A TEXTURAL ANALYSIS OF THE STRAIN STATE OF A SHEAR ZONE

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ABSTRACT

The intergranular surface area of a deformed rock can be used to describe its strain state. The strain state will be a function of strain-rate and temperature. The Little Eau Claire River shear zone is shown to develop polygonized and microfractured grains leading to an overall increase in intergranular surface area per unit volume with increasing strain-rate. The strain state is considered a function of strain-rate only, since plagioclase compositional data indicates that the entire shear zone was raised to temperatures very near the crest of the peristerite solvus during the deformational episode.

The total rock intergranular surface area per unit volume increases from 12.37 mm^2/mm^3 to 82.84 mm^2/mm^3 in a sheared quartz monzonite. This is a quantitative measure of change in strain state with increased shearing. The phase-phase surface areas of quartz, plagioclase, and K-feldspar, plotted as a function of changing strain state, show distinct and different granulation profiles. All three indicate that the deformational mechanisms dominant in the shearing of the quartz monzonite led to increases in the phase-phase surface areas. It is suggested that the mechanisms responsible for this phase-phase surface area increase are grain microfracture and polygonization and subsequent grain-boundary sliding. Grain growth by recrystallization occurs but is not the dominant deformational mechanism.

The peristerite solvus has been intersected during shearing. Only the fine-grained plagioclase fraction is able to equilibrate with the highest temperatures reached near the crest of the peristerite solvus.

A TEXTURAL ANALYSIS OF THE STRAIN STATE OF A SHEAR ZONE

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I am grateful to my family for their guidance and assistance throughout my studies, both graduate and undergraduate.

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To all of you my thanks and my hopes for freedom of purpose and fulfillment of ideals. "....yes, I get by with a little help from me friends."

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INTRODUCTION

The purpose of this paper is to develop a model characterizing the response of intergranular surface area and plagioclase compositions to dynamic metamorphism. These parameters are chosen since they are sensitive to the energy environment associated with dynamic metamorphism and are easily measurable.

The surface energy of grains in a crystalline aggregate has long been considered a significant variable in petrogenesis (DeVore, 1959; Spry, 1969). The intergranular surface area of a polycrystalline aggregate is intimately related to the surface energy and can be easily quantified using stereologic techniques developed by metallurgists and recently applied to geologic problems (Ehrlich et al, 1972).

During low temperature metamorphism plagioclase compositions are sensitive indicators of the metamorphic thermal history since sodic plagioclase compositions are controlled by the peristerite solvus (Crawford, 1966).

MODEL: Surface Area Response to Dynamic Metamorphism

The strain state of a deformed rock is a function of the temperature and strain-rate of deformation. Variations in the final strain state will indicate the relative magnitude of the strain-rate, provided that the temperatures across the deformed interval are relatively constant. One quantitative measure of the strain state of a deformed rock is its total-rock intergranular surface area per unit volume (Sv).

During dynamic metamorphism, the effect of high strain-rates is to impede the onset of grain growth by recrystallization at a given temperature (Carter, 1971). Therefore, such high strain-rates will favor a grain polygonization process over a recrystallization grain growth process during the reduction in the strain energy of the system. Polygonization, wherein dislocations rearrange themselves into sub-grain boundaries enclosing relatively strain-free cyrstals (Carter, 1971), will lead to a dramatic increase in the intergranular surface area per unit volume of a crystalline mosaic providing subsequent sub-grain boundary sliding and rotation occur.

Prior to and contemporaneous with the onset of polygonization, brittle failure induced by transgranular microcrack propagation will lead to the development of cracked grains (Kingery, 1960). Micro-crack nuclei will be present initially in the large primary grains and more will be produced as dislocations pile up at natural barriers such as grain boundaries, impurities, etc., (Kingery, 1960). If subsequent rotation and sliding occurs along these transgranular fractures, microcrack propagation will also lead to an increase in intergranular surface area per unit volume.

Within a shear zone, recrystallization grain growth will be favored over recovery processes when the temperatures produced by frictional heating are sufficiently high to overcome the impeding effects of high strain-rates, and favorably oriented grains will grow at the expense of their neighbors (Carter, 1971) resulting in a decrease in intergranular surface area per unit volume. The surface area decrease would result from the destruction of phase-phase boundaries during normal grain growth.

Microfracture and polygonization will dominate as the deformational mechanisms of shearing when the high strain-rates are capable of impeding the onset of recrystallization grain growth and the intergranular surface area per unit volume should increase as a direct function of strain-rate. Steady-state flow will not be achieved and grain growth by recrystallization will not dominate unless temperatures during post-tectonic relaxation remain sufficiently high to promote it.

If polygonization and microfracture are the most significant deformational modes during shearing, then the fraction of the intergranular surface area attributable to like phases in contact with one another should increase with increasing strain-rate, since this type of boundary will be generated by both processes. Host grain polygonization phenomena should be identifiable in the rock mosaics (Hobbs, 1968). If grain growth by recrystallization predominates, such like-like phase boundaries will be destroyed. Curved grain boundaries indicative of grain growth should be observed (Coble and Burke, 1963).

The model proposed is that mylonites are the result of extremely high strain-rates, impeding recrystallization grain growth and promoting microcrack induced brittle fracture and grain polygonization.

MODEL: Plagioclase Compositional Response to Dynamic Metamorphism

As frictional heating increases during dynamic metamorphism, plagioclase compositions will be increasingly controlled by the peristerite solvus. Assuming equilibrium conditions and an initially homogeneous plagioclase compositional population across the shear zone, the plagioclase compositions should imprint the thermal regime affecting a given sheared rock. Temperatures associated with the crest of the peristerite solvus at equilibrium range between 600^{o}C and 650^{o}C (Crawford, 1966). If temperatures across the shear zone cover the range of the peristerite solvus, then it is expected that with increasing temperature albite will develop, then the two-feldspar regime will be encountered, and finally the crest of the peristerite solvus will be exceeded. There should be a gradation from an albitic phase to a two-plagioclase compositional population to a single Ca-bearing plagioclase compositional population, assuming equilibrium has been achieved. An apparent peristeritic plagioclase compositional population has been previously reported in the Scourie shear zone, Scotland (Beach, 1973).

THE LITTLE EAU CLAIRE RIVER SHEAR ZONE

A series of parallel to subparallel shear zones trending approximately N30°E are exposed in the PreCambrian rocks of Marathon County in central Wisconsin (LaBerge, 1972; LaBerge and Myers, 1973). The Little Eau Claire River shear zone occurs within this belt and intersects a quartz monzonite on the western margin of the Wolf River Batholith. Hand sample textural variation in the sheared quartz monzonite ranges from primary igneous to an ultramylonite over a lateral interval of less than four miles (LaBerge, 1972). Extreme textural changes occur within a severely sheared one-mile section on the northern side of this larger interval.

The Little Eau Claire River shear zone was selected for this study because of its obvious textural variability and also because it is compositionally similar to a regionally metamorphosed grandiorite previously studied for surface area variation (Ehrlich et al, 1972). The quartz monzonite (Fig. 1) has slightly less plagioclase and slightly more quartz and potassium feldspar than the granodiorite, but compositions are close enough for textural comparisons to be made.

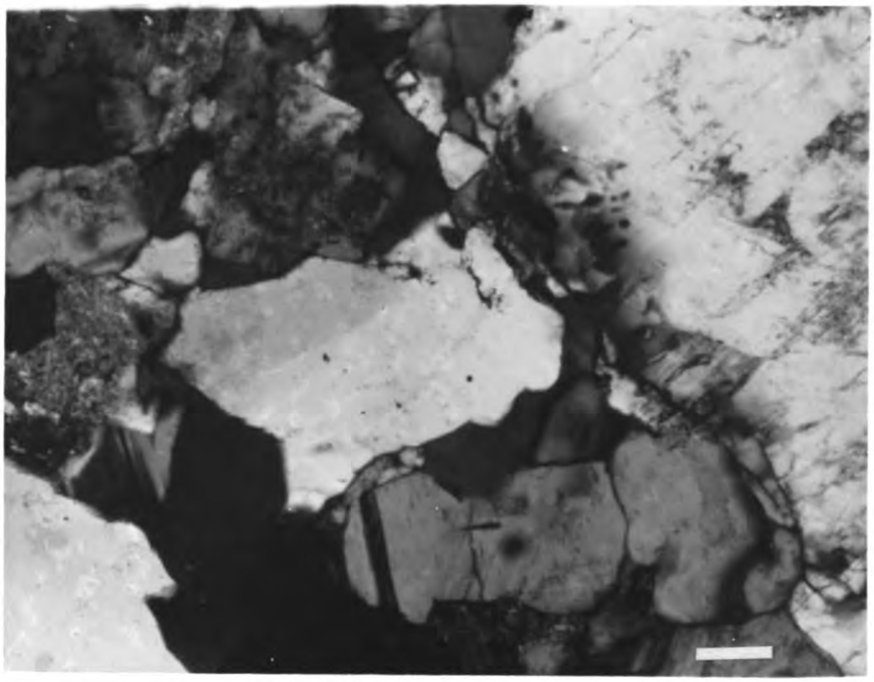
Shear Zone Mineralogy

Modal per cent of quartz and plagioclase across the Little Eau Claire River shear zone show slight variations not unlike those expected in a normal igneous intrusive. Plagioclase and quartz exhibit average modal values of 35% and 34% respectively. Potassium feldspar

Figure 1. Photomicrographs of relatively unsheared quartz monzonite, Little Eau Claire River shear zone. A and B. Note the large grain size of the primary quartz, K-feldspar, and plagioclase. C and D. Compositional zoning is common in the primary plagioclase grains. Transgranular microfracture occurs in many of the plagioclase phenocrysts. E and F. Microcracks in these quartz phenocrysts have been filled by opaques. When post-cracking grain boundary sliding occurs during shearing, the quartz grains will become optically discontinuous across the crack boundary, leading to an increase in measured quartz-quartz surface area per unit volume.

scale - - - 100 μ

A



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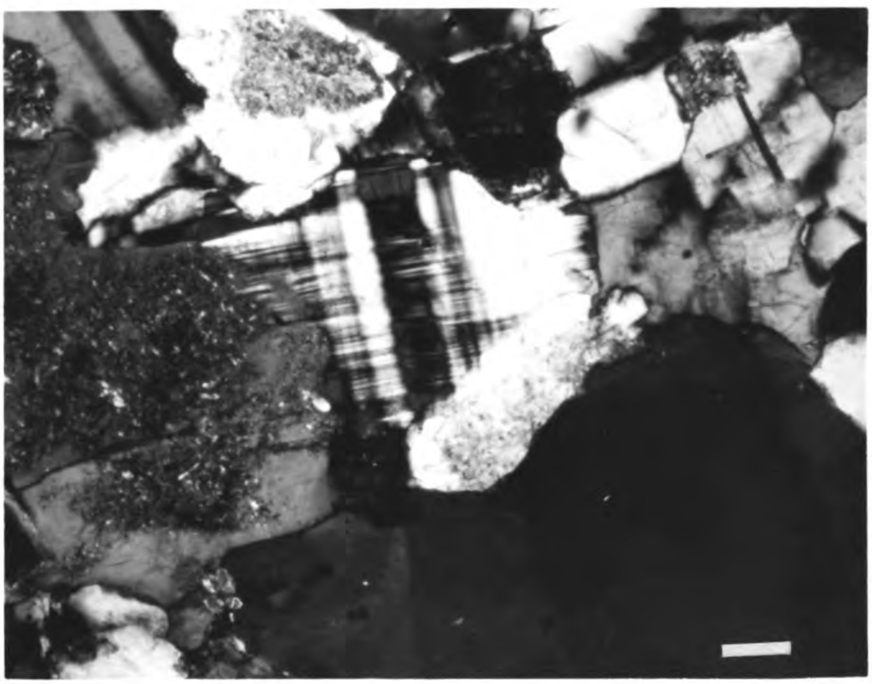

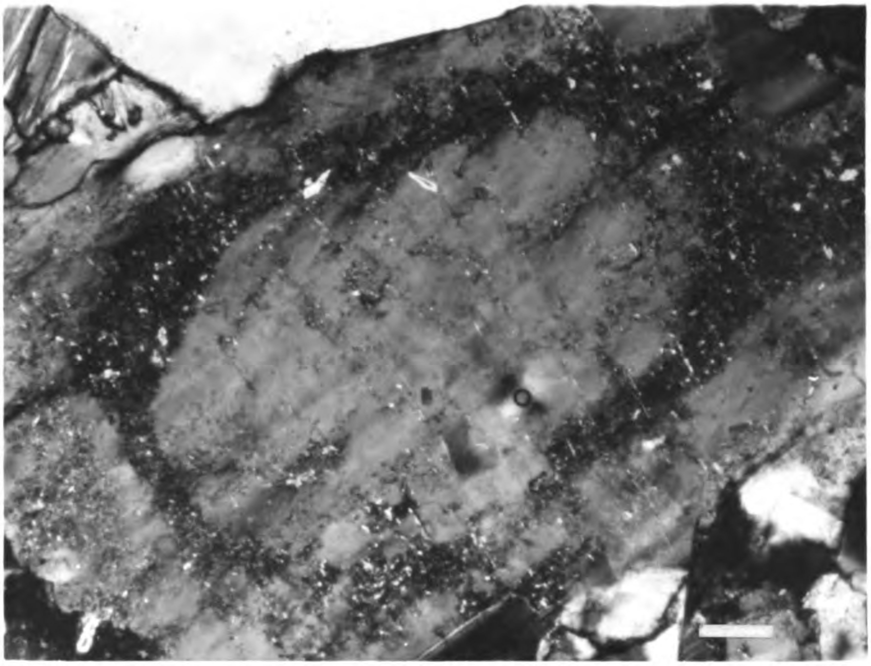

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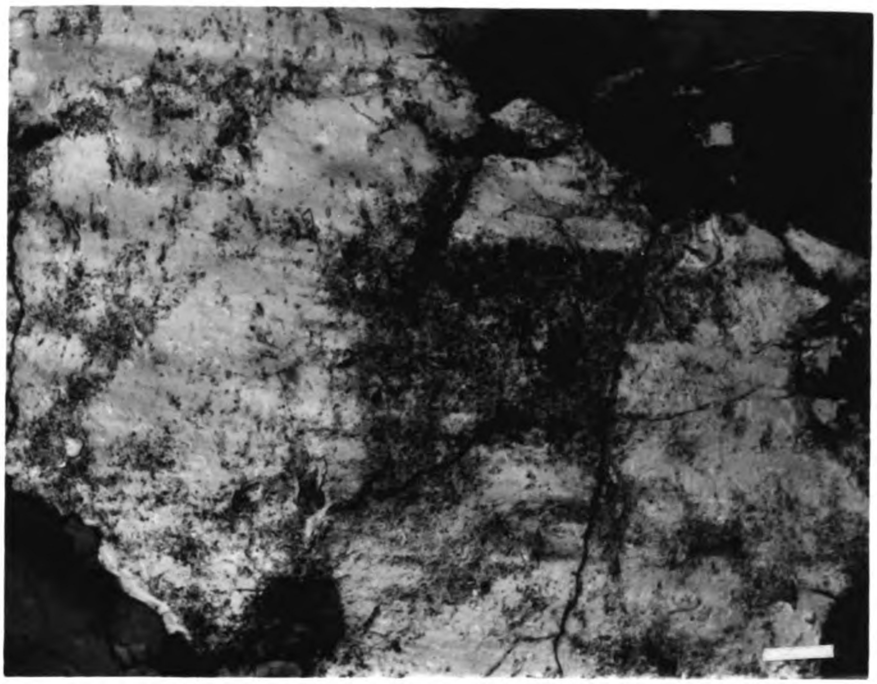
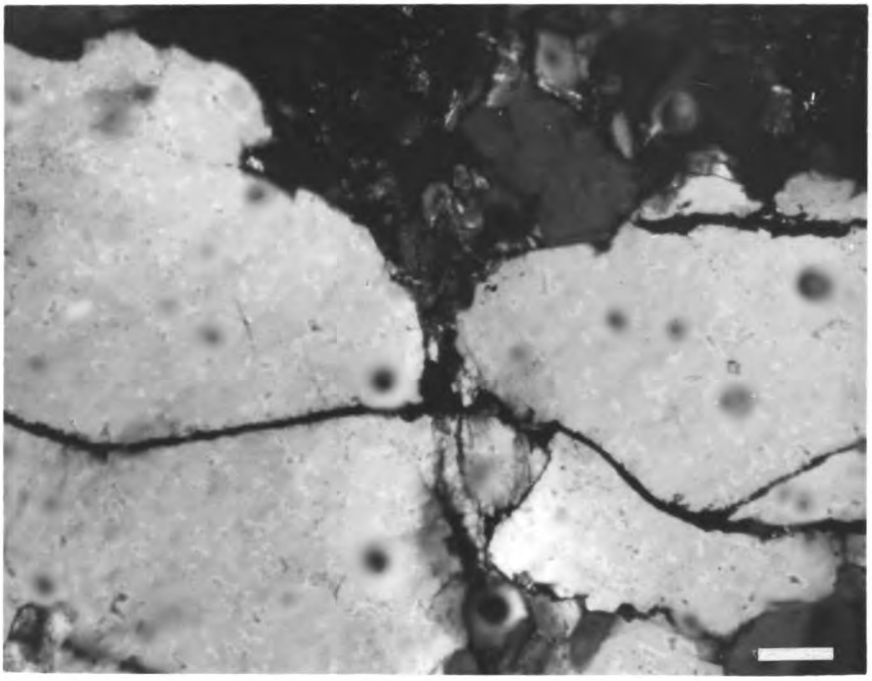
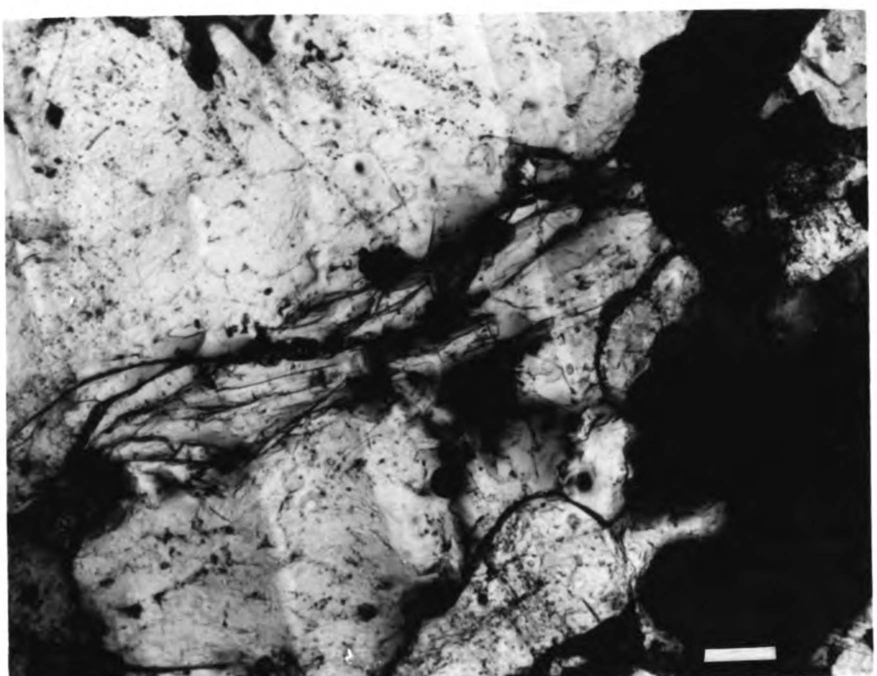


D

E



F



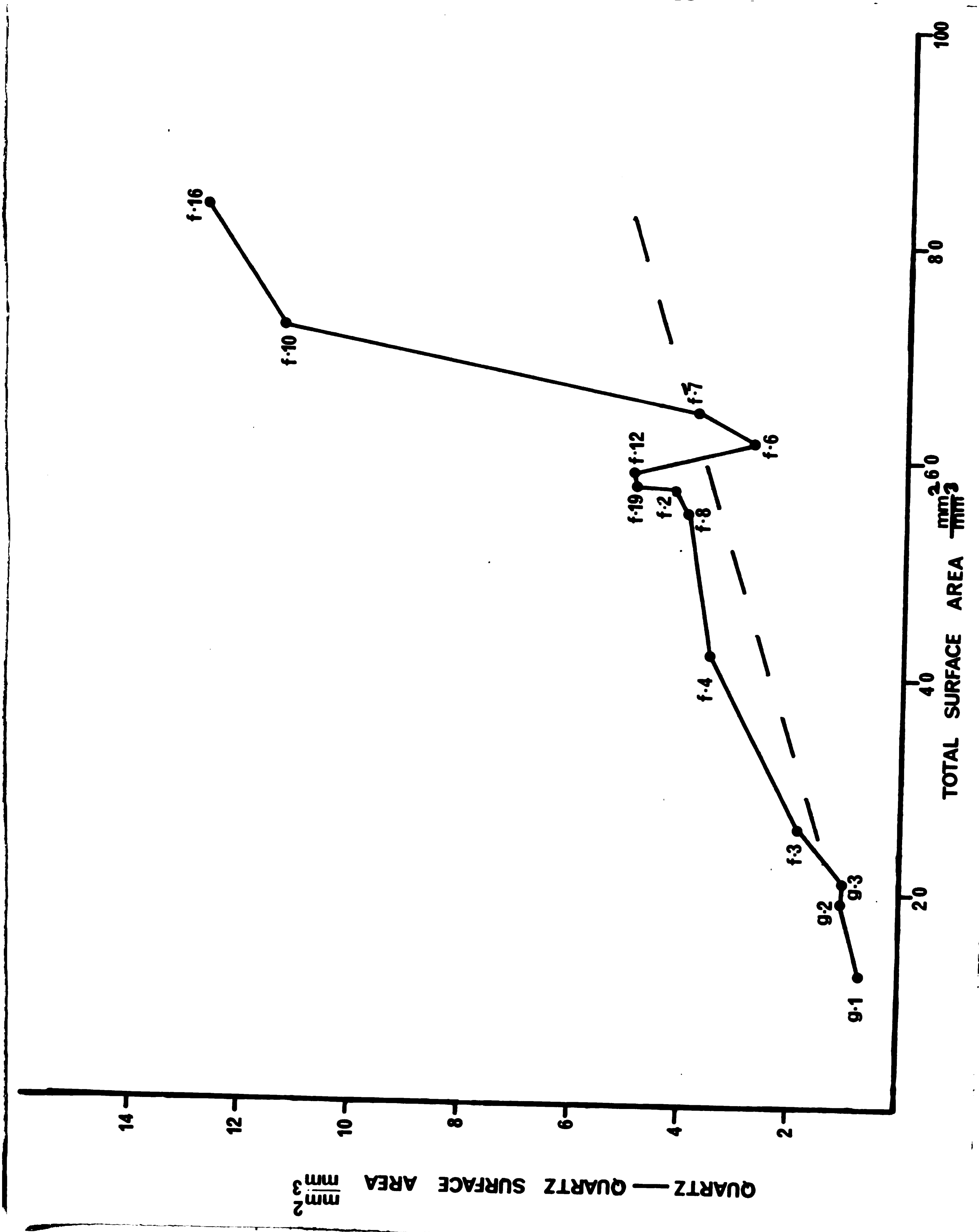
is more variable across the shear zone, averaging 25% in the less sheared samples and dropping to less than 5% in the extremely sheared samples. Hornblende, biotite and magnetite are minor phases in the less sheared samples. Biotite, muscovite, epidote, and hematite are accessory minerals in the more severely sheared samples.

Surface Area Per Unit Volume (Sv)

The three-dimensional surface area per unit volume (Sv) of a mosaic of contiguous grains is equal to twice the number of intersections of intergranular boundaries with randomly placed test secants of known length imposed on a two-dimensional thin section through that aggregate (DeHoff and Rhines, 1968; Underwood, 1970). Units of surface area are mm^2/mm^3. The total rock intergranular surface area can be partitioned into its constituent components, like-like boundaries (α-α boundaries), and unlike boundaries (α-β boundaries). In this study, the phase-phase surface area will refer to that fraction of the total rock intergranular surface area per unit volume attributable to like mineral phases in contact with one another and sharing mutual grain boundaries (α-α boundaries).

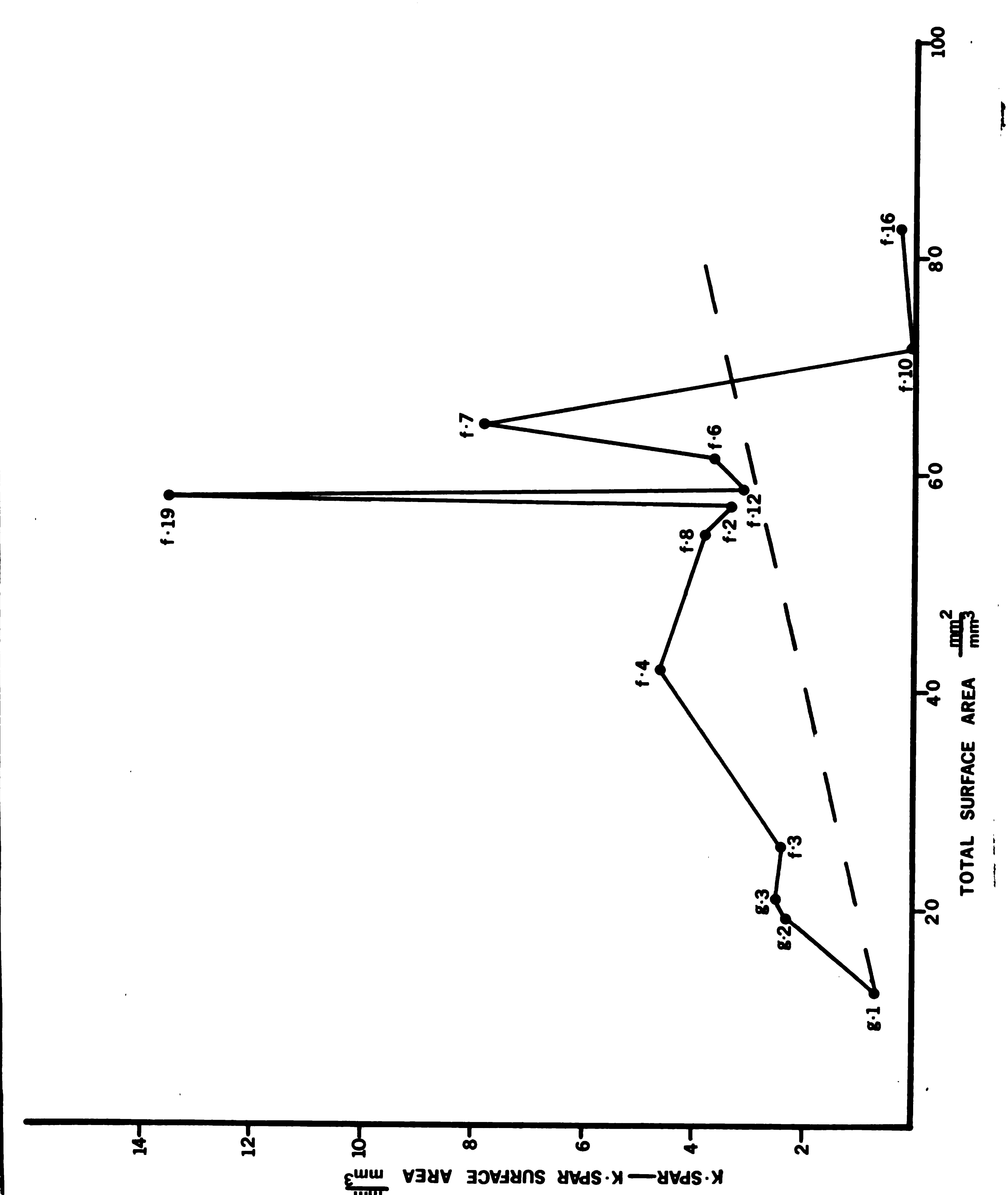
Within the Little Eau Claire River shear zone, quartz-quartz, K-feldspar-K-feldspar, and plagioclase-plagioclase surface areas have been documented. These variables are presented graphically as a function of total-rock surface area. The variation of interest in this study is the change in phase-phase surface area as a function of increasing strain-rate. In a given outcrop of a sheared rock, there can be extreme variation in strain state over relatively small intervals (Ramsay and Graham, 1970). This variation will be reflected in

Figure 2. Plot of quartz-quartz surface area per unit volume versus the total rock surface area per unit volume (S_V) -- a quantitative measure of the strain state of the deformed rocks. The dashed reference line indicates the ratio of quartz-quartz surface area per unit volume to S_V to be expected if a one-to-one correspondence exists between changes in these two variables. In the low-shearing zone, such a correspondence seems to exist, but as shearing intensifies, a greater percent of S_V is contributed by quartz-quartz boundaries, since microfracture and polygonization followed by grain-boundary sliding dominate -- thus selectively producing such like-like phase boundaries.



f·16
f·10
f·7
f·6
f·12
f·19
f·2
f·8
f·4
f·3
g·3
g·2
g·1
20
40
60
80
100
TOTAL SURFACE AREA mm²/mm³
14
12
10
8
6
4
2
QUARTZ — QUARTZ SURFACE AREA mm²/mm³

Figure 3. Plot of K-feldspar-K-feldspar surface area per unit volume versus S_V. The rapid departure from the dashed reference line indicates the generation of cracked and polygonized K-feldspar grains during shearing. The rate of increase is greater than for quartz-quartz boundaries until the intermediate shearing intensities are reached, where a rapid loss of K-feldspar from the system occurs. This may result from increased mobility of potassium as more and more subgrain boundaries become available to aid in atomic diffusion.


K·SPAR—K·SPAR SURFACE AREA mm²/mm³
2
4
6
8
10
12
14
TOTAL SURFACE AREA mm²/mm³
20
40
60
80
100
g·1
g·2
g·3
f·3
f·4
f·8
f·2
f·12
f·19
f·6
f·7
f·10
f·16

the degree of granulation achieved within a particular specimen. Generally, development of a fine-grained fraction is the observable variation used to determine degree of granulation. However, changes occur not only in the size of grains but in the shape of grains as well. Surface area is a fundamental textural parameter sensitive to both size and shape of grains within a rock. Textural inhomogeneities in size and shape of grains are obvious across the shear zone, and these inhomogeneities reflect the variations in strain-rate. Therefore, within a shear zone, the total rock intergranular surface area is a much more accurate indicator of shear intensity than is the spatial distribution of samples within the outcrop. For this reason, the phase-phase surface area is plotted as a function of total-rock surface area to indicate the response of phase-phase surface area to increasing strain-rate.

A reference line is included in all three graphs to facilitate comparisons between the "granulation profiles" of the individual mineral phases. The line represents that amount of phase-phase surface area expected if a direct one-to-one functional relationship exists between phase-phase and total-rock intergranular surface area. The initial ratio between the phase-phase and total-rock surface area in the relatively unsheared quartz monzonite is used to construct this line for each phase. It is emphasized that this is a reference line and no particular petrogenetic significance is attached to it. Measured total-rock intergranular surface area increases from 12.37 mm^2/mm^3 in the relatively unsheared quartz monzonite to 82.84 mm^2/mm^3 in the most severely sheared sample.

Figure 4. Plot of plagioclase-plagioclase surface area per unit volume versus S_v. The per cent of S_v contributed by plagioclase-plagioclase boundaries increases dramatically across the shear zone. An initial increase in plagioclase-plagioclase boundaries through post-cracking and post-polygonization sliding is followed by the development of even finer grained plagioclase subgrain mosaics, presumably by continued subgrain polygonization.

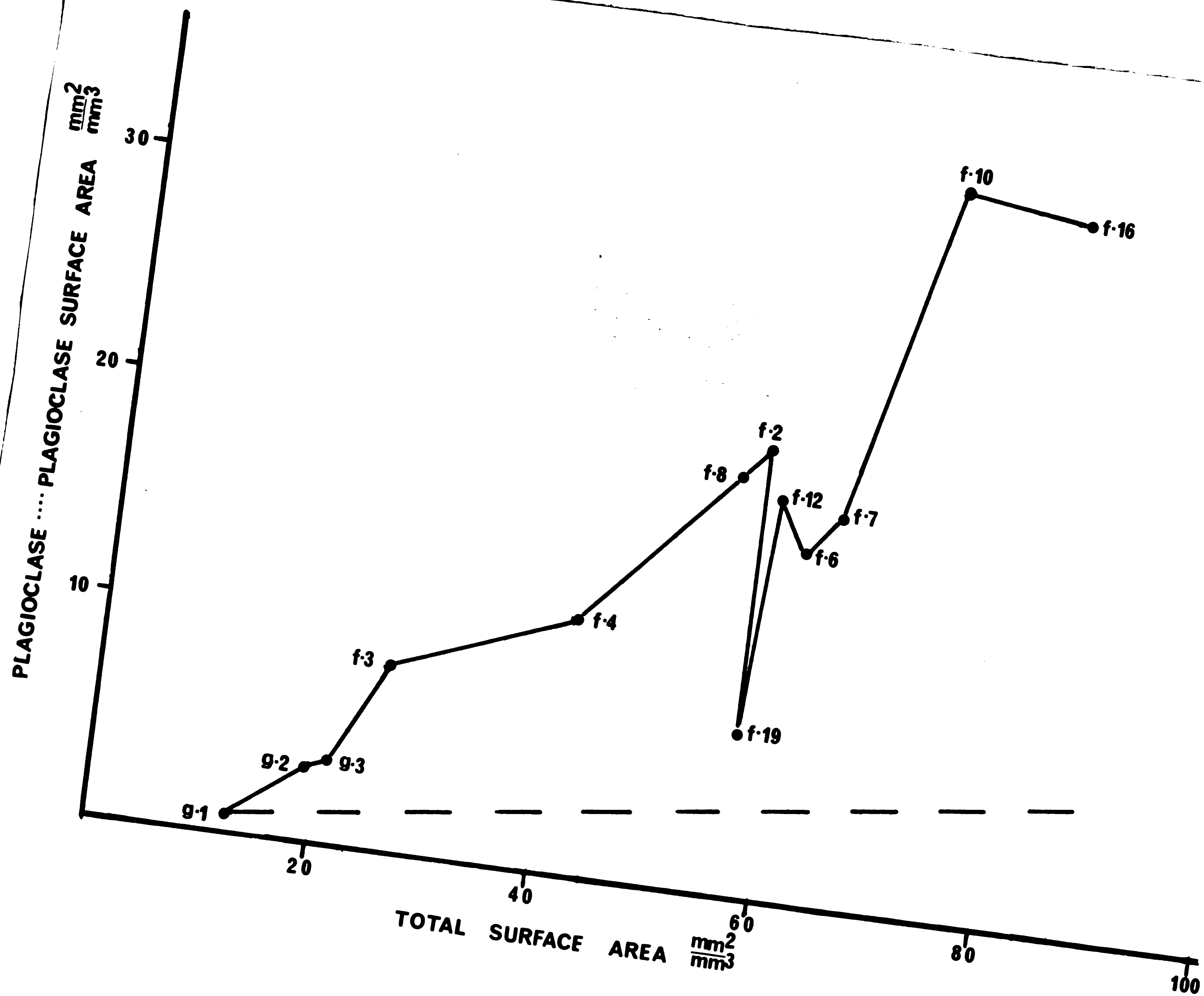
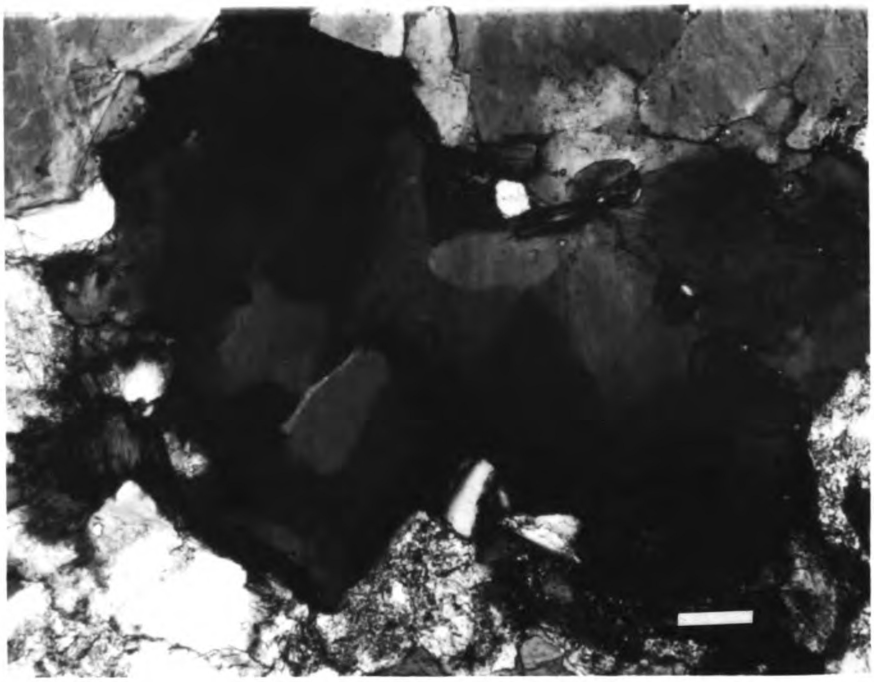
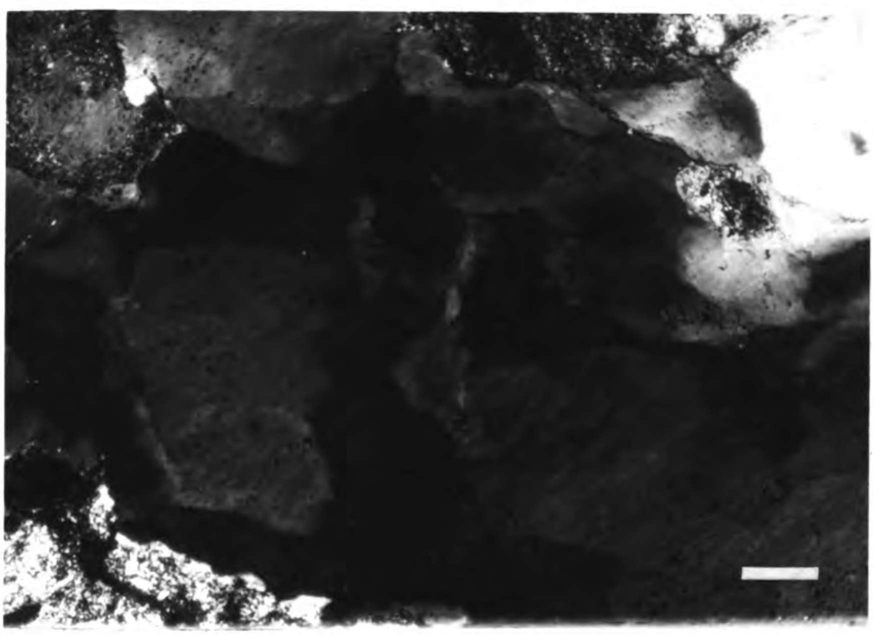

PLAGIOCLASE .... PLAGIOCLASE SURFACE AREA $\frac{mm^2}{mm^3}$
30
20
10
TOTAL SURFACE AREA $\frac{mm^2}{mm^3}$
20
40
60
80
100
g·1
g·2
g·3
f·3
f·4
f·8
f·2
f·19
f·12
f·6
f·7
f·10
f·16

Figure 5. A and B. Quartz polygonization leads to minor optical offsets in strained primary crystals. Subsequent grain boundary sliding will lead to unstrained optically heterogeneous quartz mosaics. C and D. Polygonization and subsequent grain boundary sliding produce well-defined plagioclase subgrain mosaics.

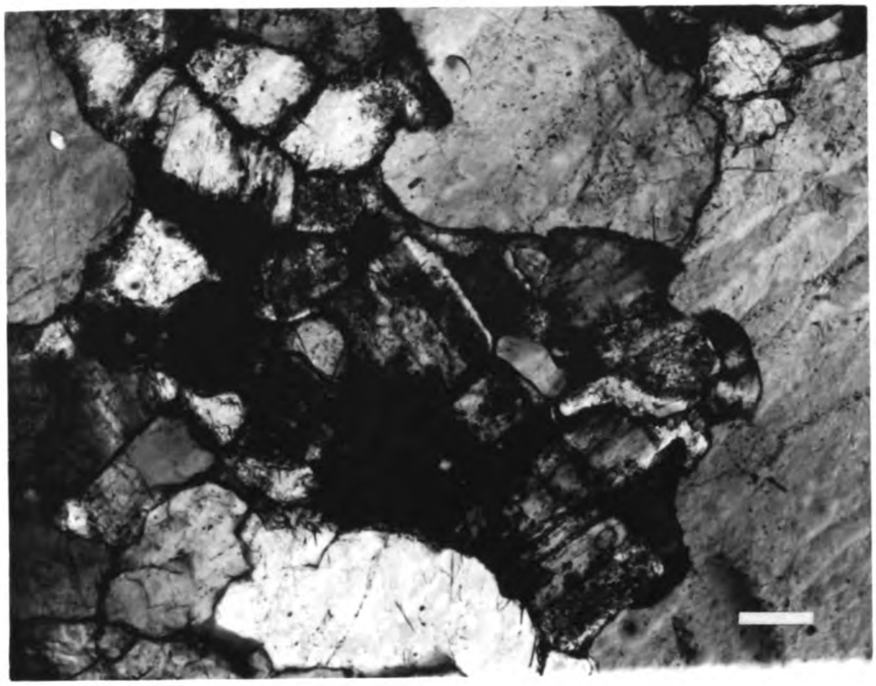
scale - - - 100 μ



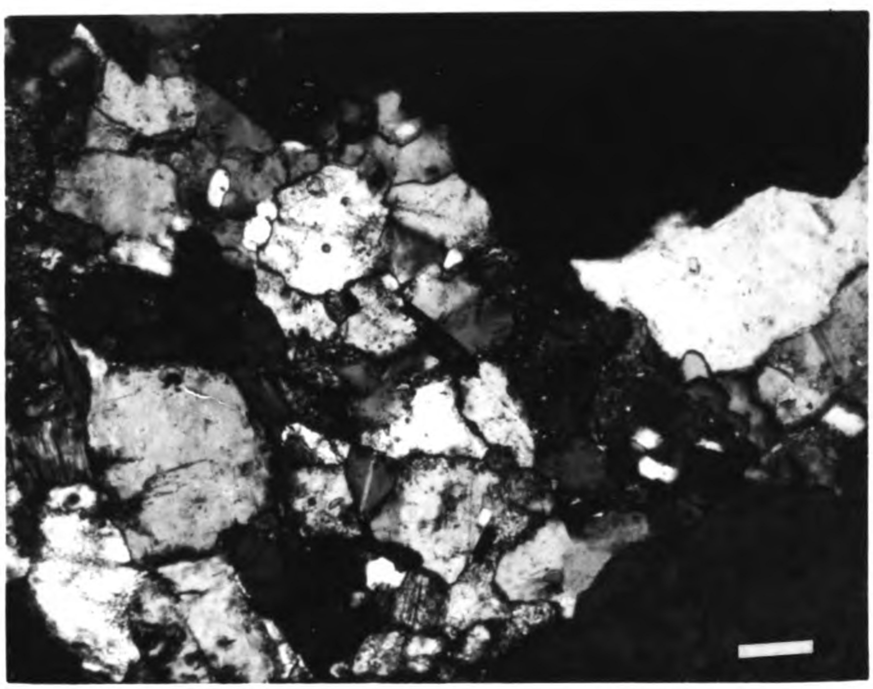
A



B



C



D

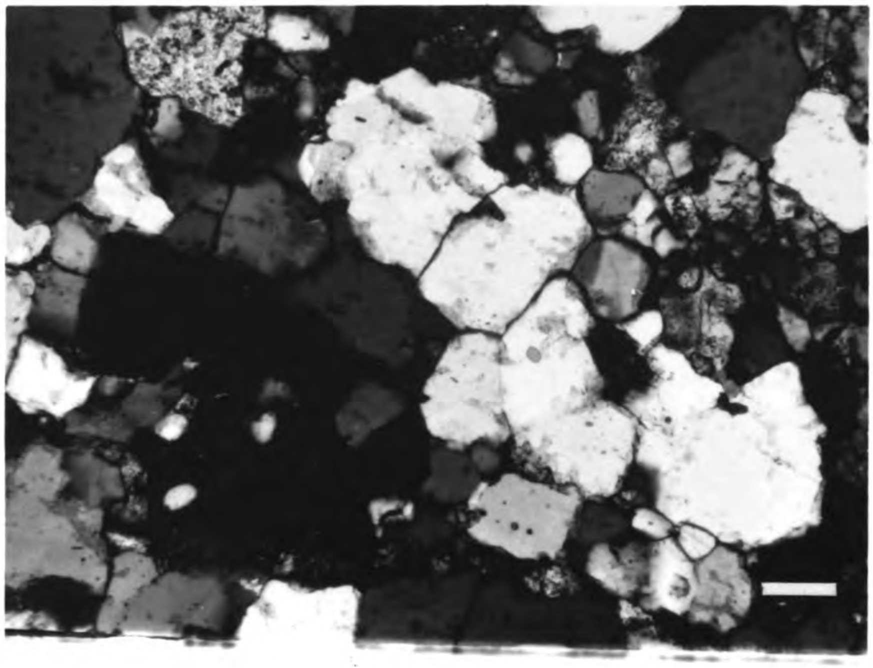
Quartz-quartz surface area (Fig. 2) increased from .70 mm^2/mm^3 in the relatively unsheared quartz monzonite to a high of 12.48 mm^2/mm^3 in the most severely sheared sample. The quartz-quartz surface area does not deviate appreciably from the one-to-one reference line in the low-shearing interval. The intermediate zone shows a slight increase in the rate of quartz-quartz surface area development, and a rapid increase in surface area development is evident in the highly-sheared zone. The K-feldspar-K-feldspar surface area (Fig. 3) ranges from an initial low of .63 mm^2/mm^3 to a high in the intermediate shearing interval of 13.55 mm^2/mm^3. In the highly-sheared zone, K-feldspar is lost from the system. K-feldspar-K-feldspar surface area deviates much more rapidly from the one-to-one reference line than does quartz-quartz surface area. Measurements are somewhat erratic in the intermediate zone, but several very high phase-phase surface area samples are recorded.

Plagioclase-plagioclase surface area (Fig. 4) ranges from a low of .77 mm^2/mm^3 in the relatively unsheared quartz monzonite to a high of 32.02 mm^2/mm^3 in the highly-sheared zone. The plagioclase-plagioclase surface area in the highly-sheared rock is 41 times that of the unsheared rock. The plagioclase-plagioclase surface area shows a marked deviation from the one-to-one reference line in the low-shearing zone and systematically increases through the intermediate and highly-sheared zones.

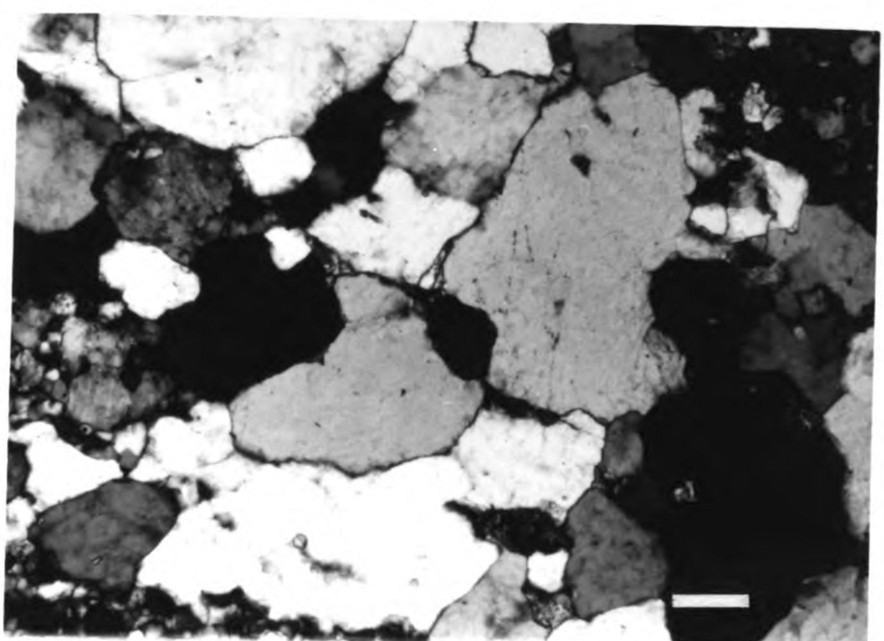
Microtextural Features

All three of the mineral phases of interest show evidence of host-grain microcracking (Fig. 1E, F, G) and polygonization (Fig. 5) in thin section. Those samples from the low-sheared zone show fractures

Figure 6. . A and B. Strain-free quartz mosaics resulting from post-polygonization grain boundary sliding. The mosaics are generally ovate in outline.
scale - - - 100 μ



A

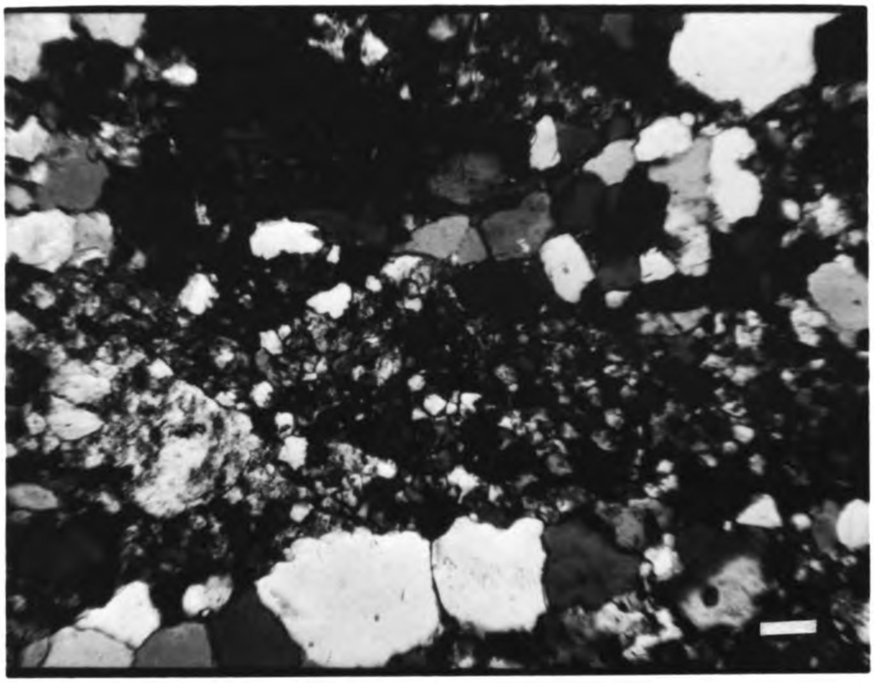


B

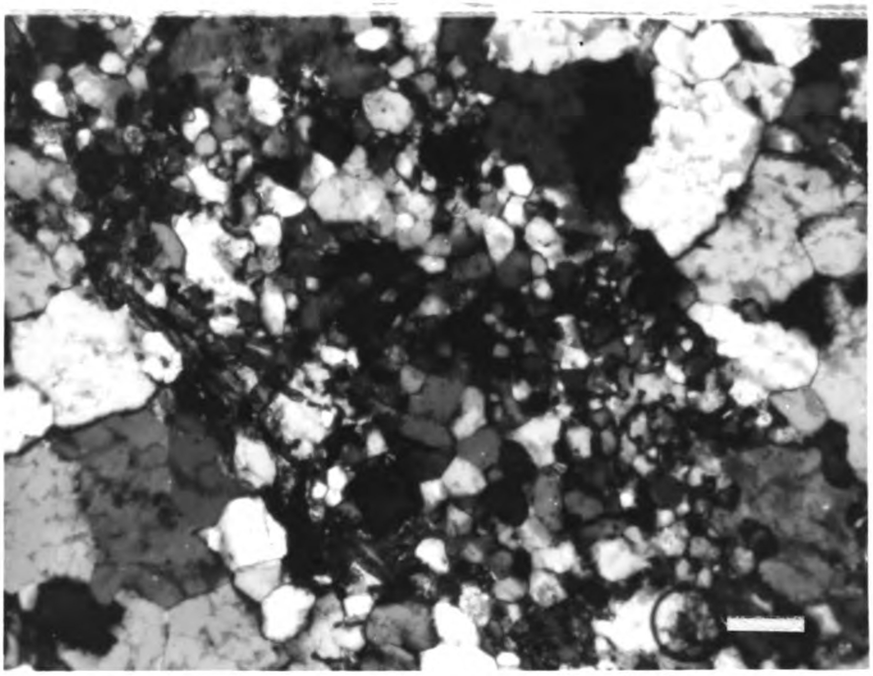
Figure 7. A and B. The development of finely crystalline plagioclase subgrain mosaics is the result of continuing subgrain polygonization with increasing strain rates. Grain boundary sliding under shear stress produces an augen-like outline around the polygonized "ghost" plagioclase porphyroclasts. C, D, and E. Polygonal shapes characterize the fine-grained plagioclase. F. Some larger subgrains are preserved within the finer-grained material.

scale · · · 100 μ

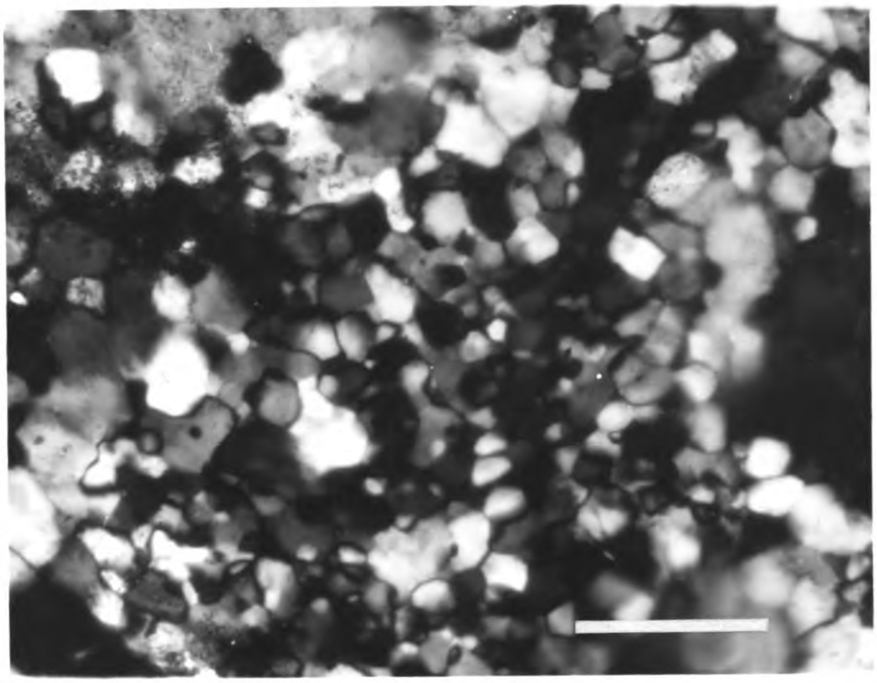
A



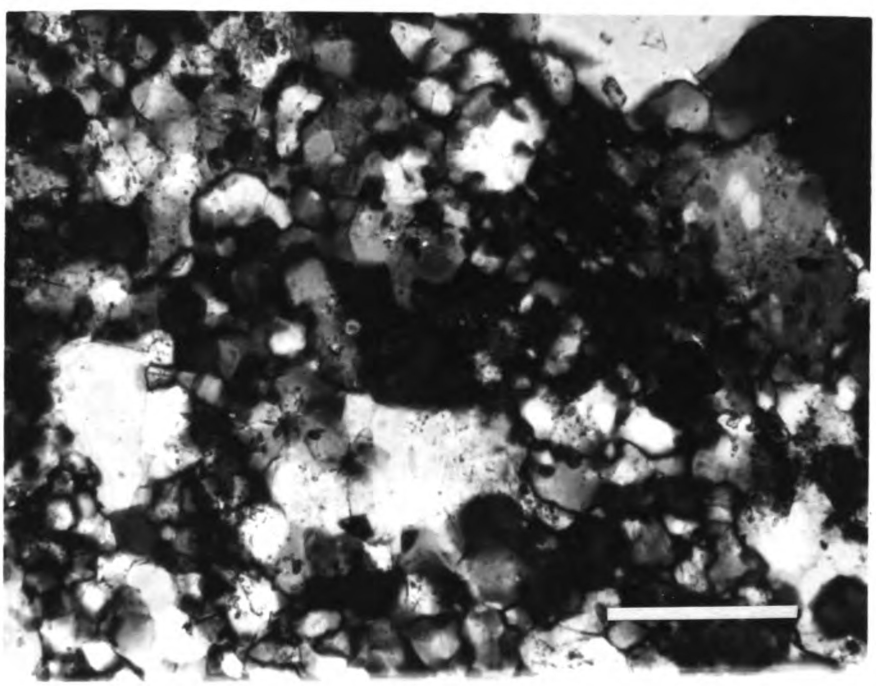
B



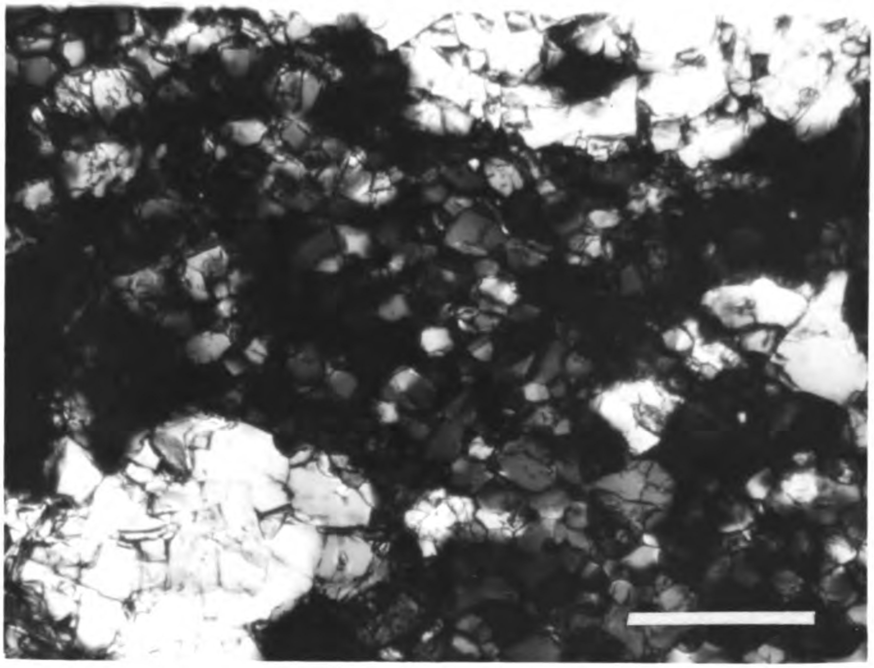
C



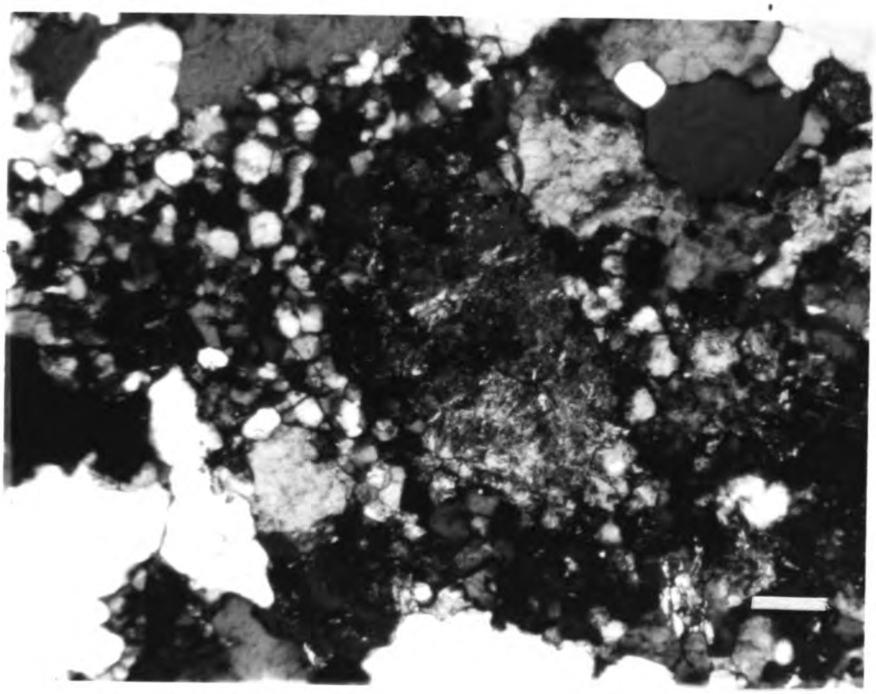
D



E



F



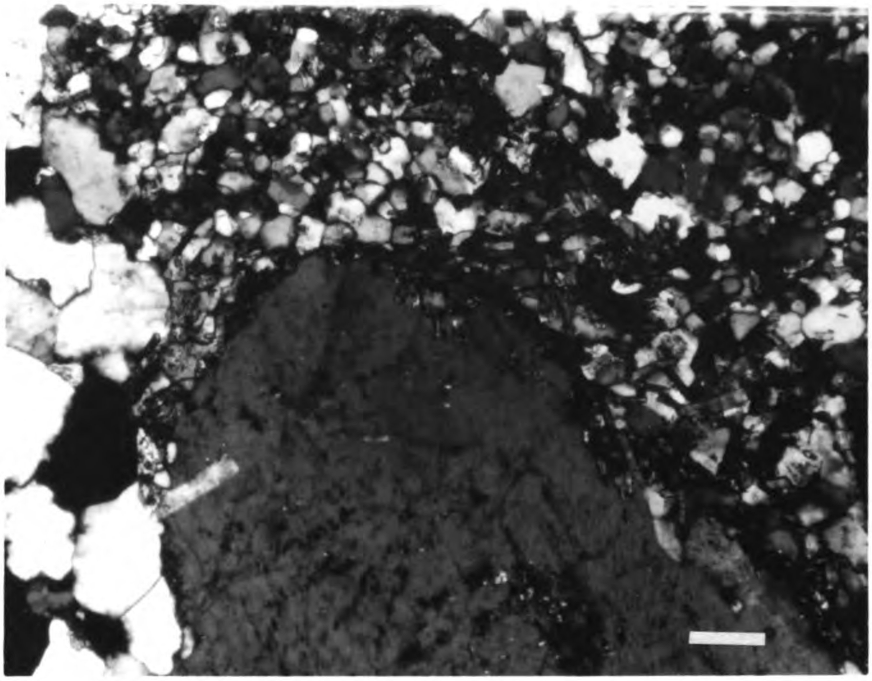
in many of the larger porphyroclasts. In the intermediate and highly-sheared zones, quartz grains develop a stretched vein-like texture with rectangular subgrains (Fig. 6). Plagioclase and K-feldspar polygonize rapidly thus developing subgrain mosaics (Fig. 7). Many polygonized plagioclase porphyroclasts are stretched into ovate augen structures (Fig. 7A, B).

Textural disequilibrium (Fig. 7F, 8A, B) is evident throughout the shear zone. A polygonized stretched plagioclase grain may well be spatially close to a fractured remnant of a larger primary plagioclase porphyroclast. Such broken fragments exist in all samples, many with igneous zoning still intact. The intensely sheared sample that exhibits the highest plagioclase-plagioclase surface area contains many such fragments embedded in a finely crystalline matrix.

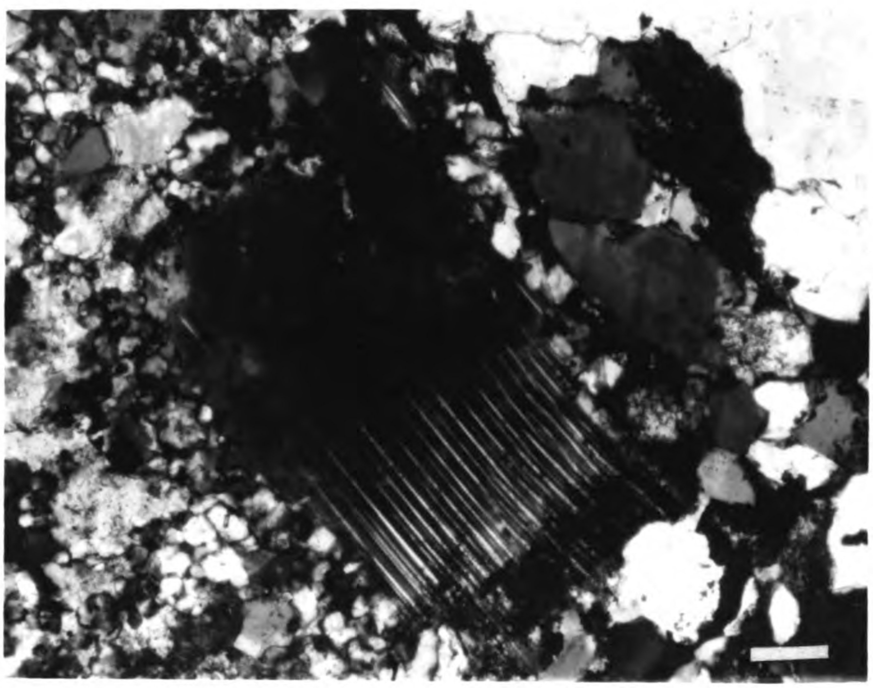
Figure 8. A and B. Textural disequilibrium is commonplace across the shear zone. Large primary porphyroclastic plagioclase grain fragments are often spatially close to totally polygonized plagioclase host grains.

scale···100 μ

A



B



INTERPRETATION OF SURFACE AREA RESULTS

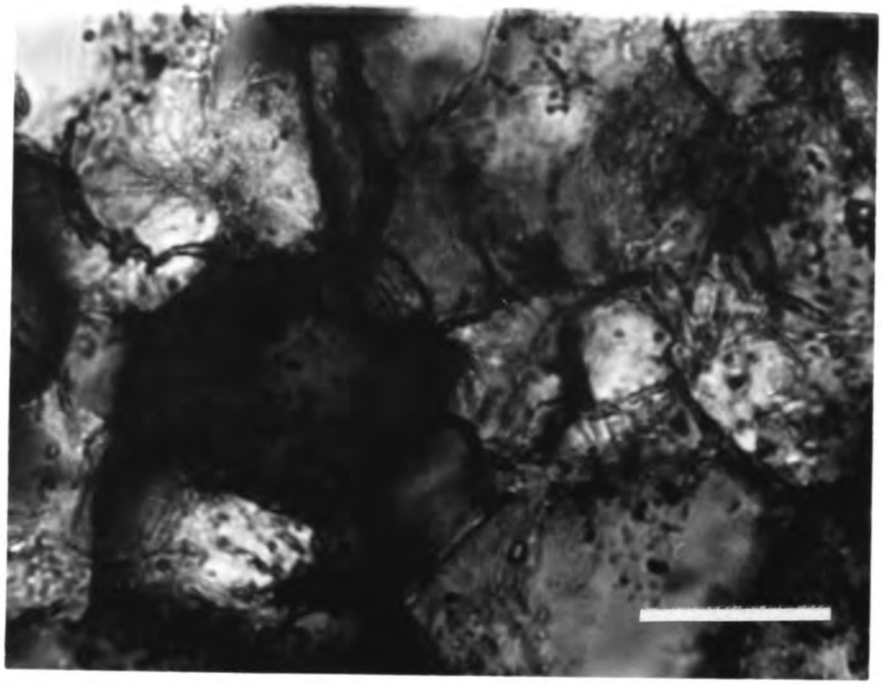
The dramatic increases in phase-phase surface area documented in this study support the contention that brittle grain microfracture and host-grain polygonization were the dominant deformational mechanisms in the Little Eau Claire River shear zone. An initial reduction in grain size is caused by microcrack propogation (Fig. 1D, E, F). Crack nuclei are abundant in large primary crystals and will significantly alter the deformational behavior of these crystals at lower strain-rates. With increasing strain-rate, work-hardening intensifies and increased frictional heating activates polygonization as a strain recovery process (Carter, 1971). Both microfracture and polygonization increased the phase-phase surface area of the rock mosaic.

Granulation profiles for quartz, K-feldspar, and plagioclase show distinct differences. Quartz-quartz surface area is much less than K-feldspar and plagioclase in the lower and middle zones and much less than plagioclase in the highest-sheared zone. In experimental syntectonic quartz deformation, no significant recovery occurs until temperatures of $800^{o}C$ - $900^{o}C$ (Hobbs, 1968). Grain size of quartz at low strain-rates is 10 times that at high strain-rates (Hobbs, 1968). However, the presence of water greatly affects the deformational habit of quartz. The presence of epidote veining within the shear zone suggests the presence of a fluid phase, which would enhance the ability of all silicates to recover. The difference in surface area response of the three phases may reflect differences in physical properties of these phases as well as differences in primary grain size and modal percents. The relatively lower values of quartz-quartz and K-feldspar-K-feldspar surface area as compared to plagioclase-plagioclase surface area may indicate that recrystallization grain growth more readily offsets the effects of microfracture and polygonization in these phases than in the plagioclase within the shear zone. Detailed microscopy (Fig. 9A, B) reveals that it is not until the extremely sheared samples that curved grain boundaries indicative of recrystallization grain growth occur in the fine-grained plagioclase. This indicates that the major deformational mechanism in plagioclase was grain microfracture and polygonization since these processes will generate high plagioclase-plagioclase surface areas. Recrystallization grain growth did occur but was impeded by the high strain-rates. In the most severely sheared samples, the strain-rates were high enough to severely impede quartz grain growth by recrystallization, and a very fine-grained quartz fraction developed. It is likely that the development of stretched augen and vein-like grains of quartz, K-feldspar, and plagioclase was caused by a high-temperature deformational mechanism such as grain-boundary sliding (Elliott, 1973; Kingery, 1960; Kirby and Raleigh, 1971) occurring after the development of subgrain mosaics.

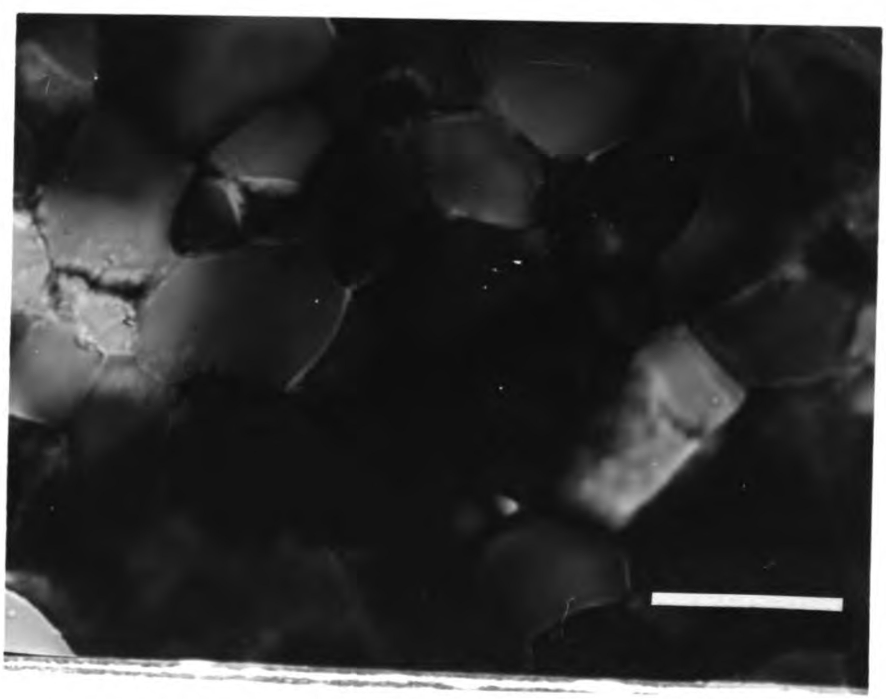
The disappearance of K-feldspar from the system is difficult to evaluate but perhaps can be explained with the aid of the surface area data. Several very high K-feldspar-K-feldspar surface area measurements occur in the intermediate sheared interval immediately before the loss of K-feldspar. A possible interpretation of the data is that the polygonization of the K-feldspar, which is indicated by the

Figure 9. A. Plagioclase subgrain boundaries are angular within the zone of intermediate shearing.
B. Plagioclase subgrain boundaries become curved within the zone of intense shearing, indicating the activation of recrystallization grain growth.
scale...25μ

A



B



high surface area measurements, aided in the atomic diffusion of potassium from the feldspar lattice. Each new subgrain boundary serves as a potential perfect source or sink for atomic vacancies, thus enhancing diffusion of potassium out of the system.

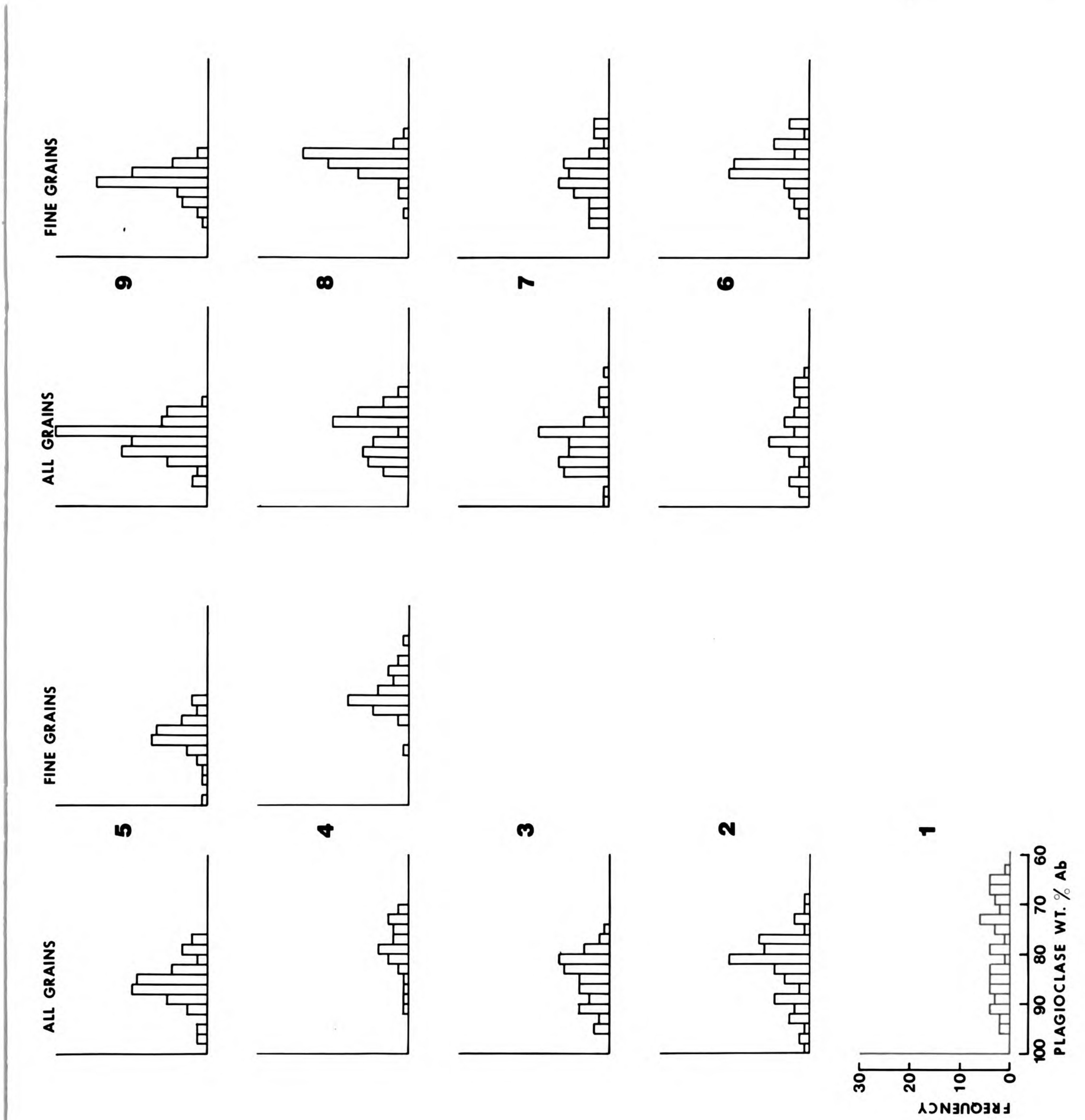
PLAGIOCLASE COMPOSITIONS

All Grains

The dramatic variation in plagioclase-plagioclase surface area within the Little Eau Claire River shear zone documents the intense textural readjustment of plagioclase associated with the shearing episode. Plagioclase composition, a sensitive petrogenetic indicator, also responded to the energy conditions of the shear zone.

Plagioclase compositions were recorded using an ARL EMX microprobe. In the initial sampling, compositions were recorded for each plagioclase grain encountered on parallel line traverses across thin sections from ten selected samples within the shear zone. When large porphyroclastic plagioclase grains or fragments were encountered, compositions were recorded at standard 5 micron intervals across the grains. This compositional data reflects not only variation between the finely crystalline plagioclase matrix grains, but also the variation within and between the larger porphyroclasts. The data are presented in frequency histograms with class intervals of 2% Ab (Fig. 10, all grains). Because of textural and compositional disequilibrium encountered in samples from the shear zone, it is reasonable to assume that the position of the compositional modes of these frequency diagrams most closely indicates those compositions that for any particular sample represent an attempt by the system to reach equilibrium. In other words, if the compositions are indeed responding to the temperatures and strain-rates associated with the deformation, then a mode should

Figure 10. Plagioclase compositions determined by an ARL EMX microprobe are presented in histograms with class interval 2% Ab. Compositions were recorded for samples within the entire population of plagioclase grains in each thin section (labelled "all grains") and also for samples within the fine-grained fraction exclusively (labelled "fine grains"). Thin sections are numbered in order of increasing S_v. Mode positioning is used to most closely approximate the stable compositions for each sample. Compositional modes within "all grains" indicate a possible peristeritic reaction within the plagioclase. The apparently unimodal calcic populations developed within the "fine grains" suggest that the entire shear zone eventually reached temperatures near the crest of the peristerite solvus (600^{o}-650^{o}C) and only the fine-grained plagioclases equilibrated with these temperatures.


ALL GRAINS
FINE GRAINS
ALL GRAINS
FINE GRAINS
1
2
3
4
5
6
7
8
9
FREQUENCY
30
20
10
0
100
90
80
70
60
PLAGIOCLASE WT. % Ab

develop at or near the most stable compositions for a given temperature and strain-rate. An examination of the histograms using this criterion reveals an interesting compositional variation across the shear zone.

The initial relatively unsheared sample 1 shows an obviously hetergeneous plagioclase compositional population. This is reflected in the zoning evident in the primary igneous grains. Using total-rock surface area as an indication of the intensity of shearing, it is apparent from samples 2 and 3 that at low to moderate frictional heating and relatively minor granulation a marked decalcification of the plagioclase occurs. Compositions are pushed towards higher albite percents and the distributions tighten considerably. As total-rock surface area increases (sample 4), a distinct compositional subpopulation with a mode centered between 78-80% Ab is indicated. Sample 5 exhibits a calcic mode between 84-88% Ab and also the first appearance of a high-albite subpopulation between 94-98% Ab. Samples 6 and 7 show variation in calcic and albitic mode development, another indication of compositional disequilibrium within the shear zone. In sample 8, the two modes have converged and subpopulations are centered between 82-84% Ab and 88-90% Ab. Sample 9 exhibits a somewhat skewed normal distribution with an intense mode between 84-86% Ab.

<u>Interpretation Plagioclase Compositions: All Grains</u>

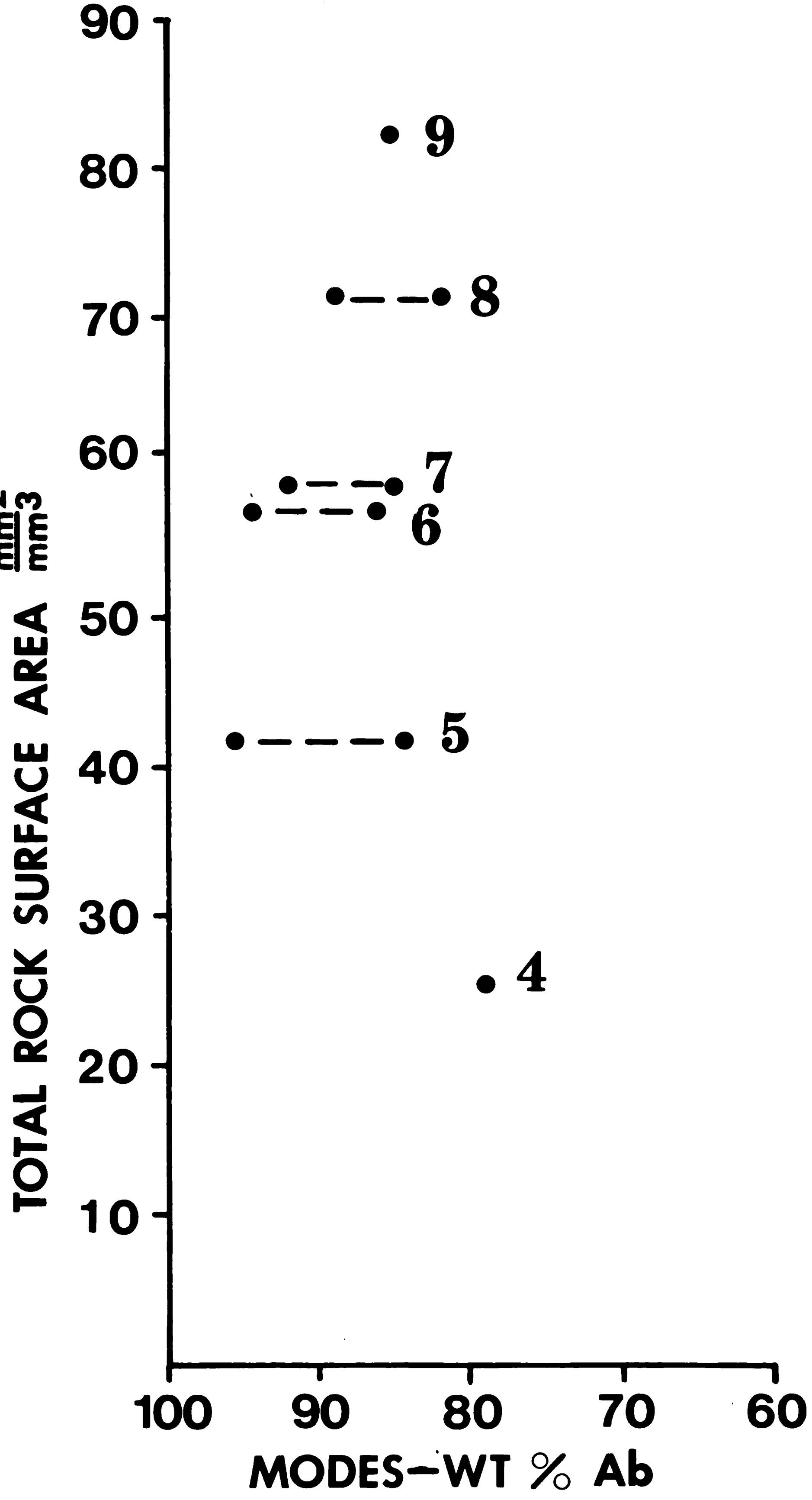
The less sheared samples show marked decalcification of the plagioclase feldspars, perhaps aided by the effects of microfracture and beginning polygonization. The calcic arm of the peristerite solvus is indicated by the compositional population of sample 4 and the increasingly sheared samples by our measurements have strong indications of bimodal populations until the highly-sheared samples 8 and 9 are encountered. Here the distributions tighten and 9 appears to be nearly normally distributed. Beach (1973) has interpreted plagioclase compositional variation in the Scourie shear zone as evidence for a peristeritic reaction within the sheared interval. A similar interpretation can be made from this data, and a hypothetical peristerite solvus (Fig. 11) is presented based on mode positioning (in % Ab) versus the shearing intensity based on total-rock surface area. Due to the compositional and textural disequilibrium apparent across the shear zone, no attempt is made to accurately describe a peristerite solvus for these rocks. Rather, a trend is indicated which suggests that a peristerite-type reaction has occurred in these rocks. The data suggest that the two highly-sheared samples have attempted to equilibrate with temperatures very near or slightly above the crest of the peristerite solvus.

Plagioclase Compositions Within the Fine-Grained Fraction

Microfracture and polygonization have developed a fine-grained subpopulation within the intermediate and highly-sheared samples from the shear zone. In order to establish what effect the development of this fine-grained fraction has had on plagioclase composition, a second compositional sample was recorded from selected fine-grained areas within the six thin sections whose plagioclase compositions were interpreted as peristeritic. The data are again presented in frequency histograms with a class interval of 2% Ab (Fig. 10, fine grains).

In the less sheared samples 4 and 5, very little difference can be seen in comparison with the whole grain assemblage histograms.

Figure 11. Plot of "all grains" compositional mode positions (in % Ab) versus S_v to illustrate the development of a peristeritic trend in plagioclase compositions with increased shear intensity.


TOTAL ROCK SURFACE AREA mm2/mm3
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
100
90
80
70
60
MODES—WT % Ab

However, in the more intensely sheared samples, obvious differences can be noted. The compositional distributions within the fine-grain material tighten, and modes indicate a calcic compositional population in each of the highly-sheared samples. Apparently, the albitic and calcic limbs of the peristerite solvus are approximately equal within the fine-grained material. This indicates that the frictional heating associated with shearing eventually raised the entire shear zone to a temperature near the crest of the peristerite solvus. The fine-grained material formed by the shearing was able to equilibrate with this temperature, the coarser material was not. The albitic side of the peristerite solvus therefore occurs within the coarser grain fragments, and represents compositional disequilibrium within the coarse-grained plagioclases.

CONCLUSIONS

Quantitative surface area data and qualitative thin section observations support the hypothesis that strain-rates within the Little Eau Claire River shear zone were sufficiently high to impede recrystallization grain growth as the major deformational mechanism. A comparison with surface area measurements of the regionally metamorphosed Cross Lake granodiorite (Ehrlich et al, 1972) exemplifies the differences between a predominantly recovery phenomenon such as is seen in the shear zone and the recrystallization phenomena within the regionally metamorphosed rocks. In the Cross Lake granodiorite, normalized plagioclase surface area shows a very high initial surface area in the middle greenschist facies. Then, as the metamorphic grade increases, the surface area decreases systematically until an apparent equilibrium value is reached. The plagioclase-plagioclase surface area (unpublished data) shows the exact same trends. The initial surface area high is attributable to early granulation effects in the greenschist facies. It is possible that within these rocks the strain-rates were high enough to foster recovery over recrystallization grain growth in the greenschist facies, much as in the shear zone. However, as soon as the temperatures became sufficiently high, recrystallization grain growth became dominant and the surface area decreased. In the middle amphibolite facies, an apparent steady-state flow regime is attained, as recrystallization grain growth and nucleation of new grains balance one another to achieve an equilibrium surface area configuration.

Within the Little Eau Claire River shear zone, temperatures were not high enough to promote recrystallization grain growth as the dominant mechanism due to the strain-rates associated with the deformation. No dramatic decrease in plagioclase surface area occurs across the shear zone. Whole rock surface area increases as more and more granulated phases occur. Therefore, it is concluded that within shear zones developing classical mylonitic textures, strain-rates are extremely high, leading to grain microfracture and polygonization and subsequent grain boundary sliding as the dominant deformational mechanisms.

Plagioclase compositional data indicate temperatures associated with the dynamic metamorphism of the Little Eau Claire River shear zone exceeded the crest of the peristerite solvus. Temperatures in the range of 600°C - 650°C are indicated (Crawford, 1966). Strain-rates necessary to impede recrystallization grain growth in plagioclase at these temperatures may be reproducible in laboratory experiments.

The data also suggest that the ability of plagioclase to equilibrate with the temperatures generated during shearing was kinetically enhanced by the intergranular surface area generating processes of microfracture and polygonization.

The N30°E trending shear zones of central Wisconsin must result from a tectonic episode capable of producing strain-rates high enough to explain the observed textures and inferred temperatures documented in this study.

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