Strain analysis of Archean rocks from the Virginia Horn area, NE Minnesota

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Abstract

The Virginia Horn refers to the structure where the outcrop pattern of the Biwabik Iron Formation makes a sharp bend southward and then back north as a part of a broad, gently plunging anticlinal and synclinal flexure, near the city of Virginia in northeastern Minnesota, exposing supracrustal rocks of Archean age within the core of the anticline. Three deformation events have affected these rocks (Jirsa and Boerboom 2003). Strain analysis on three graywacke samples from the area was performed in order to determine whether the small-scale structures present in the rocks are consistent with the megascopic structure. Specifically, the R_f/Φ phi method proved to be reliable and consistent when applied to these samples. The strain data show that graywackes from the area exhibit a degree of flattening consistent with the D_2 deformation.

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Introduction

A complexly deformed sequence of Archean supracrustal metavolcanic and metasedimentary rocks and minor felsic intrusions are exposed in the core of a broad anticlinal flexure in the Biwabik Iron Formation of northeastern Minnesota referred to as the "Virginia Horn" (Figure 1, Welsh et al., 1989; Jirsa and Boerboom, 2003). At least three episodes of deformation have affected these rocks, and a major fault/shear complex cuts through them (Welsh, 1989; Jirsa and Boerboom, 2003). Jirsa and Boerboom (2003) detail the structural history of this area. The purpose of this study is to attempt strain analysis in order to further document the strain history of these rocks.

Geologic Setting

The Archean rocks of northeastern Minnesota, including those exposed within the Virginia Horn, are considered to be an extension of the Wawa Subprovince of the Superior Province (Jirsa and Boerboom, 2003). The supracrustal rocks specific to the Virginia Horn have been intruded by the Giants Range Batholith directly to the north, and are separated by it from similar rocks in the Vermilion district to the north. Unconformably overlying this complex of Archean rocks are the sedimentary rocks of the Animikie Group, which include the Biwabik Iron Formation.

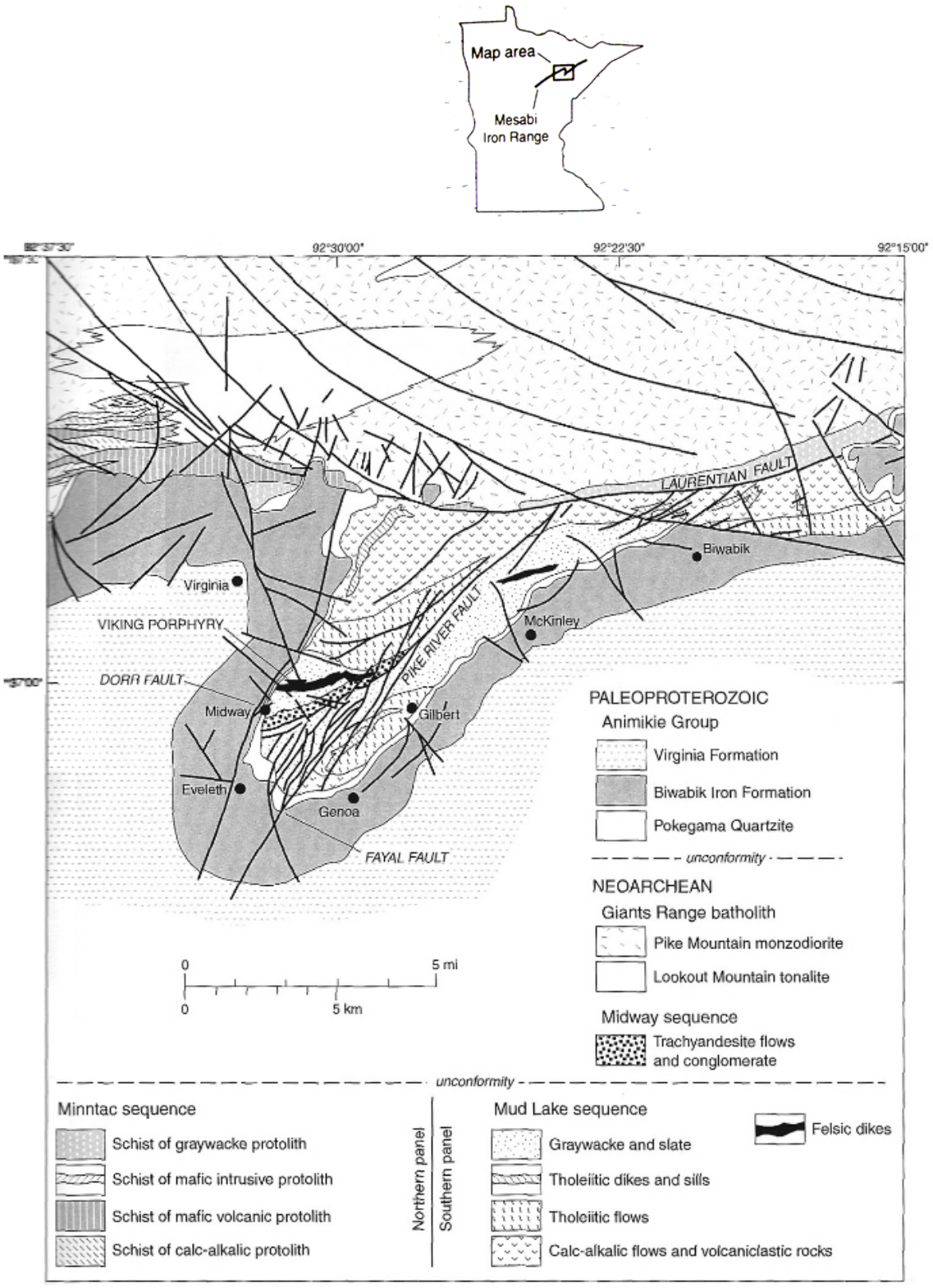


Figure 1. Map of the Virginia Horn in northeastern Minnesota

Previous Work

The first detailed study of the area was done by Sutton (1963). As an extension of earlier work along the Laurentian Divide, J. Welsh began a detailed mapping project in the Virginia Horn, where he began to work out the detailed structural geology, and identified the Pike River Fault (Welsh 1989, Welsh et al., 1989; Welsh et al., 1991). Jirsa and Boerboom (1998, 2003) produced a detailed geologic map of the area, and summarized the geology in detail. They divided the rocks of the area into three groups: the Minntac, Mud Lake, and Midway sequences.

The Minntac sequence of rocks is composed mainly of schists of volcanic and sedimentary origin, which have been metamorphosed to middle amphibolite grade. It occurs in the northwestern part of the area where it is intruded by the Giants Range Batholith.

The Mud Lake sequence is believed to be of similar age to the Minntac sequence, though it experienced lower grade metamorphism, ranging from prehnite-pumpellyite to chlorite greenschist facies. This group consists of northern and southern suites of metavolcanics, separated by a main body of graywacke and slate. The graywackes are turbidites with thin layers commonly graded, and fine- to medium-sized grains with planar-laminated bedding.

The Midway sequence is embedded within the Mud Lake sequence and consists predominantly of conglomerates interlayered with a few trachyandesite flows that are fault bounded with the other Mud Lake sequence rocks. The conglomerates are composed of rocks from the Mud Lake sequence, indicating it formed after this sequence. The Mud Lake and Midway sequences were intruded by a gold-bearing quartz-feldspar porphyry named the Viking Porphyry.

Jirsa and Boerboom (2003) describe three deformation events that affected these rocks. D_1 deformation involved folding, but very little metamorphism. A large syncline that folded the rocks of the Mud Lake sequence is interpreted to have formed during this event (Figure 2), and is believed to have formed concurrently with deposition, tilting these rocks to a near vertical orientation. D_2 is characterized by isoclinal folding with a steeply plunging axis, accompanied by regional metamorphism. A prominent cleavage, S_2, formed during this event. D_3 consists primarily of later faults in the area.

Of special significance is the Pike River Fault system, trending almost along the fold axis of the Virginia Horn. Rocks along this fault exhibit ductile shear and are very phyllonitized. Map patterns and rock formations suggest mainly sinistral movement (Welsh et al, 1991, Jirsa and Boerboom 2003). Jirsa and Boerboom (2003) suggest that this movement initiated during D_1 deformation, before the formation of the Mud Lake Syncline. Pull apart structures then developed and were concurrently filled by the conglomerates and flows of the Midway sequence; however, later kinematic indicators (such as minor folds) show dextral movement of the fault, suggesting reactivation of the fault in a later stage of deformation (Welsh et al, 1989; Jirsa and Boerboom, 2003). Jirsa and Boerboom did not, however, attribute this dextral movement to any specific deformational event. Welsh (pers.comm.) thinks that this later reactivation might be Penokean. This combination of faulting and direction change could be a possible factor in the formation of the overall Virginia Horn structure (Welsh pers.comm).

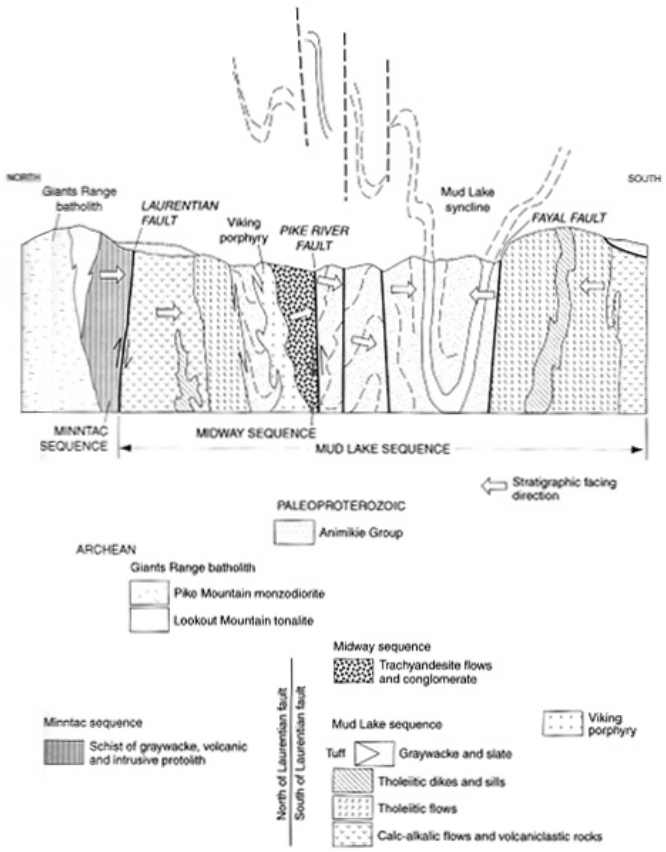


Figure 2. Cross section of the Virginia Horn showing locations of the three named sequences by Jirsa and Boerboom (2003)

Methods

Sample Collection

Oriented samples from the Horn area were collected during previous fieldwork by J. Welsh. These include graywackes from the Mud Lake sequence. All samples were oriented with respect to the S_2 prominent foliation. For each sample faces were cut and labeled A, B and C. A and B lie perpendicular to S_2 with face A cut essentially in the horizontal plane, and face B essentially in the vertical plane; face C lies in the plane of foliation (see figure 3).

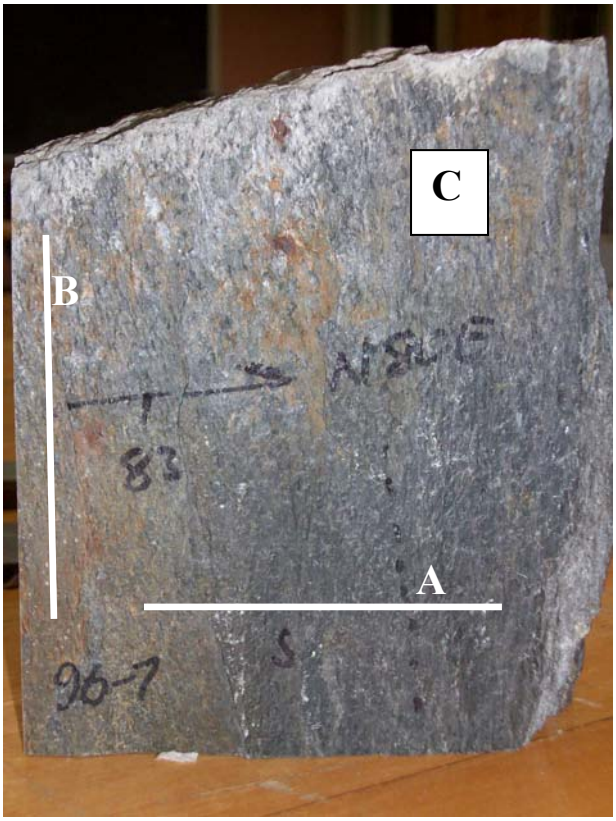


Figure 3. Example of an oriented greywacke from the Mud Lake Sequence. The white lines indicate direction of faces A and B, with face C lying within the plane of the rock-face.

Strain Analysis

The R_f/Φ method was used to assess the strain character of these rocks. The method, developed by Ramsay (1967) and Dunnet (1969), and later modified by Lisle (1985), can be used to provide reasonably consistent strain data from this area. The method provides a way to achieve the finite strain ellipse of a rock body using objects that were not originally circular (i.e. elliptical) and show no original fabric. It is based on measuring the axial ratio of the final strain ellipse of an object (R_f) and the angle between the long axis of the strain ellipse and the trace of foliation (Φ), which is S_2 for these samples. These can be compared to the original axial ratios and angular orientations for the object (R_i and theta, Θ, respectively), and used to determine the axial ratio for the strain ellipse of the entire rock sample (R_s).

Three graywacke samples, 6, 7, and 11, were chosen for this test because of more obvious signs of deformation, such as prominent S_2 cleavage. Quartz grains were chosen due to more distinguishable grain boundaries and a more likely chance that dissolution or mass change of the grain had not occurred. Using a Motic Images 3100 digital microscope camera and software, grains were measured for R_f values. Forty grains per section were measured for long and short axes of each grain's projected strain ellipse, along with the angle phi (Φ).

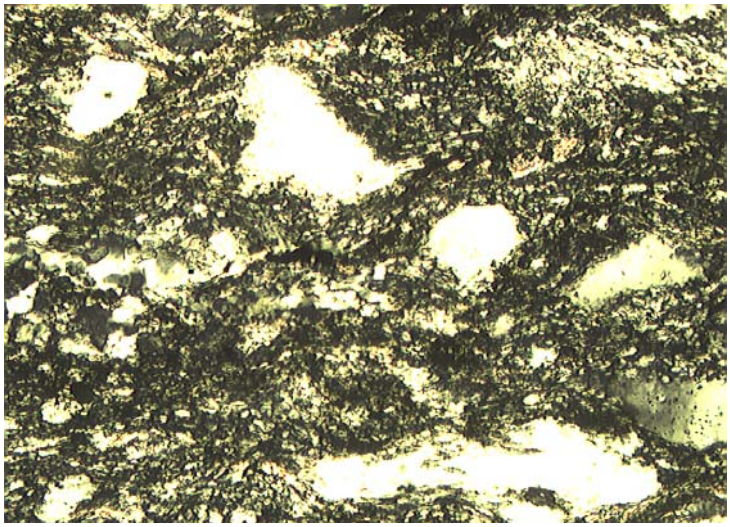


Figure 4. Example of a thin section from sample 6, section B. R_f and Phi data were obtained from visible quartz grains. The direction of foliation is straight across the slide.

Once all data had been collected I_{sym} tests were performed to assure that the data is consistent with the original assumption that no previous fabric was present in the rock. This test consists of determining the harmonic mean of the R_f values and the vector mean of Φ values, and by plotting them as lines with the R_f versus Φ data. When the two means are graphed as lines, they produce four quadrants within the plot. I_{sym} is a function of the number of data points in each quadrant (for more information see Lisle, 1985). The values of I_{sym} are then compared to critical values from the literature as presented in Table 1. For an I_{sym} value higher than the critical value for the sample size and projected R_s value the sample can be considered to have contained no original fabric. If a previous fabric were present, the

final R_s value would be a measure of the strain on that fabric, and not of the original host rock, and indicate need of further testing and manipulation in order to achieve a clear history of the deformation of the original host rock.

Table 1. Critical I_{sym} values as taken from Lisle (1985). These values are based on a 95% confidence interval, and are based on both sample size and projected R_f values based on the harmonic mean of the data, which tends to slightly overshoot the R_s value.

	Sample Size Number of grains				
Rs	20	30	40	100	200
1.5	0.3	0.51	0.6	0.74	0.82
2	0.5	0.63	0.73	0.8	0.86
3	0.5	0.63	0.73	0.8	0.87
5	0.5	0.63	0.73	0.82	0.87
10	0.6	0.63	0.73	0.82	0.87

If samples fit this original assumption, the plots can then be overlain with R_s value plots, as provided by Lisle (1985). An example is shown in Figure 5. The appropriate R_s value is selected from the overlay that shows the best fit. From this plot the strain ellipse ratio (R_s), original axis ratios (R_i), and orientations (Θ) for the rock sample can be determined.

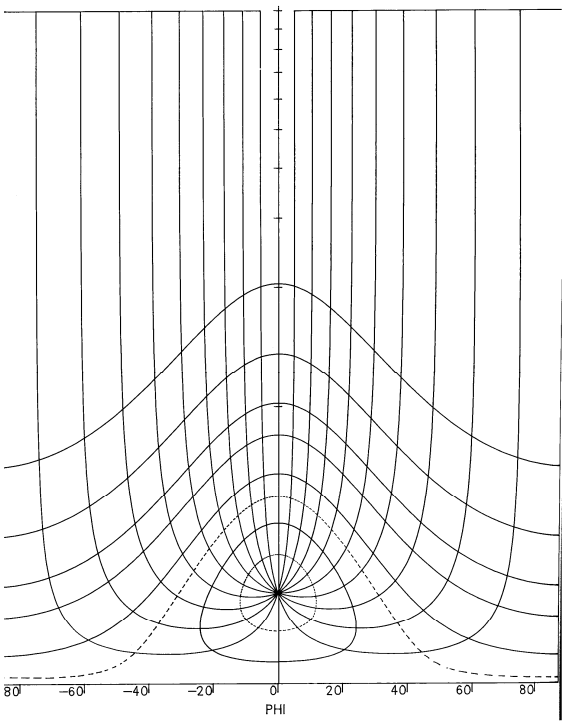


Figure 5. Example R_s plot. This represents a finite strain ratio of 1.7. Plotted points (R_f vs. Phi) are matched to the R_i and theta curves on the chart.

The resulting R_s values for each sample were then compared to determine if the results are consistent. Upon discovering this was the case all data were plotted together to determine an average R_s.

Results

Symmetry data for the curves are presented in Table 2. These values are higher than the critical values (0.6 to 0.73) for sample sizes of 40 (and 120 for the full sample) (Table 1, Lisle 1985). Passing this I_{sym} test indicates a more likely chance that no original fabric was present in the original rock, and further analysis can continue directly towards finding an R_s value without any need for further manipulation.

Table 2. I_{sym} data for sample 6, 7 and 11. These values surpass the critical values given by Lisle (1985) indicating that the rocks had no original fabric prior to deformation

Sample	I_{sym}
6A	0.75
6B	1.3
6C	0.615
7A	0.90
7B	1.23
7C	0.974
11A	0.95
11B	1.05
11C	0.833

R_f/Φ plots were then constructed. The combined R_f/Φ plots containing all data points are shown in Figure 6a, b, c for each face: A, B and C. The values for each individual sample are listed in Table 3. Averaging these data, final strain ratios were determined to be A:1.9, B:2.0, and C:1.5 (All the R_f/Φ hard data can be found in the Appendix, along with all other R_s plots not presented here).

Table 3. Final R_s values for the three samples and their combined total. As seen, this method is consistent throughout the samples.

Sample	Slide	R_s
6	A	1.8
	B	2
	C	1.5
7	A	1.9
	B	2.2
	C	1.7
11	A	1.7
	B	1.9
	C	1.6
Combined	A	1.9
	B	2.0
	C	1.5

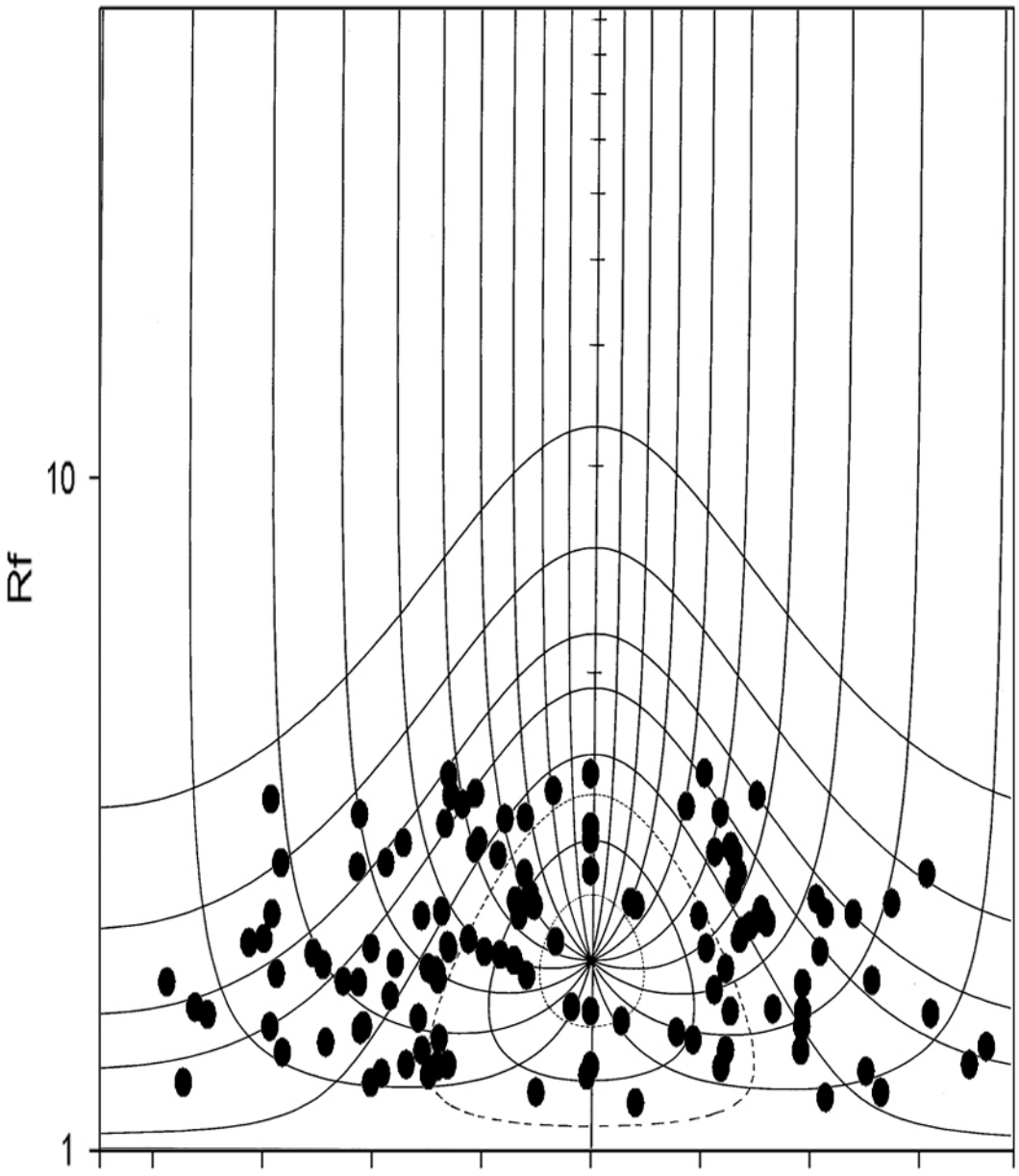


Figure 6a. R_s plot of the combined data for face A of samples 6, 7 and 11. The average R_s value is 1.9. The horizontal axis is Φ in increments of 20 degrees

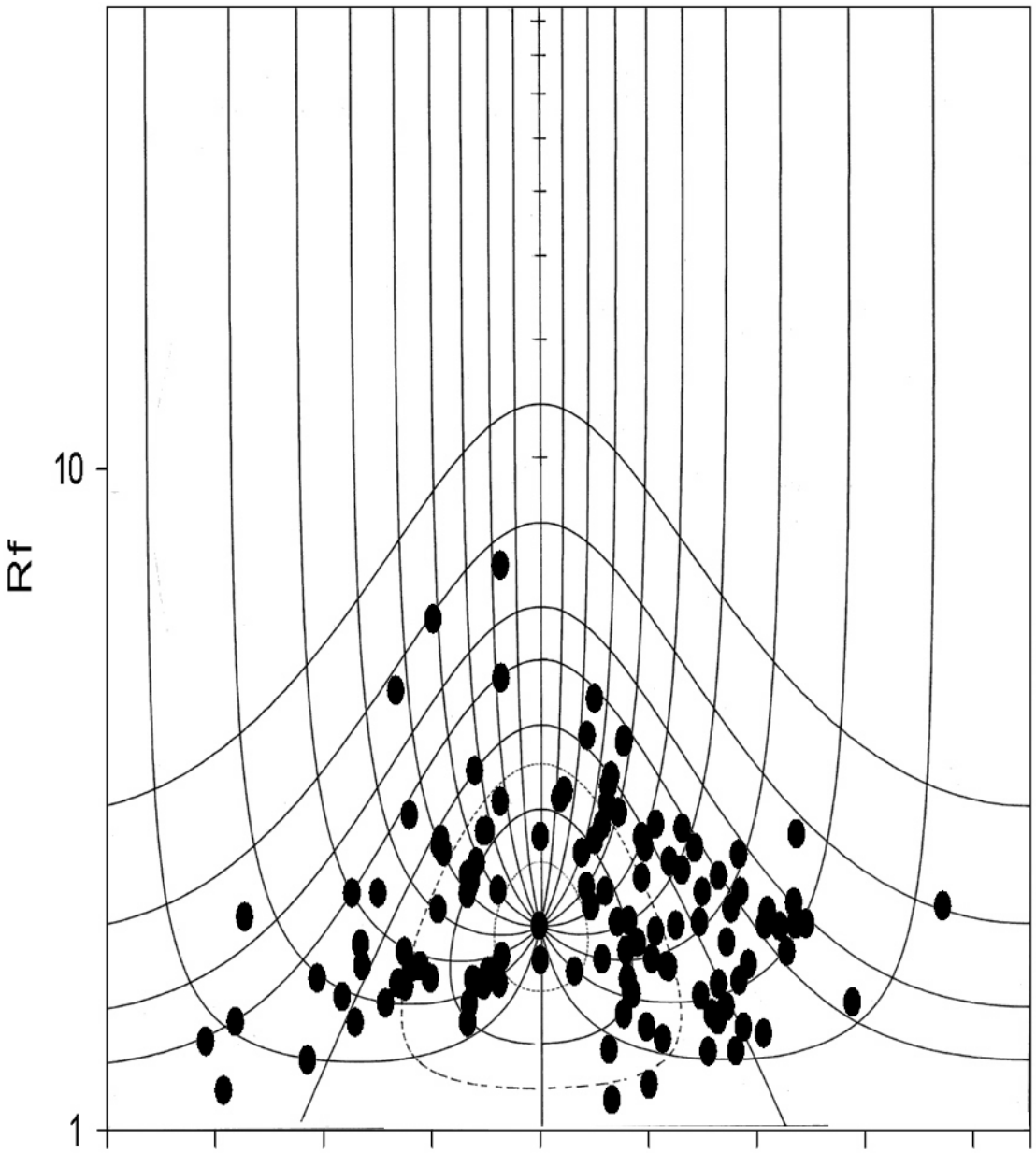


Figure 6b. R_s plot of the combined data for face B of samples 6, 7 and 11. The average R_s value is 2.0. The horizontal axis is Φ in increments of 20 degrees

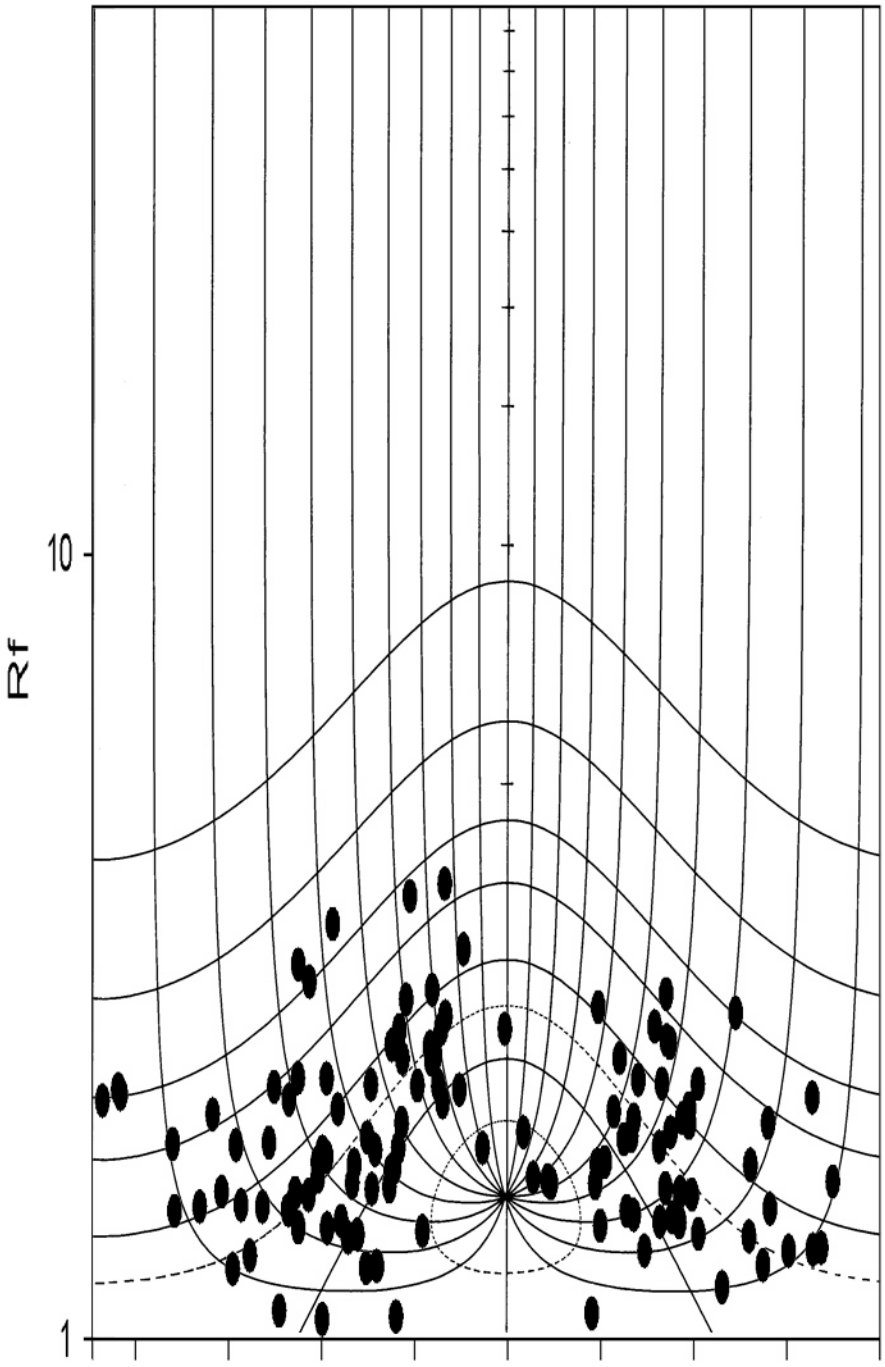


Figure 6c. R_s plot of the combined data for face C of samples 6, 7 and 11. The average R_s value is 1.5. The horizontal axis is Φ in increments of 20 degrees

Discussion

Based on strain ratios as determined, A: 1.9, B: 2.0, and C: 1.5, the strain ellipse for these rocks is therefore oriented such that S_1: B, S_2: A, and S_3: C. A Flinn diagram was constructed (Fig. 7). This pattern suggests deformation is mainly plane strain, with perhaps some flattening. This flattening is in the plane of S_2 foliation, as might be expected, and indicates a correlation between the strain in these rocks and the D_2 deformational event of the Horn area. That S_1, though weak, is in the vertical plane is also consistent with the steeply plunging fold axes of F_2.

Because these measurements were done with quartz grains, which are fairly resistant, the amount of strain attributed to the Virginia Horn area based on this data is most likely on the low end of a possible range of values. More pronounced strain is evident in other clasts, especially volcanic rock fragments, but it was difficult to make out individual grain boundaries due to alteration effects. Should it become possible to measure these grains, more pronounced R_s values will likely result.

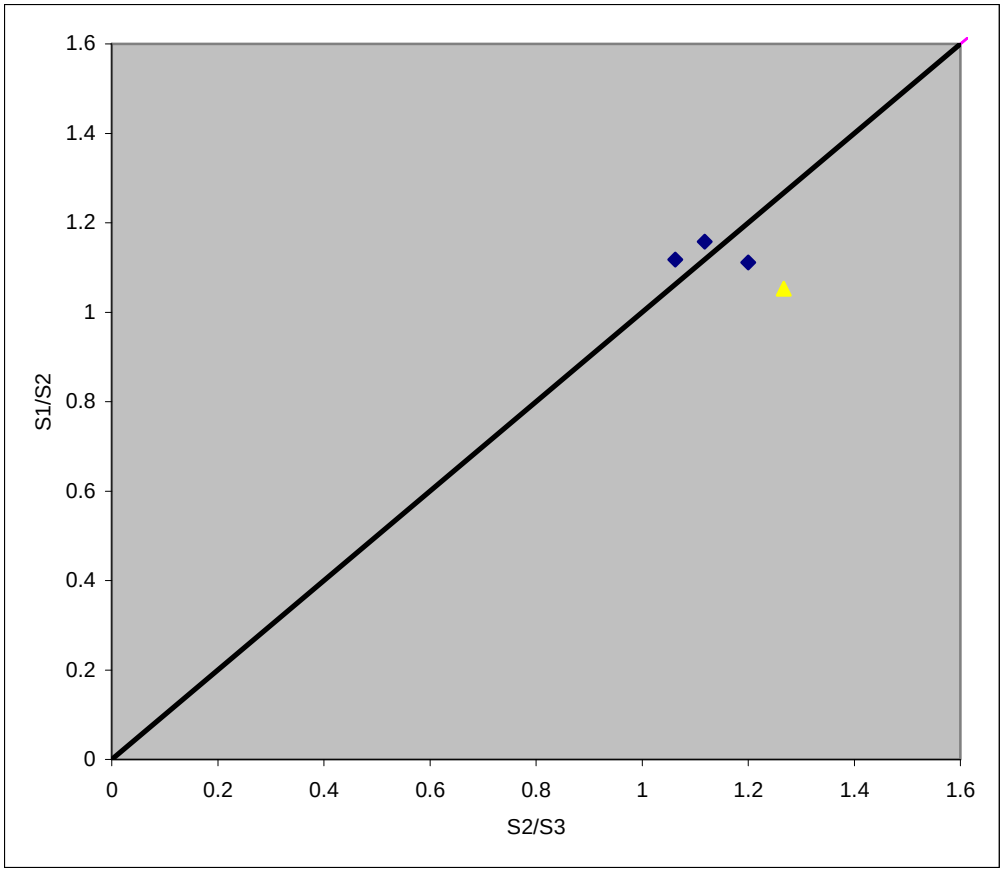


Figure 7. Flinn diagram of the strain ellipse for the samples taken, and a combined sample. All plot closely to the plain strain line, far enough along the x-axis to show a degree of flattening within the plane of cleavage.

Future Work

Future work for this project would include applying this method of strain analysis to more samples. Likewise, this method of analysis could be extended to the conglomerates of the area, to see if any difference in strain history is present. Similarly, this method could be extended to rocks from the shear zones, as these rocks are likely to show a different strain history.

Performing this method on different clasts might also yield more information. This study was done on quartz grains as they are easier to distinguish amongst the other clasts. It is however quite obvious looking at the thin sections that more deformation can be seen in

the volcanic clasts making up the matrix. A study of these could present a more pronounced strain value.

Conclusion

The data produced for the three samples were fairly consistent, indicating reliability of the method when applied to rocks from the Virginia Horn. The R_s values were generally around 1.9, 2, and 1.5 for faces A, B and C respectively, and indicate orientation of the strain ellipse as S_1: B, S_2: A, and S_3: C.

These values show evidence of plane strain, where the S_1 and S_2 axes of the strain ellipse are about equal, and both are slightly larger than S_3. These two longer axes lie within the plane of foliation. This indicates degree of flattening within the plane of cleavage (S_2), consistent with development during D_2 deformation.

Appendix 1: R_f/Φ data

Sample	Rf A	Phi A	Rf B	Phi B	Rf C	Phi C
6	1.30	-38.2	1.11	13.2	1.47	-66.2
	1.63	-72.3	1.87	15.8	1.46	-47.2
	2.00	21.1	1.83	-7.1	2.10	-14.9
	1.79	51.4	1.56	-28.6	1.24	-28.1
	2.19	32.2	1.63	16.6	1.43	35.5
	1.26	-40.2	2.34	8.5	1.06	-39.9
	2.68	-37.4	3.14	-7.4	3.14	-9.5
	1.79	-45.2	1.69	-12.5	1.88	-22.8
	1.61	0	2.28	-13.5	2.11	33.2
	2.64	-42.6	1.32	31	1.53	39.6
	3.62	-25.9	2.63	7.6	1.54	-61.5
	1.33	-28.1	1.46	-13.4	1.73	-39.8
	2.00	-25.9	1.67	-7.6	1.76	32.6
	3.06	-26.6	1.18	20.1	1.29	29.4
	2.68	-56.6	1.43	19.6	1.39	19.9
	3.04	0	2.64	-17.9	1.96	-36.5
	2.58	61.4	4.50	10	1.58	9.3
	2.61	0	3.18	3.6	2.60	49
	2.05	-6.4	2.75	10	1.41	32.7
	3.43	-6.8	3.95	8.6	2.00	-14
	1.22	-10	1.87	45.5	1.81	-30.2
	1.34	0	1.38	22.6	1.76	-58.4

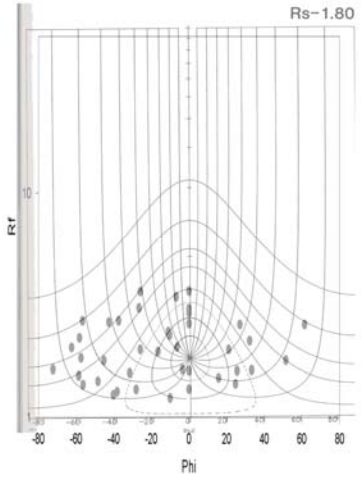
	2.91	0	2.86	26.2	1.74	-28.5
	1.83	-57.4	2.07	14.2	3.38	-37.6
	1.96	-16.5	2.10	-54.6	1.52	-42.8
	1.61	25.5	1.60	29.6	1.75	-5.4
	2.25	-58.2	1.70	16.1	1.07	-24
	1.63	33.3	2.06	49	1.29	60.4
	1.50	15.7	1.81	0	1.70	-39
	1.53	-58.6	2.05	41.4	2.15	-45.1
	2.40	-11	1.28	-43	1.41	-35.8
	1.58	-31.5	1.77	23.7	1.54	37.1
	1.45	-48.4	1.77	-22.2	1.64	-25.1
	1.64	-3.5	2.00	21.3	2.30	-15.6
	1.41	24.7	2.05	47.1	1.56	-25.4
	2.32	-10.3	2.18	9.3	3.80	-13.5
	2.58	27	1.50	15.4	2.27	-16.4
	1.40	-56.3	2.30	36.9	1.36	41
	3.64	0	1.56	-13.1	1.23	-30.4
	2.04	-62.4	2.31	-7.8	2.15	-38.9
	2.12	27.7	2.68	28.5	2.05	-83.2
	1.46	18.7	3.86	15.4	1.34	-34.3
	2.22	30.8	2.43	32.9	1.78	-51.3
	1.60	62.1	2.81	47.3	3.67	-21
	3.17	-42.2	1.46	-56.3	1.46	56.4
	2.82	-21.2	2.62	36.6	1.60	5.5
	2.77	26.2	3.00	-24.2	1.77	-72
	2.07	-59.7	5.94	-19.8	2.37	-24.9
	1.87	-29.7	2.78	18.7	1.65	-24.4
	1.83	-28	1.67	32.9	2.75	34.1
	2.78	22.7	3.43	13	1.68	-40.8
	1.33	23.8	3.32	12.5	2.57	-13.4
	3.12	-15.6	4.83	-7.3	1.56	33.9
	1.60	-70	3.90	15.5	2.48	-0.6
7	2.24	19.8	1.46	-34.2	2.03	65.5
	1.53	-41.5	2.91	21.3	1.44	27.1
	2.24	-30.9	1.92	17.9	2.71	-21.8
	3.33	-58.4	1.79	38.4	2.28	24.1
	1.31	50.3	2.43	-13.4	1.75	-23.5
	2.07	27.2	2.30	29.9	1.36	-32.3
	1.97	-50.7	2.19	74.3	2.08	-83.7
	2.27	-27.2	2.54	-11.8	1.53	-45.7
	1.92	-14	4.63	-26.7	1.38	-38.8
	2.06	-22.3	2.21	46.8	2.65	19.5
	1.78	-77.4	2.76	-18.4	1.66	52.2
	2.88	-20.4	1.15	-58.5	2.50	31.6
	2.25	48	1.74	-9.6	1.59	69.9
	3.64	20.8	1.32	36.1	3.00	-45
	3.28	-23.4	2.84	-10	1.16	46.1

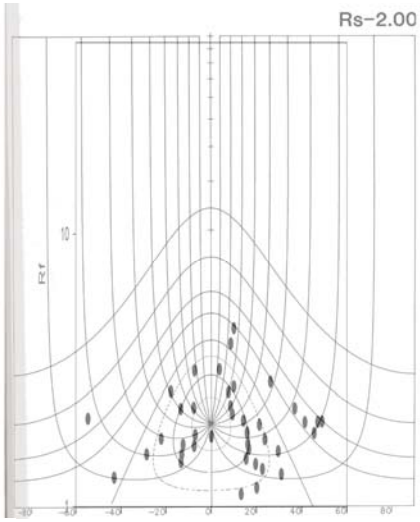
	1.30	-29.6	1.93	34.4	1.67	52.2
	2.32	8.3	3.13	12.3	2.40	34.2
	1.73	22.6	1.54	34.3	1.09	-49.1
	3.18	23.7	1.67	-26.3	2.27	-22.6
	2.33	55	2.30	12	1.83	35
	2.58	-12.1	2.17	35.2	1.67	19.2
	1.56	5.6	1.69	36.7	1.61	-40.8
	1.82	-11.7	2.04	25	1.45	25.6
	2.35	-13.7	2.68	19.3	2.38	34.9
	2.24	-13.1	7.15	-7.4	1.97	39
	2.37	41.2	1.91	-33.2	1.91	37.6
11	1.87	24.7	1.33	12.7	2.09	-50.2
	2.87	-34.2	1.65	-25	2.01	-87.1
	1.41	38.4	2.29	-30	1.68	20.9
	2.25	42.9	2.70	-18.7	1.88	56
	3.38	-25.5	1.74	6.3	1.45	-71.6
	2.44	26.1	2.16	-18.9	1.41	36.9
	1.43	72.3	1.77	23.3	1.35	51.9
	2.75	-16.9	2.15	41.9	2.48	-14.3
	1.89	-48.9	3.26	4.4	1.58	-33.4
	3.25	17.5	2.48	26.1	1.88	39
	1.26	-74.4	2.41	18.7	2.02	-47
	1.52	-42.1	1.77	-32.9	2.08	-10.4
	1.18	8.2	1.47	32.8	1.30	65.6
	3.38	30.4	2.55	23.8	2.47	-23.3
	1.29	-0.7	1.43	37.5	1.31	67.4
	1.41	-30.8	1.70	-20.3	2.85	-42.6
	1.85	-28.4	2.83	-10.5	2.10	-19.4
	1.53	38.6	1.50	31.7	1.67	-33
	1.34	-33.7	1.86	-25.1	1.24	54.9
	1.80	-27.9	2.38	-12.8	1.55	-29.2
	1.34	69.2	1.56	57.6	1.28	-55.4
	2.34	7.3	1.59	-36.6	1.47	-52.7
	1.98	-19.4	3.50	-12.1	1.93	-63.4
	2.02	-26.1	2.78	0	2.11	-29.4
	1.22	53	1.61	17	1.58	18.8
	2.83	25.6	2.89	11.4	1.95	22.8
	1.20	42.9	1.70	-9.9	1.79	25
	3.13	-11.9	1.82	20.6	1.08	18.1
	1.70	-36.6	1.66	-10.5	1.48	-57.3
	3.40	-21	1.70	-41.2	2.35	-16.7
	1.90	-35.7	2.08	16.3	2.14	28.1
	1.78	-42.4	1.82	11.4	1.90	27.1
	2.16	29.1	1.40	41.2	1.23	-59.1
	1.98	41.9	1.76	-24	1.83	3.4
	1.61	38.7	2.07	29.4	2.11	40.9
	1.77	38.7	1.36	-61.8	1.59	8.6

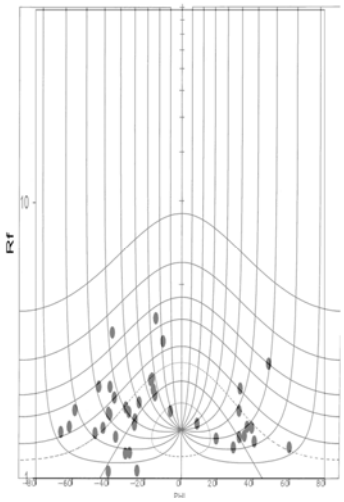
	2.00	-40.1	2.04	44.2	1.37	-18.3
	2.28	31.2	2.04	-0.2	1.38	-45
	1.47	-27.7	3.03	14.4	1.81	26.6
	1.34	-26.1	2.29	-34.8	2.78	-16.2

Appendix II: R_s Plots for samples 6, 7 and 11 (following page)

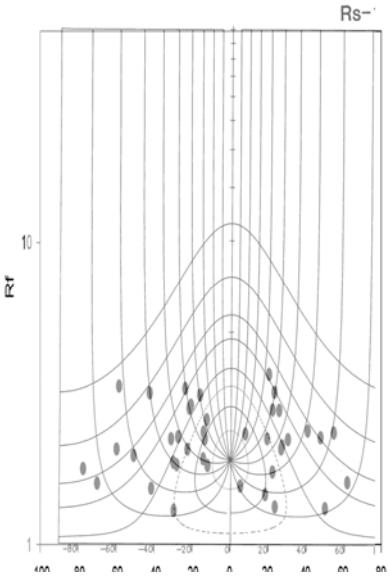
A **B** **C**

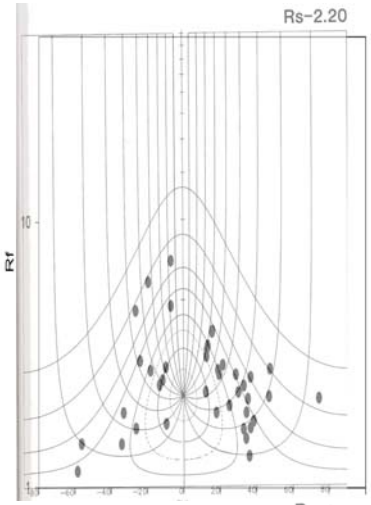


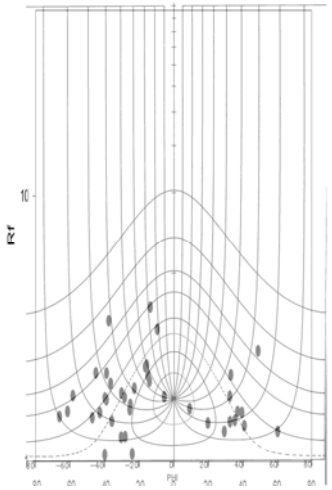




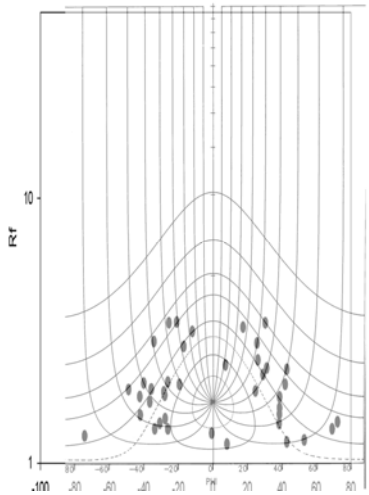
6

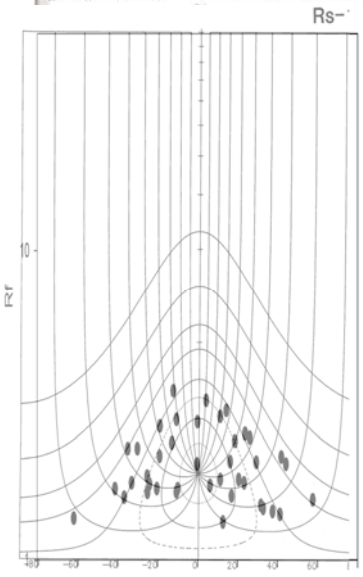


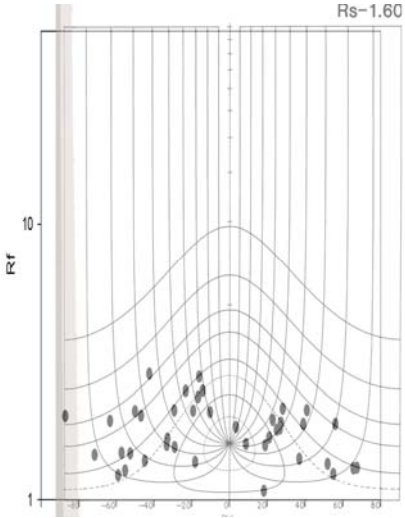




7







11

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