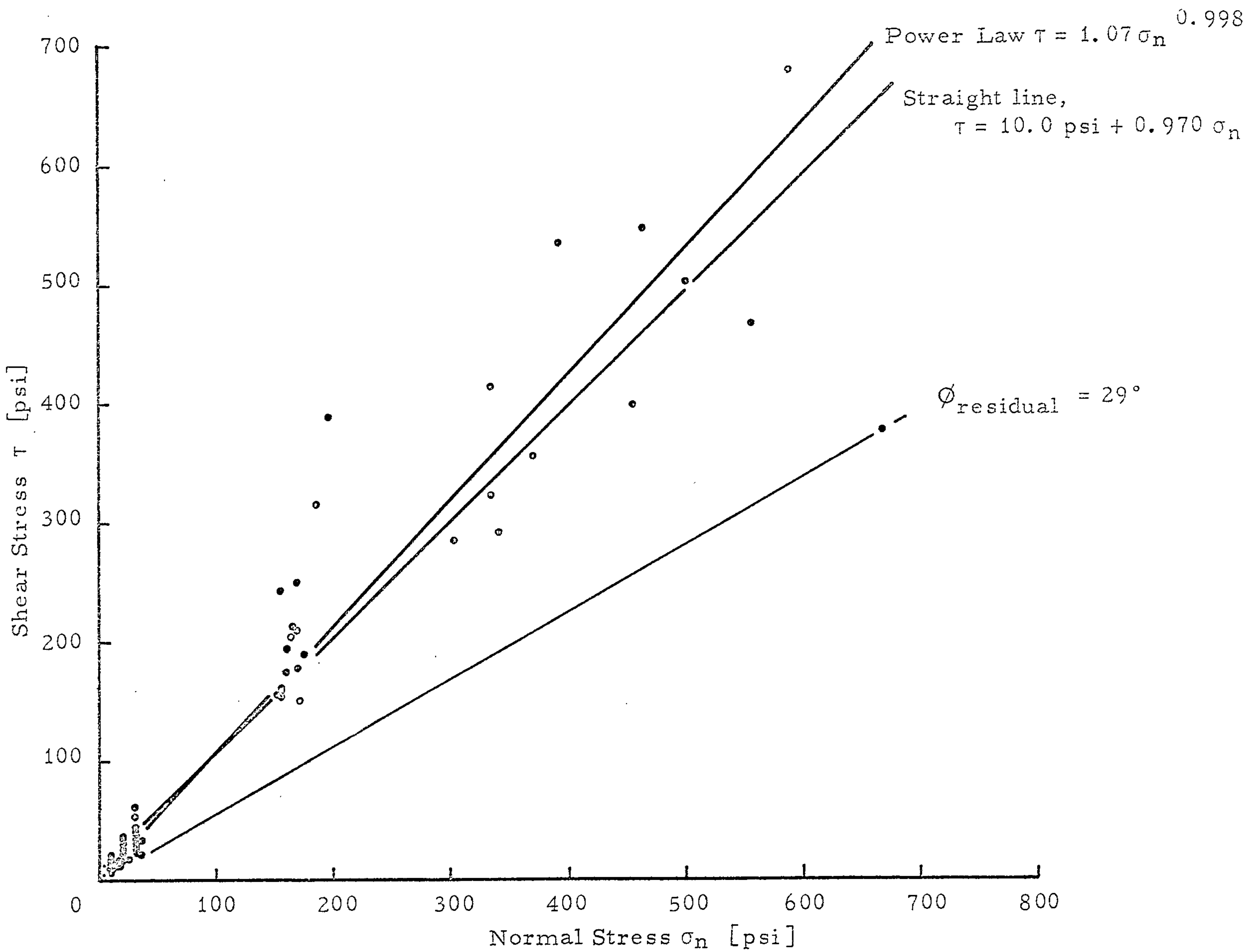

FIGURE 4: Peak Shear Resistance at Low and High Normal Stresses in Direct Shear Tests.

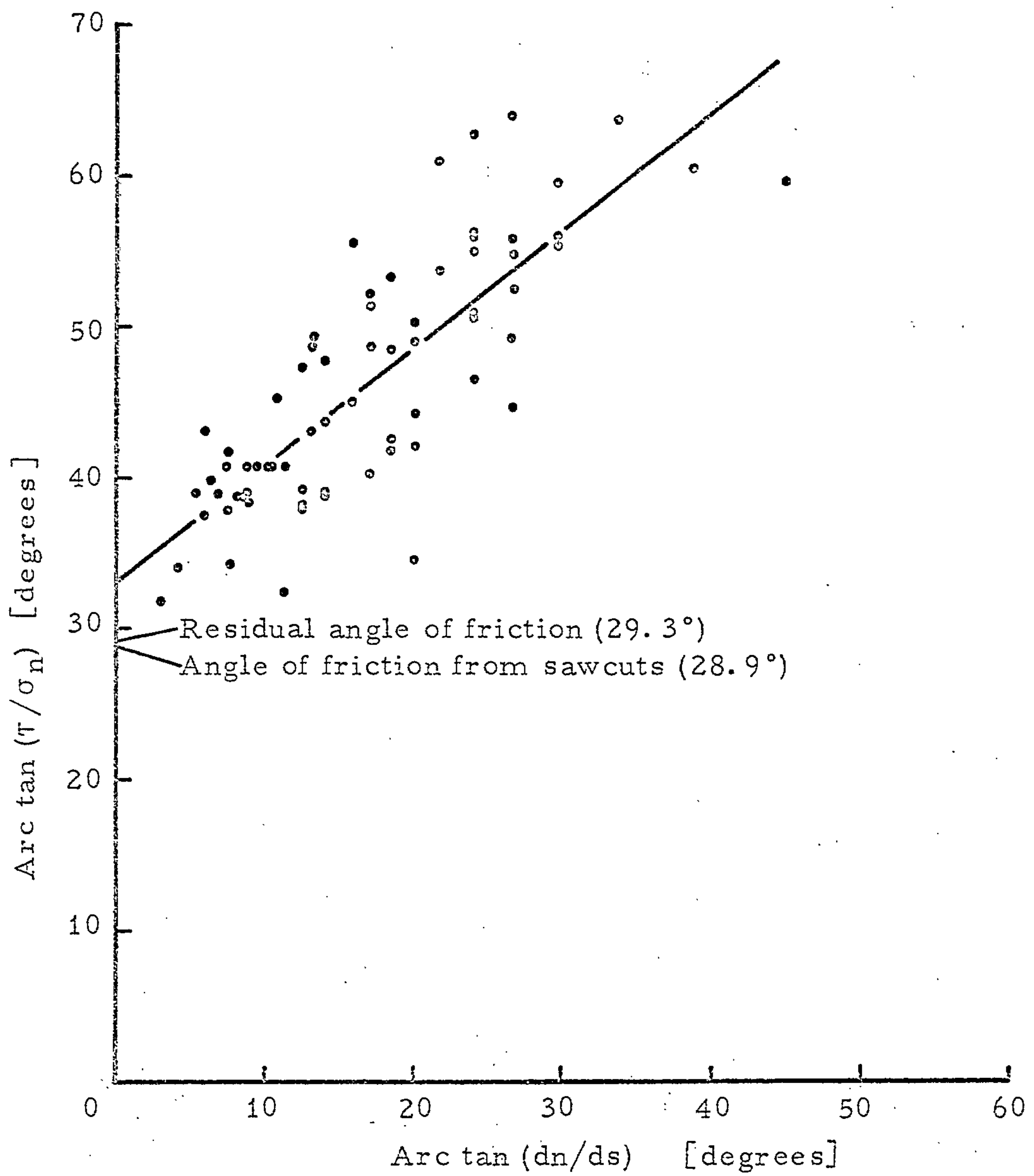

FIGURE 5: Calculation of Angle of Friction at Zero Dilatancy for All Samples.

APPENDIX A

TEST DATA

Results from Direct Shear Tests

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
Quartz-chlorite gneiss									
1, contains biotite and garnets, clean very rough geological fracture, 10% slickensided, sharp irregular asperities up to ≈ .15 in. high, sheared along slickensides, vertical, good surface contact, 6.1 in.^{2}									
	16	16.9	46.6	24.0	.035	29.0	22.6	1.0	300
	26	25.7	44.7	26.6	.025	23.2	18.1	1.0	300
	36	32.5	42.1	20	.035	28.7	22.1	1.0	300
	164	205	51.3		.065	43.83		1.005	180
	328					43.53		1.0	248
	492					41.13		1.0	252
2, contains biotite, clean moderately smooth geological fracture, 100% slickensided, thin calcite covering ≈ 60%, irregular asperities up to ≈ .05 in. high, few sharp asperities, sheared along slickensides, 17° left of vertical, very good surface contact, 6.5 in.^{2}									
	16	10.9	34.3	7.6	.08	22.9	26.7	1.0	190
	26	17.5	34.0	4.1	.07	25.9	29.9	1.0	227
	36	22.3	31.8	2.9	.095	25.2	28.9	1.0	271
	154					36.9		1.01	187
	308					39.5		.955	210
	462					38.4		.975	210
3, contains biotite, clean rough geological fracture, 85% slickensided, thin calcite covering ≈ 15%, asperities up to ≈ .15 in. high, mostly ≈ .08 in. high few sharp asperities, sheared along slickensides, 30° left of vertical, poor surface contact, 4.2 in.^{2}									
	10					30.8*		1.0	215
	20					24.9*		1.0	264
	30					27.6*		1.0	264
	238					37.8		1.0	155
	476					37.7		.975	165
	714					36.5		1.05	200

* Residual shear resistance.

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
4, contains biotite and garnets, clean very rough geological fracture, 80% slickensided, calcite covering < 10%, sharp interlocking asperities up to ≈ .15 in. high, undulation A ≈ .15-.3 in., sheared along slickensides, 8° left of vertical, poor surface contact, 4.2 in.^{2}									
	10	6.9	34.6	20.0	.225	19.7	14.6	1.0	223
	20	16.2	39.0	14.0	.240	30.8	25.0	1.0	300
	30	23.3	37.9	12.5	.235	32.4	25.4	1.0	300
	238					45.6		.905	220
	476					44.6		.755	184
	714					42.0		.895	210
5, contains biotite and garnets, clean rough geological fracture, 50% slickensided, several interlocking asperities up to ≈ .15 in. high, several protruding garnets, sheared along slickensides, 35° left of vertical, good surface contact, 6.4 in.^{2}									
	10	9.4	43.2	13.2	.025	31.4	30.0	.77	155
	20	19.5	44.3	20.0	.015	29.4	24.3	.54	110
	30	25.8	40.7	10.3	.025	30.5	30.4	.73	145
	156					41.9		1.0	210
	313					39.9		1.0	270
	469					37.2		.995	240
6-1, contains biotite and garnets, clean moderately rough geological fracture, 100% slickensided, minor calcite, several interlocking asperities up to ≈ .12 in. high, undulation A ≈ .15 in., sheared along slickensides, 25° left of vertical, very good surface contact, 5.9 in.^{2}									
	10	9.4	43.2	6.0	.035	26.6*	37.2	.945	214
	20	22.7	48.6	13.2	.0075	20.9*	35.4	.925	240
	30	25.8	40.7	10.3	.0425	27.5	30.4	.93	210
	170	150.9	41.6		.20	34.6		1.015	205
	339	291.5	40.7		.235	36.3		.995	300
	509					37.2		.960	220

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
6-2, contains biotite, clean rough geological fracture, 95% slickensided, patches of calcite covering ≈ 30%, dull asperities up to ≈ .08 in., smooth undulation A ≈ .15 in., sheared along slickensides, 27° left of vertical, poor surface contact, 5.1 in.^{2}									
	10	7.8	38.0	12.5	.025	25.7*	25.5	.97	210
	20	19.1	43.7	14.0	.0125	32.9*	29.7	.915	201
	30	24.5	39.2	12.5	.03	32.1*	26.7	.955	210
	196					41.7		1.01	245
	392					41.8		.840	260
	588					39.5		1.0	240
7, contains biotite, clean moderately smooth geological fracture, 95% slickensided, patches of calcite covering ≈ 15%, dull asperities up to ≈ .08 in. high, sheared along slickensides, 15° left of vertical, good surface contact, 6.0 in.^{2}									
	10	8.0	38.7	8.1	.125	26.6*	30.6	.98	192
	20	15.5	37.8	7.4	.11	25.8*	30.4	1.05	229
	30	23.8	38.4	8.7	.115	25.5*	29.7	1.0	265
	167	177.5	46.8		.150	43.4		1.0	190
	333					40.2		.985	205
	500					39.1		1.0	215
8, contains biotite, clean smooth geological fracture, 100% slickensided, minor calcite, no sharp interlocking asperities, smooth undulations A ≈ .04 in., sheared along slickensides 15° left of vertical, good surface contact, 5.8 in.^{2}									
	10					20.8*		1.05	223
	20					21.8*		1.0	267
	30					22.5*		1.0	330
	172					35.0		.960	190
	345					34.4		1.0	175
	517					37.0		1.005	200

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
9, contains biotite, clean rough geological fracture, 95% slickensided, patches of calcite covering ≈ 10%, asperities up to ≈ .12 in. high, large undulation A ≈ .12 in., L = 1.6 in. ⊥ to shear direction, sheared along slickensides, vertical, poor surface contact, 2.5 in.^{2}									
	14.8	13.2	41.7	7.6	.22	31.3	34.1	.485	102
	20	17.2	40.7	9.5	.08	25.6	31.2	.525	120
	30	23.0	37.5	5.9	.10	28.1	31.6	.485	175
	400					41.7		1.0	185
	800					42.8		.995	190
	1200					38.9		.995	165
9-A, contains biotite, clean very rough geological fracture, iron oxide covering ≈ 10%, calcite covering 5-10%, sharp interlocking asperities up to ≈ .25 in. high formed by intersection of gneissosity with shear plane, ridges and troughs parallel to direction of shearing, sheared top down, 20° left of vertical, very good surface contact, 6.0 in.^{2}									
	10	20.2	63.6	33.7	.01	30.3*	29.9	1.0	236
	20	34.0	59.5	29.7	.015	33.7*	29.8	1.05	240
	30	44.7	56.1	24.0	.03	35.0*	32.1	1.01	195
	167	250.0	56.3		.025	43.5		1.0	230
	333	413.3	51.1		.065	42.1		1.0	220
	500	503.3	45.2		.115	41.3		1.0	210
10, contains biotite, clean very rough geological fracture, 95% slickensided, patches of iron oxide covering ≈ 10%, irregular asperities up to ≈ .12 in. high, large undulations A ≈ .15 in. L ≈ .8 in. ⊥ to shear direction, sheared along slickensides, 15° right of vertical, poor surface contact, 2.1 in.^{2}									
	17.6	11.2	32.4	11.3	.12	22.1	21.1	1.01	159
	20	16.2	39.0	8.7	.145	34.2	30.3	1.45	190
	30	24.0	38.7	8.4	.12	33.4	30.3	.96	176
	476					42.0		.96	180
	952					41.8		.995	190
	1429					40.7		1.005	180
11, no test.									

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
12, clean very rough geological fracture, no slickensiding, diagonal ridges and troughs formed by intersection of gneissosity with shear plane, sharp interlocking asperities up to ≈ .3 in. high, sheared top down, vertical, good surface contact, 5.1 in.^{2}									
	10	17.1	59.6	45.0	.0075	42.4	14.6	.94	200
	20	29.0	55.4	29.7	.03	39.5	25.7	1.005	171
	30	52.9	60.5	38.7	.005	40.8	21.8	1.01	189
	196	388.2	63.2		.020	47.7		1.0	180
	392	535.3	53.8		.060	49.0		.94	220
	588	680.4	49.2		.10	45.9		1.0	225
13, clean rough geological fracture, 50% slickensided, thin calcite covering < 10%, asperities up to ≈ .08 in. high, large interlocking diagonal undulation A ≈ .4 in., L = 6.2 in., sample glued together for testing, sheared along slickensides, vertical, good surface contact, 5.1 in.^{2}									
	10	13.4	53.3	18.4	.08	43.6	34.9	.995	231
	20	29.6	56.0	24.0	.06	42.4	32.0	.97	180
	30	37.6	51.4	17.1	.095	42.5	34.3	.91	143
	196					48.5		1.0	210
	392					45.0		.895	230
	588					42.0		1.0	192
14, contains biotite, clean rough geological fracture, 30% slickensided, interlocking asperities up to ≈ .25 in. high, mainly ≈ .1 in. high, sheared along slickensides, 32° left of vertical, very good surface contact, 6.3 in.^{2}									
	10	11.6	49.2	26.6	.005	20.1*	22.6	.85	150
	20	18.4	42.6	18.4	.055	22.4*	24.2	.985	191
	30	26.8	41.8	18.4	.025	22.2*	23.4	1.005	190
	159	193.7	50.7		.010	41.0		1.01	168
	318					41.4		1.0	185
	476					40.4		1.005	190

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
15, contains biotite and garnets, clean moderately smooth geological fracture, 95% slickensided, minor calcite coating, asperities up to ≈ .08 in. high, large undulation A ≈ .12 in., L = 2in. parallel to shear direction, sheared along slickensides, 17° right of vertical, good surface contact, 5.7 in.^{2}									
	10	14.6	55.5	15.9	.015	26.6*	39.6	1.005	152
	20	25.8	52.2	17.1	.0675	33.3	35.1	1.0	256
	30	34.9	49.3	13.2	.05	33.2	36.1	1.0	246
	175	189	47.2		.045	42.6		1.01	190
	351					43.6		1.005	230
	526					38.7		1.005	160
16-1, contains biotite, clean rough geological fracture, 95% slickensided, thin calcite covering ≈ 35%, several interlocking asperities up to ≈ .15 in. high, undulation A ≈ .12 in., L ≈ 3 in. parallel to shear direction, sheared along slickensides, 15° right of vertical, good surfact contact, 6.1 in.^{2}									
	10	11.0	47.7	14.0	.12	37.9	33.7	1.005	217
	20	21.6	47.3	12.5	.08	36.4	34.8	1.005	219
	30	30.2	45.2	10.8	.135	38.0	34.4	1.005	235
	164	213.1	52.4		.095	48.6		.635	150
	328					46.7		.995	185
	492					45.0		1.0	195
16-2, contains biotite, clean rough geological fracture, no slickensiding, interlocking asperities up to ≈ .15 in. high formed by intersection of gneissosity with shear plane, undulation A ≈ .4 in., L = 2 in. ⊥ to shear direction, sheared top down, vertical, very good surfact contact, 6.5 in.^{2}									
	10	12.2	50.6	24.0	.04	32.2	26.6	1.01	243
	20	29.7	56.0	29.7	.03	32.6	26.3	1.015	210
	30	39.1	52.5	26.6	.01	35.3	25.9	1.005	195
	154	243.1	57.6		.020	52.2		.730	180
	308					49.1		1.015	190
	462	547.7	49.9		.46	47.0		1.015	

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
17, contains biotite, clean moderately smooth geological fracture, 95% slickensided, calcite covering centre 60%, smooth undulations and asperities up to ≈ .04 in. high, large step across sample ≈ .2 in. high restricting shear movement, sheared along slickensides, bottom down due to large step, 23° right of vertical, good surface contact, 5.4 in.^{2}									
	10	8.1	39.0	5.4	.045	31.2*	33.6	1.01	212
	20	16.7	39.8	6.3	.12	27.9	33.5	1.055	220
	30	24.2	38.9	6.7	.025	31.2*	32.2	1.005	188
	152	153.5	45.2		.070	43.2		1.015	170
	303	286.4	43.4		.100	41.8		1.005	155
	455	398.5	41.2		.115	39.4		1.005	200
18-1, contains biotite, clean moderately rough geological fracture, 60% slickensided, patches of calcite covering ≈ 20%, asperities up to ≈ .04 in. high, large undulations A ≈ .45 in., L > 3.4 in. ⊥ to shear direction, sample has several pieces glued together, sheared along slickensides, 16° left of vertical, good surface contact, 5.4 in.^{2}									
	10							.41	95
	20							.405	99
	30					36.5		.38	97
	185					47.2		1.01	240
	370					41.7		1.005	240
	556							1.0	175
18-2, contains biotite, clean rough geological fracture, no slickensides, patches of calcite covering ≈ 10%, sharp asperities up to ≈ .15 in. high, diagonal undulations A ≈ .2 in., L = 2.7 in. sheared top down, vertical, good surface contact, 5.4 in.^{2}									
	10	14.3	55.0	24.0	.065	34.4	31.0	1.025	150
	20	28.5	54.9	26.6	.04	37.5	28.3	1.005	183
	30	60.9	63.8	26.6	.02	41.2	37.2	1.025	180
	185	314.8	59.6		.01	41.4		1.005	190
	370	356	43.9		.075	38.7		1.0	170
	556	466.7	40.0		.185	37.9		1.02	180

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
19, contains biotite, clean moderately smooth geological fracture, 95% slickensided, patches of calcite covering ≈ 20%, smooth asperities up to ≈ .08 in. high, sample has pieces glued together, sheared along slickensides, vertical, poor surface contact, 4.5 in.^{2}									
	10					20.7*		.75	149
	20					29.3*		.705	171
	30					22.2*		.70	142
	222					31.0		.60	95
	444					31.0		.70	120
	667	375.6	29.4		.070	28.1		.64	
20-1, contains biotite, clean rough geological fracture, 95% slickensided, minor patches of calcite, sharp interlocking asperities up to ≈ .12 in. high, sheared along slickensides, 30° left of vertical, good surface contact, 6.0 in^2									
	10	19.3	62.7	24.0	.015	38.7	38.7	1.005	144
	20	27.3	53.8	21.8	.015	32.3	32.0	1.005	236
	30	34.0	48.6	17.1	.025	35.4	31.5	1.005	213
	167	209.2	51.4		.030	44.7		1.0	230
	333	321.7	44.0		.070	41.0		1.01	185
	500					40.5		.9005	200
20-2, contains biotite, clean moderately smooth geological fracture, 95% slickensided, asperities up to ≈ .08 in. high, few interlocking asperities, sheared along slickensides, 35° left of vertical, good surface contact, 6.3 in.^{2}									
	10	14.8	55.9	26.6	.035	27.3*	29.3	1.005	213
	20	24.6	50.9	24.0	.0275	29.4*	26.9	1.0	217
	30	34.0	48.5	18.4	.05	31.1*	30.1	1.005	242
	159	175.4	47.7		.030	40.5		1.01	180
	318					40.7		.960	200
	476					39.4		1.0	200

Rock Type, Sample No., Fracture Description, Shear Direction, Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
21, contains biotite, clean moderately smooth geological fracture, 95% slickensided, dull interlocking asperities up to ≈0.8 in. high, sheared along slickensides, 20° left of vertical, very good surface contact, 6.6 in.^{2}									
	10	11.5	49.0	20.0	.02	31.2*	29.0	1.005	261
	20	36.1	61.0	21.8	.01	31.2*	39.2	1.005	196
	30	30.0	45.0	15.9	.015	31.6*	29.1	1.0	211
	152	154.5	45.6		.045	40.4		.975	195
	303					40.9		1.0	190
	455					39.5		1.0	
22-1, contains biotite, clean moderately rough geological fracture, 90% slickensided, thin patches of calcite covering ≈ 40%, smooth interlocking asperities up to ≈ .12 in. high, sheared along slickensides, 20° left of vertical, good surface contact, 6.5 in.^{2}									
	10	8.0	38.7	14.0	.025	25.9	24.7	1.005	257
	20	17.2	40.7	11.3	.03	29.6	29.4	1.015	216
	30	36.0	50.2	20.0	.01	31.6	30.4	1.005	218
	154	156.9	45.6		.03	42.0		1.0	180
	308					41.2		1.0	195
	462					38.3		1.0	195
22-2, contains biotite, clean rough geological fracture, 85% slickensided, minor sulphide mineralization, asperities up to ≈ .15 in. high, some interlocking asperities, undulations A ≈ .15 in., sheared along slickensides, vertical, good surface contact, 6.5 in.^{2}									
	10	8.6	40.7	8.7	.17	30.3	32.0	1.01	192
	20	16.9	40.2	17.1	.0225	30.3	23.1	1.015	198
	30	25.8	40.7	7.4	.325	29.4	33.3	1.01	220
	154	158.5	45.7		.055	39.2		1.01	185
	308					36.5		1.01	195
	462					34.7		1.0	175

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
S-7-1 Sawcut, 6.0 in.^{2}									
	10					25.8*		1.01	209
	20					27.9*		1.005	228
	30					28.6*		1.005	253
	166.7					36.5		1.0	170
	333.3					37.8		1.0	195
	500.0					37.7		.98	170
S-7-2 Sawcut, 6.0 in.^{2}									
	10					22.6		1.005	150
	20					23.2		1.005	177
	30					26.1		1.0	175
	166.7					40.4		1.0	170
	333.3					40.7		1.0	200
	500.0					40.7		1.0	215
S-7-3 Sawcut, 6.0 in.^{2}									
	10	4.6	24.6		.195	19.3		1.005	178
	20	8.2	22.2		.215	15.8		1.005	162
	30	13.8	24.8		.155	21.0		1.005	165
	166.7					31.8		1.0	170
	333.3					32.4		1.0	210
	500.0					33.2		1.0	200
S-22-1 Sawcut, 5.8 in.^{2}									
	10					16.3		1.005	132
	20					20.3		1.01	158
	30					19.0		1.005	137
	172.4					31.8		1.0	155
	344.8					35.9		1.0	205
	517.2					36.0		1.01	195

Rock Type Sample No. Fracture Description Shear Direction Size Shear Surf. (in.^{2})	Normal Stress, σ_n (psi)	Peak Shear Stress, τ (psi)	Peak arc tan (τ/σ_n)	Peak Dilation arc tan (dn/ds)	Peak Shear Displacement (in.)	Post Peak arc tan (τ/σ_n)	Calculated Residual arc tan (τ/σ_n)	Total Displacement (in.)	Time (seconds)
S-22-2, Sawcut, 5.9 in.^{2}									
	10	3.6	20.0		.165	16.1		1.005	229
	20	7.2	19.8		.12	14.9		1.005	252
	30	11.9	21.6		.085	16.8		1.005	277
	169.5					31.0		1.0	180
	339.0					36.9		1.015	165
	508.5					35.5		1.025	205
S-22-3 Sawcut, 6.0 in.^{2}									
	10					25.0		1.01	135
	20					27.1		1.01	141
	30					24.4		1.01	227
	166.7					36.9		1.0	180
	333.3					38.1		1.005	180
	500.0					37.2		1.0	185