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Origins of cleavage in the Wallace Formation Superior Montana

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ORIGINS OF CLEAVAGE IN THE WALLACE FORMATION, SUPERIOR, MONTANA

by

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Origins of Cleavage In the Wallace Formation, Superior, Montana (63 pp.)

Director: David M. Fountain DMF

Structural analysis indicates that the Wallace Formation in the Superior area can be divided into four domains. Two of the domains are intensely cleaved and the attitude of cleavage in one domain is parallel to the attitude of cleavage in the other. A third domain, which is relatively undeformed, lies between the cleaved domains. The fourth domain is made up of slumped units which are surrounded by the relatively undeformed third domain. Slaty cleavage of variable, but generally poor, quality has developed in the slump domain.

The presence of slaty cleavage in slumped units which show no evidence of subsequent deformation indicates that some slaty cleavage developed prior to any substantial burial or lithification, perhaps through dewatering. The regional slaty cleavage present in two of the domains is the product of post-lithification flattening during folding. Soft sediment dikes are parallel to slaty cleavage and appear to be genetically related. However, their very limited distribution does not allow regional application of prelithification processes such as dewatering.

The tectonic process responsible for regional slaty cleavage is thought to be northeasterly gravity glide and thrusting away from the Idaho batholith. Tear faults immediately south of the Superior area trend perpendicular to fold axial plane and slaty cleavage attitudes in the study area suggesting that thrust faulting overlapped the Superior area.

The juxtaposition of cleaved and uncleaved domains is thought to be the result of block faulting whereby an uncleaved domain has been down dropped between cleaved domains from a stratigraphically higher zone of lesser strain. Alternately, strike-slip faulting along the Boyd Mountain fault has offset cleavage formed prior to the faulting.

ACKNOWLEDGMENTS

My thanks to Drs. Dave Fountain, Bob Weidman, and Tom Margrave for their professional guidance in the production of this manuscript, Dr. Jim Talbot for suggesting the problem, and Dr. Don Winston whose observations in the field helped bring things in focus.

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CHAPTER I

INTRODUCTION

Purpose

The Superior area (Fig. 1) is one of contrasting structural styles (Campbell, 1960). In particular, slaty cleavage may be well developed or non-existent depending upon the location within the area. This study is an attempt to define structural domains within the area and determine the origin of slaty cleavage where present.

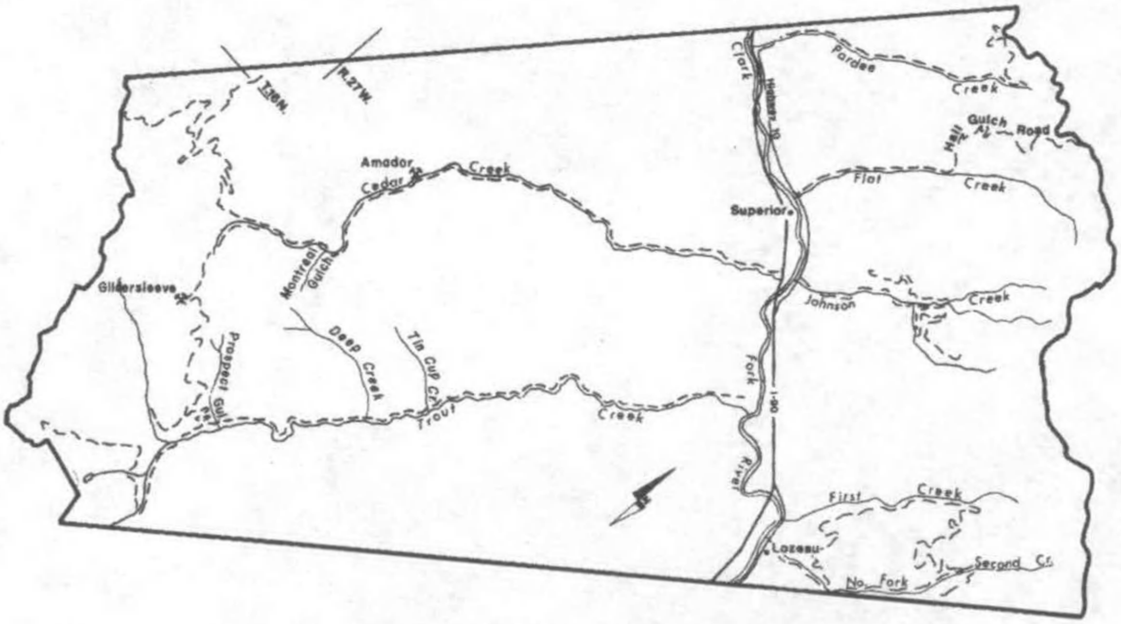


Fig. 1. Location of study area

To accomplish this, field descriptions, photographs, and attitudes of structural features such as fold axes, fold axial surfaces, cleavages, bedding cleavage intersections and bedding attitudes were recorded. Fifty oriented rock samples were collected for thin section and fabric study.

Previous Work

Wallace and Hosterman (1956) produced a stratigraphic and general structure map of western Mineral County, and Campbell (1960) did the same in the northern one-half of the Superior area. Their interests were primarily reconnaissance and economic geology. However, they did make a few structural notations. Both recorded a variance in structural styles and the presence of axial plane slaty cleavage in some outcrops. Neither author offered hypotheses for the difference in structural styles or the origin of cleavage.

Clark (1967) and Norwick (1972) both studied slaty cleavage in western Montana and northeastern Idaho, and arrived at quite different conclusions regarding its origin. Clark (1967) studied cleavage in the Wallace Formation of the Coeur d'Alene mining district and concluded that slaty cleavage resulted from dewatering during the Middle Precambrian. Norwick (1972) on the other hand, concluded that slaty cleavage in the Prichard Formation of western Montana and in the Coeur d'Alene mining district was predominantly a product of syntectonic recrystallization in a non-hydrostatic stress field during the Mesozoic.

Tectonic Setting

The Superior area is situated on or near two major tectonic elements. The northern boundary of the Idaho batholith is located forty-five kilometers south of the town of Superior. The Boyd Mountain fault, which is the principal element of the Montana Lineament in this area, runs through Superior and bisects the study area (Fig. 2).

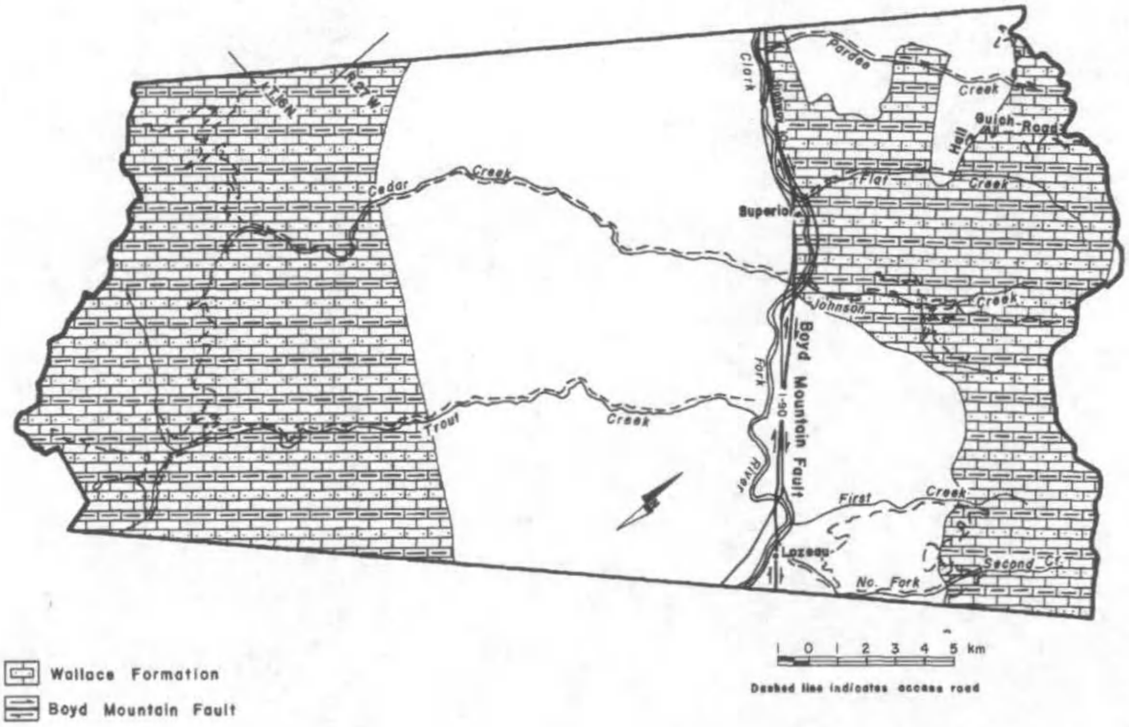


Fig. 2. Map showing the distribution of the Wallace Formation and the position of the Boyd Mountain Fault.

The emplacement of the Idaho batholith created a gravity potential in the intruded sediments which culminated in Mesozoic thrusting (Hyndman, Talbot and Chase, 1975). These thrusts are radially distributed around the northern and eastern portions of the batholith (Talbot, 1976). It is possible that thrusts off the Idaho batholith extend into or through the Superior area.

The Montana Lineament (e.g., Weidman, 1965), alternately referred to as the Osburn Fault zone (McMannis, 1965), the Coeur d'Alene lineament (Moody and Hill, 1956) and the Lewis and Clark lineament (Smith, 1965; Harrison, et al., 1974), is a poorly understood zone of faulting. It extends westward for approximately 700 kilometers from east of Billings, Montana to Coeur d'Alene, Idaho. Formation of cleavage related to faulting along the lineament has been suggested in other areas (Wallace and Hosterman, 1956; Harrison, et al., 1974) in addition to the Superior area (Campbell, 1960). The lineament zone is 30 kilometers wide in the Superior area. The locus of deformation, however, has been the Boyd Mountain fault along which Campbell (1960) has mapped 21 kilometers of right lateral slip and 3.3 kilometers of vertical displacement.

Stratigraphy

This study deals only with the Wallace Formation (Fig. 2), a heterogeneous formation composed of finely laminated sequences of quartzite, argillite, limestone, dolomite and mixtures thereof. The percentages of each rock type vary through the section, but in the Superior area they are as follows: 65 percent thin-bedded, light gray, slightly sericitic quartzite, some of which is dolomitic; 15 percent black argillite; and 20 percent medium to dark gray, silty dolomitic limestone or siltstone with interbedded molar tooth structures and calcareous stromatolites (Campbell, 1960). The formation reaches a total thickness of approximately 3,400 meters and is believed to have been deposited quite rapidly in the subsiding Belt basin (Campbell, 1960). The probable maximum depth of burial was an additional 3 to 5 kilometers (Campbell, 1960).

Metamorphism

Low-grade regional metamorphism of the Wallace Formation caused the recrystallization of quartz grains and the formation of sericite. Argillite and quartzite have been converted to phyllite and foliated quartzite by dynamic metamorphism adjacent to some fault zones (Campbell, 1960).

CHAPTER II

STRUCTURAL ANALYSIS

General Statement

Differences in deformational styles north and south of the large strike-slip faults of the Montana Lineament have been noted by several workers (e.g., Weidman, 1965; Harrison et al., 1974). Wallace and Hosterman (1956) pointed out that, in western Mineral County, Montana, tight overturned folds are common north of the Osburn fault, but are the exception on the south side.

A similar situation exists in the Superior area across the Boyd Mountain fault (Fig. 2) where Campbell (1960) delineated northern and southern domains of contrasting structural parameters.

Structural analysis conducted during this study revealed that not only were there differences north and south of the Boyd Mountain fault, but that a small unnamed fault further subdivides the area south of the Boyd Mountain fault into separate domains. A zone of soft sediment slump occurs south of the Boyd Mountain fault as well, creating a third domain. The study area then is divided into domain I north of the Boyd Mountain fault and domains II, III and IV south of it (Fig. 3).

Domain I. Campbell (1960) mapped a large portion of the study area north of the Boyd Mountain fault which, in this study, includes the Wallace

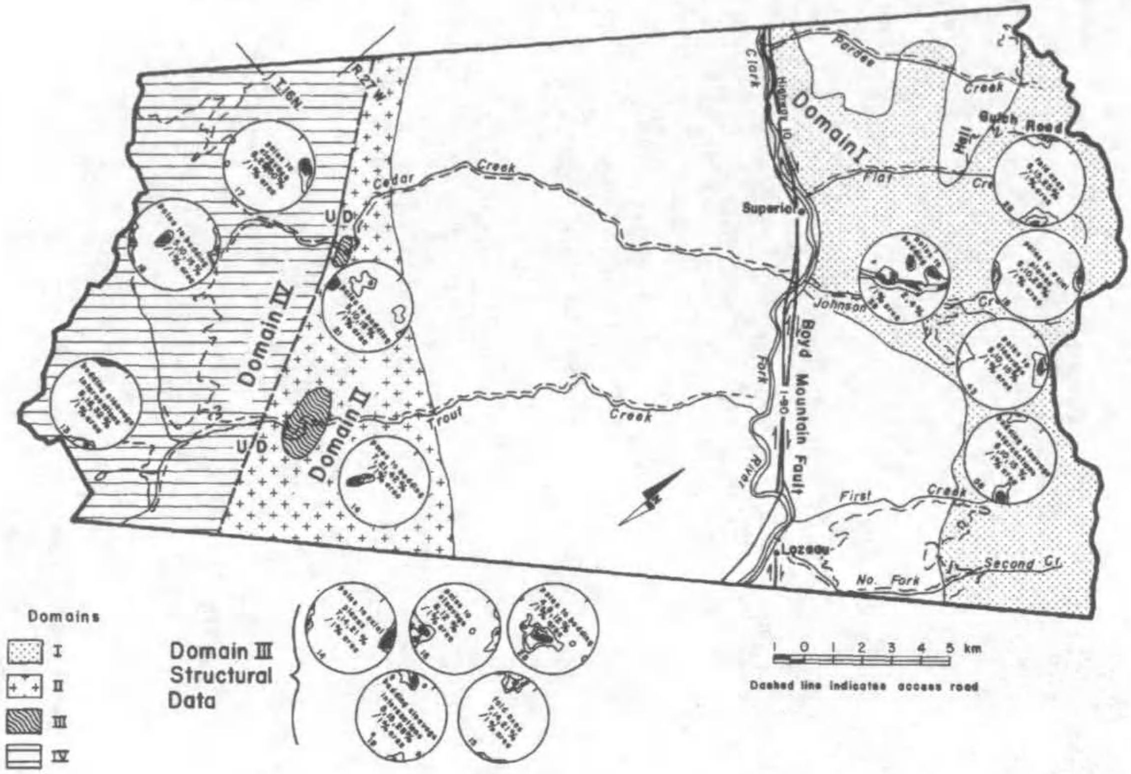
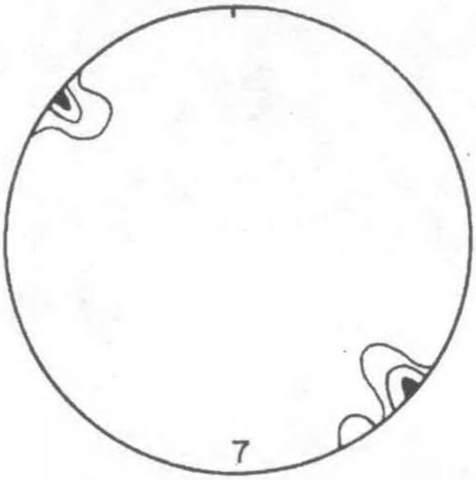


Fig. 3. Structural domains of the Superior area and the equal area plots of data gathered within each domain.

Formation outcrops along Pardee, Flat, Johnson, First, and Second (North Fork) Creeks, and old Highway Ten from 0.1 km east of Superior to 1.2 km east of Superior, and Halls Gulch (see Fig. 1). He was able to delineate the axial trace of several macroscopic folds for distances of up to five kilometers. These macroscopic folds are the dominant structure of domain I. All other structures in the domain are related as will be seen.

Macroscopic folds are typically tight, with steep axial surfaces, and a few are overturned toward the north. The fold hinges are usually near horizontal or plunge gently to the southeast (Fig. 4). The hinges are frequently offset by one of the anastamozing elements of the Montana lineament. Smaller folds in domain I are mainly parasitic and have the same axial surface and trace as the larger folds (Campbell, 1960). Campbell (1960) did not determine the style of folds in domain I. My observations, however, of folds of both microscopic and outcrop scale, show that they have elements of both concentric and similar styles.



15, 30, 45% per 1% area

Fig. 4. Equal area plot of macroscopic fold hinges in domain I. Average attitude 3°, S44°E.

Frequently, quartzite beds will be folded concentrically while interbedded argillite layers will thin in the limbs with respect to the hinges (Fig. 5). A given fold will generally lose its shape over a meter (i.e. the stress which caused folding has not been transmitted evenly through the section; Fig. 5).

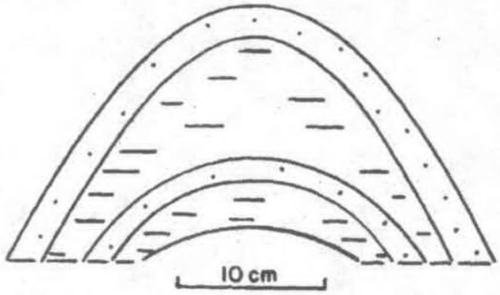


Fig. 5. Concentric and similar behavior of folded quartzite (dotted) and argillite respectively in domain I. The geometry of a fold changes over short distances from one unit to the next, this is particularly noticeable in the two quartzite units above.

Slaty cleavage is generally very well developed in domain I. It is penetrative on a regional scale in both argillite and quartzite units. Slaty cleavage generally diffracts from argillite to quartzite beds and tends to form larger angles with bedding in quartzite than in argillite. Quartzites and argillites have undergone flexural slip folding in the northern domain. Quartz-filled fractures, which are straight in quartzite, have been shortened and folded in argillites (See Plate 6, page 36). The fold axial surfaces of the folded fractures always appear to parallel the fold axial surface of larger folds in which they are contained. Occasionally cleavage in individual folds can be seen to fan divergently about fold axial surfaces, particularly in argillite units bracketed by thick quartzite beds (Plate 1).

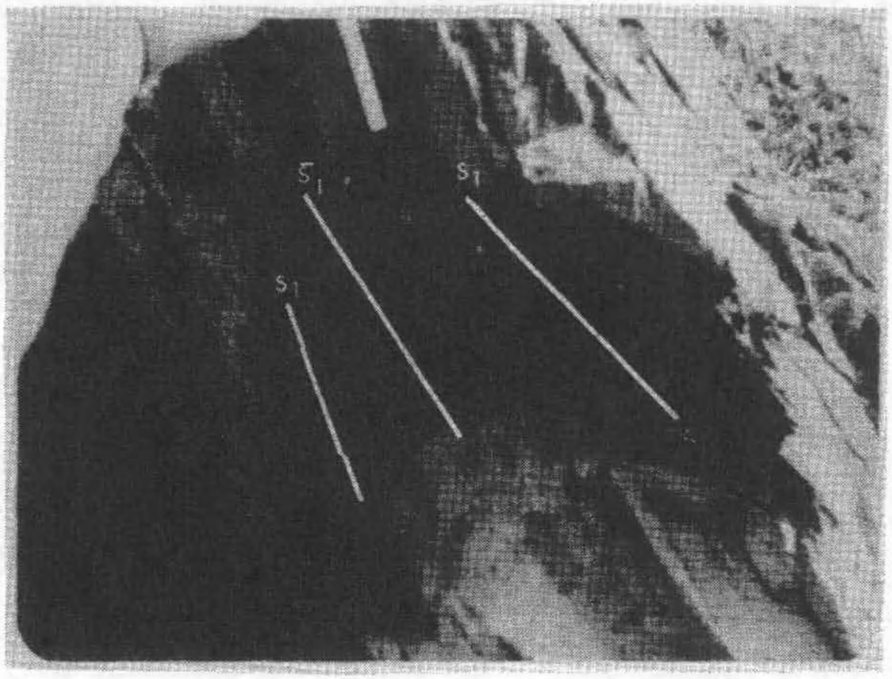
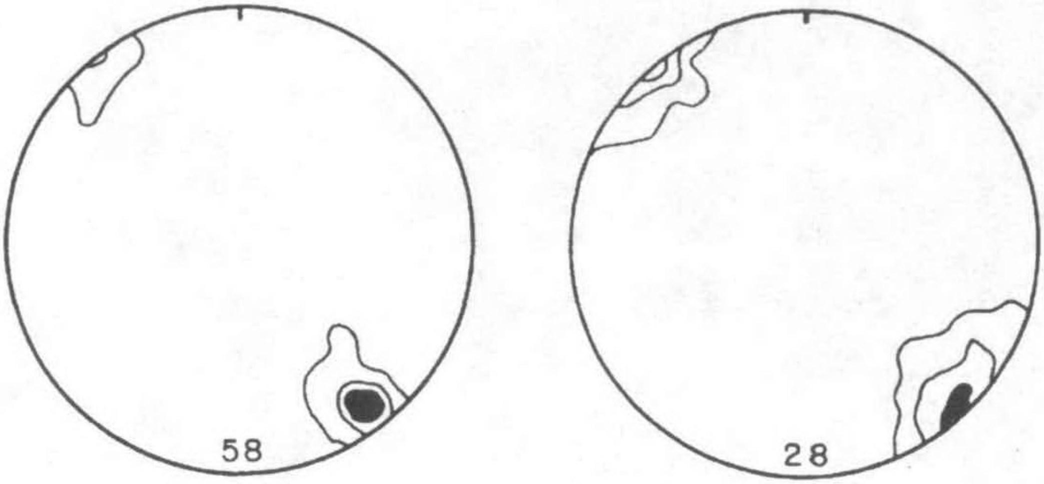


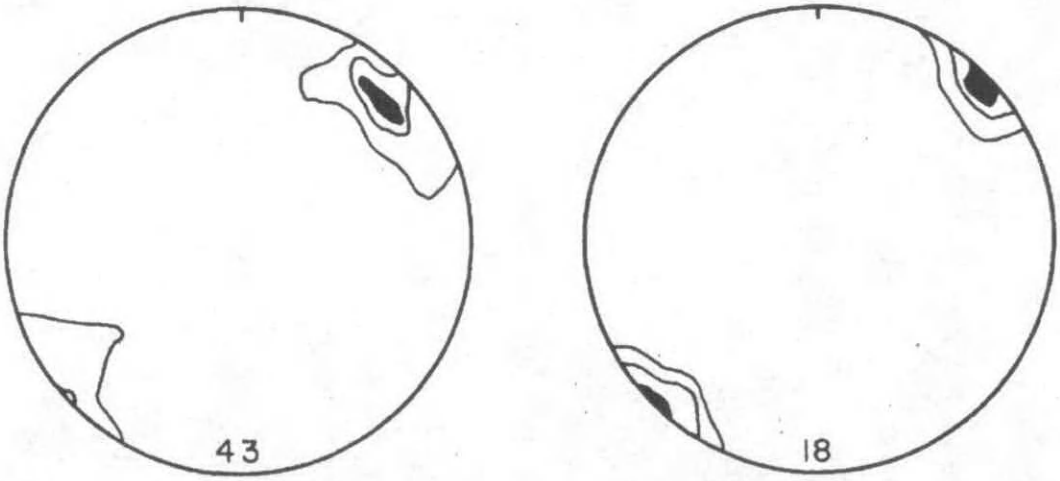
Plate 1. Divergent fanning of slaty cleavage (S_1) in argillite unit sandwiched between two quartzite units.

Regionally, cleavage planes parallel fold axial surfaces in domain I and bedding cleavage intersections define a line in space approximately parallel to fold hinges (Fig. 6). Poles to bedding define an axis of rotation similar to the one defined by observed fold axes (Fig. 7).



a. bedding-cleavage intersections
5, 10, 15% per 1% area

b. fold axes
5, 15, 25% per 1% area



c. poles to cleavage
5, 10, 15% per 1% area

d. poles to fold axial surfaces
5, 10, 25% per 1% area

Fig. 6. Comparison between the attitudes of bedding-cleavage intersections (a) and fold axis (b), and cleavage (c) and fold axial surfaces (d) in domain I.

1, 2% per 1% area

Fig. 7. Great circle defined by poles of bedding in domain I.

Numerous pre-lithification features have disturbed the otherwise moderate to finely laminated Wallace Formation in domain I. These structures, mainly in the form of tiny quartzite dikes and argillite injection structures, tend to be parallel or sub-parallel to the existing slaty cleavage. Their relationship to cleavage is debatable and will be discussed in greater detail in the following chapter.

Crenulation cleavage is always transcurrent to the consistent overall structural trend of the northern domain. Crenulation cleavages in domain I are poorly defined in outcrop and are penetrative only near shear zones. No precise attitudes were obtained on crenulation planes although several rough measurements indicate they dip steeply and trend to the northeast. The relationship of crenulation cleavage to slaty cleavage will be discussed in the next chapter.

Two or three deformational periods have affected domain I. Whether soft sediment deformation and regional folding should be treated as one event or two will be discussed in Chapter IV. The crenulation cleavage represents a final deformation. The similarities in orientation of the other structural parameters (i.e. folds, slaty cleavage, fold axial surfaces, bedding cleavage intersections and bedding attitudes) appear to be genetically related to a single event.

General Statement

Campbell (1960) described the section south of the Boyd Mountain fault and Superior as a relatively undeformed area as compared to its northern counterpart. He mapped broad, open, northerly-trending folds and a moderately well developed northwesterly trending cleavage.

This study indicates that, although much of the southern domain is only moderately deformed or even undeformed, other portions have been intensely compacted and cleaved. Three different deformational styles and attitudes were recognizable in the study area south of the Boyd Mountain fault. Thus it has been subdivided into separate domains II, III, and IV.

Domain II. Domain II is a zone of little deformation by comparison to the rest of the Superior area. Relatively undisturbed portions of the section occur in both the Trout and Cedar Creek drainage (Fig. 3).

The Trout Creek portion of domain II exhibits a poor mimetic bedding plane cleavage defined by burial metamorphosed clays. The area has been gently warped or folded (Campbell, 1960). In Trout Creek, the domain extends from the Wallace-Spruce contact (2 km. northeast of Tin Cup Creek) southwest to the approximate area of Prospect Gulch, with the exception of a 400 meter slump zone which occurs within that interval, which is part of domain III. The Wallace Formation maintains a very consistent strike near N45°W (Fig. 3), throughout much of this distance. Dips are consistently northeast becoming steeper from northeast to southwest. No folds were observed in domain II.

A similar sequence in the Cedar Creek area belongs in domain II. Undeformed Wallace Formation in the Cedar Creek drainage is bracketed by the Spruce Formation contact near the Amador Mine on the northeast, and a large diabase dike which follows a high angle fault on the southwest. The fault is located on the Cedar Creek road 0.5 kilometers southwest of Montreal Gulch. Harrison (1974) mapped this fault as a normal fault with domain II downdropped with respect to domain IV (Fig. 3). The relatively undisturbed beds in Cedar Creek also trend northwest and dip to the northeast. Attitudes near several small high angle faults, however, are quite divergent from the dominant direction above. The small faults caused minor warps in the adjacent units. Structures of more regional scope do not occur.

Domain III. A discontinuous zone of soft sediment slump composes domain III (Fig. 3). Slump zones may be up to 100 meters thick, 400 meters wide, with unknown lateral extent. They reoccur along a line south of the Boyd Mountain fault which trends N10°W, beginning 0.8 km. southwest of Deep Creek on the Trout Creek road and continuing well beyond the confines of this study (Campbell, 1960). The slump zone is exceptionally large in Trout Creek. A very thin slump zone 10 meters thick and 20 meters long interrupts the undeformed section in Cedar Creek 0.1 kilometer north of the diabase dike described in the section on domain II.

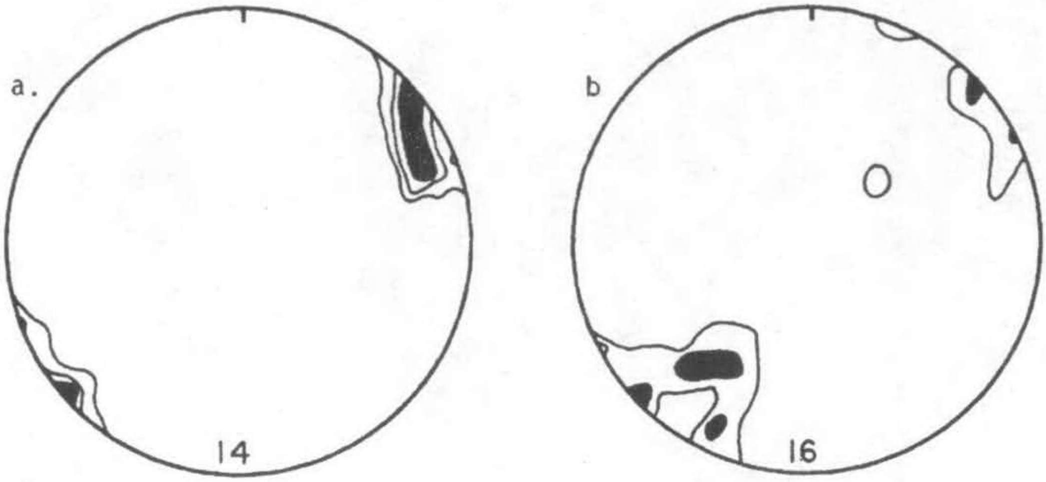
Collectively these two outcrops compose a rather unique domain. The cause and nature of these slump zones is poorly understood. Chevillon (1977) believes that similar slump zones in the St. Regis Formation in the Coeur d'Alene mining district occurred prior to complete lithification. He theoreized that earthquakes triggered the slumps which then slid downslope with resultant mixing of sediment.

The lack of deformation in units overlying slump zones make it clear that slump was a surface process involving the top hundred meters or more of the sedimentary pile. Units underlying the slumps show scour and fill, and have been warped or folded about axes perpendicular to the slump transport direction. Slumped sediment was at least partially lithified prior to slumping as the more quartz-rich units form angular breccias. Argillites, on the other hand, behaved plastically (Godlewski, 1977).

On a small scale basis, there appears to be no order to the structural styles and attitudes of domain III structures. For instance, fold axial surfaces and/or cleavage planes may vary in attitude over a few feet in the outcrop; cleavage planes may be transcurrent to fold axial surfaces by up to 40°, and are rarely penetrative for more than a few feet. The degree of cleavage development may vary over short distances as may fold interlimb angles; fold shape is not maintained for any distance (i.e. a tightly folded quartzite may lie within a few centimeters of a planar quartzite). The abrupt contrasts in structural styles indicates that stress was transferred through the deforming body in a very uneven fashion.

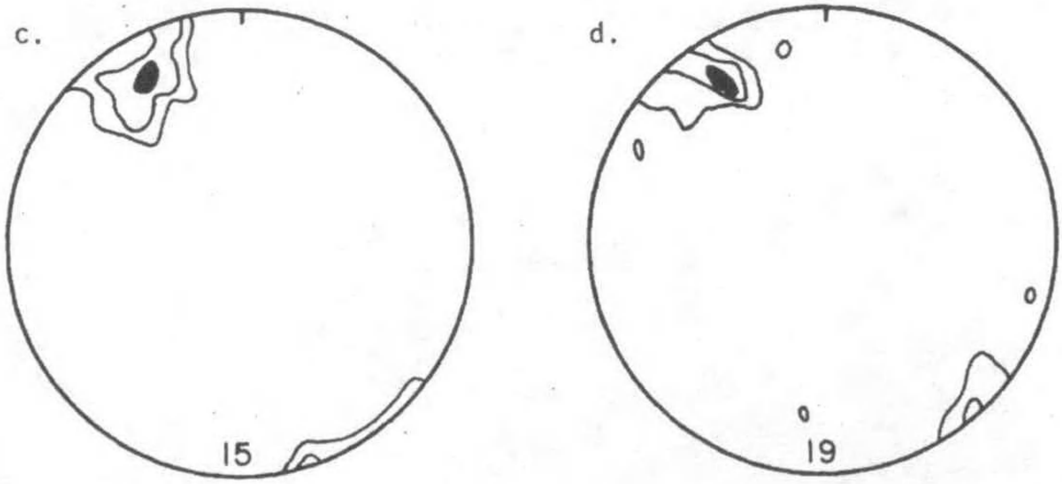
When plotted on an equal area net the attitudes of fold axial surfaces and cleavage are somewhat dispersed. The average attitude of both planar features is, however, similar (Fig. 8). Other structural parameters, although also widely dispersed, have average attitudes which indicate a common origin with folding and cleavage. In particular, fold axes and bedding/cleavage intersections (Fig. 8) define similar lines which trend in the same direction as the strike of fold axial surfaces and cleavage.

The fact that domain III structures often appear unrelated on a small scale basis, but maintain consistency through a 400 meter outcrop indicates that lithologic and lithification contrasts between layers probably altered local stress patterns within the slump zones; however, crude regional (400 meters) attitudes representing the slump event were established.



fold axial surfaces
7, 14 21% per 1% area

poles to cleavage
6, 12% per 1% area



fold axis 7, 14 21%
per 1% area

bedding-cleavage intersections
5, 15 25% per 1% area

Fig. 8. Comparison between the attitudes in domain III for: fold axial surfaces (a) and poles to cleavage (b), and fold axes (c) and bedding-cleavage intersections (d).

Quartzite dikes which intrude adjacent argillite units are especially common in domain III. The dikes which may be only a few cm to 50 cm in length generally intrude the argillites at some small angle to cleavage. They occur in both cleaved and uncleaved portions of the slump zone. Chevillon (1977) described similar structures in the Coeur d'Alene mining district as "water escape" structures. He noticed that abundance of these structures increased with proximity to slump zones. The morphology and angular relationships of quartz dikes to cleavage becomes clearer in thin section and will be discussed in the next chapter under "flow dikes".

Another structure commonly associated with slump zones are "pull apart structures" (Smith, 1968). "Pull aparts" occur in quartzite units and have a staircase appearance with each step down-dropped with respect to its upslope neighbor (Fig. 9). Smith (1968) described these features as tensional, resulting from down slope sliding creating a pull on the up-slope sediment.

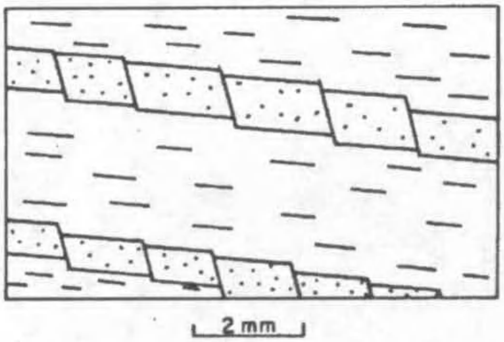
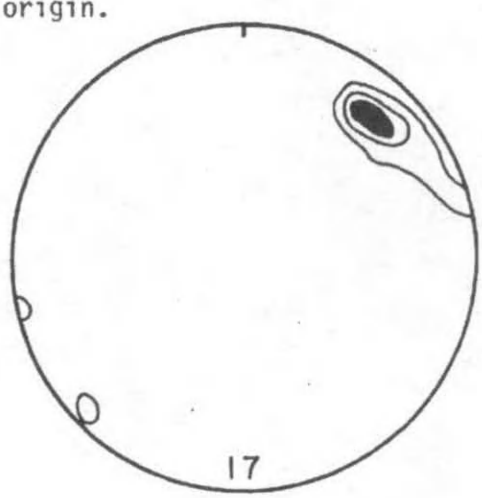


Fig. 9. The small offsets in quartzite units containing "pull-apart structures" do not cut more than one unit.

Domain IV. Domain IV includes the southernmost portion of the study (Fig. 3). The boundary between domains IV and II could not be precisely located in the Trout Creek drainage. The boundary in the Cedar Creek drainage, however, is defined by the fault and diabase dike described previously as the southern boundary of domain II. Domain IV extends to the southwest for at least 2 kilometers past the Gildersleeves Mine turn-off (see Fig. 1) beyond which the Wallace Formation is severed or poorly exposed.

The distinguishing feature of domain IV is a well-developed slaty cleavage. The cleavage strikes consistently to the northwest and generally dips steeply to the southwest (Fig. 10). The cleavage penetrates both argillite and quartzite units and is diffracted from one unit to the next. The equal area plot of poles to cleavage in domain IV defines a maximum almost precisely coincident with the poles to cleavage plot of domain I. This coincidence of attitudes suggests the two cleavages may have a common origin.



5, 25, 50% per 1% area

Fig. 10. Poles to cleavage in domain IV.

Only a few folds were recognized in domain IV and then attitudes could not be accurately measured. The folds which were identified, like the folds of domain I and domain III, had both concentric and similar elements. Argillite units tended to thin in the limbs relative to the hinges while folded quartzites generally maintained a uniform thickness from hinges to limbs. Unlike the localized fold geometries in slump zones (domain III), folds in domain IV and domain I maintain shape over moderate distances, indicating a greater competence at the time of deformation.

Crude strain indicators were found in domain IV. In particular, molar tooth structures have been flattened into a preferred orientation parallel to slaty cleavage. Molar tooth structures in the Cedar Creek drainage have tear drop shapes and may have a primary elongation either parallel or perpendicular to bedding (Clark, 1970). Length-width ratios measured on 67 of these structures (Table 1) in domain IV were elongate parallel to cleavage with an average linear ratio of 2.1 to 1. Cleavage in the area where the count was made was at several different angles to bedding. The 2.1 to 1 ratio is strictly qualitative as the original shapes of the structures is only crudely known. However, the section has clearly been shortened normal to cleavage, and extended in the plane of flattending.

A second crude strain indicator in domain IV is oversteepened ripple marks. Flanks of naturally occurring ripple marks do not exceed 30" from the horizontal (Talbot, personal comm., 1974). Two sets of quartzite ripple marks in the Cedar Creek drainage have been flattened to

Table 1. Molar tooth structures in domain IV have been flattened in a plane parallel to cleavage. The following measurements were made in a plane perpendicular to slaty cleavage.

Length(cm)	Width(cm)	Length/Width	Length(cm)	Width(cm)	Length/Width
3.1	1	3.10	1.1	.5	2.20
4.2	2.4	1.75	4.1	1.9	2.16
3.8	1.3	2.92	3.1	2.3	1.36
2.3	.8	2.87	4.0	2.0	2.00
3.5	1.0	3.50	1.6	.6	2.67
2.9	.6	4.80	3.1	3.0	1.03
2.2	2.0	1.10	3.8	2.5	1.52
2.4	1.4	1.71	1.4	1.2	1.17
2.2	1.3	1.69	3.8	3.3	1.15
2.3	1.4	1.64	2.8	1.6	1.75
2.2	1.6	1.38	3.6	2.4	1.50
1.4	.7	2.00	2.9	2.1	1.38
3.2	1.5	2.13	2.2	1.1	2.00
2.7	1.1	2.45	3.3	1.3	2.54
2.5	1.1	2.27	1.6	1.8	.89
2.8	2.1	1.33	2.3	1.2	1.91
2.5	1.8	1.39	2.5	1.5	1.67
1.5	.9	1.67	2.2	1.3	1.69
3.0	1.0	3.00	1.5	.9	1.67
2.6	2.2	1.18	2.7	1.0	2.70
2.2	.8	2.75	2.2	2.5	.88
3.0	1.7	1.76	2.4	.8	3.00
2.2	.7	3.14	2.5	1.0	2.50
1.3	.4	3.25	1.7	1.1	1.55
2.0	1.6	1.25	.7	.5	1.40
1.7	3.9	0.44	6.8	1.9	3.52
1.5	1.2	1.25	3.1	1.5	2.11
2.3	1.3	1.77	3.5	1.2	2.96
2.3	.9	2.56	3.0	1.9	1.65
1.4	.7	2.00	4.0	.7	5.71
1.8	1.1	1.64	5.2	1.2	4.30
2.5	1.8	1.39	2.3	1.9	1.29
1.6	1.0	1.60	5.2	.9	5.67
			3.5	1.1	3.18

Average = 2.1/1

the extent that the flanks of the ripples form a 60° angle with the bedding plane (Fig. 11). Several joint sets expose the ripples and cleavage to three dimensional analysis. Cleavage forms an angle of 18° with the ripple axial surface. The squashed nature of the ripple marks adds credibility to a flattening interpretation for domain III units suggested by molar tooth structures.

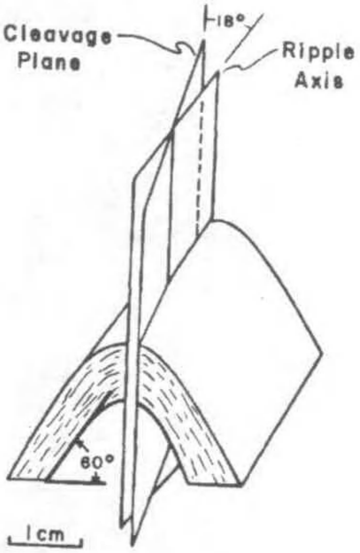
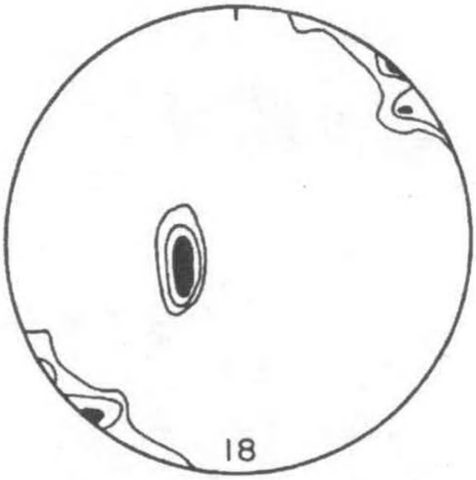


Fig. 11. Oversteepened ripple marks in domain IV indicate the rocks in this domain have been shortened normal to cleavage.

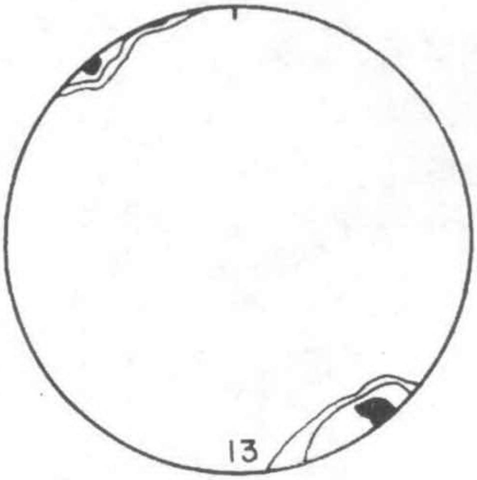
Bedding attitude plots in domain IV define two maxima (Fig. 12). One maximum defines an average strike and dip of N30W 23° NE, the other indicates an average strike of N34W with a vertical dip. The two maxima are separated by a vertical fault with one group of similar attitudes on one side of the fault and another group of consistent attitudes on the other. The fault is defined by a nearly vertical shear zone which is much narrower and probably smaller than the fault separating domains II and IV. The amount of throw on either fault was not determined during this study. A detailed study, however, of Wallace Formation stratigraphy in the future might be able to determine the extent of these offsets.



5, 10, 15% per 1% area

Fig. 12. Poles to bedding plots for domain IV indicate a consistent northwest strike. However, dips define two maximum one near vertical and the other near horizontal.

Bedding cleavage intersections in domain IV define a maximum which plunges 3°, S41°E (Fig. 13).



Bedding-cleavage intersections
8, 16, 32% per 1% area

Fig. 13. Consistent bedding-cleavage intersection direction in domain IV.

Summary

The common contrast in structural styles which occurs across much of the length of the Montana Lineament (e.g. Wallace and Hosterman, 1956; Campbell, 1960; Weidman, 1965) can be extended to include the Superior area and the Boyd Mountain fault.

Structural styles and attitudes north of the Boyd Mountain fault are consistent (Table 2) and have been placed in a single domain (I). Structures south of the Boyd Mountain fault are quite varied and have been subdivided into three domains, II, III, and IV. Domain II is relatively undeformed when compared with the other domains. Domain III

Table 2. Structural trends by domain.

Structural element	I	II	III	IV
poles to bedding	great cir. N48E, 82SE	N35W, 25SW	no maxima	two maxima N30W, 23NE N34W, 75SW
bedding cleavage intersection	10° S38E	NA	16°N33W	3°S41E
cleavage	N43W 74SW	NA	N37W 68NE	N45W 72SW
fold axis	7°S43E	NA	20°N31W	none recorded
fold axial surface	N44 W, 88SW	NA	N33W, 77SW	none recorded

is a zone of soft sediment slump. A slaty cleavage of variable quality has developed in the slumped areas. The cleavage varies in attitude on a meter-by-meter basis. When considered over the entire slump domain, however, it does maintain a consistent attitude. Domain IV is separated from domain II by a normal fault, with domain IV upthrown relative to domain II (Harrison, et al., 1974). Unlike domain II, slaty cleavage is well developed in domain IV. The average attitude of slaty cleavage in domain IV is nearly parallel to the average cleavage in domain I (Table 2).

CHAPTER III

MICROSCOPIC STRUCTURES

Introduction

Maxwell (1962) proposed that slaty cleavage in the Martinsburg shale of the Delaware Water Gap area of Pennsylvania and New Jersey is the product of tectonic dewatering of rapidly buried sediments. According to the dewatering theory, connate waters are expelled vertically when laterally directed tectonic stress cause pore fluid pressures to exceed lithostatic pressure. The high pore pressure reduces the competence of beds to extreme plasticity or even fluidity. The water then, carrying pelitic material, streams out of the sediment along fine channelways forming dikes. Mica is rotated by passing water producing an alignment (a planar cleavage) with an attitude parallel to that of the dikes.

The theoretical aspects of dewatering which have since been applied to many terranes, rest heavily on the lack of cohesion illustrated by some dikes (Alterman, 1973) and the parallelism of clastic dikes and cleavage (Maxwell, 1962; Moensch, 1966, 1970; Braddock, 1970; Clark, 1970; Powell, 1972, 1976; Alterman, 1973, 1976). Thus, the thin section analysis which follows, deals with soft sediment structures as well as post lithification features, as slaty cleavage may have formed before or after complete lithification.

Pre-Lithification Features

Microscopic examination of rocks from the Wallace Formation in the Superior area reveal features which are clearly pre-lithification phenomena. Most of these structures indicate bedding disruption in which either a quartzite unit intrudes an argillite unit or vice-versa. The intrusions are of four morphologically distinct types.

The earliest pre-lithification structures are sand squirts. Sand squirts are up to three centimeters long and are usually less than one-half a centimeter wide with irregularly rounded tabular shapes (Plate 2). They have very narrow connecting points with the source sand and intrude fine grained argillite at all angles to bedding and cleavage.

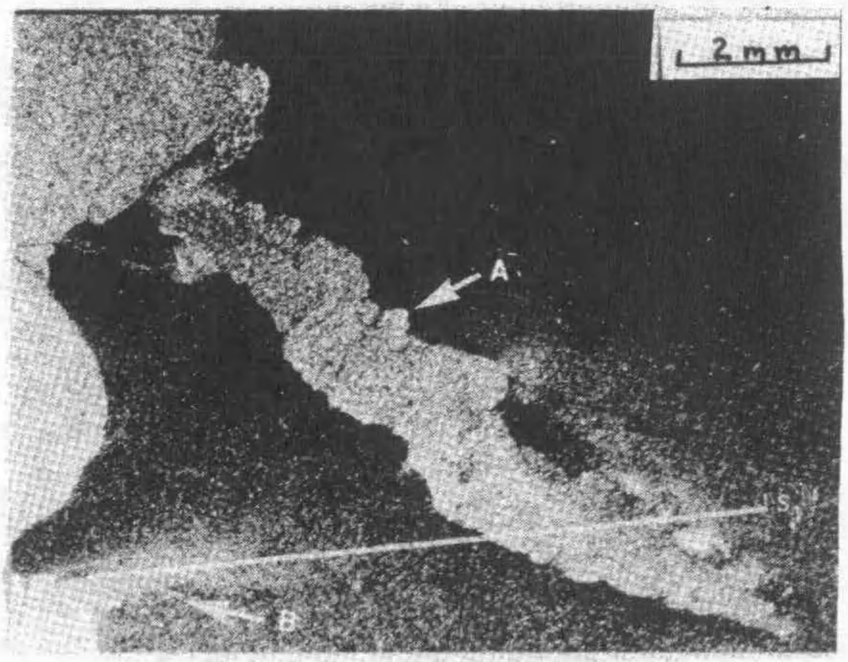


Plate 2. A. Rounded boundaries of sand squirts
B. Fan dike parallel to slaty cleavage S_1

Sand squirts are folded with axial surfaces parallel to slaty cleavage. The squirts are cut by slaty cleavage and were deformed by soft sediment processes. Thin veils of quartzite emanate from the sand squirts up-section into the overlying argillite. The sand veils were injected parallel to slaty cleavage and parallel a second soft sediment structure, fan dikes. Although sand squirts have little importance in terms of interpretation of deformational history, they are widely distributed and it is important that they be differentiated from structures which are related geometrically to cleavage.

Fan dikes are so named because they tend to spread in a fan shape when they enter an argillite unit. They are composed of sand and are relatively long and thin (Plate 3). A typical fan dike in quartzite

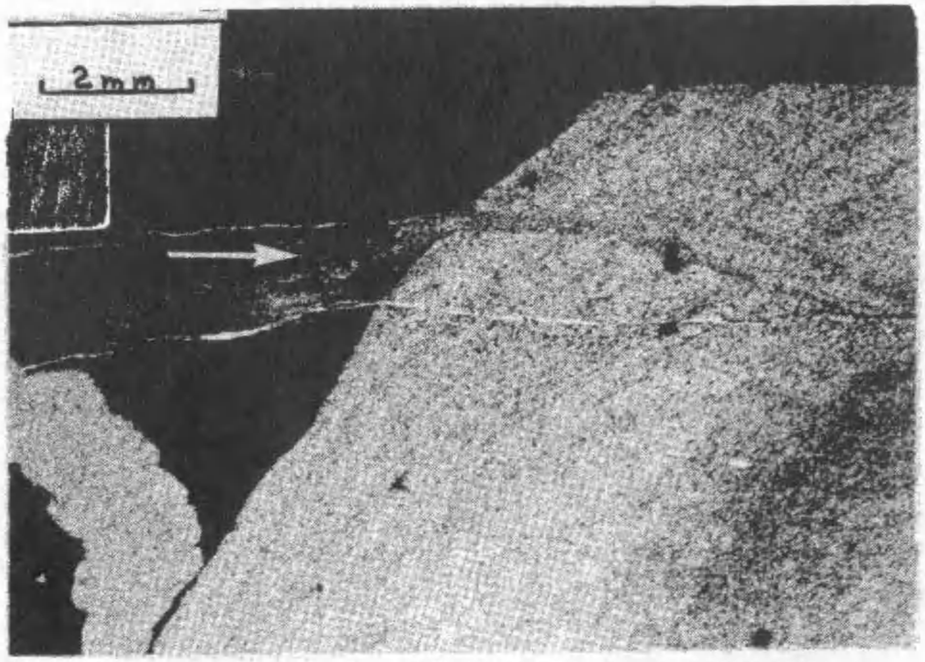


Plate 3. Fan dike (arrow) expands where injected into argillite.

will be 20 to 40 microns thick fanning abruptly to 100 to 150 microns thick before fading into the argillite. Lengths were not measured as the dikes transcend the length of all thin sections at one end or the other. Some of them exceed 7 centimeters in length. Fan dikes are recognizable in both quartzite and argillite units. They exceed the width of some quartzite argillite layers and apparently intruded argillite from quartzite under pressure. They are pinched at the locus of injection. The fan portion of the dike is composed of individual quartz grains and groups of quartz grains isolated in argillite. Each grain, or group of grains, is preferentially elongate parallel to slaty cleavage. The narrower portion of the dikes within the quartzite layers can only be recognized by the preferred dimensional elongation of quartz grains in the dike (Plate 3) as opposed to the non-orientation of grains adjacent to the dike. Fan dikes generally form an angle of less than 10^0 with slaty cleavage (Table 3) and likewise tend to parallel the axial surfaces of similar folds.

Fan dikes are difficult to recognize in the field. They were recognized in outcrop along U.S. Highway 10, 0.1 km to 0.6 km east of Superior, and in thin sections taken from First Creek drainage both in the northern domain (Fig.14). It is quite likely that they are more widely distributed although there are many intensely cleaved, folded and finely interbedded, pure quartzites and argillites which do not contain fan dikes or any other soft sediment structure.

Table 3. Angles between cleavage, clastic fan dikes and bedding in a thin section perpendicular to cleavage.

Pair	Dike ∠ clev.	Cleav. ∠ Bed.	Dike ∠ Bed.
1	8°	87°	79°
2	0°	75°	75°
3	13°	65°	52°
4	7°	55°	48°
5	0°	86°	86°
6	9°	87°	84°
7	10°	88°	78°
8	9°	88°	83°
9	4°	84°	88°
10	11°	80°	89°
11	11°	59°	48°
12	12°	29°	41°
Average	7.8°	73.6°	70.9°

Flow dikes, a third soft sediment structure, are also composed of quartzite. They are like fan dikes to the extent that they appear to be injected as a fluid, but they differ in that the quartzite grains

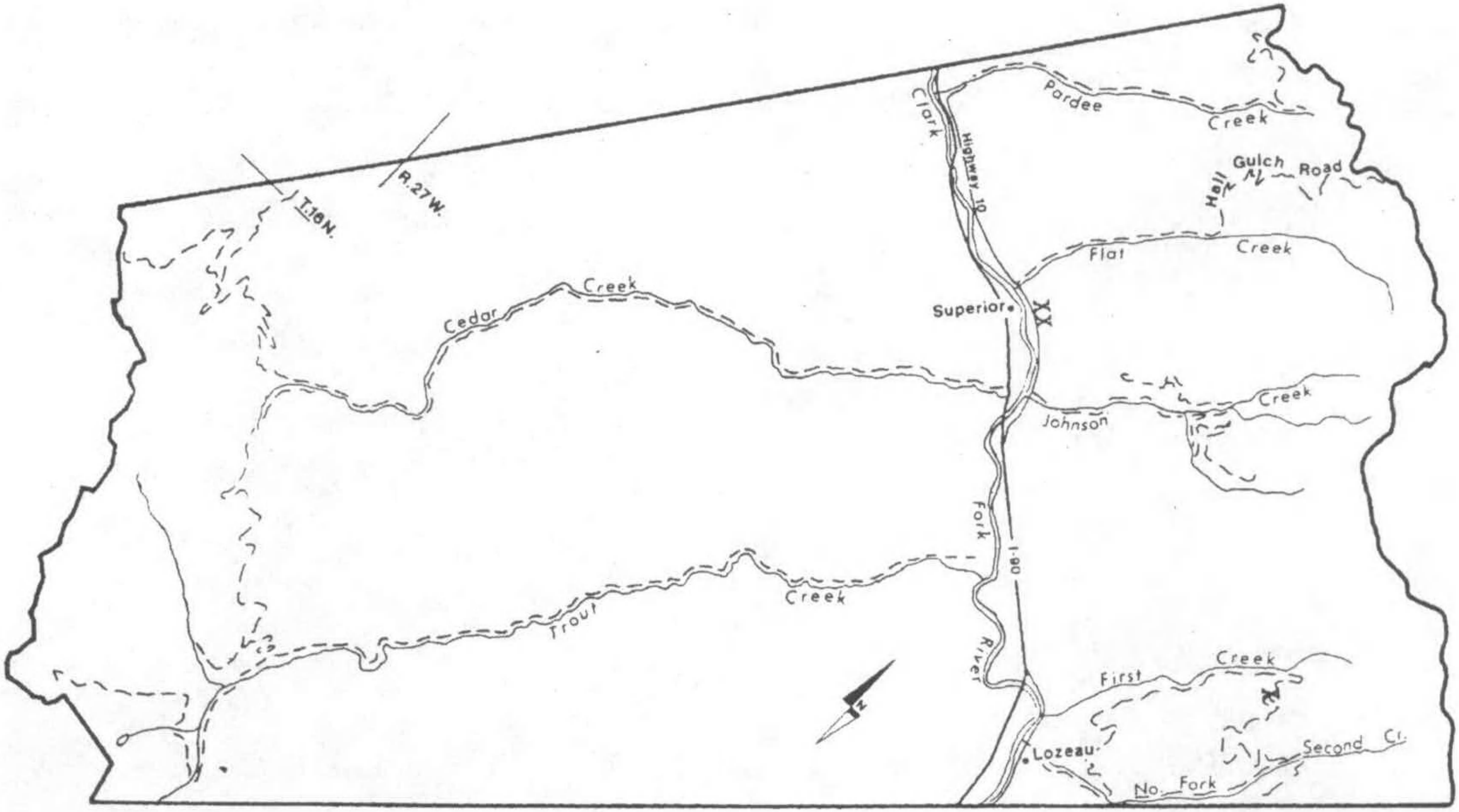


Fig. 14. Fan dikes located on this map by X were identified only in domain I north of the Boyd Mountain fault

maintain contact throughout the length of the dike. Thin sections of flow dikes rarely contain single quartz grains isolated in argillite. Flow dikes are more common than fan dikes and are particularly abundant in association with pull-apart structures (Chapter II) and known slump zones (see Fig. 3). They assume many shapes and sizes and were injected both up and down section. Their only consistent property is a tendency to thin with distance from the source sand. Flow dikes are generally sub-parallel to slaty cleavage (Table 4). Those dikes which are at a high angle to cleavage are folded and the axial surfaces of those folds are parallel to slaty cleavage (Plate 4).

Table 4. Angular difference between cleavage, flow dikes, and bedding in a thin section perpendicular to cleavage.

Pair	Dike $\angle$ Cleav.	Cleav. $\angle$ Bed.	Dike $\angle$ Bed.
1	14°	27°	41°
2	17°	25°	42°
3	28°	27°	55°
4	29°	19°	48°
5	6°	32°	38°
6	2°	9°	7°
7	5°	16°	21°
8	20°	8°	28°
Average	15°	20.4°	35°

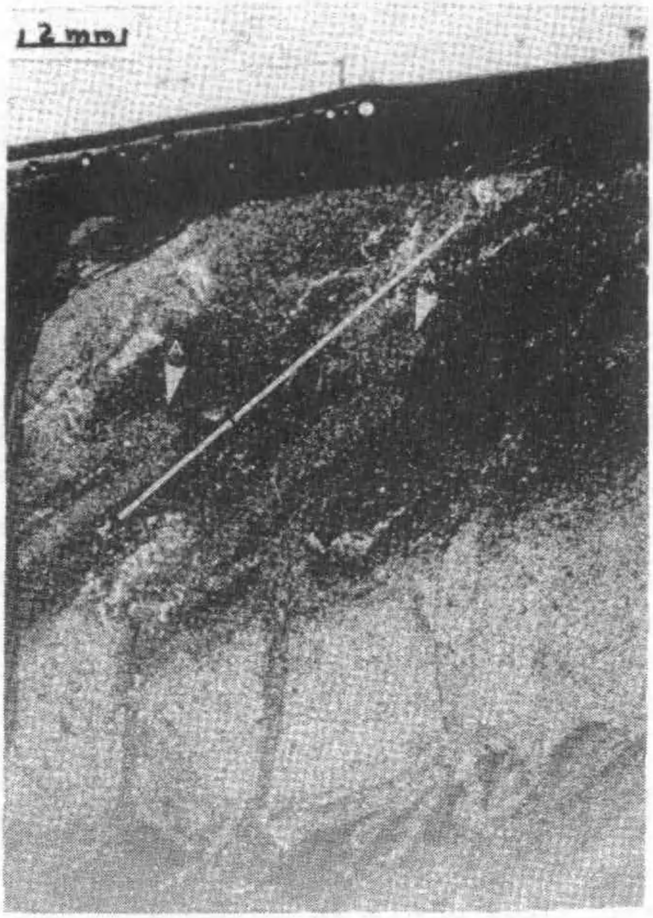


Plate 4. Folded flow dikes (A) appear to be geometrically related to cleavage S1. Argillite injection structures have breached the quartzite layer in at least two places.

Argillite injection structures (Clark, 1970), the fourth common soft sediment feature of the study area, sometimes occur in conjunction with fan dikes. Injection structures are three dimensional, wedge shaped bodies (Plate 5) that thin up-section and pinch out within or breach overlying quartzite beds. Occasionally an argillite injection structure on one side of a quartzite unit will be matched by a corresponding fan dike

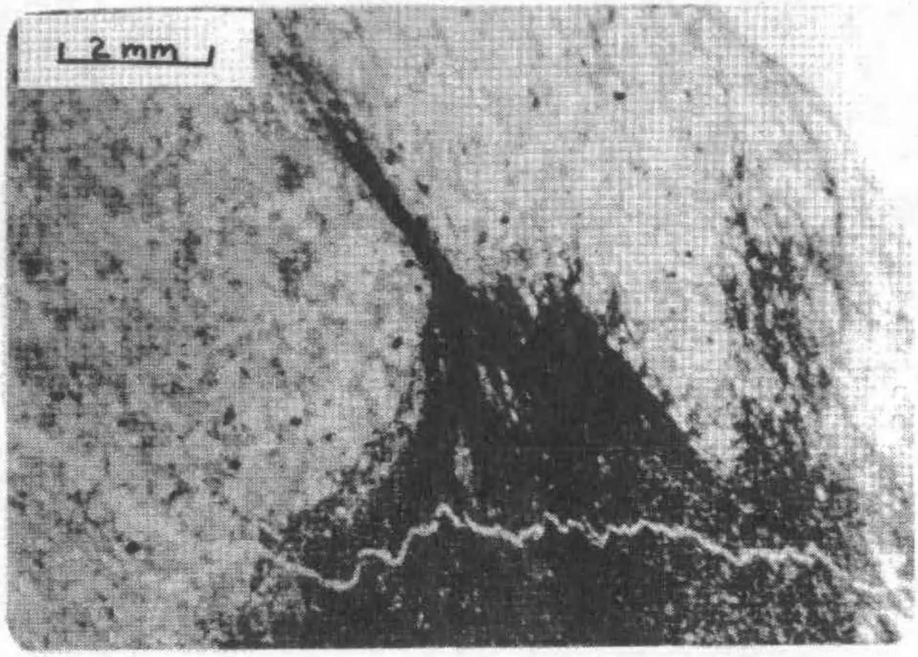


Plate 5. Well defined slaty cleavage in wedge shaped argillite injection structure. The thin, white, wiggly line in the lower portion of the plate is a folded quartz-filled fracture. Slaty cleavage, axial surfaces of the folded fracture, and the long dimension of the argillite injection are all nearly parallel.

on the opposite side. Injection structures are consistently elongate parallel to cleavage surfaces. Furthermore, they are common at the hinges of folds suggesting that they were injected at the same time the folds developed. Cleavage is better developed and more sharply defined in argillite injection structures than it is in argillite between structures. The disruption, or sometimes bisection, of the quartzite beds into which the argillite was injected suggests that the quartzites were sufficiently unconsolidated at the time of intrusion and were reshaped by the argillite. Argillite injection structures were found in the northern domain most often in association with other pre-lithification features, in slumped units, and rarely, in the absence of any other soft sediment features.

Pre-lithification structures described thus far are conspicuously absent from the more carbonate-rich layers of the Wallace Formation. With the exception of some flow dikes, these features are restricted to rather pure argillite-quartzite interfaces. The pre-lithification structures occur only in cleaved domains. None were found in the underformed domain. Fan dikes occur only in domain I while argillite injection structures and flow dikes occur in domain I and domain III as well. None of the pre-lithification features just discussed are widespead in any cleaved domain; however, they are absent altogether in domain II where cleavage is absent.

Dynamothermal Features

Most of the features relevant to the problem of cleavage genesis are clearly post-lithification structures. Brittle fractures have been replaced by quartz veinlets in cleaved domain I and IV. These veinlets are planar structures generally only one grain thick (approximately 20 microns). In thin section these quartz veinlets appear as straight lines in quartzite but are folded and sheared in argillite (Plate 6).

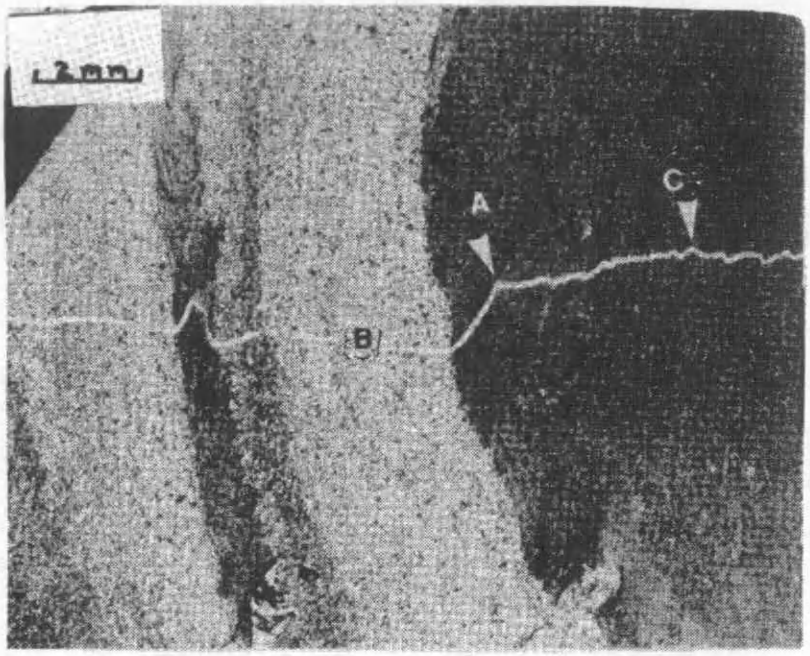


Plate 6. The quartz veinlet in this photomicrograph has been shortened in argillite (interval A to C) and remains relatively undeformed in the quartzite B.

Deformed veinlets are folded such that the axial surfaces of the folds parallel slaty cleavage. One such veinlet taken from the roadcut just east of Superior, cuts an argillite injection structure (Plate 5). Axial surfaces of the folded fracture (veinlet), a post-lithification structure, parallels the injection direction of an argillite injection structure, a pre-lithification structure.

Individual cleavage planes owe their quality to the degree of preferred orientation of the constituent platy minerals (Wilson, 1960). The angular distance between the basal cleavage of muscovite and slaty cleavage was measured on one hundred grains in thin sections of a well cleaved argillite, and a moderately cleaved siltite, both from domain I. Histograms of the occurrence of muscovite slaty cleavage angles (Fig. 15a,b), show that while muscovite in argillite is slightly better aligned with cleavage than muscovite in siltite, the difference is slight. This indicates that the abundance of slaty minerals may be as important as the degree of preferred orientation.

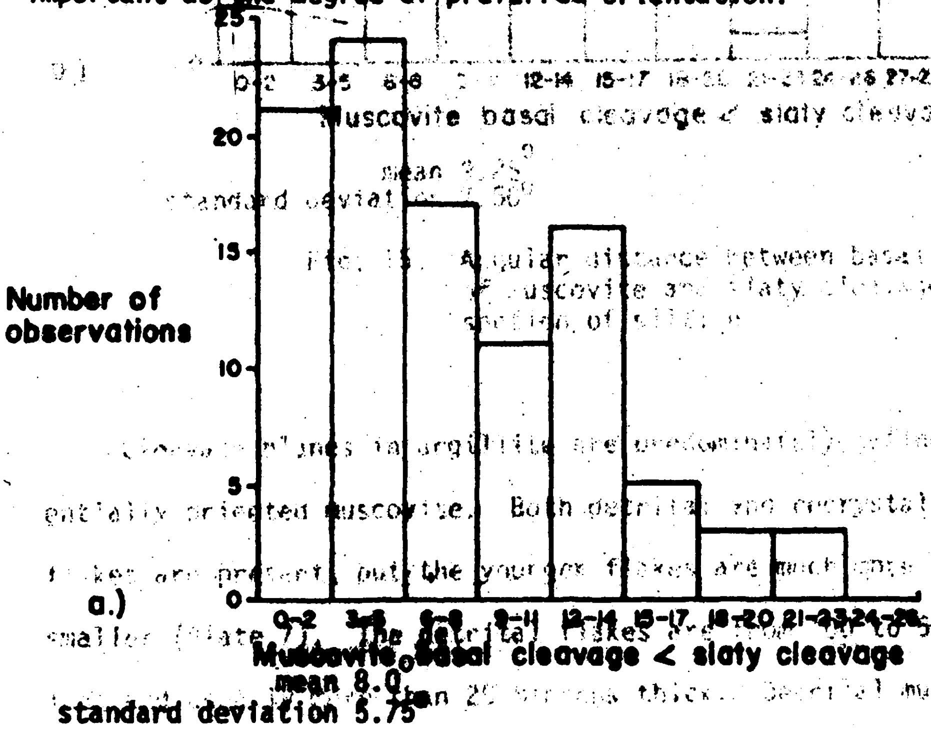
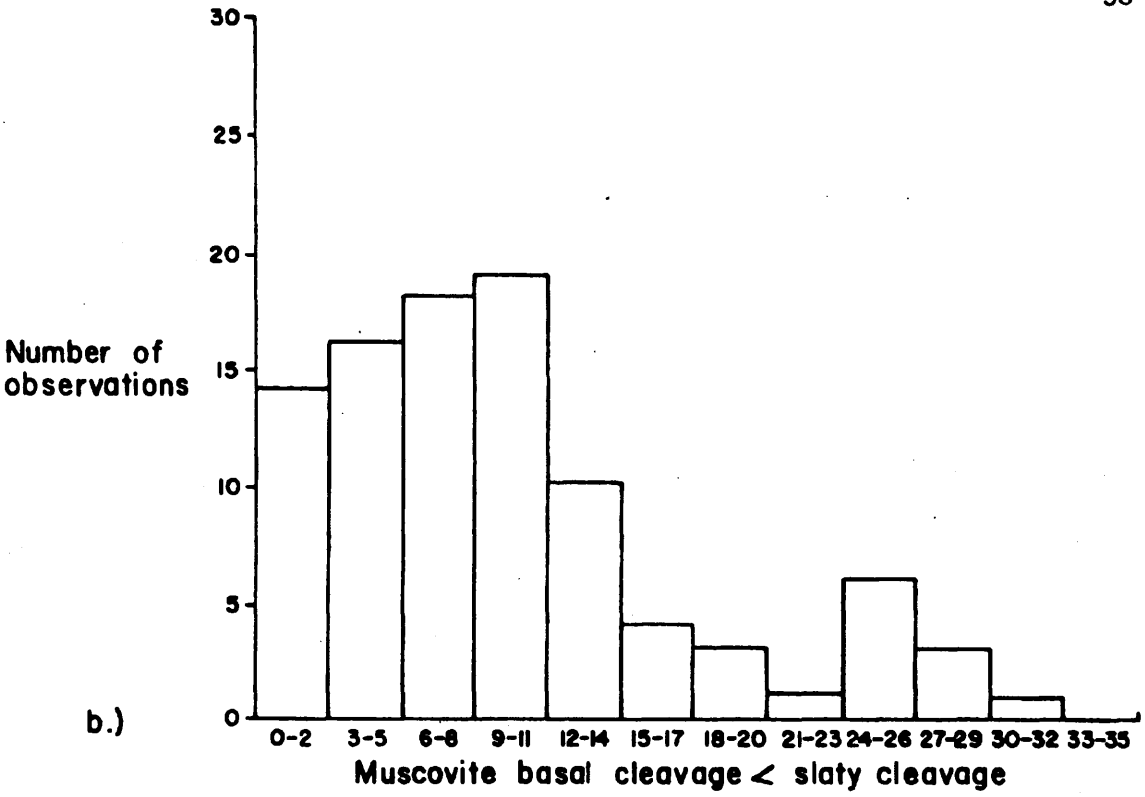


Fig. 15. Angular distance between basal cleavage of muscovite and slaty cleavage in a thin section of argillite.



mean 9.25°
standard deviation 7.50°

Fig. 15. Angular distance between basal cleavage of muscovite and slaty cleavage in a thin section of siltite.

Cleavage planes in argillite are predominately defined by preferentially oriented muscovite. Both detrital and recrystallized muscovite flakes are present, but the younger flakes are much more abundant and smaller (Plate 7). The detrital flakes are from 100 to 500 microns long and usually more than 20 microns thick. Detrital muscovite is commonly less well oriented than secondary muscovite, but, may be preferentially elongate sub-parallel to bedding thus having no bearing

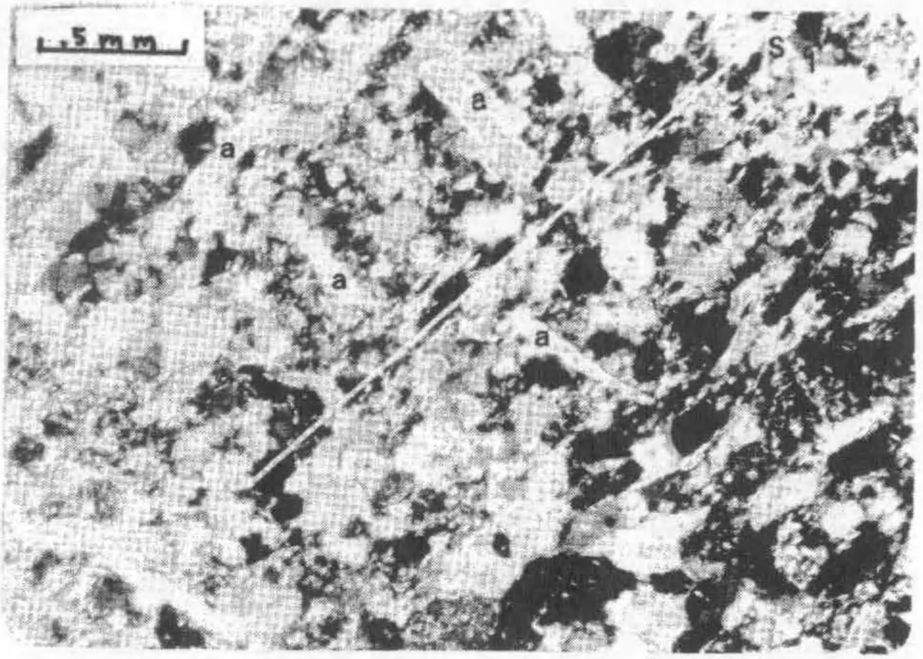


Plate 7. Photomicrograph of muscovite (light tone) in argillite: Large detrital grains (a) are here perpendicular to the imposed fabric S_1 defined by small secondary muscovite grains.

on cleavage quality. Detrital flakes have a greater tendency to be bent or broken than do secondary flakes. Secondary flakes are generally less than 50 microns long and range down to submicroscopic size. In most argillites, secondary muscovite is undeformed and has a strong dimensional elongation parallel to cleavage. Secondary muscovite is widely distributed in both domain I and domain IV.

Exceptionally large needle shaped chlorite crystals have grown parallel to cleavage in pressure shadows of what is thought to be diagnetic pyrite cubes (D. Winston, personal comm.). The chlorite blades grow parallel to cleavage from pyrite faces. The crystals may be up to 600 microns long and 200 microns thick exceeding the size of nearby grains ten fold. The large chlorite blades were observed only in domain IV of Cedar Creek.

The number of cleavage partings per unit thickness in a given terrane, is directly proportional to the percentage of clay minerals present (Wilson, 1961). Thin sections of cleaved rocks in the Superior area reveal that cleavage is poorly defined in light quartz-rich areas and intense in the darker argillites. Individual quartz grains in uncleaved quartzite tend to be equidimensional while those in the more argillaceous units are elongate parallel to cleavage. Quartz grains which are actually in contact with cleavage surfaces have been truncated where they contact the cleavage planes (Plate 8). Groshong (1976) interpreted this phenomenon to pressure solution. The best examples of quartz truncations occurred in the domain I, poorer subplanar examples were found in domain IV.

Cataclastic Features

Two cleavage directions can often be discerned in domain I, particularly in or near fault zones. One cleavage is the regional slaty cleavage which trends northwest, and has a very steep dip. The second cleavage is defined by the hinges of sharply plicated or sygmoidal mica

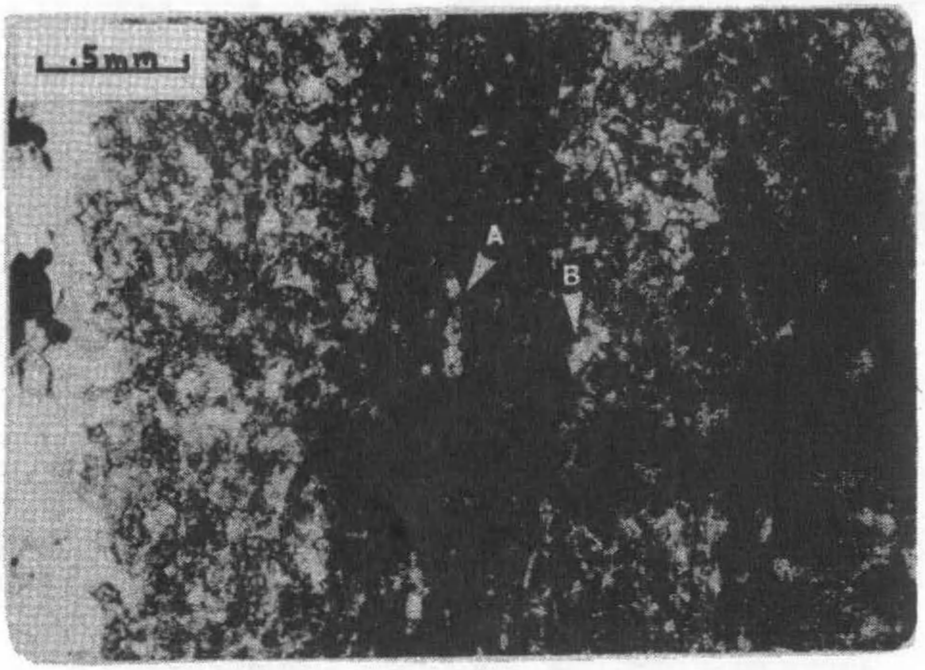


Plate 8. (A) Doubly truncated quartz grain in argillite.
(B) Dimensionally equant quartz grains in quartzite.

grains (Plate 9) which compose the regional slaty cleavage. The second cleavage, a crenulation cleavage is planar and penetrative over short distances (generally less than 10 meters). Individual planes are usually spaced from 500 microns to two or three millimeters. Crenulation cleavages are transcurrent to fold axial surfaces (Plate 10) and occur only at high angles to slaty cleavage.

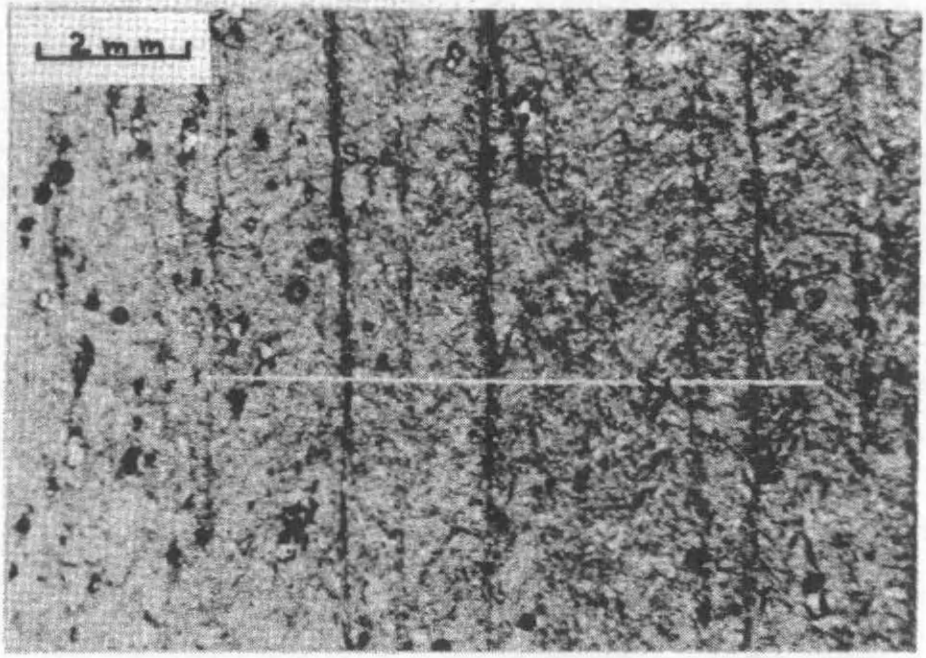


Plate 9. Crenulation cleavage (S2) has deformed slaty cleavage (S1). The average S1 direction is indicated by the white line.

Crenulation cleavage attitudes were difficult to measure due to its imperfect development. However, the crenulations appeared to be near vertical planes which trend between N5°E and N40°E.

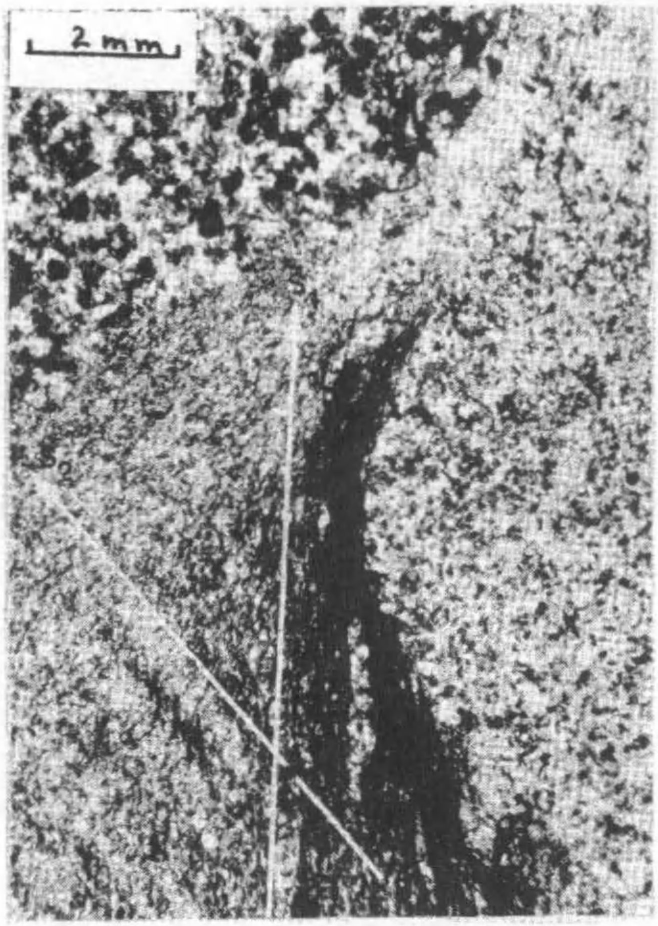


Plate 10. Crenulation cleavage S2 is transcurrent to S1 and the long dimension of an argillite injection structure.

Summary

Microscopic examination of the Wallace Formation presents what would appear to be conflicting evidence regarding the origin of cleavage in the Superior area.

The presence of fan dikes and argillite injection structures parallel to cleavage and flow dikes sub-parallel to cleavage argue that they must have formed synchronously with cleavage. Isolated grains associated with fan dikes and the fact that both fan dikes and argillite injection structures breach quartzite units indicate that both structures must have preceded lithification.

Post-lithification processes which appear related to cleavage are widely distributed. Folded quartz-filled fractures, secondary muscovite and large secondary chlorite grains are oriented parallel to cleavage suggesting a genetic relationship with cleavage. Flattened flow dikes sometimes imply a post-lithification date also, as they frequently appear to have rotated into near parallelism with cleavage (e.g. Plate 4). Truncated quartz grains have been subjected to pressure solution along cleavage planes.

An event, or events, which followed the formation of slaty cleavage has crenulated regional slaty cleavage in some parts of domain I.

CHAPTER IV

CLEAVAGE FORMING PROCESSES AND EVENTS

Cleavage Forming Processes

The origin of slaty cleavage is an argument which is over a century old. A tendency in the past has been to attribute slaty cleavage to a single process, either recrystallization (Leith, 1905, 1923; Harker, 1932; Kamb, 1959; Woods, 1974), or some mechanical process: flattening (Sorby, 1853; Van Hise, 1896; Ramsey, 1967; Deiterich, 1969), shearing (Becker, 1893; Turner, 1948; Sander, 1930), or more recently, dewatering (Maxwell, 1962; Moensch, 1966, 1970; Braddock, 1970; Clark, 1970; Powell, 1972, 1976; and Alterman, 1973, 1976). A study of these many excellent papers leads to the inevitable conclusion that all of these processes are effective, and that the predominance of a given process is a function of the unique terrane under study.

Processes which have affected slaty cleavage in the Superior area are mechanical and chemical, pre-lithification and post-lithification.

Domain III provides clear evidence that some slaty cleavage formed prior to lithification in the Superior area. Domain III, the slump domain, is surrounded by the relatively undeformed domain II. Accordingly, the only deformational period that slaty cleavage could develop was during slumping. The dewatering process seems to be the best explanation for the origin of cleavage in slump zones as it is hard to imagine that any other processes were active during slumping. The abundance of flow dikes and argillite injection structures found in the slump domain lend support to a dewatering mode of cleavage genesis.

Domain III which involved only the top 100 meters of sediment in slumping is very different from the vastly larger terranes to which the dewatering hypothesis has previously been applied. Dewatering of the Martinsburg Formation of Pennsylvania and New Jersey, for example, is thought to have occurred over 90 square kilometers and at depths in excess of 2100 meters (Alterman, 1973). These terranes are thought to have dewatered under extreme pressure from the sedimentary pile as well as a directed tectonic stress (Maxwell, 1962). The result of dewatering the Martinsburg Formation is thought to be a well developed regionally penetrative slaty cleavage like those in domains I and IV of this study.

No portions of domain IV and a very limited portion of domain I contain evidence that would suggest that slaty cleavage formed through the process of dewatering. Soft sediment fan dikes which occur along U.S. 10 and in First Creek are always parallel to slaty cleavage and as such, do suggest dewatering. The improbable strain history necessary to produce parallelism between the two initially nonparallel structures is supportive evidence that slaty cleavage formed during dike injection. If fan dikes and slaty cleavage were not related, then cleavage in these areas should transect the dikes at all angles. According to Alterman (1973), a fan shaped dike and the isolation of quartz grains in it demonstrates a lack of consolidation in the deforming units and a high pore fluid pressure at the time the dike formed. The fan shape is thought to result from forced injection due to high pore fluid pressure and the rapid collapse of dewatering paths in the reservoir in the direction of maximum compressive stress. Groshong (1976) argues that isolated grains in sedimentary dikes are the product of remobilized consolidated rocks under stress or metamorphic conditions; however, isolated grains require cohesionless sand. Remobilized rock is cohesive (Alterman, 1976). Fan dikes then would not have formed under other than pre-lithification conditions.

Argillite injection structures are the only other structure in the study area which indicate that dewatering has occurred at depth. Clark (1970) maintains that argillite injection structures in the Wallace Formation of the Coeur d'Alene mining district are a dewatering phenomenon, and that localized areas of strong slaty cleavage in the structures are the product of greatest fluid motion. The fact that injection structures are nearly parallel to slaty cleavage in the Superior area and penetrate or breach quartzite units suggests contemporaneity between the structures and cleavage and a pre-lithification origin for both. Although argillite injection structures were found in all the domains except II, they, like fan dikes, are not common.

Areas discussed in this report in which cleavage appears to be related to dewatering at depth must include only areas of fan dike occurrence. The isolation of grains and the fan shape of the dikes indicates that, unlike argillite injection structures which are common in the shallow slump domain III, fan dikes were injected under pressure at depth. Fan dikes were found only in isolated outcrops in First Creek and on U.S. Highway 10 just east of Superior. It is not entirely clear how far these zones extend, as fan dikes are small and hard to identify in the field.

The nature of the deformation which produced fan dikes has not been determined in this report. Their limited distribution suggests a limited deformation such as a slump zone. However, this is speculative as no evidence of slumping was found in conjunction with fan dikes except a few pull-apart structures in First Creek drainage. If the structures did form during a period of slumping, the isolation of grains and fan shape suggests they occurred in a more deeply buried slump zone like the ones described by Moore and Geigle (1974) in the Aleutian Trench, and the Gulf of Mexico, in contrast to the shallow slump zone described in domain III of this report.

An explanation for the coincidence of fan dikes and slaty cleavage is evident in a thin section from rocks along Highway 10 east of Superior. In this particular thin section (see Plate 5), an argillite injection structure has been cut diagonally by a quartz veinlet (Chapter II). The quartz veinlet (post-lithification) has been folded such that the axial surfaces of folds parallel the long axis of an argillite injection structure (per-lithification), and cleavage. It would appear that both pre- and post-lithification strains followed identical paths, or paths similar enough so that argillite injection structures and any pre-lithification cleavage which might have been present, rotated into parallelism with regional slaty cleavage without folding or crenulating respectively. This interpretation is favored because flow dikes that form large angles with cleavage are usually folded while those which are nearly parallel to cleavage like fan dikes are always straight. Because regional slaty cleavage post-dates fan dike development, the fan dikes should be folded by subsequent events if strain paths were substantially different from the path responsible for the primary injection of the dike. Since the dikes are not folded one can assume the two strain paths were similar.

Regional slaty cleavage in the Superior area is predominantly a post-lithification product. Several processes have affected slaty cleavage including flattening, intragranular slip, and dissolution and recrystallization. The dominant cleavage forming process has been that of flattening during folding. Fold axial surfaces in domains I and IV parallel slaty cleavage. Occasionally cleavage exhibits divergent fanning within a fold. Clark (1970) demonstrated experimentally that divergent fanning formed perpendicular to the direction of maximum shortening or parallel to the plane of flattening. Many pre-cleavage structures can be seen to have flattened in the plane of the cleavage both in domain I and IV. Quartz veinlets have been flattened during folding in both cleaved domains. The folds are oriented with axial surfaces parallel to cleavage. Flow dikes in domain I can be seen to converge with slaty cleavage through flattening. Similarly oversteepened ripple marks and molar tooth structures have been flattened into the plane of cleavage in domain IV.

Quartz veinlets have been flexed in such a manner as to suggest that quartzites have been transposed on argillite toward the anticlinal hinge of similar folds. Cohesion between the quartzite and argillite and the relative competence of the quartzite probably caused some motion in the argillite by flexural-slip. This relation seems to hold near quartzite/argillite interfaces but soon gives way to flexural flow in thick argillites not capable of transmitting shear stress. Simple shear then appears to be functional in zones of high ductility contrast but gives way to flexural flow in thicker units.

Small recrystallized muscovite grains are abundant in all four domains. The flakes are subparallel to slaty cleavage in the cleaved domains I, III, IV and define a poor mimetic bedding plane cleavage in domain II. The presence of the grains in the relatively undeformed domain indicates that at least some of the grains were not a part of dynamic deformation. Secondary muscovite grains are probably a product of burial metamorphism and serve only to enhance slaty cleavage quality by occupying some preexisting anisotropy in the intergranular framework.

The second chemical process under consideration is that of growth perpendicular to maximum compressive stress. Evidence that recrystallization occurred in this manner is not widely distributed in the Superior area; however, large chlorite crystals in the cleaved southern domain growing in pressure shadows of hematite crystals have benefited from a directed stress. The chlorite grains are in the shadows parallel to slaty cleavage. Quartz grains isolated in argillite tend to be truncated wherever they contact a cleavage surface. Some of the truncated grains show indistinct quartz overgrowths in their own pressure shadows. Quartz grains in nearby quartzites tend to be equant indicating that the elongate grains have been subjected to pressure solution and recrystallization. These two examples of recrystallization are never penetrative and as such it is doubtful that the effect on regional slaty cleavage is great. Truncated grains in particular, appear to occur only in discrete zones (perhaps of intense strain) of argillite.

The final process which has affected cleavage in the Superior area is intragranular slip. Two cleavage directions can often be discerned in or near fault zones in domain I. The second cleavage is defined by the hinges of sharply plicated or sygmoidal mica grains which compose slaty cleavage. The plicated grains are thought to result from slip along the basal plane of a flexed mica (Turner and Weiss, 1963). The second cleavage is a crenulation cleavage and establishes that motion has occurred along some of the elements of the Montana lineament since the imposition of regional slaty cleavage.

Possible Relationships between Cleavage and Tectonics

The tectonics responsible for the various slaty cleavages seen in the study area is very much a speculative matter given the data available at this time.

It was determined during this study that the processes of dewatering are limited in areal extent and cannot, therefore, account for regional slaty cleavage. Likewise regional metamorphism alone cannot account for the macroscopic folds and flattening processes that appear to be intrinsically related to slaty cleavage. More likely, regional metamorphism accompanied or followed activity along elements capable of producing regional slaty cleavage in the Superior area, the Montana Lineament and/or the Idaho batholith.

A cursory examination of the cleavage distribution in the study area indicates that neither the Montana Lineament or the Idaho batholith alone can explain the dominal distribution of slaty cleavage. The normal fault which separates domains II and IV must be taken into account as must vertical and/or lateral motion along the Boyd Mountain fault.

The Boyd Mountain fault is the principal element of the Montana Lineament in the Superior area. Campbell (1960) mapped a right lateral offset of 21 km on it, and it is to this fault that any major lineament related stress patterns in the Superior area must be attributed. The fold axial surfaces and secondary faults in the Superior area are completely contrary to the attitudes predicted by Moody and Hill (1956) for second order folds produced by a right lateral strike-slip fault. Several other difficulties also exist regarding a lineament-induced origin for slaty cleavage. First, the quality of cleavage does not increase with proximity to the fault as would be expected if the fault were the source of cleavage formation (Wallace and Hosterman, 1956). Second, it is difficult to account for the difference in slaty cleavage development between domains II and IV both of which are south of the Boyd Mountain fault.

The alternative which best fits the evidence found during this study is that gravity glide and related thrusting off the Idaho batholith extended across the study area and subsequent normal faulting has juxtaposed sections deformed at different depths within the thrust sheet.

Middle and late Cretaceous gravity glide and thrusting off the Idaho batholith has been documented for 180 kilometers around the northeast corner of the batholith (Flood, 1974; Karrison et al., 1974; Hyndman et al., 1975; Wiswall, 1976). Although thrusting has not been proven in the Superior area, it has been suggested by Hyndman and Talbot (1973). Talbot (personal comm., 1974) contended that a thrust sheet extends across the entire study area and halfway across the Ninemile Valley to the north. Twelve kilometers northwest of the town of Superior, Harrison et al. (1974) have mapped a thrust sheet (Fig. 16) which overrides the Ninemile Fault (the principal element of the Montana Lineament in the Ninemile Valley). Additionally, Harrison (1974) mapped several thrust sheets and northeast-trending tear faults within 5 kilometers of the southwest margin of the study area. Although no thrust sheets were observed during this study, the extended continuity of thrust sheets (180 km) and the proximity of the Idaho batholith (Fig. 16) indicates that thrusting away from the Idaho batholith over the study area is a reasonable hypothesis.

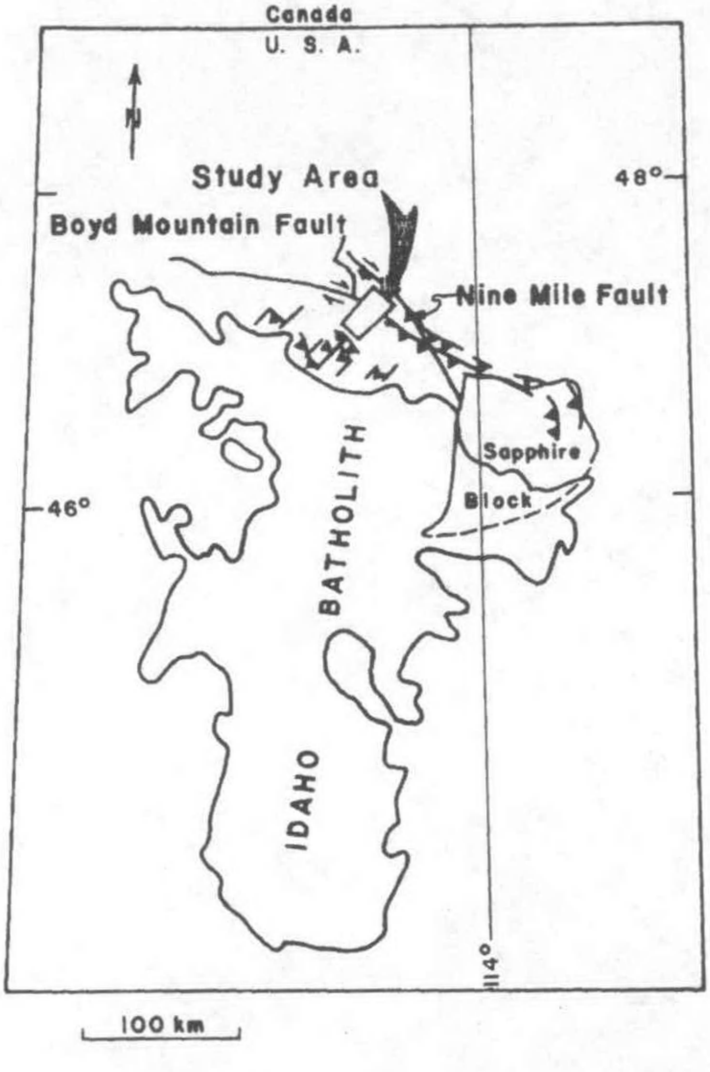


Fig. 16. Map showing the Boyd Mountain fault, the Ninemile fault, and the Idaho batholith and related thrusts known to exist on the northeast flanks of this pluton. (after Harrison et al., 1974, and Hyndman, et al., 1975)

This hypothesis is strengthened when the directions of translation of known thrust sheets south of the study area are compared to slaty cleavage attitudes in the study area. The average trend of eight tear faults (Harrison, 1974) just south of the Superior area is N44°E, nearly perpendicular to regional fold axes and slaty cleavage maxima in domains I and IV. A simple compression parallel to translation is easy to envision, however, work in other areas around the batholith indicate that vertical fold axial surfaces and slaty cleavage are somewhat atypical of thrusting off the Idaho batholith. Shear, drag and rootless folds, as well as horizontal and shallow dipping fold axial surfaces are more common near the batholith, particularly in or near the zone of décollement (Flood, 1974; Harrison et al., 1974; Hyndman, et al., 1975). Vertical fold axial surfaces and cleavage have been recognized, however, toward the toe of the Sapphire block in the Flint Creek range, and Kehle (1970) states that folds in the upper portion of a glide block may be concentric and upright. Only the latter interpretation is consistent with the data obtained during this report. Folds of all scales in the Superior area have concentric elements, the axial surfaces are consistently near vertical and have developed through the processes of flattening rather than bedding transposition.

Certain structural parameters indicate that the regional slaty cleavages of domains I and IV may have formed at the same time. The average attitudes of the cleavage in domain I is N43W 74° SW while in domain IV it is N45W 72° SW. Second, the cleavage-forming processes which have affected the two domains are also similar. In particular, flattened quartz veinlets and molar tooth structures, as well as oversteepened ripple marks in domain IV indicate the same type of deformational processes which flattened quartz veinlets and flow dikes in the domain I.

If the cleavages in domains I and IV are related, then somehow the intervening uncleaved units must be explained. The solution may be the faults which define the boundaries of both domains. Campbell (1960) established that the Boyd Mountain fault has a 3.3 kilometer component of dip slip with the northern block upthrown and a 21 kilometer component of right-lateral strike slip. Harrison (1974) mapped domain II as a down dropped with respect to domain IV. A common relation between the cleaved domains exists in that both have been upthrown relative to domain II. Crenulation cleavages imposed on slaty cleavage associated with fault zones as well as juxtaposed cleavage styles are strong evidence that faulting has occurred since the imposition of regional slaty cleavage.

Summary

Many processes are responsible for the formation of slaty cleavage in the Superior area, with the dominant process being flattening during folding. Thrusting away from the Idaho batholith over the Superior area appears to be the most likely cause of the folding. The juxtaposition of cleaved and uncleaved domains is almost certainly a product of the faults which form the boundaries of the cleaved domains.

CHAPTER V

SUMMARY AND CONCLUSIONS

Structures in the Superior area define four domains: a slump domain (III), a cleaved domain (IV), and a relatively undeformed domain (II) south of the Boyd Mountain fault, and a cleaved domain (I) north of it.

Deformation in the slump domain (III) occurred prior to any substantial lithification or burial. The presence of non-penetrative, incipient slaty cleavage in these slumped units indicates that cleavage-forming processes can be effective shortly after deposition.

Regional slaty cleavage in domain I and IV is the product of post-lithification processes. Evidence that cleavage formed during a pressurized dewatering event is extremely limited in areal extent. Even where such evidence exists, post-lithification processes are superimposed on the dewatering fabric.

Post-lithification cleavage forming processes recognized during this study include flattening during folding, intracrystalline glide, and dissolution and recrystallization. Of these processes, only flattening during folding is ubiquitous in cleaved outcrops.

The lengthy continuity (180 kilometers) of thrusting away from the Idaho batholith southeast, east, and northeast of the study area, and the consistent tear fault attitudes to the south which are perpendicular to an axial plane cleavage, suggests thrusting may also have occurred in the Superior area. Although the vertical axial surfaces and cleavage of the Superior area are not typical of thrusted areas nearby, these differences may simply be functions of depth during deformation.

Slaty cleavage in domains I and IV appears to have a common origin. Structural attitudes and cleavage-forming processes in the two domains are nearly identical. Both cleaved domains occur on the upthrown side of faults which are thought to have large components of dip slip. In addition, the southern boundary of domain I (the Boyd Mountain fault) has a large component of right lateral strike-slip. It is possible that the cleaved domains were deformed by the same thrust sheet and that the intervening undeformed domain was downdropped from a zone of less strain and/or that the large strike slip component along the Boyd Mountain fault has separated the correlating domains.

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