THE BURNTSIDE LAKE FAULT ZONE:
A STUDY OF TWO FAULTS IN BASSWOOD LAKE

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INTRODUCTION

The purpose of this study was to determine the relative displacement along two faults in the Burntside Lake fault zone, Vermilion District, northeastern Minnesota (Fig. 1). An additional objective was to assess the intensity of deformation along the faults by examining the mechanisms by which the rocks accommodated strain. Study of oriented thin sections cut from rocks systematically collected in the field provided the bulk of the observations used in interpreting these aspects of the area's deformational history.

The dominant rock type exposed in the Basswood Lake area is a hornblende granite gneiss. In outcrop this unit displays amphibolite rafts which range in size from centimeters to meters. A less abundant rock type is a biotite migmatite schist which occasionally displays relict bedding, and contains biotite rafts comprising more than fifty percent of the exposure. Leucocratic granite, migmatite granite, and hornblende adamellite are rarely exposed in the fault zone. Present in all rocks are intrusions of pink granite presumed associated with the Vermilion Batholith, the main body of which is located four miles north of Basswood Lake. Deformational features were more evident in the pink granite intrusions, and most samples were collected at these outcrops.

OBSERVATIONS

Mineralogy

Quartz, plagioclase, and orthoclase feldspars are the chief components of all the samples. Microcline is particularly prominent, and several plagioclase feldspars display igneous zonation and perthitic textures. The most common mafic minerals are biotite and chlorite. The latter ranges in morphology from cleaved grains to thin convoluted layers at the margins of quartz and feldspar grains. Zircon occurs frequently, apatite less so, and a few occurrences of opaques are noted. Sericite is present as a weathering product, and muscovite is sometimes present in zones of very high strain. In these high strain zones grain size reduction has increased the surface area of feldspar grains which is conducive to the following reaction:

$$\underset{\text{(potassium feldspar)}}{3KAlSi_3O_8} + 2H^+ \rightarrow \underset{\text{(muscovite)}}{KAl_3Si_3O_{10}(OH)_2} + 6SiO_2 + 2K^+.$$

Deformation mechanisms

Characterization of the fault zone also depends on a qualitative assessment of the degree of strain at various locations.

Brittle fracture: Brittle fractures, in the form of microcracks and microfaults, are most common in the feldspar porphyroclasts. Because feldspars have two cleavage directions, on the (010) and (001) faces, and sluggish thermally activated deformation mechanisms (Tullis and Yund, 1987), they are less likely to deform as plastically as the more ductile matrix of quartz. They may accommodate strain by fracturing on cleavage planes or on planes parallel to the plane of maximum and intermediate stress (Simpson, 1986).

Cataclastic deformation: In order to accommodate strain, a less ductile porphyroclast may develop several submicroscopic fractures that coalesce and produce characteristics suggestive of plastic deformation. This form of deformation is evidenced in several specimens by the patchy or undulose extinction of feldspar grains (Tullis and Yund, 1987). Kinking of feldspar porphyroclasts, displayed by bent twinning or cleavage planes, is also a reflection of cataclastic flow (Tullis and Yund, 1987) (Fig. 6).

Myrmekites: Some potassium feldspar porphyroclasts show a relationship between the incremental strain axes and the formation of myrmekitic intergrowths of quartz and oligoclase (Simpson and Wintsch, in press). Myrmekites are formed on the sides of the porphyroclasts that lie in a plane perpendicular to the incremental shortening directions (Simpson and Wintsch, in press).

Plastic deformation:

Dislocation creep -- With continuing strain the molecular framework is altered such that dislocations are propagated within the crystal structure. Undulose quartz extinction is an optical manifestation of an excess of dislocations of a particular sign that cause the lattice to bend or rotate. Narrowly spaced dislocation walls are reflected as banded extinction in quartz (White, 1976).

Dynamic recrystallization -- A recovery mechanism demonstrated in quartz is the formation of strain free subgrains within the boundaries of a larger grain. If a collection of dislocations reaches a grain boundary, the boundary will migrate outwards and eventually a new strain free grain will 'pinch off'. The new grains are particularly notable in quartz, and may orient themselves parallel to the incremental stretching direction producing grain shape preferred orientation.

Where deformation of the crystalline lattice is intense, nucleation of recrystallized grains may occur. Neoblasts may be localized in deformation bands or as a mantle at the periphery of a feldspar porphyroclast (Nicholas, 1987). If matrix grain size is sufficiently reduced by cataclastic and/or plastic processes, porphyroclast recrystallization may extend into 'tails' that reflect the shear sense the specimen has undergone. Two types of partially recrystallized porphyroclasts are defined: (1) sigma porphyroclasts and (2) delta porphyroclasts (Fig. 2). Generally delta porphyroclasts occur under higher strain conditions (Simpson, 1986).

"S" and "C" surfaces (shearing and cisaillement) are encountered only in the samples that have undergone the greatest amount of strain. The "S" surfaces are recognized by grain shape preferred orientation, usually of elongated quartz. "C" surfaces are slip planes that separate "S" surfaces from each other and reflect the flow direction (Fig. 5).

The mechanisms by which the Basswood Lake samples accommodated strain were the criteria used to classify them into four groups.

Brittlely deformed rocks: These samples display such features as microcracks and microfaults, patchy feldspar extinction, and kinked feldspars. Undulose quartz extinction is also present in many cases, but because recrystallization has not occurred, these samples are not placed in the next category.

Protomylonites: These samples demonstrate quartz and feldspar grain boundary migration, feldspar nucleation, myrmekites, and well rounded feldspar porphyroclasts. Megacrysts comprise more than fifty percent of the rock.

Orthomylonites: These samples possess sigma porphyroclasts. Microscopic mylonitic foliation is developed and megacrysts comprise ten to fifty percent of the rock.

Mylonites with ultramylonite zones: These samples possess very fine-grained zones where matrix grains are less than 0.5mm in diameter. Muscovite is often concentrated here. They display delta porphyroclasts and S-C surfaces.

Summary of data

Mylonitic foliation: As illustrated in Figure 3, mylonitic foliation orientations are consistent along the Pipestone Bay fault trace. Strike of mylonitic foliation varies along the inferred Jackfish Bay fault trace but the dip consistently approximates ninety degrees. One sample in this area yields a mylonitic foliation that approximately parallels the inferred Jackfish Bay fault trace.

Bearing of shear sense: The dominant shear sense bears approximately N60E and is nearly horizontal along the Pipestone Bay fault trace. The bearings of the shear senses along the Jackfish Bay fault trace are not consistent (Fig. 4).

Intensity of deformation: Protomylonites are the most abundant category of deformed rocks in the study area. Two zones containing mylonites with ultramylonite zones occur parallel to the Pipestone Bay fault trace. In general the intensity of deformation decreases with increasing distance from this fault. A similar trend is not as evident along the inferred Jackfish Bay fault trace.

Brittle deformation: Fault breccia is encountered in mylonitic rocks in the fault zones. Brittle deformation features such as slickensides were also encountered in regions of otherwise ductile deformation. These slickensides are within a few degrees of horizontal and parallel the two fault traces.

INTERPRETATIONS

Ductile faulting

A well developed shear zone approximately parallels the Pipestone Bay fault trace. Shear sense in the zone is sinistral. The location of the shear zone is deduced from varying degrees of deformational intensity. The strike of the shear zone ranges from N64E to N85E, and the dip is nearly vertical. Evidence for the orientation of the shear zone is derived form several measurements of the orientation of mylonitic foliations.

In the area of the Jackfish Bay fault trace the attitudes of mylonitic foliations reflect splays trending north from the inferred Jackfish Bay fault trace. Shear sense along these splays is dextral. There is not conclusive evidence that justifies locating a continuous shear zone in this area.

Brittle faulting

There have been episodes of brittle faulting which postdate the mylonitization. These episodes occurred in the pre-existing zones of weakness established by the sinistral shear zone of the Pipestone Bay fault. Areas of ductile deformation along the Jackfish Bay fault were also the sites of later brittle faulting.

Assessment of intensity of deformation

The degree of deformation varies widely within the study area. Because the strain in a large scale shear zone is seldom homogenously distributed, there will be zones where strain has not be localized, and samples from these areas will demonstrate low deformational intensity (Simpson, 1987). Another factor that appears to influence the mechanisms by which a rock fractures, is the amount of quartz. For example, some samples do not possess features indicative of intense deformation, despite the fact that they are directly in the shear zone. These samples have little if any quartz matrix and the feldspars are closely packed, showing a low degree of even brittle deformation. The reason for the scarcity of quartz in some samples may be related to pressure solution and mass transfer mechanisms (Etheridge and Vernon, 1981). Phyllosilicates and opaques along clast margins parallel to foliation provide evidence of solution and mass transfer during deformation (Etheridge and Vernon, 1981).

The most effective strain softening mechanisms arise by formation of very fine grains or from the introduction of an aqueous fluid (Etheridge and Vernon, 1981). The evidence for pressure solution and concentrations of muscovite in very fine-grained ultramylonite zones is an indication of the presence of this fluid. Those samples demonstrating evidence of pressure solution, but not possessing other features of plastic deformation, are problematic regarding the assessment of the deformational intensity to which they have been subjected. They may have been subjected to a lower degree of deformation. Hence the lack of mylonitic features. Or strain may have been intense but localized, and was accommodated by pressure solution.

The presence of mantles of recrystallized feldspar grains around strained porphyroclasts indicates that the temperature at which mylonites were formed was not less than 450 degrees Celsius. This temperature must be attained before recrystallization of feldspar will take place by nucleation (Gates, *et al*, 1986). However, the temperature likely did not exceed 450 degrees Celsius by a great deal because many samples show relict igneous textures such as plagioclase zoning and perthites.

Samples demonstrate a predominance of crystal plastic deformation. But microscopic brittle deformation features, such as patchy feldspar extinction and microcracking, frequently occur. Depth of mylonitization is therefore estimated to be 15 km, at the boundary of the brittle/ductile transition zone and the ductile deformation zone (Simpson, 1986). It is also possible that the brittle deformation features were produced later at a shallower depth.

CONCLUSIONS

The relative strike-slip displacement along the Pipestone Bay fault is sinistral. The zone of the fault is a ductilely deformed shear zone. The shear sense of the Jackfish Bay fault is difficult to determine due to interference from faulting to the northwest. The Jackfish Bay fault may be associated with the ductile shear zone which is responsible for the dextral shear sense evidenced in samples collected along this fault, although the bearing of the shear sense does not parallel the inferred Jackfish Bay fault trace.

There have been at least two episodes of faulting in the study area. The earlier period produced ductile shear zones where the intensity of deformation varies based on distance from the fault, composition, and mechanisms of strain localization. Rocks accommodated strain by cataclastic fracturing, dislocation creep, dynamic recrystallization, and pressure solution/mass transfer.

A later period of brittle faulting occurred in the established areas of weakness of the shear zones. This faulting was not as continuous as the ductile faulting, but occurred in portions of the older shear zones or in splays off them.

REFERENCES CITED

Etheridge, M. A. & Vernon, R. H., 1981, A deformed polymict conglomerate - the influence of grain size and composition on the mechanism and rate of deformation: Tectonophysics, v. 79, p. 237-254.

Gates, A. E., Simpson, C., and Glover, L., III, 1986, Appalachian Carboniferous strike-slip faults: An example from Brookneal, Virginia: Tectonics, v 5, p. 119-133.

Nicholas, A., 1987, Principles of Rock Deformation: D. Reidel Publishing Company, p. 208.

Simpson, C., 1987, Methods of Kinematic Analysis:: Short course, Arizona State University.

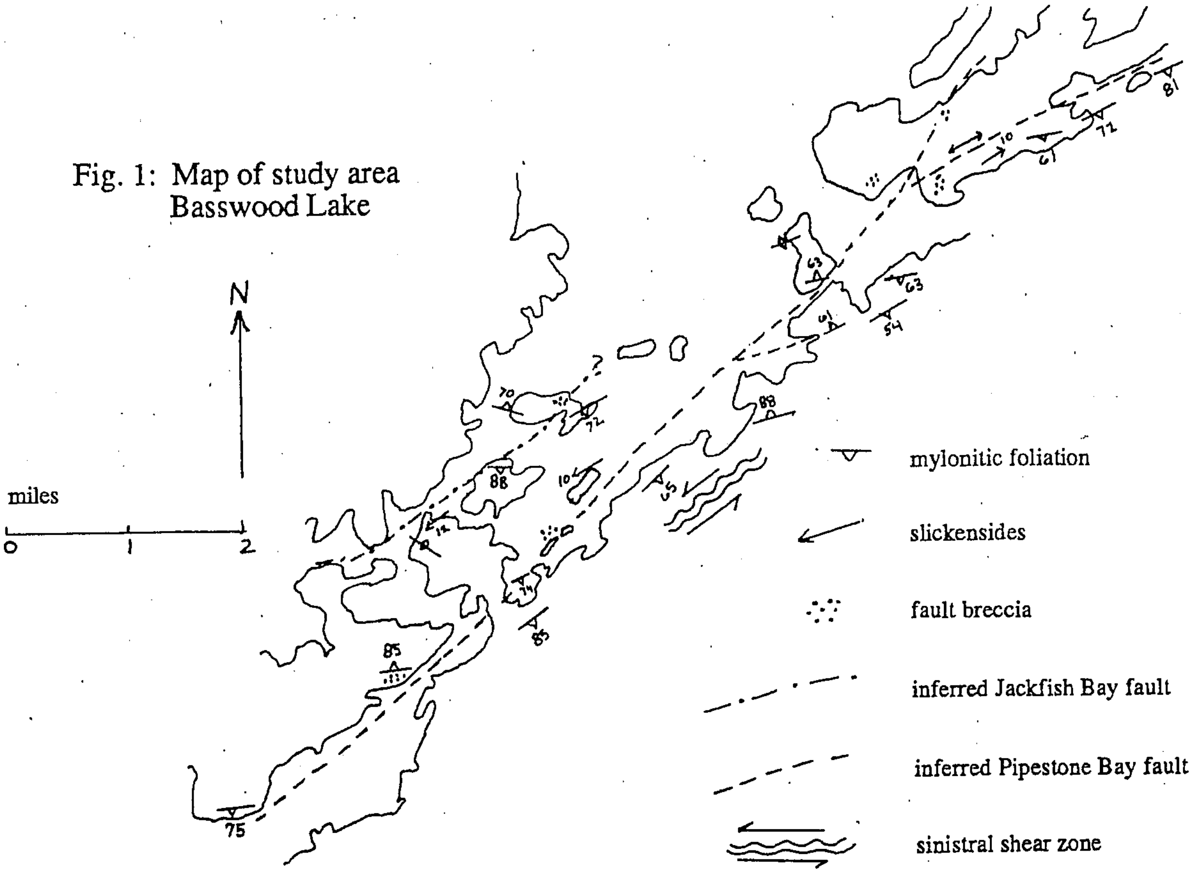
---1986, Determination of movement sense in mylonites: Journal of Geologic Education, v. 34, p. 246-261.

Simpson, C., & Wintsch, R. P. W., (in press), Evidence for deformation - induced replacement of K-feldspar by myrmekite: Journal of Metamorphic Petrology.

Tullis, J. A. & Yund, R. A., 1987, Transition from cataclastic flow to dislocation creep of feldspar: Mechanisms and microstructures: Geology, v. 15, p. 606-609.

White, S. H., 1976, The effects of strain on the microstructure, fabrics and deformation mechanisms in quartz: Philosophical Transactions, Royal Society, London Series A, v. 283, p. 69-86.

Fig. 1: Map of study area
Basswood Lake



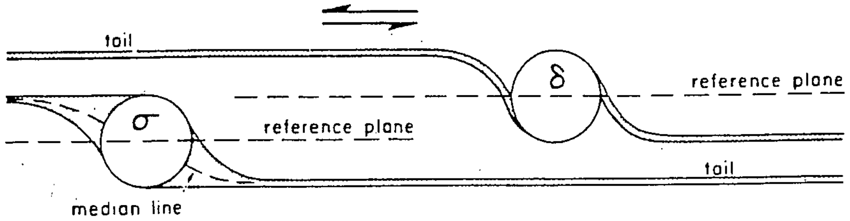


Fig. 2: How recrystallized porphyroclast tails indicate shear sense. From Simpson 1986.

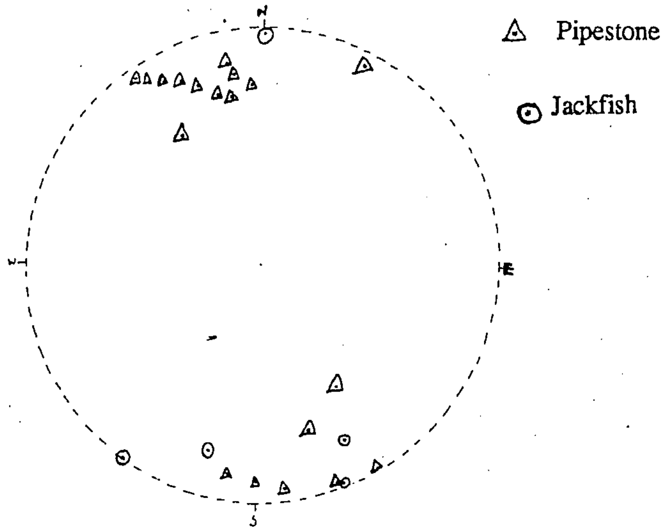


Fig. 3: Poles to mylonitic foliation along the two faults

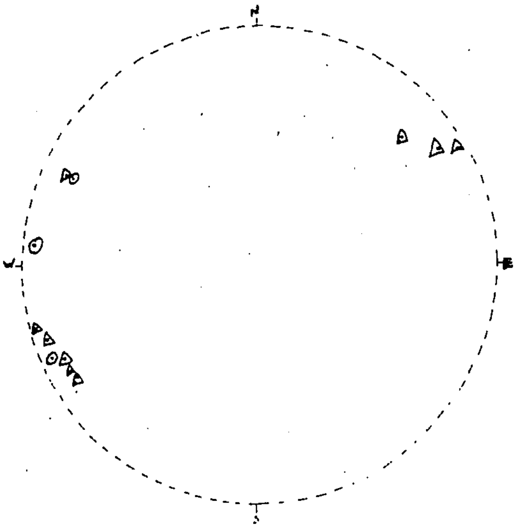


Fig. 4: Plunge and bearing of shear sense along the two faults

Fig. 5: S-C surfaces and sigma porphyroclasts in mylonitic rock. Shear sense is dextral.

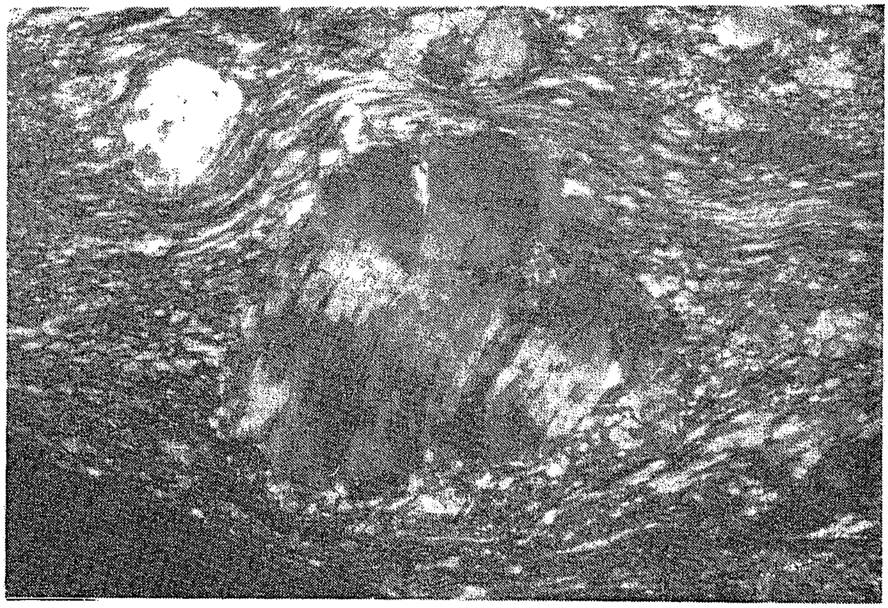


Fig. 6: Kinked feldspar and grain shape preferred orientation in mylonitic rock. Shear sense is dextral.