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Geochemistry Of Seine River Metaconglomerates From Mine Centre, Ontario: Interpreting Fluid Flow And Volume Changes During Deformation With Implications For Strain Analysis

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Abstract

Ductile shear zones are formed by tectonic plate interactions and are thought to be deep-seated equivalents to faults. Shear zones can act as both conduits for zone-parallel flow and barriers to cross-zone flow. Fluids have major impacts on deformation; they can alter deformation mechanisms, metamorphic reactions, and strain accumulation. Even though fluid is such an important factor in deformation, it is difficult to study due to its transient nature. Geochemical analyses may determine whether fluids assisted in depletion of soluble elements, resulting in volume changes. This method has demonstrated significant volume loss, up to 70%, in some shear zones, but none in others. The Seine River metaconglomerates are located in the Rainy Lake region of northwestern Ontario, Canada truncated by the Quetico Fault and the Seine River- Rainy Lake Fault. The metaconglomerates deformed under greenschist facies conditions; the presence of carbonate alteration suggests that fluid flow was an important factor during deformation. Whole rock geochemistry was performed on clasts from the metaconglomerate using X-ray fluorescence. Results from 61 analyzed samples show a high degree of variability and no significant changes in composition from low to high strain sites. For example, in granitoid clasts, the mean concentration of SiO_2 is 66.32% (st. dev. of 6.71%) at low strain and 69.06% (st. dev. of 5.67%) at high strain. The high variability and overlap of data for all major elements indicates either A) no significant clast volume change occurred between low and high strain regions or B) any major element geochemical change is masked by a large variability in initial compositions. If the latter is the case, then in order to capture any consistent alteration within the population of clasts as the result of fluid alteration, we may require a larger sample size or additional methods such as microscopy.

Keywords: **Shear Zone, Geochemistry, Fluid-Rock Interaction**

1. Intent:

Significant strain can accumulate in a ductile environment during geologic deformation forming a tabular shear band with defined boundaries of shear zone and wall rock.[9] Deformation caused by the collision of continental plates is influenced by the rock's mechanics. Temperature generally increases with depth in the earth. Materials act plastically as temperatures increase,[10] so that rocks generally fault and fracture in the upper crust and deform ductilely with depth, often localizing into shear zones.

The movement of fluids in shear zones is complex. Fluids can move more easily through shear zones or can alternatively be blocked by a shear zone.[22] If alteration occurs during fluid-rock interaction, the region may experience grain size reduction, changes in mineral composition, and an increased rate of reactive softening.[9] As fluids move through a shear zone, mobilization of soluble elements may change the volume. Studies that were able to estimate volume change in shear zones using geochemical methods often record volume loss.[1,15,22] While other studies, have geochemical data that indicate no volume change.[1,21, 22] Volume change poses a problem for strain analysis because, in most cases, structural geologists work under the assumption that there was no significant change in volume.[4,22] Laboratory results are typically used to determine rheological properties for rocks. Fluids may significantly change rock rheology by various mechanisms including lowering the crystal lattice yield point resulting in strain softening. Therefore, the competence of the material will differ dramatically affecting strain analysis and the tectonic interpretation of the area.[9] Fluid movement transports soluble elements; however, the relationship between shear zones, fluid movement, and precious earth elements is unknown.

While understanding fluids in natural shear zones is clearly important, they are difficult to study due to their transient nature. One way to learn some aspects of ancient fluid flow is through studying the effect fluids impart on rock composition. This study attempts to add to the dataset of fluid movement through shear zones by examining a kilometer-wide shear zone in the Rainy Lake Region. Bulk chemistry data obtained from X-ray fluorescence (XRF) should determine if major chemistry changes occurred during deformation, potentially altering the competence of the rocks.

2. Background:

2.1 Rheology

In a ductile setting, strain may localize in shear zones. Laboratory experiments have identified four processes that contribute to ductile shearing: recrystallization, phase change, hydrothermal alteration, and hydrolytic weakening. The localization of ductile shear zones is often accompanied by rock weakening through a variety of mechanisms. Water weakening processes dominate in shallow to intermediate depths; therefore, small amounts of water incorporated in the rock lowers material strength, hence lowering the stress need for deformation. The lower crust is a higher temperature and pressure environment.[10] This geothermal gradient results in material deformation under lower stress conditions. Further weakening is produced by the reduction in grain size that often accompanies ductile deformation. Some deformation processes such as superplasticity and diffusion are enhanced with fine grain size. Fine grains also reduce the diffusion distance water can penetrate into the grain interior, thus promoting hydrologic weakening.

2.2 Shear zones

Shear zones are common structures in the subsurface. Ductile shear zones experience deformation at medium to high temperatures. The size of a shear zone can vary from millimeters to kilometers and the amount of displacement varies by just as great a magnitude. Shear zones have sigmoidal foliation traces across the axis perpendicular to the plane of shear, and the strain intensity increases closer to the center. Lineation usually develops in the foliation plane and aligns in the shear direction with strain accumulation. In a parallel-sided shear zone with monoclinic symmetry, the area experiences deformation localized in that area only.

Each shear zone is inherently unique, but generalizations are made about their geometry, shear sense and volume to extrapolate laboratory experiments and mathematical models to real-world situations. A simplified geometry of a tabular, parallel-sided unit with intense deformation, undeformed wall rock, and a lack of discontinuities is often assumed; however any of these parameters can vary in natural shear zones. In classic studies, simple shear was the only kinematic model for the formation of shear zones.[16] However, many shear zones studied in detail have different components of deformation (including pure shear and/or flattening) during strain.[1,4,5,22] In these cases, processes maintaining strain compatibility are needed because ductile environments are generally thought to leave no room to move extruded material.[1, 21] In some cases volume loss due to removal of soluble elements via fluids can aid in strain compatibility. For example, apparent oblate strain may include dissolution volume loss caused by syn-shearing fluids, and this can cause narrowing of shear zones. Equations measure the mobility of soluble elements out of the system by forming a ratio of the wall rock composition and the shear zone composition. Typical immobile elements during deformation are Ti, Al, and Zr; if volume loss did occur via loss of soluble elements, these immobile elements increase in volumetric concentration within the shear zone.

2.3 Fluids and Deformation

Fault zones at all levels represent potentially high permeability fluid conduits, and it is common to have material transport during fluid flow[11]. The properties of fluid flow and rheology of fault rocks is influenced by the variability of spatial and temporal relationships of different deformation mechanisms, during strain in shear and fault zones. Pore compaction caused by ductile creep, precipitation of hydrothermal minerals, pore creation caused by microcracking, or connectivity of pores can influence the direction of fluid flow. Minerals present give insight into the temperature, fluid chemistry, and evolution of the system.

For example, in the study by Yonkee et al. (2013) from the Willard Thrust system in Utah, the diamictites experienced differences in strain accumulation and microstructures depending on clast type.[22] Bulk composition geochemical data from XRF were used to reveal changes in matrix and clast composition between sites across a strain gradient. Changes in chemistry are thought to relate to the differences in fluid temperature, composition, and pathways. Variations in the microstructures, mineralogy, grain size, thickness, and fluid flow in shear zones, both in the transport direction and perpendicular to transport, are indicative of deformation conditions. In the transport direction, variations may also be the result of differences in deformation mechanisms.[15] Motion along structures may affect subsequent deformation. For example, thrust faults may introduce different material into the fault area and deform differently under new conditions. Perpendicular to the transport direction variations may occur if, for example, the fault intersects other formations altering deformation behavior.

3. Geologic Setting:

The Rainy Lake Region, located at the boundary between Ontario, Canada and Minnesota, USA (Figure 1) was assembled during repeated collisions between small allochthonous terranes.[12,20] Collisions occurred during tectonic activity between a volcanic arc and adjacent terranes approximately 2.7 Ga. During collision the Quetico subprovince (metasedimentary unit of amphibolite grade) and Wabigoon subprovince (metavolcanic and plutonic rocks of greenschist grade) experienced dextral shearing and north- south shortening, creating an overall dextral transpression.[2,5,7,19,20] The Rainy Lake region is located along the border of the Quetico and Wabigoon subprovinces between the Quetico fault and Seine River-Rainy Lake fault; the two major faults largely behaved in a ductile fashion.[2] The two faults form a wedge shaped kilometer wide shear zone that converges 150 km to the east.[17] Confined within the non-tabular shear zone is an accumulation of rock units including the Seine Group, composed of metamorphosed conglomerates and interbedded sandstones, found in the eastern tip of the wedge (Figure 2).[19]

One study focused on determining strain in major constituent clast types within the Seine metaconglomerate, which included metagranitoid, felsic metavolcanic, and intermediate to mafic metavolcanic clasts.[4] Conglomerates contain great strain markers, as clasts can be analyzed to determine strain magnitudes of the area.[5] Strain analysis results show felsic metavolcanic clasts have values of 0.64 to 1.78 with a mean value of 1.30. Mafic metavolcanic clasts have values of 0.67 to 2.40 with a mean value of 1.29. Granitoid clasts have values 0.21 to 1.04 with a mean value of 0.51.[4] Samples from the same site have varied strain magnitudes depending on clast composition. The strain values from the mafic clasts are considered best proxies for bulk strain and are used to classify strain magnitude of individual outcrops (Table 1). Considering the inconsistencies in effective viscosity ratios amongst granitoid clasts with increasing strain, the presence of fluid could explain the deviation from linear deformation and apparent strain softening.[4]

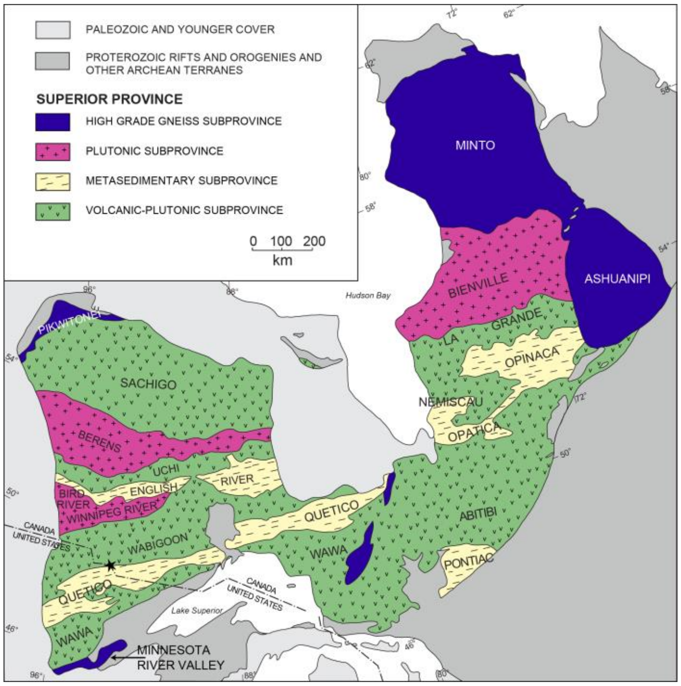


Figure 1: Map of Superior Province (From [4] modified after [3] and [13]). Study area starred (Rainy Lake Region) on the map with metavolcanic-plutonic Wabigoon subprovince to the north and metasedimentary Quetico subprovince to the south.

Table 1: Mafic clast strain magnitudes for the selected sites used in this study from Czeck et al., 2009. Mafic clasts were considered the best proxy for bulk strain. Site locations on Fig. 2.

Site	Mafic Clast Strain Magnitude (octahedral shear strain)
I	1.29
N	1.18
S	0.67
W	1.90
Y	1.60
Z	1.75

4. Methods:

4.1 Sample Selection:

Metaconglomerate clast samples were chosen from three low strain and three high strain locations using bulk strain estimates determined in the previous study[4] (Figures 2, 3; Table 1). 26 low and 35 high strain rocks samples were analyzed using the clast groupings used in the previous study, which grouped clasts based on similar appearance: 1) felsic metavolcanic clasts (ten from low and thirteen from high strain sites) 2) mafic metavolcanic clasts (nine from low and twelve from high strain sites) 3) metagranitoid clasts (seven from low and ten from high strain sites). Clasts were separated based on visible differences in color; lighter colored pebbles being classified as Felsic, darker pebbles classified as Mafic, and lighter colored pebbles with a coarse grained texture classified as Granitoid. This method for classification is the same procedure employed when grouping pebbles in the field during the first step of strain analysis.[4]

4.2 XRF Sample Preparation

Each sample was crushed and weighed to approximately 1 gram. The samples were dried for 24 hours at 105 °C. Loss on ignition was done to determine the amount of water present in the sample, as this mass would ultimately be lost during fusion process. Another dried 1 gram sample was fused using 1 gram of ammonium nitrate (oxidizing, agent) and 10 grams of a lithium metaborate: lithium tetraborate flux, that contains a 1% LiBr nonwetting agent. The flux and powdered sample was fused at approximately 1050°C using a Claisse M4 Fluxer.[14] The fused beads were analyzed to determine major and minor elemental composition using a Brunker S4 Pioneer XRF. The calibration curve was generated according to McHenry (2009) methods, using eleven USGS rocks standards.[14]

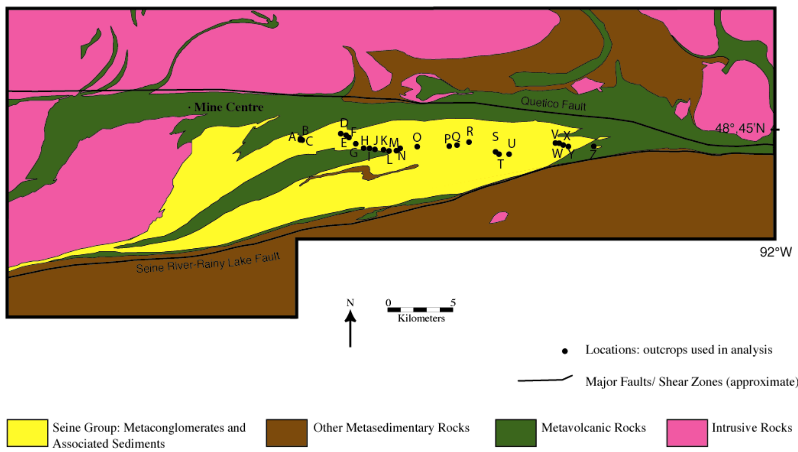


Figure 2. Simplified map of a portion of the wedge-shaped region formed during collision between the Wabigoon (north of Quetico Fault) and Quetico (south of Seine River- Rainy Lake fault) subprovinces[4]. The yellow unit is the Seine Group, the target of this study, consisting of metaconglomerates and associated metasedimentary rocks. Sites A-Z are strain analysis sites from Czeck et al. 2009. Although no general spatial pattern of strain magnitudes exists, high strain sites selected for geochemical analysis in this study (W, Z, and Y) are clustered near the east side of the shear zone and lower strain sites (S, I, and N) are further west.

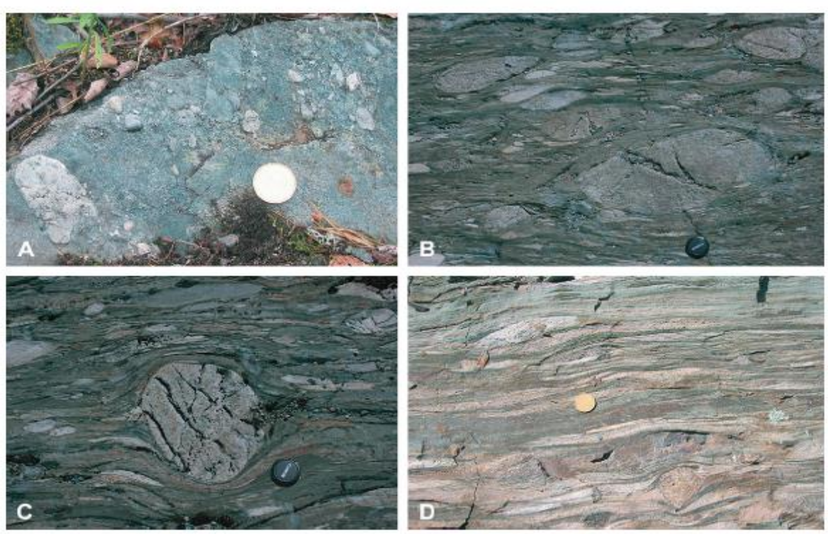


Figure 3: Examples of weakly (a), moderately (b,c) and strongly (d) strained sites. A and D use the Canadian dollar and B and C use a camera lens for scale (from [4]).

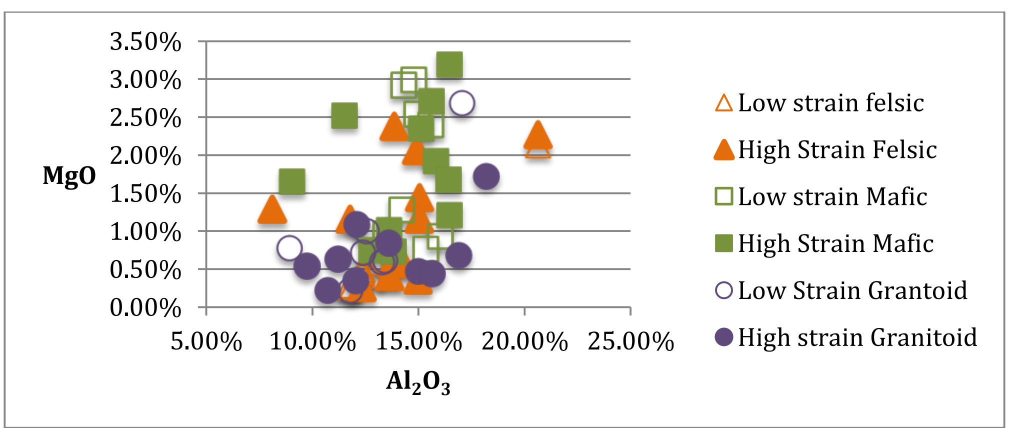
5. Results:

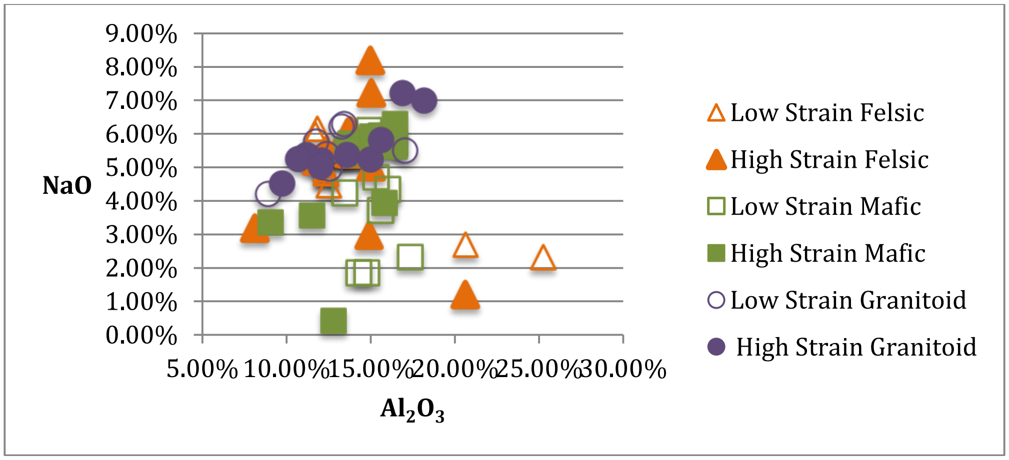
As seen from the geochemical data (Figure 5 and Table 2), this classification scheme (Granitoid, Mafic, and Felsic) simplifies the categories. The XRF results indicate that the average mafic clast composition ranges between andesitic to rhyolitic based on silica content, [18] and similarly, the compositions of all clast types fit mixed classifications. Modifications to clast categories were not made to group individual clasts to the geochemical data directly so that the results could be directly related to the previously conducted strain analysis.

There is no apparent chemical enrichment or depletion of elements seen in the metaconglomerate's major element constituents (Table 2). The mean compositions and standard deviation for all clast types overlap for high and low strain sites. Bivariate plots were used to compare potentially mobile elements against immobile aluminum (Figure 5), however there were no apparent trends found using this method that would suggest enrichment or depletion of elements in high strain samples compared to low strain samples.

Table 2: Results of XRF analysis, in wt. % oxide. In all cases, the mean concentrations of elements are indistinguishable between low and high strain when the standard deviation is taken into account.

	Granitoid Clasts				**Mafic Clasts**				**Felsic Clasts**			
	Low Strain (n=2)		**High Strain** (n=8)		**Low Strain** (n=9)		**High Strain** (n=12)		**Low Strain** (n=10)		**High Strain** (n=13)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Na_2O	5.48%	0.73%	5.49%	0.78%	3.84%	1.54%	4.34%	2.15%	4.71%	1.27%	5.24%	1.85%
MgO	0.94%	0.80%	0.59%	0.28%	2.13%	1.24%	1.68%	0.88%	0.77%	0.74%	1.13%	0.73%
Al_2O_3	12.77%	2.42%	12.63%	2.23%	15.11%	1.15%	13.15%	4.43%	14.54%	4.59%	13.99%	2.74%
SiO_2	66.32%	6.71%	69.06%	5.67%	64.03%	4.57%	67.16%	8.94%	66.15%	10.96%	68.90%	5.00%
P_2O_5	0.13%	15.00%	0.10%	0.07%	0.15%	0.05%	0.16%	0.13%	0.14%	0.18%	0.11%	0.06%
K_2O	0.96%	0.41%	0.66%	0.29%	2.10%	0.84%	1.20%	1.25%	2.25%	2.36%	1.25%	1.59%
CaO	5.08%	4.07%	4.74%	2.06%	1.67%	1.45%	2.20%	1.31%	3.99%	4.59%	1.82%	1.31%
TiO_2	0.26%	0.23%	0.31%	0.17%	0.75%	0.39%	0.58%	0.35%	0.37%	0.35%	0.46%	0.35%
Fe_2O_3	2.55%	2.40%	1.79%	0.99%	6.09%	3.26%	5.43%	1.91%	2.14%	2.19%	3.93%	1.59%




9.00%
8.00%
7.00%
6.00%
5.00%
4.00%
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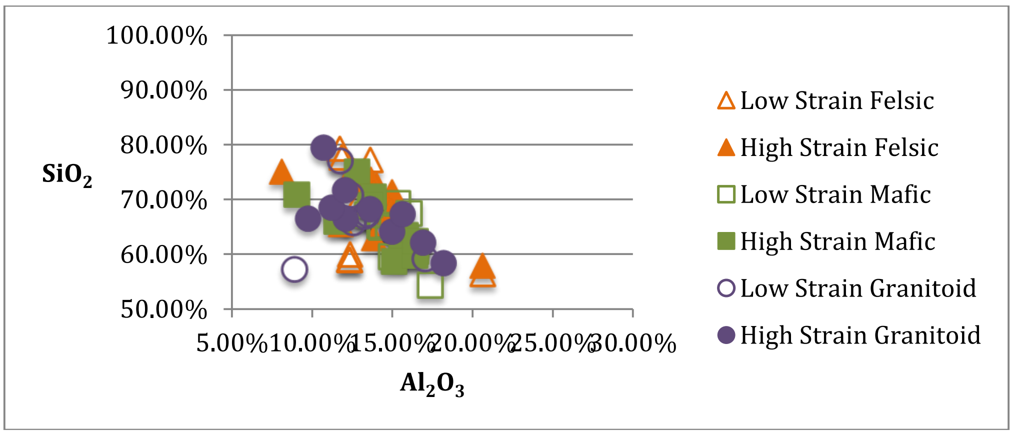
NaO
5.00% 10.00% 15.00% 20.00% 25.00% 30.00%
Al_2O_3
Low Strain Felsic
High Strain Felsic
Low Strain Mafic
High Strain Mafic
Low Strain Granitoid
High Strain Granitoid


100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
SiO_2
5.00% 10.00% 15.00% 20.00% 25.00% 30.00%
Al_2O_3
Low Strain Felsic
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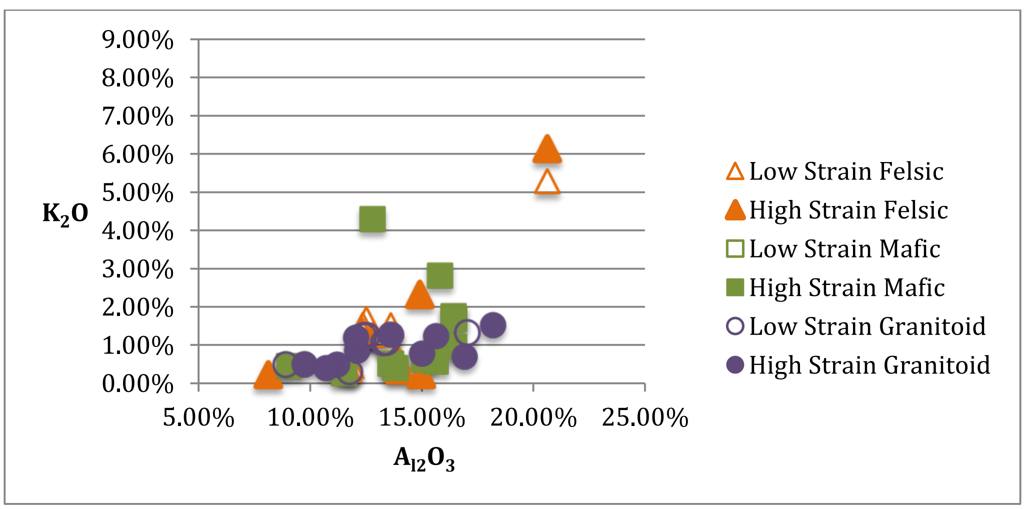
Low Strain Mafic
High Strain Mafic
Low Strain Granitoid
High Strain Granitoid


9.00%
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Low Strain Felsic
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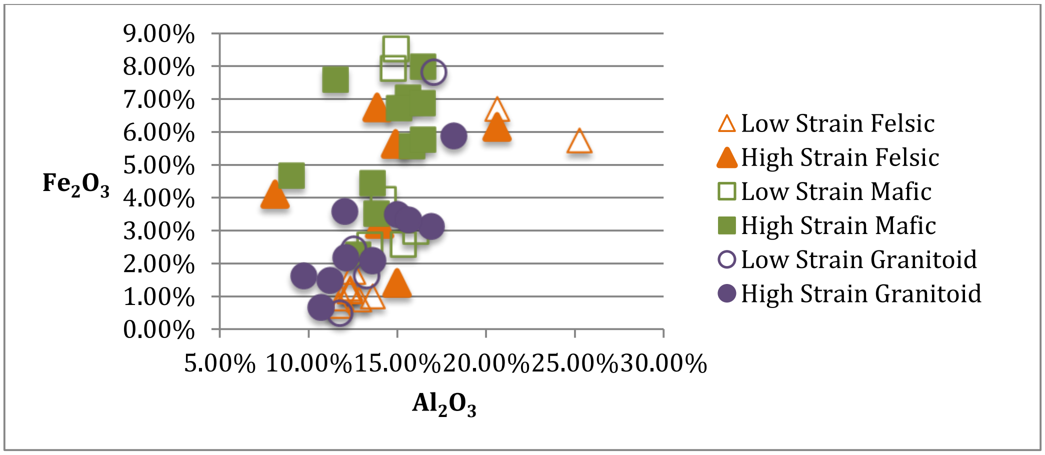

Figure 5: Plots of major and minor element concentrations determined using XRF. All graphs are compared with Al_2O_3, which is generally thought to be immobile. Fe, Na, K, Si, Mg, and Ca are generally thought to be mobile and Ti is thought to be immobile. For each plot, clasts are divided into groupings of granitoids, mafic volcanics, and felsic volcanics clasts at high and low strain sites. The results show a high degree of variability in clast composition, even within a particular clast type at a particular site. There is no clear relationship between composition and strain magnitude.

6. Interpretation:

Understanding fluid interaction is difficult because of the transient nature of fluids.[4] Evidence for fluid rock interaction is seen in varying degrees depending on strain magnitude throughout the shear zone. However geochemical analysis fails to show any consistent differences between elemental abundances of high-strain and low-strain samples of the same clast type. Directly interpreting the data, it appears no distinguishable bulk volume change occurred. Alternatively, the lack of apparent volume change could instead be related to the heterogeneous nature of conglomerates. This heterogeneity makes it difficult to interpret whether fluid altered the rocks as it moved through the shear zone. Conglomerates start with a variety of compositions due to different sources, even amongst the same clast type. Since the origin of each pebble is unknown, all clasts can have a different starting composition and the range in starting compositions could mask any signal of systematic geochemical change during deformation. The small population could cause a high variety within clast types. Data from additional samples could lower the standard deviation because the smaller the sample size, the greater the effect outliers have on the mean. An alternate interpretation is that there was bulk geochemical alteration in the sheared rocks, but it did not vary between high and low strains; instead, alteration was relatively uniform throughout the deformed rocks. The lack of an undeformed protolith does not allow rigorous testing of this alternate explanation.

7. Future Work:

The current study focuses on the geochemical analysis of clasts with felsic metavolcanic, mafic metavolcanic, and metagranitoid compositions from low to high strain sites. XRF could not identify any depletion or enrichment of major and minor elements based on analyzing the data using bivariate plots. Additional clasts should be analyzed which could lower the standard deviation, as seen in other studies[22], and provide a pattern to see if enrichment or depletion occurred. Microstructural analysis of samples from the area could show recrystallization, phase changes, hydrothermal alteration, or hydrolytic weakening which would show whether fluid altered the region.

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