A STRUCTURAL ANALYSIS OF PROTEROZOIC METASEDIMENTS NORTHERN FALLS RIVER, BARAGA COUNTY, MICHIGAN

Thesis for the Degree of M. S.

MICHIGAN TECHNOLOGICAL UNIVERSITY

KEVIN M. SIKKILA

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By

Kevin M. Sikkila

A THESIS

Submitted in partial fulfillment of the requirements

for the degree of

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This thesis, "A structural analysis of Proterozoic meta-sediments, northern Falls River, Baraga County, Michigan", is hereby approved in partial fulfillment (15 credits) of the requirements for the degree of MASTER OF SCIENCE IN GEOLOGY.

DEPARTMENT: Geology and Geological Engineering

William J Gregg
Thesis Advisor

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Head of Department

29 May 1987
Date

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ACKNOWLEDGEMENTS

Word for word, line for line, this little chunk of text was probably the most difficult to write. Residence in one particular place for a number of years greater than "several" results in an accordingly large number of people who, in one way or another, have exerted some form of influence on you. With the passage of time, the mind tends to assimilate the effect and forget the cause. Good friends of a few years hence become vague speculations at two in the morning. However, some constants persist, and I will address my attention to these.

First of all, I wish to thank my advisor, Dr. William Gregg, for his assistance and tolerance throughout the field investigation and the composition of the text. I would also like to thank the other members of my committee, Dr. T.J. Bornhorst, Dr. S.C. Nordeng and Dr. A.M. Johnson.

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The thesis is the largest academic hurdle that the average masters student contends with; a fact that, in

itself, should be sufficient in making the completion of a thesis an ambitious undertaking. One should not become too preoccupied with the search for some form of external justification regarding one's own particular piece of research. To do so is to plunge giddily into a future of long nights spent in gloomy contemplation of the transitory nature of man and his works. This, needless to say, is counterproductive, and not a lot of fun. One proven way of avoiding this dreary pitfall is to surround yourself with individuals who are capable of dealing with you as you are without too much difficulty, while at the same time nurturing your own ability to keep everything in its proper sense of perspective. So in addition to the official assistance offered by those mentioned above, I would like to take the time to salute the somewhat diverse crew listed below for their effects on the environment in which this manuscript was created, to say nothing of the length of time that was needed to create it:

To John Carlson, for handguns, ice fishing ("the sport of kings") and the finer aspects of suburban fascism.

To Arthur Schneider and obnoxiousness as an art form.

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ABSTRACT

The Baraga Basin is a crescentic regional structural feature trending east-west across northern Baraga County in the Upper Peninsula of Michigan. It contains deformed and metamorphosed sediments of the Lower Proterozoic Michigamme Formation, and is bounded by Archean rocks of the Northern Complex to the south and northeast. Field investigations in the Basin have been largely confined to northward-flowing streams that contain sufficient exposure for detailed mapping. In this study, the westernmost of these streams, the Falls River, was mapped from its mouth in the village of L'Anse to a point one mile upstream to the south.

The slates and metagreywackes of the Falls River are characterized by three roughly coaxial systems of folds. Style group B_1 consists of a series of tight to isoclinal overturned folds with axes that plunge shallowly to the west-northwest and east-southeast, and axial surfaces that dip southward. The overall vergence of the B_1 system suggests that the field area is located on the long limb of a B_1 regional fold. The axial-planar foliation associated with this style group (S_1) typically dips to the southwest. Microscopically, S_1 varies in appearance from a well-developed continuous slaty cleavage in pelites to an irregular domainal rough cleavage in the greywackes. In nearly all cases, chlorite defines the cleavage fabric. A system of S_1-parallel thrusts is also associated with this

style group.

In the northern part of the Falls River, style group B_2 occurs as a series of gentle folds and asymmetric flexures in S_1 cleavage and S_1-parallel faults. B_2 fold profiles in the southern part of the field area are typically tight. B_2 axial surfaces are vertical to southward-dipping. Fold axes are horizontal and trend roughly east-west. S_2 crenulation cleavage is developed near B_2 hinges. Cleavage microstructures vary in morphology from zonal to discrete and are more strongly developed to the south.

B_3 deformation is characterized by macroscopic folds which overprint B_2 style group elements in the south portion of the field area. In this region, originally east-west striking, nearly vertical S_2 crenulation cleavage planes have been rotated more than 70 degrees along a roughly east-northeast trending horizontal axis. A steeply dipping S_3 cleavage appears as a series of fractures and irregular seams of dark residual material that overprints S_2. The latter cleavage has a strike coincidental with the rotational axis of the earlier S_2 fabric.

The development of large-scale nappe folds and allochthonous thrust sheets during the Penokean Orogeny has been proposed by several authors in recent years. Although it may not be the only mechanism capable of producing the structural features observed at this and other locations in the Baraga Basin, it is a tectonic model that is consistent with known field evidence.

INTRODUCTION

The Baraga Basin (Fig. 1) is a large crescentic structural depression, approximately seven miles in length, trending roughly east-west across northern Baraga County and northwestern Marquette County in Michigan's Upper Peninsula. The Basin, which contains deformed and metamorphosed sedimentary rocks of the Lower Proterozoic Baraga Group, is bounded to the south and northeast by the Archean-age rocks of the Northern Complex. Late Proterozoic Jacobsville Sandstone unconformably overlies the area to the northwest.

Description of structural features in the Baraga Basin has been the subject of M. S. theses by Van Roosendaal (1985) and Runge (in preparation). These field studies were situated in the eastern and central portions of the Basin, respectively. The work presented here concerns the styles of deformation present in this large regional feature at its western extremity. Approximately fifty-four hundred feet of the northernmost segment of the Falls River, located in sections 5, 8 and 9, T 50 N, R 33 W, Baraga County, Michigan (Fig. 2), was intensively mapped during the course of this investigation.

The main body of field work for this project was conducted between the months of July and November, 1985, with additional field work in July and August of 1986. 31 stations (0 through 30) were established at various intervals and a line surveyed in with a Suunto compass and a

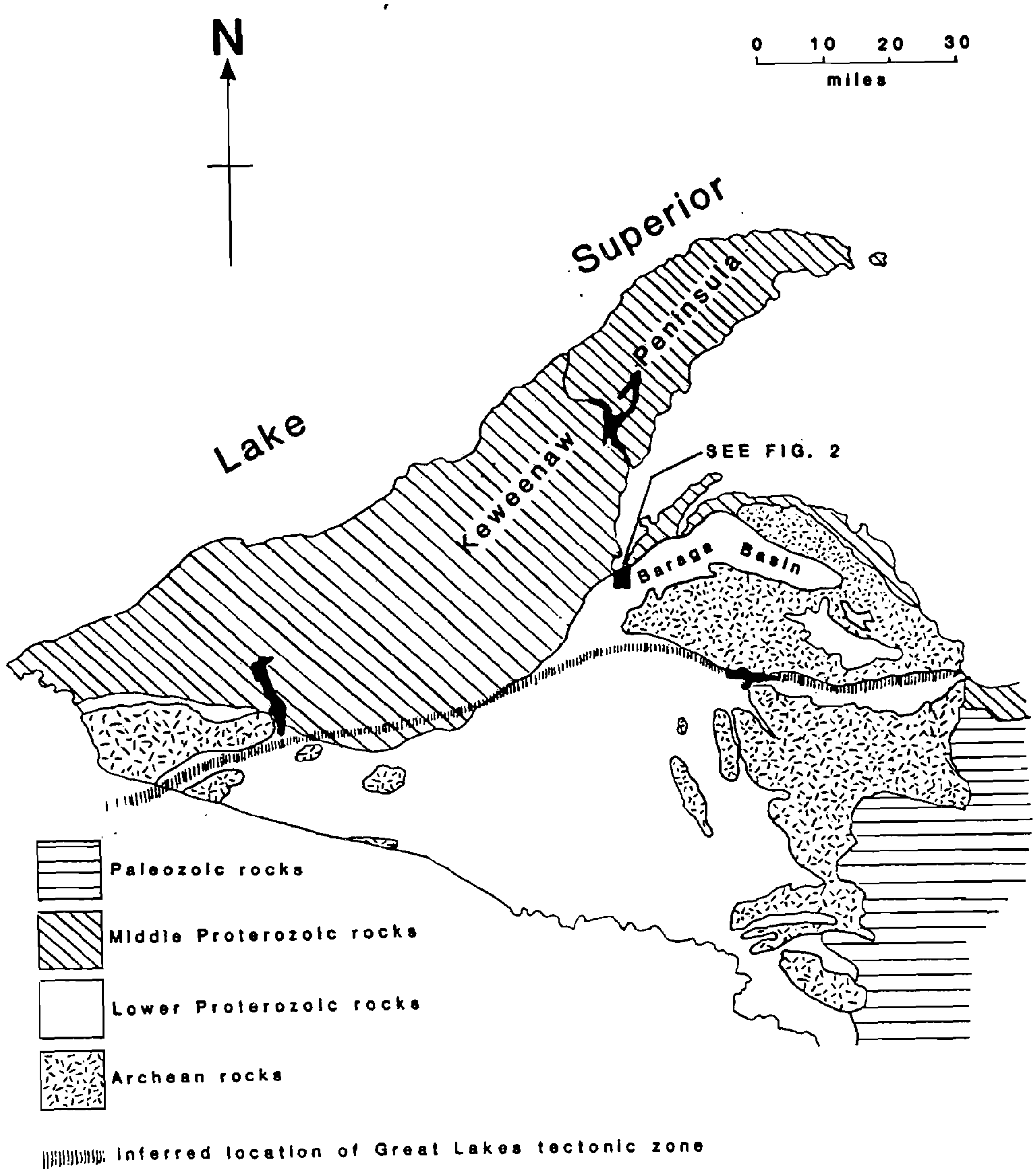

Figure 1. Generalized bedrock geologic map of the western Upper Peninsula of Michigan (modified from James, 1955 and Sims et. al., 1980).

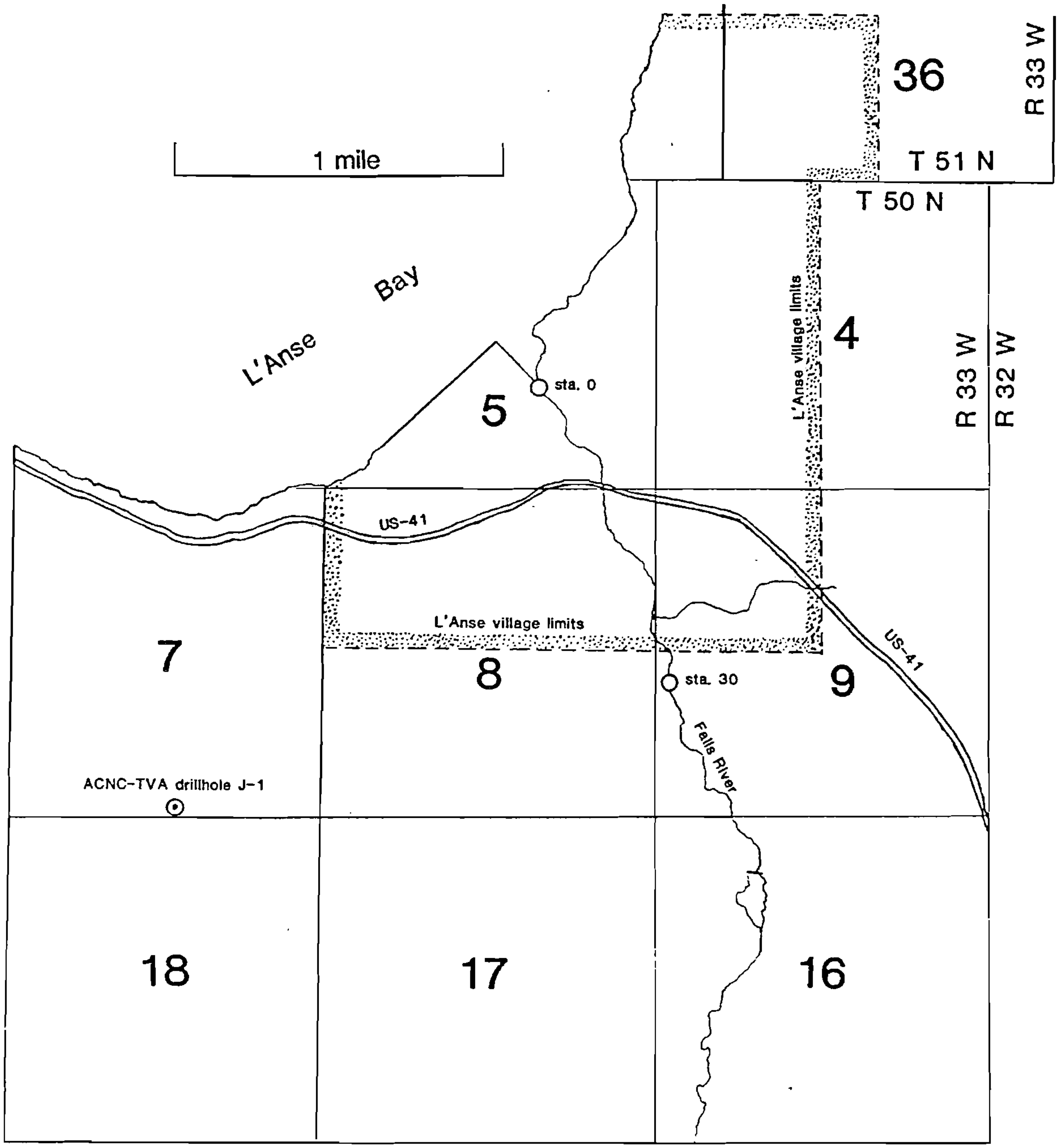

Figure 2. Location map of field area in Baraga County, showing source of drillhole data featured in report by Hoffman (1983).

fiber tape. A detailed map of outcrop outlines, lithology and structural features was then constructed at a scale of twenty feet to the inch. A Brunton pocket transit and a carpenter's level were used to obtain attitudes of the various fabric elements. Oriented hand samples were taken at strategic intervals for later study.

Laboratory work consisted of the microscopic study of thin sections for the purpose of petrographic identification, recognition of bedding surfaces (where bedding was mesoscopically obscure), and description of microstructural features. A lack of recognizable passive strain markers in the rocks of the field area prevented any attempts at quantitative deformational analysis.

REGIONAL GEOLOGY AND TECTONIC SETTING

Introduction

The age of the rocks in the western Upper Peninsula discontinuously span nearly the whole length of known Precambrian time. The slates and metagreywackes that were studied in the Falls River area are part of a large Lower Proterozoic sequence that lies unconformably over the crystalline Archean basement. Radiometric age dates place the interval of deposition between 2.1 and 1.9 billion years Before Present (b.y. B.P.). Deformation and metamorphism of this sequence took place during the Penokean Orogeny, a complex series of events that is believed to have begun during the final stages of Lower Proterozoic sedimentation, culminating between 1.8 to 1.7 b.y. B.P.

Stratigraphy

Problems regarding stratigraphic relationships within the Lower Proterozoic section south of Lake Superior have existed for many years, and were compounded by inconclusive attempts at regional correlation with series and groups of similar age in neighboring Ontario and Minnesota (Leith et. al., 1935; James, 1958; Faure and Kovach, 1969). In 1970, Cannon and Gair proposed the system of nomenclature that is in current use. The entire Lower Proterozoic sequence in the western Upper Peninsula and northernmost Wisconsin (composed largely of sedimentary rocks, with some volcanic and pyroclastic horizons) was placed under the single heading of "Marquette Range Supergroup". Fig. 3 presents this revised stratigraphic column.

As can be seen from Fig. 3, the Marquette Range Supergroup sequence exhibits a distinct amount of lateral variation among the various iron-producing districts south of Lake Superior. A more detailed stratigraphic sucession has been developed for the western Marquette Range (inclusive of the Falls River area) by Cannon and Klasner (1972) and is presented in Fig. 4.

Earlier studies concerned specifically with the Lower Proterozoic geology of northern Baraga County include those by Barrett (1927), Tyler and Twenhofel (1952), Spiroff (1964), Mancuso, Laugheed and Shaw (1975), Mancuso, Laugheed, Seavoy and Shaw (1975), and Burns (1975). It is generally conceded that the metasediments of the Baraga Basin lie within the Michigamme Formation of the Baraga Group. Outcrops at the eastern end of the Basin have been specifically assigned to the upper slate member of the Michigamme Formation on the basis of abundant drillhole data (Trow, 1979). The specific position of the deformed units in the Falls River area within the Michigamme Formation is indeterminate. Drillhole data in the vicinity (ACNC-TVA J-1, as shown in Fig. 2) displays only a monotonous sequence of slates and metagreywackes, failing to strike either the

			Marquette Range	Iron River-Crystal Falls District	Menominee Range	Gogebic Range
Upper Precambrian	Keweenawan		Intrusive diabase	Intrusive diabase	Intrusive diabase	Volcanic, intrusive, and sedimentary rock
Middle Precambrian	Marquette Range Supergroup	Paint River Group		Fortune Lakes Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron-Formation Dunn Creek Slate		
		Baraga Group	Michigamme Slate Bijiki Iron-Formation Member Clarksburg Volcanics Member Greenwood Iron-Formation Member Goodrich Quartzite	Badwater Greenstone Michigamme Slate Amasa Formation Hemlock Formation	Badwater Greenstone Michigamme Slate	
			LOCAL UNCONFORMITY OR DISCONFORMITY		UNCONFORMITY	UNCONFORMITY
		Menominee Group	Negaunee Iron-Formation Siamo Slate Ajibik Quartzite		Vulcan Iron-Formation Felch Formation	Ironwood Iron-Formation Palms Quartzite
			UNCONFORMITY OR DISCONFORMITY		UNCONFORMITY	UNCONFORMITY
		Chocolay Group	Wewe Slate Kona Dolomite Mesnard Quartzite Enchantment Lake Formation	Saunders Formation	Randville Dolomite Sturgeon Quartzite Fern Creek Formation	Bad River Dolomite Sunday Quartzite
			UNCONFORMITY	UNCONFORMITY(?)	UNCONFORMITY	UNCONFORMITY
Lower Precambrian			Gneiss Greenstone	Greenstone (stratigraphic position uncertain)	Gneiss	Gneiss Granite

Figure 3. Regional stratigraphy of western Upper Michigan (Cannon and Gair, 1970).

		SUPERGROUP, GROUP, FORMATION, AND (OR) MEMBER				DESCRIPTION
PRECAMBRIAN	Precambrian Y			Diabase		Nonmetamorphosed diabase dikes
PRECAMBRIAN	Precambrian X			Pegmatite		Coarse-grained-microcline-quartz-muscovite rocks. Relatively rare but most abundant near Republic.
PRECAMBRIAN	Precambrian X			Metadiabase		Amphibolitic rock, much with relict diabasic texture. Mostly as sills in Precambrian X rocks and dikes in Precambrian W rocks. Much is probably associated with rocks of the Clarksburg Volcanics Member of the Michigamme Formation.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation	Upper slate member	Metapelite and metagraywacke.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation	Bijiki Iron-Formation Member	Mostly cherty silicate iron-formation.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation	Lower slate member	Metapelite and metagraywacke with some pyritic carbonaceous slate.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation	Clarksburg Volcanics Member	Mafic pyroclastic rocks with intercalated meta-argillite and iron-formation.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Michigamme Formation	Greenwood Iron-Formation Member	Cherty silicate iron-formation.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Baraga Group	Goodrich Quartzite		Massive to banded protoquartzite with conglomerate near base.
				UNCONFORMITY		
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Menominee Group	Negaunee Iron-Formation		Mostly cherty silicate iron-formation with oxide iron-formation near top.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Menominee Group	Siamo Slate		Laminated metapelite.
PRECAMBRIAN	Precambrian X	Marquette Range Supergroup	Menominee Group	Ajibik Quartzite		Banded to massive, light-colored quartzite.
				UNCONFORMITY		
PRECAMBRIAN	Precambrian W			Gneiss of northern and southern complexes		Complex of granitic and mafic gneiss.

Figure 4. Stratigraphic column for the western Marquette Range, Michigan (Cannon and Klasner, 1972)

Bijiki iron formation member (the marker horizon separating the upper slate and lower slate members) or Archean basement. However, a stratigraphic position within the upper slate member may be inferred on the basis of lithologic similarity.

Structures

Two major orders of Penokean-age regional structures, as defined by Cannon (1973), are identified in the western Upper Peninsula (Fig. 5). "First-order" structures are narrow troughs, broad depressions, and uplifted areas of considerable lateral extent, typified by the Marquette and Republic Troughs, the Baraga and Dead River Basins, the Archean gneissic domes of the Southern Complex, and the highlands formed by the Archean granitic rocks and greenstones of the Northern Complex. "Second-order" structures consist of smaller regional fold systems that are characterized by a regional axial-planar slaty cleavage or schistosity. In the Marquette Range, these fold systems have been recognized only in the rocks of the Marquette Range Supergroup. The relationship between the trends of these first-order and second-order features in the Marquette Range is often ambiguous. Cannon's 1973 treatise on Penokean orogenic activity in the western Upper Peninsula outlined a process of independent development as a means of explaining this apparent divergence in regional trends. The

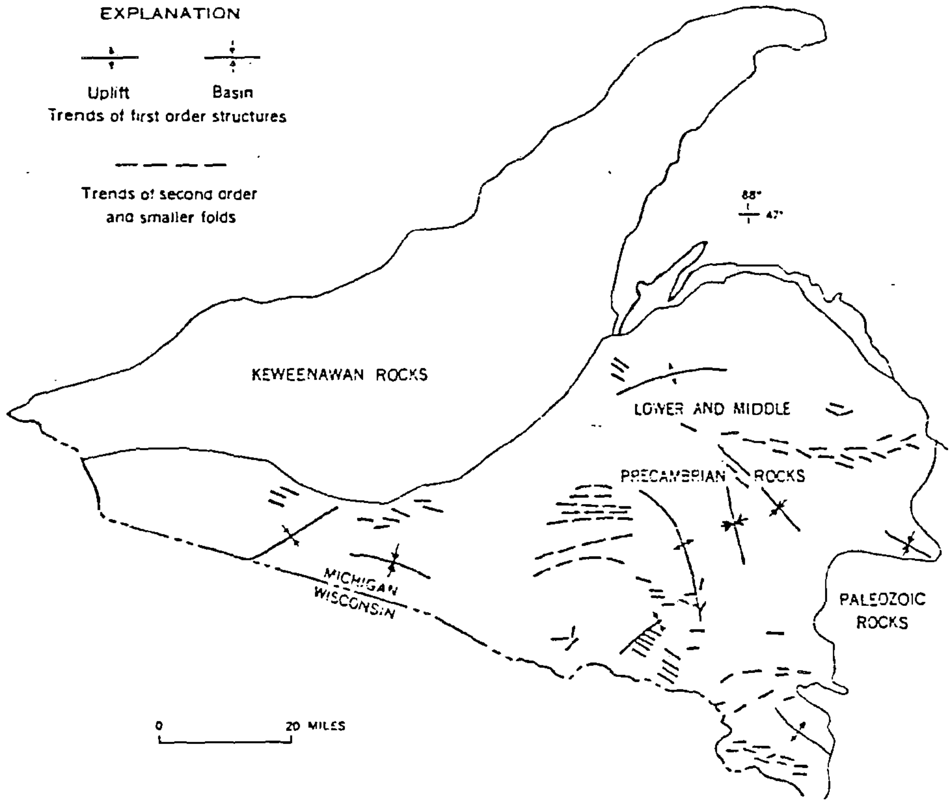

Figure 5. General trends of first- and second-order Penokean regional structure, according to Cannon (1973).

second-order folds in the Lower Proterozoic sequences record the intitial response to the onset of orogenic activity. The style of folding suggests that the compressional force was directed roughly northward. The first-order features have been interpreted as resulting from later-stage uplift and downwarping of fault-bound blocks of Archean (Northern Complex) rock, the fault systems supposedly exploiting mafic dikes or other pre-existing zones of weakness in the crystalline basement.

It has been suggested that some of the first-order depressions (the troughs in particular) were initially small-scale sedimentary basins related to pre-Penokean extension (Larue and Sloss, 1980). Penokean compressional forces were claimed to have utilized these pre-existing structures to appress and intensely deform the sediments contained within.

Metamorphism

The low-pressure regional metamorphism associated with the Penokean Orogeny was first described by James (1955). The paper refers to four apparent "nodes" of high-grade (sillimanite isograd) metamorphism in northern Wisconsin and the Upper Peninsula, with lower-grade mineral isograds forming crudely concentric patterns around them. Fig. 6 is a map of James' interpretation of the pattern of regional metamorphism in the pre-Keweenawan rocks of the western

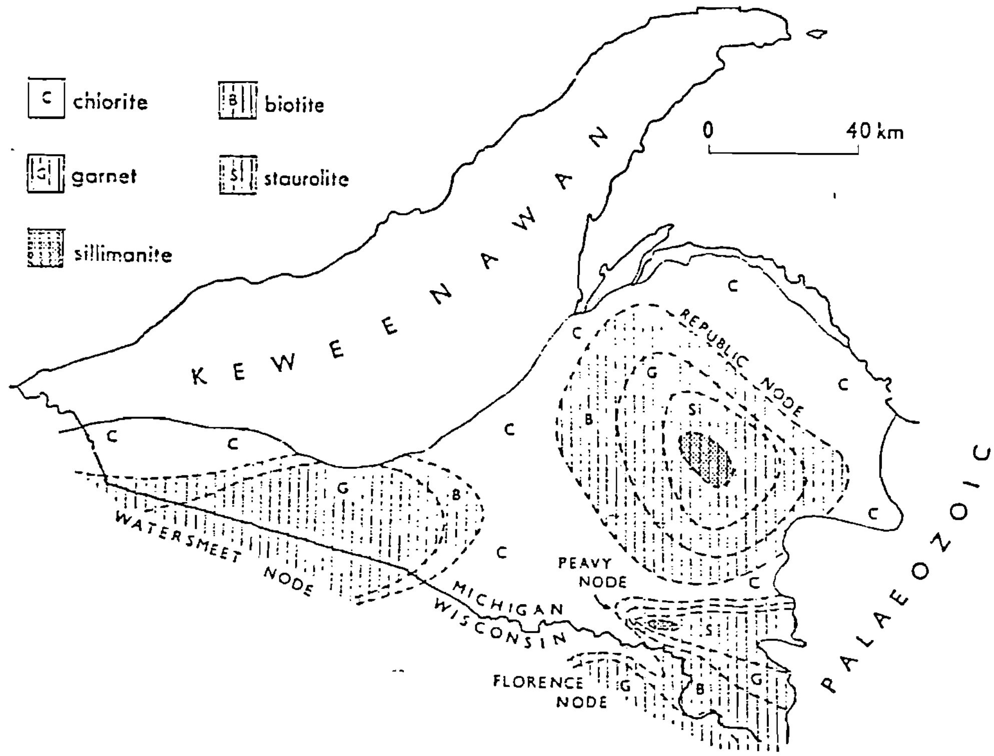

Figure 6. James' (1955) interpretation of the pattern of Penokean regional metamorphism in western Upper Michigan.

Upper Peninsula. The northern Falls River area, like most of the Baraga Basin, has been subjected to low greenschist facies metamorphism, with chlorite as the main porphyroblast mineral.

Absolute age dates for the metamorphic event have not been established, but textural and field evidence presented by James (1955) and Cannon (1973) suggest that it began during the Penokean Orogeny and continued to operate after the cessation of tectonic activity. Microstructural and microtextural evidence from the Falls River suggests that chlorite is pre-kinematic to syn-kinematic with respect to first-generation folds.

Geologic History

Depositional Environment

Cannon (1973) and Van Schmus (1976) provide a concise overview of the sedimentological and tectonic environments responsible for the formation of the Marquette Range Supergroup. A large part of the discussion that follows is borrowed from these two articles. Additional developments in recent years modify some of the generalizations made by these two authors, and will be specifically noted.

The deposition of Marquette Range Supergroup sediments is believed to have begun about 2.0 b.y. B.P., according to age dates determined for the youngest metamorphic events and intrusive activity restricted to the underlying Archean basement. The oldest rocks of Proterozoic age, the Chocolay Group, are quartzites and carbonates indicative of sedimentation in a shallow-water environment like that of a passive continental margin (miogeocline), or possibly a shallow epicontinental sea (Cambray, 1978). Some workers have suggested that extensional forces created a series of platforms and basins in the Archean basement, resulting in localized variations in sediment thickness (Larue and Sloss, 1980; Larue, 1981). The general thickening of Chocolay sediments to the south-southeast suggests that an uplifted section of the basement to the north served as the major source of detritus. Minor contributions from isolated intrabasinal highlands are inferred on the basis of recent sedimentological evidence (Sims and Peterman, 1983).

A period of mild tectonic disturbance, exemplified by uplift and partial erosion of Chocolay sediments, preceded the second major interval of deposition. This period is represented by the lower section of the Menominee Group, a sequence of sediments grading upwards from shallow-water clastics to deeper-water pelites and greywackes. Increased subsidence, perhaps related to extensional tectonic forces (Sims and Peterman, 1983; Young, 1983) resulted in locally thick accumulations of material.

The chemical precipitation of iron formation (the Negaunee, Vulcan, and Ironwood iron formations of the Menominee Group) characterized the third depositional sequence. A distinct lack of clastic material is noted within these units, although they are generally in conformable contact with the underlying slates and quartzites of the lower Menominee Group. This quiescent period was closely followed by an escalation of tectonic activity which produced compressional uplift in the Archean basement and accompanying uplift and erosion of Menominee Group rocks. These events are historically linked with the onset of the Penokean Orogeny.

The fourth stage, as represented by the Baraga and Paint River Groups, is indicative of deposition in a rapidly subsiding, deep-water eugeosynclinal environment. Pelites, siltstones and greywackes predominate over other rock types. The relative abundance of subaqueous mafic volcanics is also a characteristic of this type of environment. Limited deposition of iron formation occurred. The sediment source appears to be uplifted basement rocks located somewhere to the north and northwest. Cessation of sedimention coincided with the arrival of the main orogenic front.

The Penokean Orogeny

The term "Penokean Orogeny", first used in its present-day context by Goldich et. al. (1961), refers to an extensive period of deformation and uplift, regional metamorphism and igneous activity in the southern Canadian Shield of central Minnesota, northern and central Wisconsin, and the western Upper Peninsula of Michigan. This series of events is assigned to a time period extending from 1.9 b.y.

B.P. to 1.7 b.y. B.P. (Van Schmus, 1976), and signals the close of the Lower Proterozoic in the southern Lake Superior region.

Penokean orogenic activity produced two distinct tectonic terranes. The region to the north (the "northern Penokean terrane" of Greenberg and Brown, 1983), essentially the western Upper Peninsula and parts of central Minnesota, is characterized by deformed and regionally metamorphosed lower Proterozoic sediments (with minor volcanics) unconformably overlying the Archean basement. The other area (the "Penokean volcanic belt" of Greenberg and Brown, 1983), primarily north-central Wisconsin, is younger in age and dominated by suites of lower Proterozoic volcanics and intrusives, with associated minor sediments. Generally, Archean basement does not outcrop here.

Most of the Archean rock underlying the northern Penokean terrane consists of 2.7 billion year old granitic rocks and associated roof pendant greenstones, generally correlated with the Superior Province in Ontario and northern Minnesota. To the south, the basement is composed primarily of amphibolitic gneisses (in part migmatitic) that are up to 3.5 billion years in age. The contact between these two cratonic sequences (known in the Upper Peninsula as the Northern and Southern Complexes, respectively) runs roughly east-west through central Minnesota, part of northern Wisconsin, and the west-central Upper Peninsula (refer to Fig. 1 for the position of this structure in the

Upper Peninsula). This prominent regional structure is the "Great Lakes tectonic zone" of Sims et. al. (1980), and has been interpreted as the suture of a late Archean continental collision.

The structural contrast existing between the two Archean terranes apparently influenced later crustal processes (see Sims et. al., 1980). The southern gneissic terrane was an active participant during Penokean orogenesis, deforming contemporaneously with the overlying lower Proterozoic sediments. The relationship between the Lower Proterozoic sedimentary pile and the granite-greenstone basement of the Northern Complex is not immediately obvious. Large segments of Archean rock appear to have remained rigid during the initial development of fold systems in the Lower Proterozoic sediments of the Marquette Range. The presence of a decollement has been proposed to explain this disparity (Klasner, 1972; Cannon, 1973). Late-stage faults, shear zones and localized zones of cataclasis are purported expressions of the basement's response to compressional forces.

Although it is arguable whether plate tectonic theory is valid in certain Precambrian crustal regimes (see Greenberg and Brown, 1983), most workers feel that the similarities observed between Penokean regional features and several Phanerozoic rock suites are sufficient to justify the application of modern analogues. Several models have been proposed to help explain the styles of Penokean orogenesis. Models proposing an intercontinental collision orogeny are the most favored (Laberge et. al., 1984; Larue, 1983; Sims et. al., 1983). Most of these tectonic models are based on extensive petrological and geochemical studies of the complex Lower Proterozoic volcanic terranes of northern Wisconsin. Fig. 7 (from Laberge et. al., 1984) is one example of such a tectonic model. In this particular scenario, the sediments comprising the northern Penokean terrane accumulated on the trailing edge of a large cratonic mass (the Superior Province) to the north ("A" through "C" in Fig. 7). Periodic intervals of extensional tectonism during deposition of lower Marquette Range Supergroup rocks have been proposed in recent years (Sims and Peterman, 1983; Young, 1983). Orogenic activity initiated from the arrival of another Archean craton from the south (the area of present-day Wisconsin). Three distinct volcanic suites appear to be associated with the leading edge of this southern continent. The oldest is an island arc suite that was apparently situated over a northward-dipping subduction zone located in the center of an Early Proterozoic ocean basin ("A" in Fig. 7). The collision of the southern craton with this island arc ("B" in Fig. 7) resulted in a reversal of subduction zone polarity and the subsequent development of a younger continental arc volcanic suite on this same continental margin ("C" in Fig. 7). The final collision between the two cratonic masses ("D" in Fig. 7) severely deformed the passive margin sediments on the trailing edge

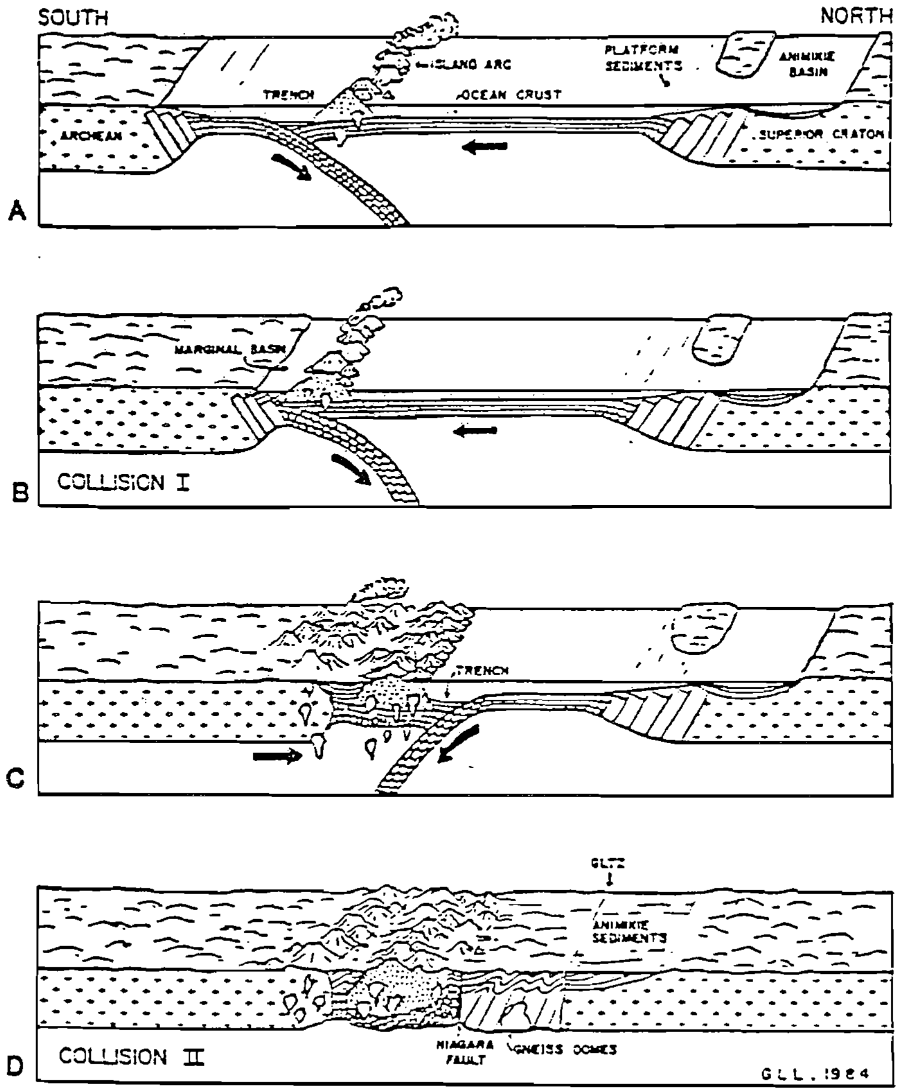

Figure 7. Proposed sequence of possible Penokean tectonic events, as developed by Laberge, et. al., 1984 (see text for explanation).

of the northern continent and the preexisting volcanic suites to the south, and resulted in caldera-type volcanism on the leading edge of the southern continent.

Although considerable useful petrologic and geochemical data have been amassed on Penokean-related features in the southern volcanic belt, the mechanical aspects of orogenesis in the northern terrane still suffer from lack of attention. The style of deformation in Baraga Group rocks of the western Marquette Range, for the most part, has not been intensively described (exceptions include Van Roosendaal, 1985). Extensive treatises of the region (Klasner, 1972; Cannon and Klasner, 1972; Cannon, 1973) contend that the second-order fold systems seen in the metamorphosed sediments resulted from a large-scale regional gravity slide off a preexisting highland somewhere to the south. These authors cite the work of Maxwell (1962), who claimed that regional slaty cleavage was the result of soft-sediment deformation. The soft-sediment theory has since fallen into disfavor (Boulter, 1974; Geiser, 1974; Wood, 1974; Zen, 1974; Geiser, 1975; Beutner et. al., 1977; Beutner, 1978a; Beutner, 1978b, Beutner, 1980), and it is now generally accepted that the formation of regional slaty cleavage is a hard-rock process.

The styles of deformation observed within the Baraga Basin region bear some marked resemblances to features exhibited in terranes containing nappes and related fold-and-thrust structures. The existence of such structural features in the lower Proterozoic sequences of the Lake Superior region has been proposed in recent years. For example, multiple deformation (as recorded by the presence of two tectonic foliations) in the lower Proterozoic Thomson Formation of east-central Minnesota has been associated with the progressive development of large-scale northward-directed fold nappes (Holst, 1984). The relationship of the overlying sediments to the granitic basement in this area is probably analagous to that seen in the Northern Marquette Range (i.e., a possible detachment surface). Other nappe structures in the region have been recognized in the south-central Upper Peninsula near the Michigan-Wisconsin border (Maharidge et. al., 1986). At this locale, the Archean gneissic terrane of the Southern Complex appears to have deformed contemporaneously with the overlying Lower Proterozoic sedimentary pile, resulting in the creation of large, recumbent basement-cored fold nappes.

DESCRIPTION AND STRUCTURAL FEATURES OF UNITS IN THE FALLS RIVER AREA

Introduction

The metamorphosed sediments of the Falls River display evidence for three deformational events. Two of these are very distinct, each possessing a prominent set of folds, cleavages, and lineations. The third event has little mesoscopic expression, field evidence existing mainly as a reorientation of earlier foliations. Other non-primary structural features in the area include faults and joints. These structural elements are described according to the system of nomenclature developed by Turner and Weiss (1963). For a discussion of the specific orientation of these various fabric elements, refer to the chapter on geometrical analysis.

Lithologies, Primary Structures, Local Stratigraphic Succession

Considerable lithologic variation exists in the field area. Slates characterize the northernmost section of the survey line, while siltstones and greywackes are the dominant rock type to the south. The central portion of the line is distinguished by a cyclical sequence of slates and coarse-grained greywackes. Hypabyssal occurrences of

Lower(?) Proterozoic igneous rocks and Keweenawan diabases are also noted in the vicinity.

Four color variations of slate occur. They are all fine-grained, the major layered silicate mineral being chlorite. In the gray and greenish-gray varieties, chlorite comprises the bulk of the mineralogy, with fine white mica (sericite?) as a minor component. Black slates contain nearly as much graphite as chlorite. Reddish slates owe their pigmentation to an abundance of finely disseminated iron oxide. Irregular grains of diagenetic(?) hematite are common in the greenish-gray and reddish varieties, with diameters ranging from 0.01 mm to 0.1 mm. Elongate porphyroblasts of chlorite, 0.2 mm to 0.4 mm in length, are also present in limited amounts. Discussion of these porphyroblasts will be reserved for later sections.

Bedding in the slates is best recognized in outcrop by the presence of thin laminae that range in color from black to red to light gray. In thin section, bedding is defined by elongate trains of finely disseminated opaque material and by thin silty lenses and layers of quartzo-feldspathic material (in part recrystallized). These layers and lenses often contain anomalous concentrations of opaque grains.

The coarse greywackes consist of medium-grained (0.3 mm to 0.5 mm in diameter) sub-angular to sub-rounded clasts of quartz, feldspar (including microcline) and lithic material, set in a sericitized and chloritized matrix that comprises 20% to 40% of the total rock volume. Detrital muscovite is not uncommon. The lithology of the clasts seems to suggest a plutonic source, and save for minor secondary chlorite, the rock appears relatively fresh in thin section. Opaque minerals are uncommon, and chlorite porphyroblasts are absent.

Although bedding in the coarse greywackes is indiscernible in thin section, sharply defined individual beds, several inches to several feet in thickness, separated by slate are clearly recognizable in the field. This interbedded sequence is restricted to the central portion of the survey line, between stations 8 and 20 (Plates I and II).

Medium-grained greywackes and siltstones dominate over other rock types in the southern section of the field area. They often occur within normally graded, interbedded sequences that often have a thin pelitic horizon associated with the stratigraphic top. The greywackes here are similar in composition to the coarser-grained units seen to the north, albeit with several notable differences. Clast sizes are consistently smaller, and they contain larger amounts of matrix material (chlorite, sericite) and irregularly-shaped opaque grains. Chlorite porphyroblasts are common and are considerably larger than those seen in the slates, often reaching 1 mm in length. Discussion of various aspects of metamorphic fabric will be reserved for a later section.

Two generations of intrusives are observed in the field area. The oldest are a small set of Lower Proterozoic(?)

mafic dikes (Fig. 8) located in the central portion of the field area (between survey stations 15 and 17 on Plate II). These rocks are severely altered, the original igneous assemblage in thin section being completely obscured by alteration products such as serpentine, sericite and an ubiquitous, unidentifiable dark brown coating (Fig. 9). Relict crystal shapes suggest an intergranular texture with abundant phenocrysts (possibly clinopyroxene and plagioclase). Vescicles and amygdules are common, the most common filling being quartz. Despite some textural variations, they all appear similar in composition. More exact identification would require analytical techniques that were deemed to be beyond the realm of this study.

The other set of intrusives are Keweenawan-age diabases, with a primary assemblage of calcic plagioclase, augite, and accessory magnetite. Textures are generally subophitic (diabasic). Minor chloritization of the augite and sericitization of the plagioclase has occurred, but for the most part they are relatively fresh. These rocks were not studied extensively, as they post-date the culmination of the Penokean Orogeny.

Small isolated outcrops of Jacobsville Sandstone occur in the northern third of the field area on the eastern lip of the river gorge (between survey stations 8 and 9 on Plate I). This coarse-grained reddish sandstone is Upper Proterozoic in age and unconformably overlies all of the other units in the field area. Although the attitude of the

Figure 8. Lower Proterozoic(?) mafic dike between survey stations 15 and 16, looking east.

Figure 9. Photomicrograph of a Lower Proterozoic(?) mafic dike from the study area (field of view is approx. 6 mm.; plane-polarized light).

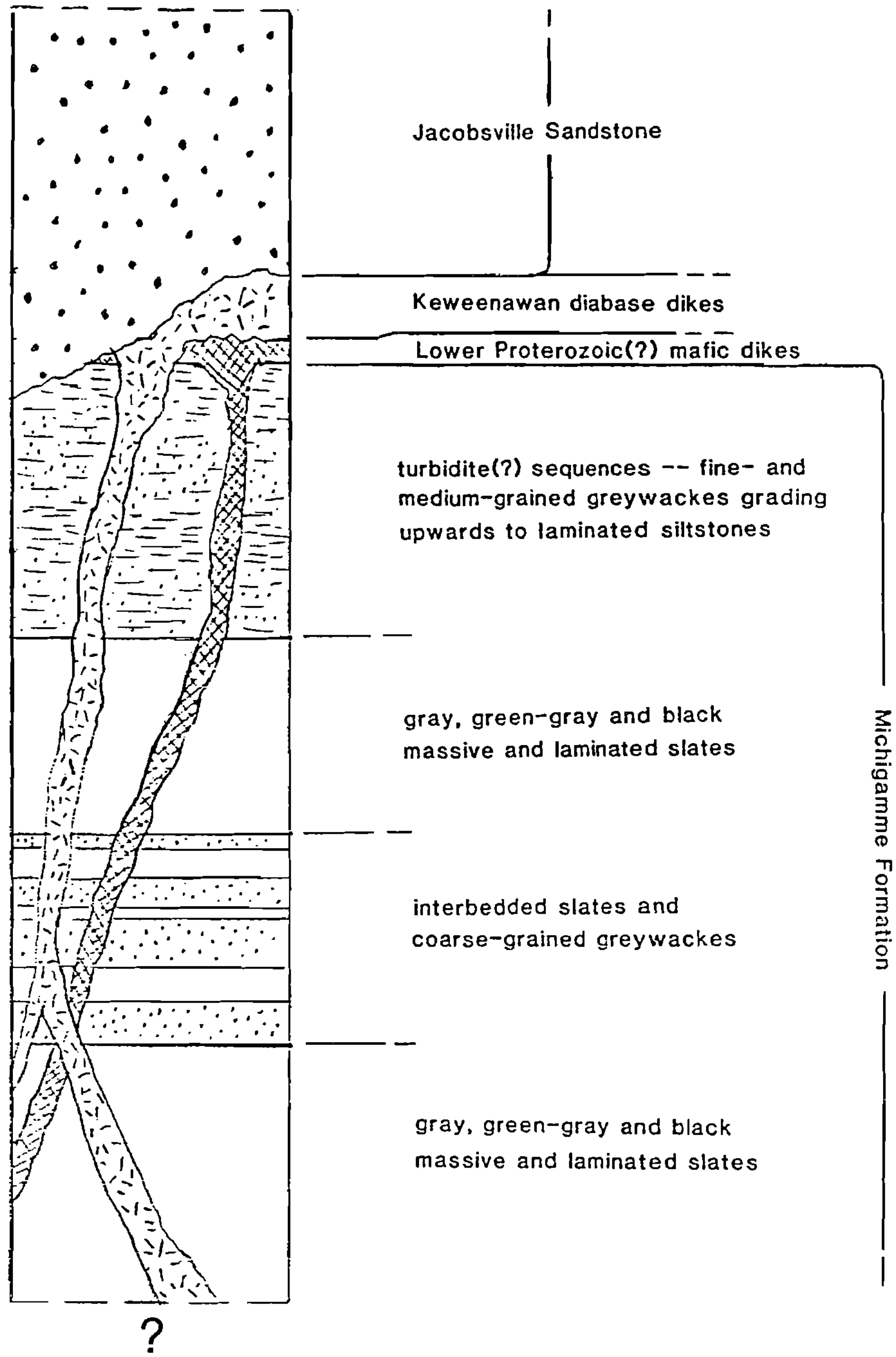

Figure 10. Stylized stratigraphic column for the study area.

angular unconformity cannnot be precisely determined at this locality, exposures along Lake Superior immediately west of the river suggest a very gentle dip to the northwest. Lack of participation in Penokean deformation precludes anything but a cursory mention of this unit.

Graded bedding in interbedded sequences of pelites, siltstones and greywackes at the southernmost extent of the survey line makes the determination of a local stratigraphic succession possible. A stylized stratigraphic column is presented in Fig. 10. This column was constructed for the purpose of displaying the relative position of the rock units with respect to each other, and is not meant to convey any sense of thickness.

Elements of Style Group B_1

B_1 folds

An extensive system of asymmetric overturned B_1 folds is evidenced on a mesoscopic scale (Plates I through III). The nomenclature used in defining the dimensions of these folds (after Fleuty, 1964) is presented in Fig. 11. Fold profiles are tight to isoclinal, and boxlike profiles are occasionally seen. Axial surfaces are inclined to the south-southwest, as reflected by the orientation of the associated axial planar cleavage (S_1). Two orders of B_1 folds are recognized. First-order folds may be quite large. Long limb heights (as defined in Fig. 11) average from 100

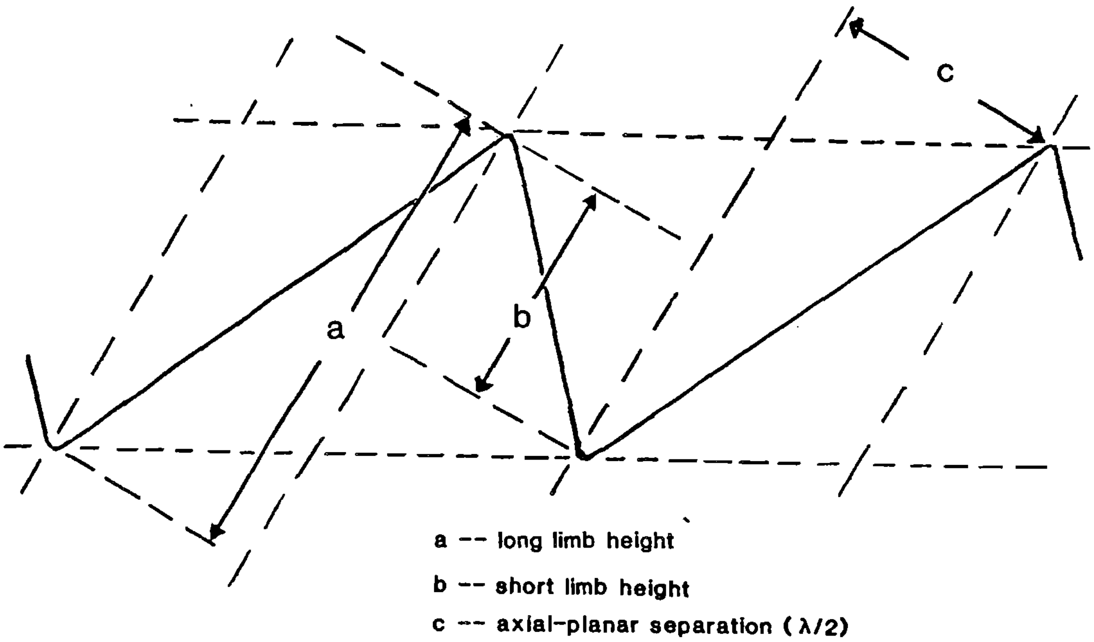

Figure 11. Explanation of system of nomenclature for dimensions of asymmetric overturned folds (after Fleuty, 1964).

Table 1. Elements of style group B_1.

STRUCTURE		DESCRIPTION
Folds	B_1	generally tight to isoclinal asymmetrical overturned first-order folds. Moderately south-southwestward-dipping axial surface in areas unaffected by later deformation. Axial planar separations = 50 ft. Long limb heights = 100-150 ft., occasionally up to 600 ft. Short limb heights = 20-50 ft., occasionally in excess of 150 ft. Shallow axial plunges, occasionally doubly plunging.
	B_1	small, second-order folds, parasitic on the first-order folds and similar in morphology.
Foliations	S_1	axial planar continuous slaty cleavage in pelitic rocks.
	S_1	axial planar domainal cleavage in grey-wackes and siltstones, degree of development being dependent on amount of matrix material originally present.
Lineations	L_1	bedding-slaty cleavage intersection lineation.
Faults		Low angle fault planes characterized by slickensides, cataclastized slate, quartz and carbonate mineralization. Reverse (thrusting) sense of movement inferred.
		Low angle fault planes characterized by truncated bedding surfaces. Reverse (thrusting) sense of movement inferred.
Joints		B_1-related joint sets probable but generally indeterminate due to multiple deformational history.

to 150 feet, and may be in excess of 500 feet. Short-limb heights (as defined in Fig. 11) average about 50 feet, occasionally exceeding 150 feet. Axial-planar separations (as defined in Fig. 11) are in the range of 50 feet. Fold axis orientations vary from horizontal to shallowly plunging (up to 20 degrees in areas affected by second-generation deformation, as described in following section), and are occasionally doubly plunging. The overall vergence in the field area is suggestive of a position on the long limb of a regional B_1 fold system, with a possible synclinal axis to the south. Figs. 12a through 12c present the appearance of some first-order B_1 folds. Second-order B_1 folds (Figs. 13a and 13b) are small in scope, often isoclinal, and are parasitic on the first-order folds.

S_1 slaty cleavage and equivalent foliations

An axial-planar S_1 cleavage is mesoscopically visible throughout the field area, the extent of development being largely dependent on lithologic type. In the slates, S_1 is a ubiquitous, generally well-developed slaty cleavage that forms prominent planar surfaces along which the rock splits and weathers (Fig. 14). A fine micaceous sheen is usually present on cleavage surfaces. In the coarse greywackes, S_1 is rough and irregular, and weathers into subparallel slabs that vary considerably in thickness. The style of S_1 in the siltstones and greywackes located at the southern end of the survey line is similar to that seen in the coarser

Fig. 12a. First-order B_1 anticlinal hinge near survey station 10, looking east.

Figures 12a through 12c. Mesoscopic appearance of some first-order B_1 folds, each displaying axial-planar S_1 slaty cleavage.

Fig. 12b. First-order B_1 synclinal hinge between survey stations 22 and 23, looking west.

Figures 12a through 12c. Mesoscopic appearance of some first-order B_1 folds, each displaying axial-planar S_1 slaty cleavage.

Fig. 12c. First-order B_1 synclinal hinge near survey station 18, looking west.

Figures 12a through 12c. Mesoscopic appearance of some first-order B_1 folds, each displaying axial-planar S_1 slaty cleavage.

Fig. 13a

Fig. 13b

Figures 13a and 13b. Mesoscopic appearance of some second-order B_1 folds.

Figure 14. General mesoscopic appearance of S_1 slaty cleavage surface and L_1 bedding-slaty cleavage intersection lineation. L_2 slaty cleavage-crenulation cleavage intersection lineation is also visible trending from lower left to upper right.

greywackes. Mesoscopic expressions of S_1 are often obscured in the latter two rock types due to later-stage foliations (see following sections).

The morphology of S_1 on a microscopic scale also depends on rock type. In the non-carbonaceous slates, S_1 forms a strong, continuous fabric defined by the preferred orientation of chlorite and minor white mica (Fig. 15). Long stringers of dusty opaque material are commonly included within cleavage domains as a solution-transfer residuum (Wood, 1974). In carbonaceous varieties, graphite replaces chlorite as the definitive platy mineral. This continuous type of S_1 cleavage fabric is the most common one in the northernmost part of the field area (north of station 11 on Plate I), due to the predominance of slates over other rock types.

The degree of S_1 development in the coarse greywackes appears to be related to the amount of matrix material present. In those rocks where matrix comprises up to 40% of the total volume, S_1 is a well-defined domainal cleavage consisting of irregular, anastomosing films of chlorite and minor white mica, enclosing lensoidal microlithons of recrystallized quartzo-feldspathic minerals (Fig. 16). In the matrix-poor (less than 20% of total volume) varieties, S_1 is not always readily apparent in thin section. An S_1-parallel flattening of clasts is occasionally present (Fig. 17). The boundaries of these clasts are often irregular, and the presence of internal granular textures

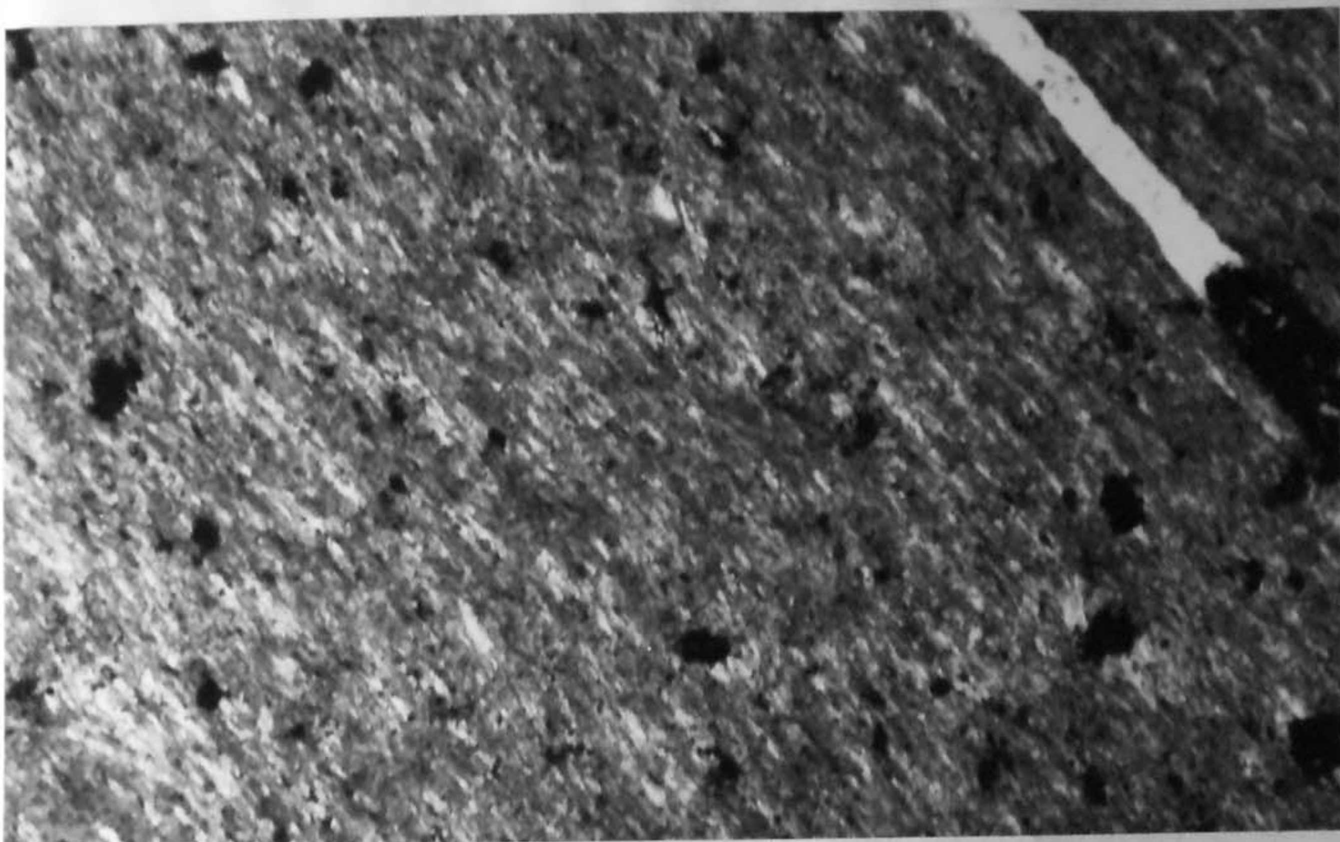

Figure 15. General microscopic appearance of continuous S_1 slaty cleavage fabric in slates (field of view is approx. 1.7 mm.; plane-polarized light).

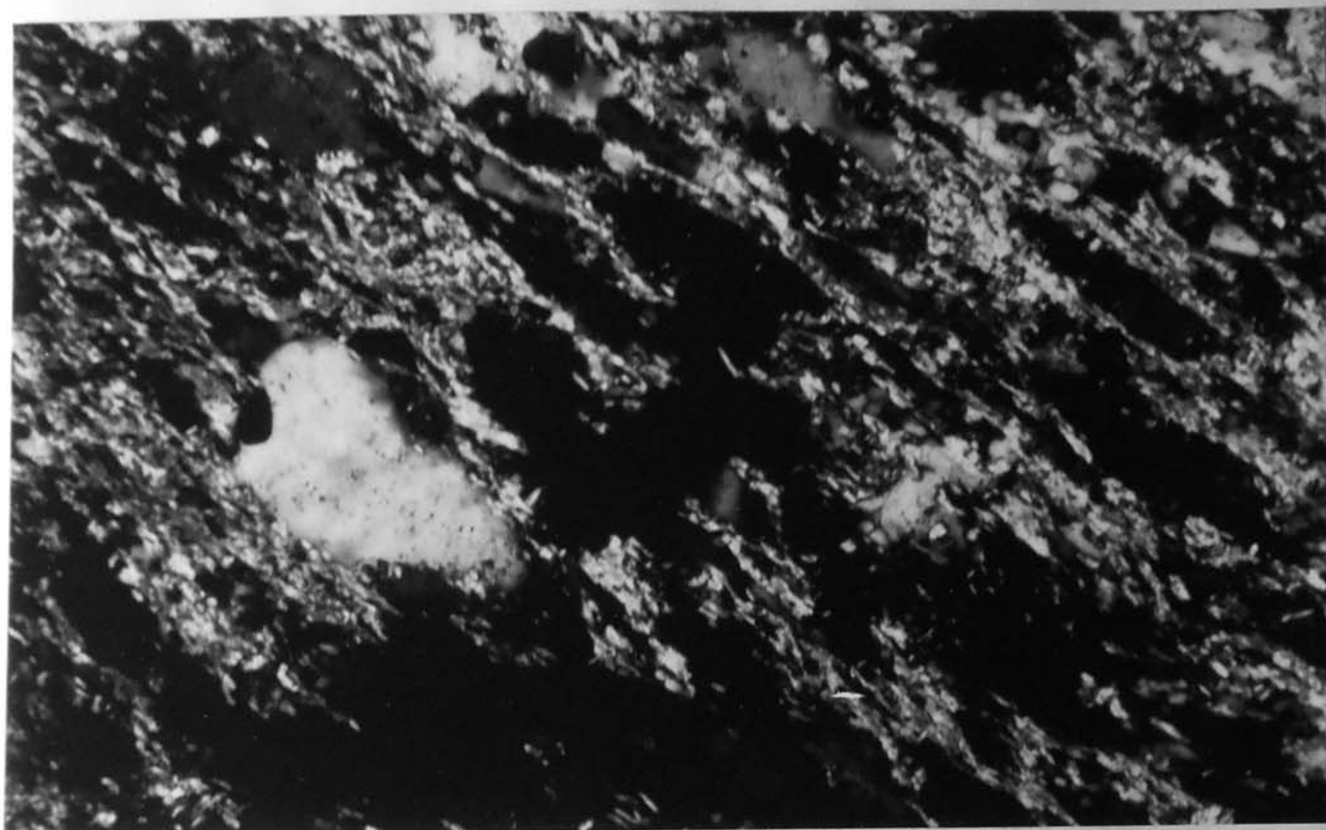

Figure 16. General microscopic appearance of domainal S_1 cleavage fabric in greywackes (field of view is approx. 1.7 mm.; cross-polarized light).

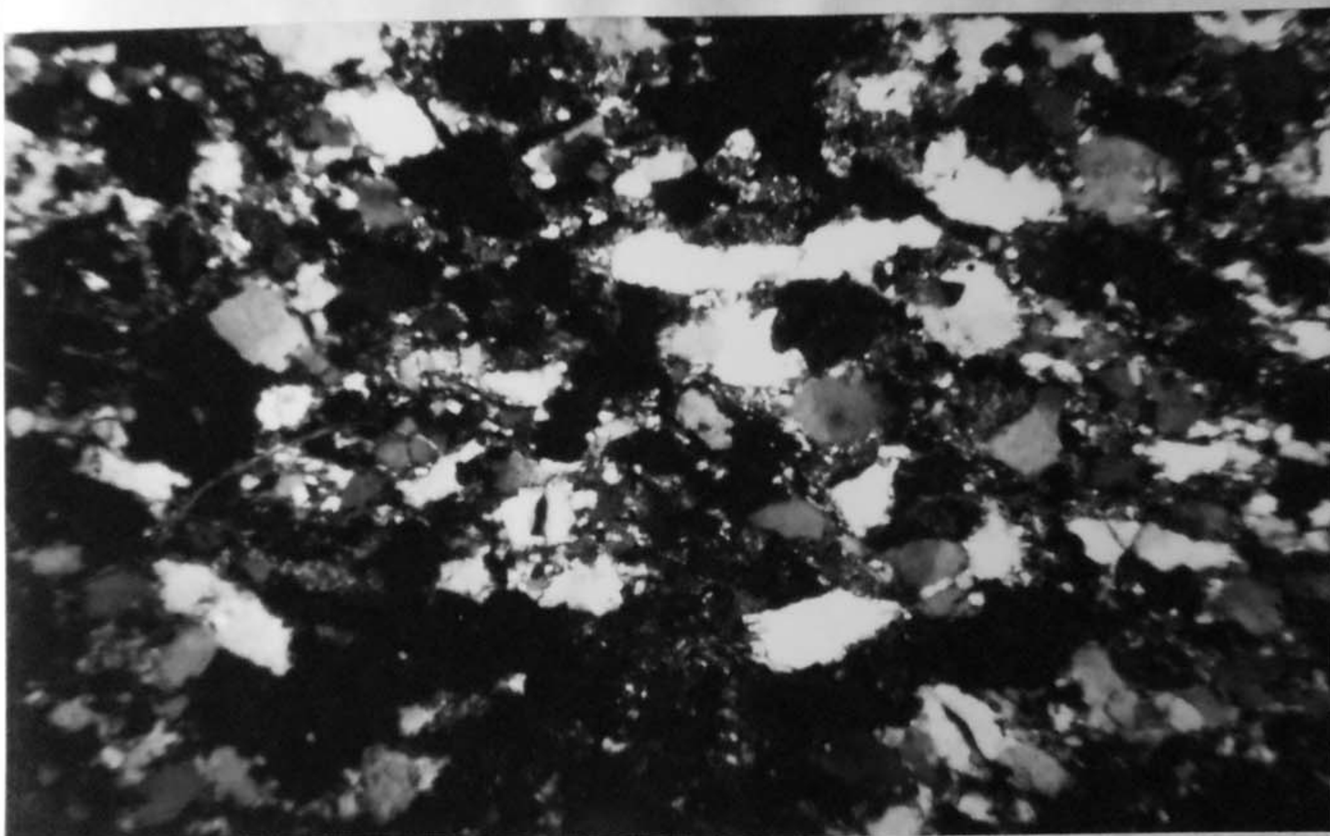

Figure 17. S_1-parallel flattening of clasts in greywackes (field of view is approx 1.7 mm.; cross-polarized light).

within many of the grains indicate that these rocks have been substantially recrystallized.

S_1 cleavage fabrics in the medium-grained greywackes are domainal and considerably better defined than those seen in the coarse-grained greywackes, due to an overall smaller clast size and a greater abundance of layer-silicate minerals (mainly chlorite). Cleavage styles within the silty portions of graded beds are similar, but the cleavage domains are noticeably narrower, presumably as a result of the greatly reduced grain size. Cleavage styles within the pelitic horizons of these units approach those seen in the slates. Generally, the southern part of the field area has been much more extensively affected by later-stage deformation than has the northern part, frustrating attempts at exact description of the original style of S_1 fabric.

L_1 bedding-slaty cleavage intersection lineation

A secondary lineation, as defined by Hobbs and others (1976), is a linear fabric element that is related to a deformational event. Common examples of lineations include rods, mullions, deformed and elongated clasts and mineral grains, and intersection lines between two foliations. This last category was the only extensively developed lineation in the field area.

The term "L_1" as used here refers to the lineation formed by the intersection of bedding (S_0) and slaty cleavage or psammitic equivalents (S_1). This lineation is generally parallel to B_1 fold axes. The best representations of L_1 in the field can be seen in the slates and result from the trace of thin bedding laminae on slaty cleavage surfaces (Fig. 14). Other examples of L_1 in the field include the weathered traces of S_1 cleavage planes along prominent bedding surfaces.

Elements of Style Group B_2

B_2 folds

B_2 deformation has visibly overprinted B_1 fabric elements throughout most of the field area. The style of B_2 folding shows wide lateral variation from north to south. Along the northern two-thirds of the survey line (north of station 24 on Plates I through III), the B_2 fold system forms an irregular series of small to large asymmetric flexures in S_1 cleavage surfaces (Figs. 18a through 18c). Within these areas, S_1 has been gently folded, crenulated and rotated from its original southwesterly dip to orientations varying from westerly-dipping to subhorizontal. Fold hinges possess a localized crenulation cleavage (S_2). The widths of the zones of rotated S_1 cleavages between the fold hinges vary from 1 foot to 100 feet. The orientation of S_2 planes indicates that B_2 axial surfaces are approximately vertical. Fold axes are approximately horizontal.

In the southern third of the field area (south of

Table 2. Elements of Style Group B_2.

STRUCTURE		DESCRIPTION
Folds	B_2	open to gentle folds and asymmetric flexures in S_1 cleavage surfaces. Nearly vertical, roughly east-west striking axial surface in areas unaffected by later deformation. Widths of deformed zones (containing folded and rotated S_1 cleavage surfaces) vary from 1 to 100 ft.
	B_2	tight symmetrical to asymmetrical folds in S_1 cleavage surfaces. Axial surfaces inclined due to later-stage deformation. Wave-lengths = 10-20 ft. Amplitudes = 5-15 ft.
Foliations	S_2	sinuous zonal asymmetrical crenulation cleavage in mildly B_2-deformed pelitic rocks.
	S_2	sinuous discrete asymmetrical crenulation cleavage in some mildly B_2-deformed pelitic rocks (uncommon).
	S_2	anastomosing zonal asymmetrical and symmetrical crenulation cleavage in strongly B_2-deformed pelitic rocks.
	S_2	subparallel strongly domainal crenulation cleavage in strongly B_2-deformed fine siltstones.
Lineations	L_2	slaty cleavage-crenulation cleavage intersection lineation.
Joints	B_2-related joint sets probable but generally indeterminate due to multiple deformational history.	

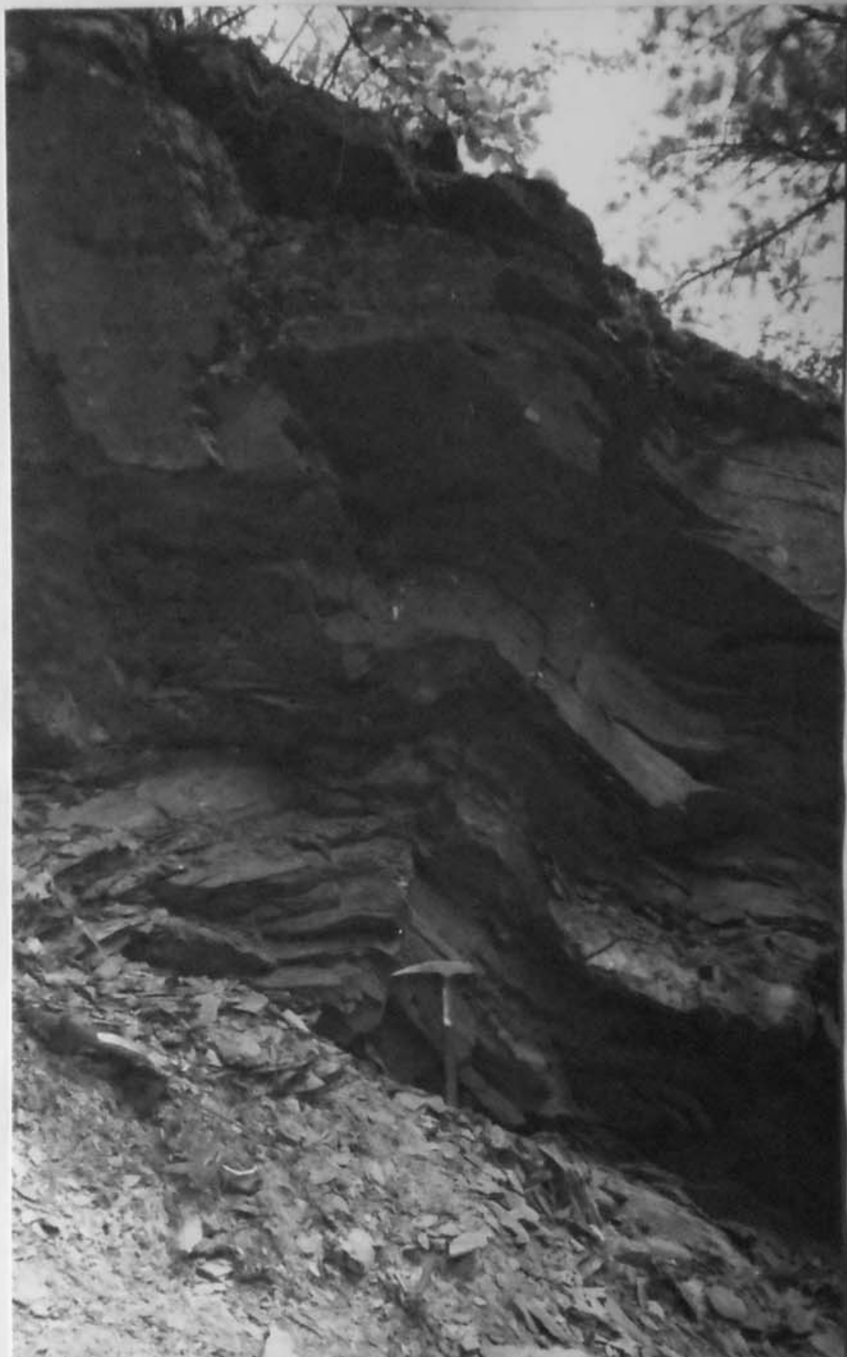

Fig. 18a. Series of small asymmetric B_2 flexures near survey station 6, looking southeast; bluff is hanging wall (upper plate) of thrust fault, with folded quartz mineralization visible to immediate right of head of rock hammer.

Figures 18a through 18c. Mesoscopic appearance of gentle B_2 folds; visibly folded surfaces are S_1 slaty cleavages; axial-planar surfaces are S_2 crenulation cleavages.

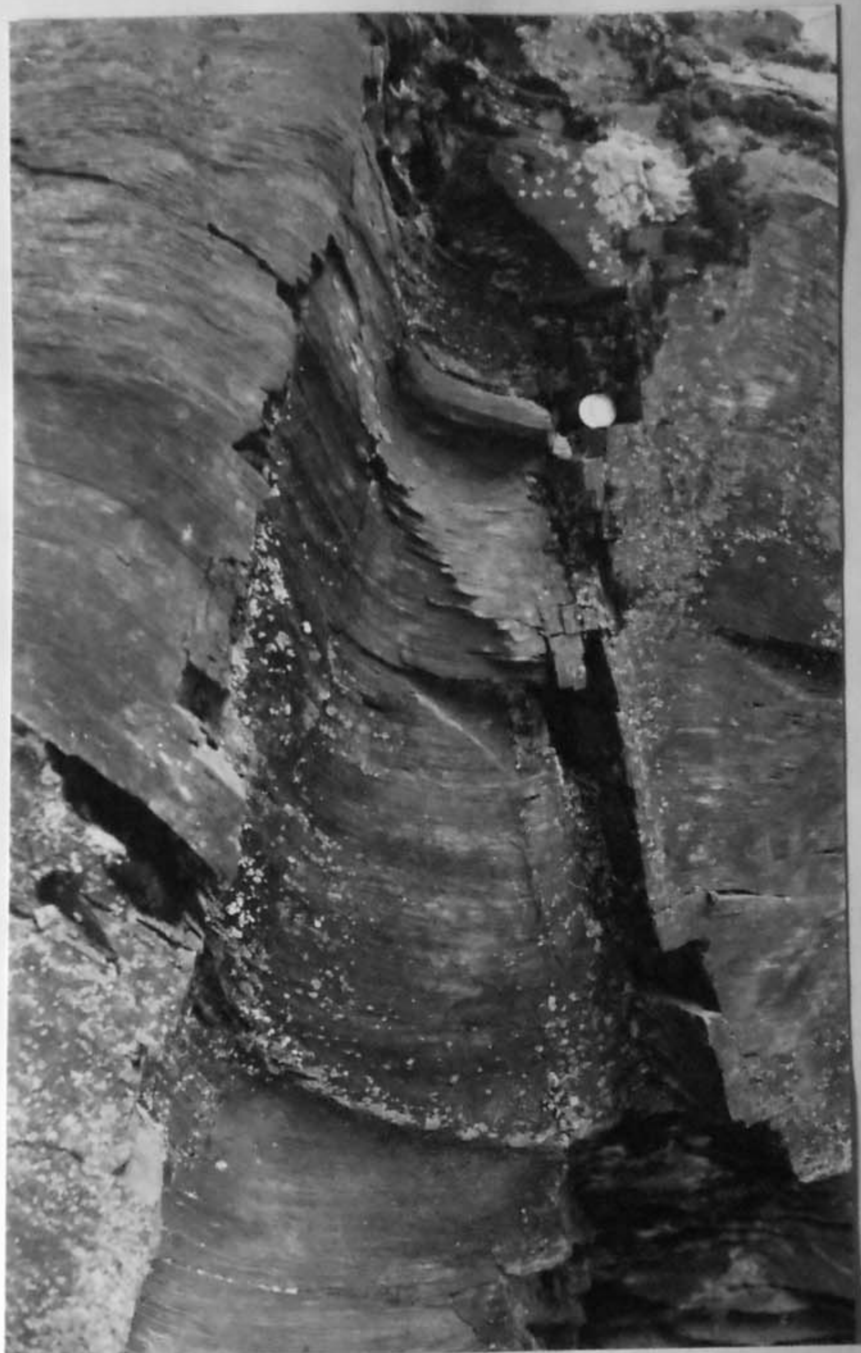

Fig. 18b. Detail of small asymmetric B_2 flexure near survey station 6, looking southeast.

Figures 18a through 18c. Mesoscopic appearance of gentle B_2 folds; visibly folded surfaces are S_1 slaty cleavages; axial-planar surfaces are S_2 crenulation cleavages.

Fig. 18c. Gentle B_2 fold between survey stations 24 and 25, looking west.

Figures 18a through 18c. Mesoscopic appearance of gentle B_2 folds; visibly folded surfaces are S_1 slaty cleavages; axial-planar surfaces are S_2 crenulation cleavages.

station 24 on Plate III), B_2 deformation is generally more intense, and the introduction of a third fold system (B_3) results in a reorientation of S_2 cleavage surfaces. Two sets of tight B_2 folds in subparallel S_0 and S_1 surfaces characterize most of this section. In the first set (between survey stations 24 and 26 on Plate III), fold profiles are symmetrical, and fold axial surfaces dip steeply to the south (Fig. 19). Profiles in the second set of tight B_2 folds (at the end of the survey line, between stations 29 and 30 on Plate III) are asymmetrical, and axial surfaces dip gently to the southwest. S_2 crenulation cleavage here is strongly developed and pervasive. The area separating these two occurrences of intense deformation (between survey stations 26 and 29 on Plate III) exhibits a gentler style of B_2 folding, with asymmetric profiles similar in appearence (albeit with smaller wavelengths) to those observed in the northern two thirds of the field area.

S_2 crenulation cleavage

The axial-planar foliation associated with B_2 occurs in the limbs of B_2 microfolds of S_1 cleavage. Where B_2 folding is gentle, mesoscopic expressions of the cleavage surfaces occur only within the B_2 fold hinge regions (Figs. 18a and 18b). In areas characterized by intense B_2 deformation, S_2 is pervasive, predominating over other foliations (Fig. 19). The most well-developed S_2 cleavage planes occur in metamorphosed siltstones located at the southern end of the

Figure 19. Mesoscopic appearance of tight B_2 anticline (upper left) and syncline (lower right) in parallel S_0 bedding and S_1 slaty cleavage, between survey stations 24 and 26, looking west; fold axial surface (as represented by pervasive S_2 crenulation cleavage) trends from lower left to upper right.

survey line, where the solution-transfer mechanisms leading to the development of crenulation cleavage (Grey, 1979) were probably facilitated by the superior permeability of these units.

Microscopically, S_2 morphology varies according to primary lithology and deformational intensity. In pelitic units throughout the northern two-thirds of the field area, where B_2 deformation is relatively mild, S_2 is defined by a mica-film type foliation developed along the short limbs of gentle asymmetric B_2 microflexures (with wavelengths from 0.2 mm to 0.5 mm) in the continuous S_1 slaty cleavage fabric (Fig. 20). Cleavage domains are moderately developed and form sinuous gradational boundaries wherein originally S_1-parallel layered silicates have been reoriented into subparallelism with the S_2 planes. Some crystallization of quartzo-feldspathic minerals may have occurred within the microlithons in areas where B_1-related strain shadows (see later sections) are present. Discrete, opaque-rich cleavage planes are commonly developed in areas where stringers of S_1-parallel finely disseminated opaques were initially abundant (Fig. 21). In the southern third of the field area, S_2 in pelitic units becomes tightly spaced and more strongly developed. The short limbs of the B_2 microfolds are steeper and wavelengths are reduced by approximately one-half. S_2 cleavage surfaces in pelites located at the southernmost extent of the survey line (south of station 28) are often anastomosing, and display a stronger partitioning

Figure 20. General microscopic appearance of sinuous zonal S_2 crenulation cleavage domains in areas of gentle B_2 folding (field of view is approx. 1.7 mm.; cross-polarized light).

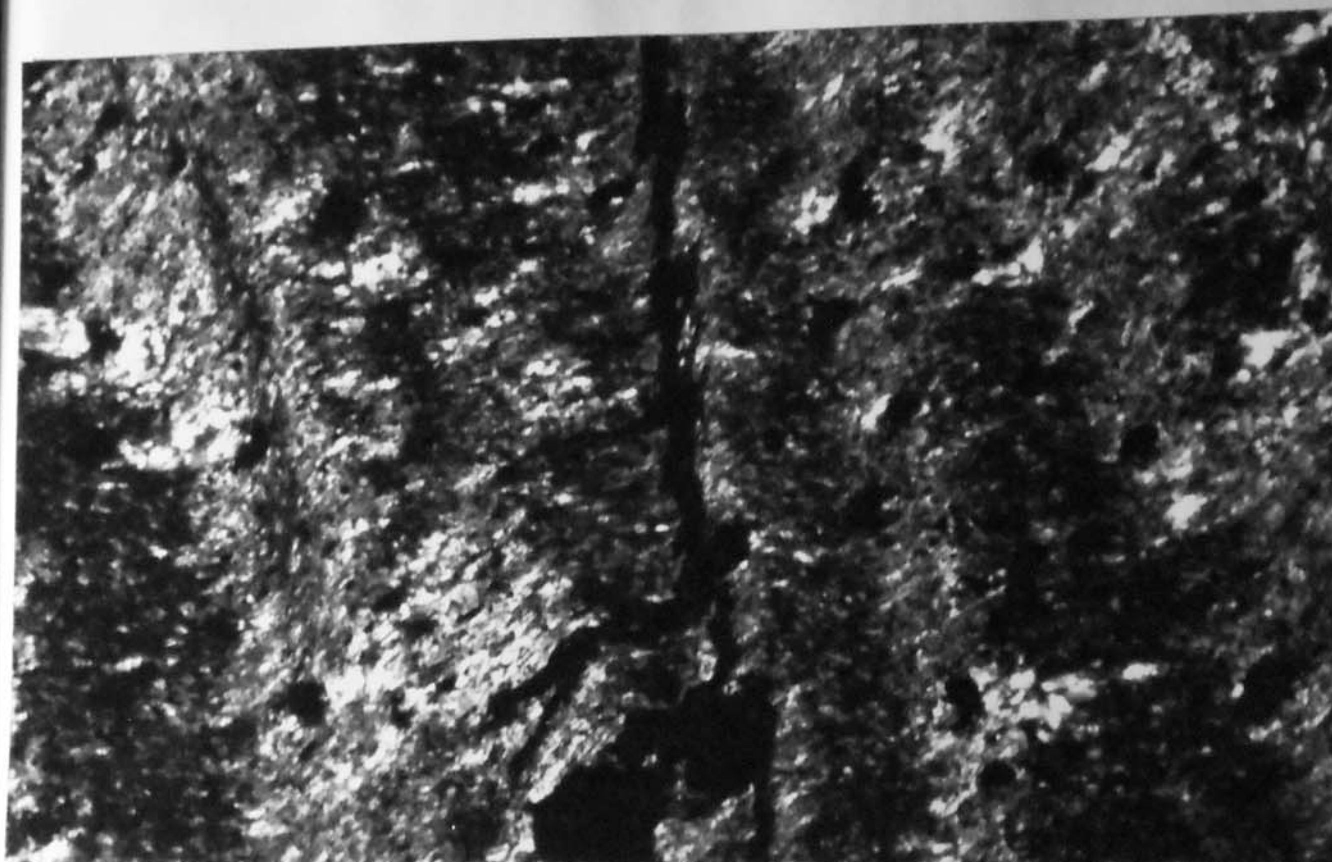

Figure 21. Microscopic appearance of a discrete S_2 crenulation cleavage domain in an area of gentle B_2 folding (field of view is approx. 1.7 mm.; cross-polarized light).

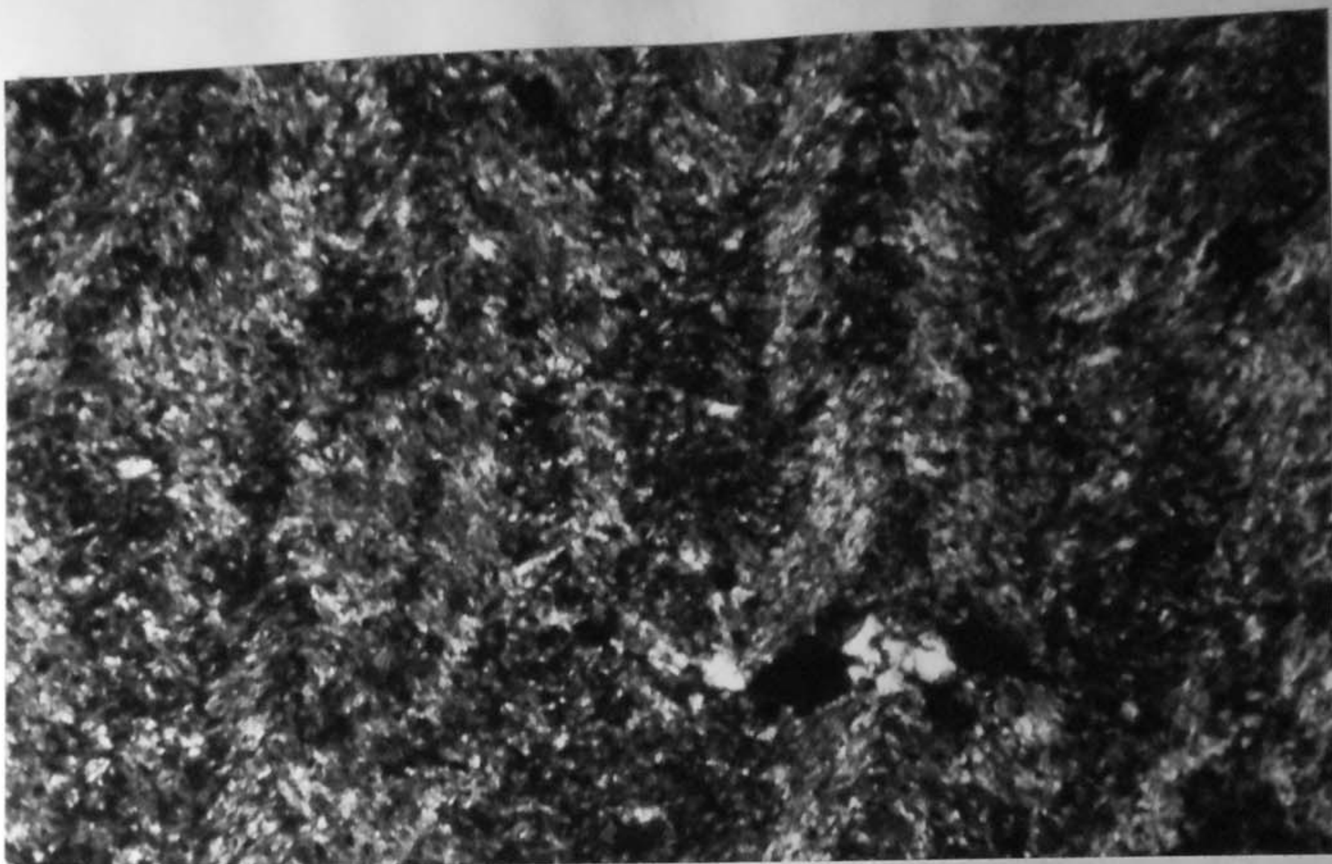

Figure 22. General microscopic appearance of anastomosing zonal S_2 crenulation cleavage in strongly B_2-deformed pelitic rocks (field of view is approx. 1.7 mm.; cross-polarized light).

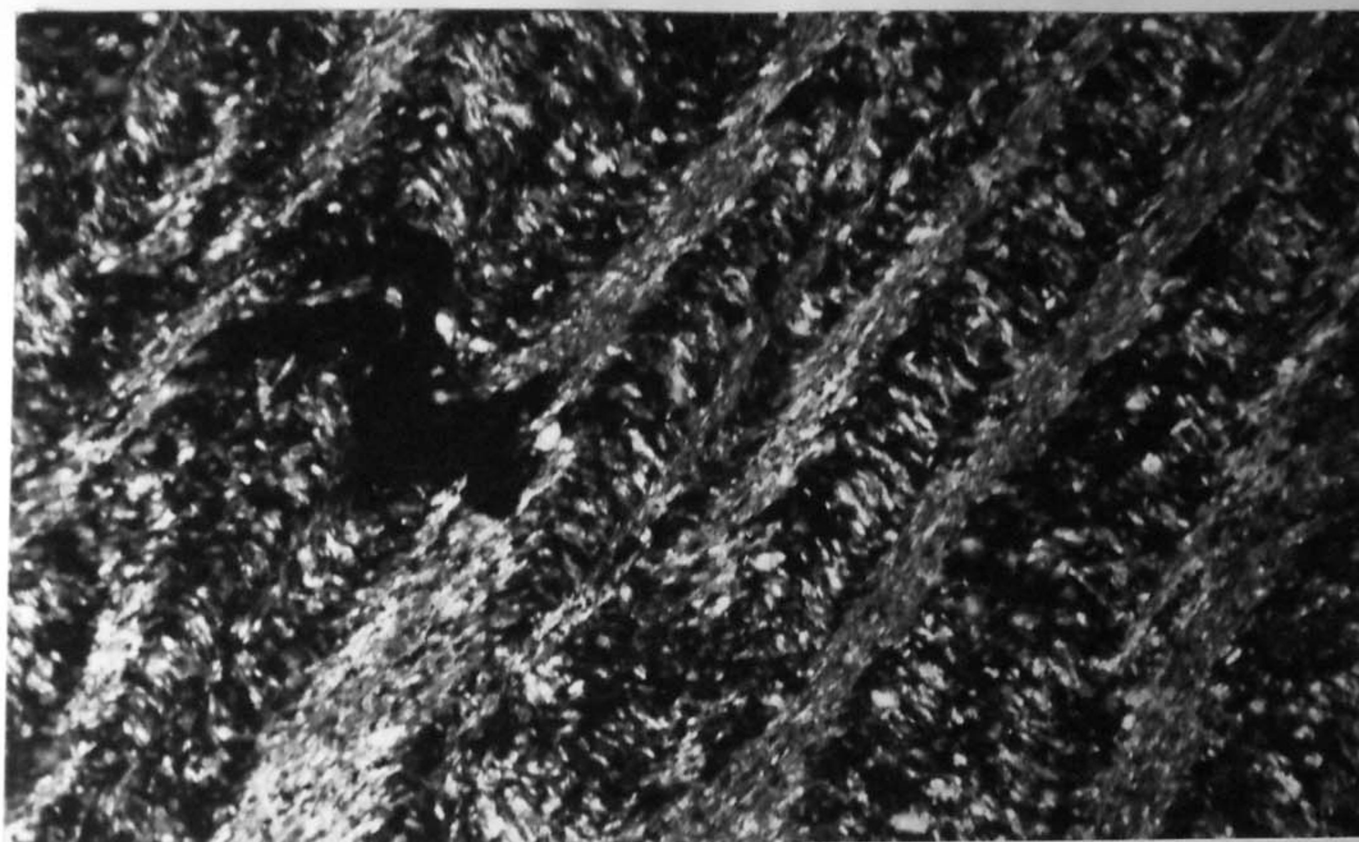

Figure 23. Microscopic appearance of strongly developed zonal S_2 crenulation cleavage in siltstones south of survey station 28 (field of view is approx. 1.7 mm.; cross-polarized light).

of quartzo-feldspathic minerals into microlithons than in similar lithologic types (slates) to the north (Fig. 22). S_2 cleavage domains in the siltstones are strongly defined, as most of the chlorite in the rock occurs along the microfold limbs (Fig. 23). Symmetrical microfolds are common and often contain cleavage domains along both microfold limbs. Generally, S_2 in greywackes is poorly-defined to absent.

L_2 slaty cleavage-crenulation cleavage intersection lineation

L_2 in the northern part of the field area is primarily seen as the trace of S_2 on S_1 cleavage surfaces and is best preserved in the slates (Figs. 24 and 14). It is generally parallel to the trend direction of the B_2 fold axes. L_2 is relatively consistent in orientation throughout the northern two-thirds of the field area. At the extreme southern end of the survey line, the lack of well-developed S_1 surfaces prevents mesoscopic expressions of L_2.

Elements of Style Group B_3

B_3 folds and S_3 spaced cleavage

The best evidence for the presence of a B_3 system is seen as the progressive reorientation of S_2 cleavage attitudes from the vicinity of station 24 southward (see Plate III). A mesoscopic system of folds is not readily

Figure 24. Mesoscopic appearance of L_2 slaty cleavage-crenulation cleavage intersection lineation on an S_1 cleavage surface in pelitic rocks.

Table 3. Elements of Style Group B_3.

STRUCTURE		DESCRIPTION
Folds	B_3	macroscopic rotation of S_2 cleavage surfaces about east-northeast-trending axis. Mesoscopic fold regions are not visible.
Foliations	S_3	steeply dipping spaced cleavage confined to southern terminus of survey line.

Figure 25. Mesoscopic appearance of steeply-dipping S_1 spaced cleavage in a siltstone outcrop between survey stations 29 and 30, looking east.

apparent. The angle of rotation of S_2 within the field area is roughly 70 degrees, the trend of the rotational axis being determined through the use of stereographic projections (see following chapter on geometrical analysis).

Outcrops of siltstone in the immediate vicinity of station 30 display a foliation that is symmetrically oriented with respect to B_3 deformation (Fig. 25). Mesoscopically, these surfaces appear as a set of closely spaced planes, 2 to 4 cm apart, upon which the rock preferentially fractures. In thin section, the cleavage traces occur either as simple fractures or discontinuous seams of dusty opaque material that crosscut preexisting rock fabric. No reorientation of layered silicates with respect to this new foliation is observed.

Miscellaneous Fabric Elements

Strain shadows

Strain shadows as defined by Stauffer (1970) are deformational features related to the solution-transfer processes that result in the formation of many tectonic fabrics (including slaty and crenulation cleavages). A pelitic matrix undergoing plastic deformation typically deflects around isolated, more mechanically competent features, forming tapered gaps in the rock fabric are that are perpendicular to the direction of maximum shortening. These gaps are commonly filled with materials such as fibrous quartz or calcite, or oriented mica.

In the field area, the most well-developed strain shadows are in the slates, where they are associated with blebs of diagenetic opaque material (hematite?) and small porphyroblasts of chlorite (Fig. 26). They are essentially a B_1-related feature, as shown by their orientation parallel to a continuous S_1 slaty cleavage fabric. The composition of the shadows appears to be predominately quartz. Strain shadows in greywackes and siltstones are smaller and poorly developed, presumably due to lithologic differences.

In areas that have been affected by B_2 deformation, the strain shadows have been systematically deformed by the microfolds that define the S_2 fabric (Fig. 27). In many cases the strain shadows are bent into conformity with the microfold shapes, but the primary effect of B_2 events is a change in volume. Shadows proximal to microfold limbs are greatly diminished in size, while those within S_2 microlithons are much larger. These relationships are reflective of the B_2-induced solution-transfer processes that remove quartzo-feldspathic material from the microfold limbs.

Chlorite porphyroblasts

Chlorite appears to be the sole porphyroblast mineral in the field area. Variations in size and abundance appear to be a function of the lithology and grain size of the host sediments. Lengths of 0.5 mm are seldom exceeded in the

Figure 26. S_1-parallel strain shadows associated with a chlorite porphyroblast (to the left) and several irregularly shaped opaque grains (field of view is approx. 1.7 mm.; plane-polarized light).

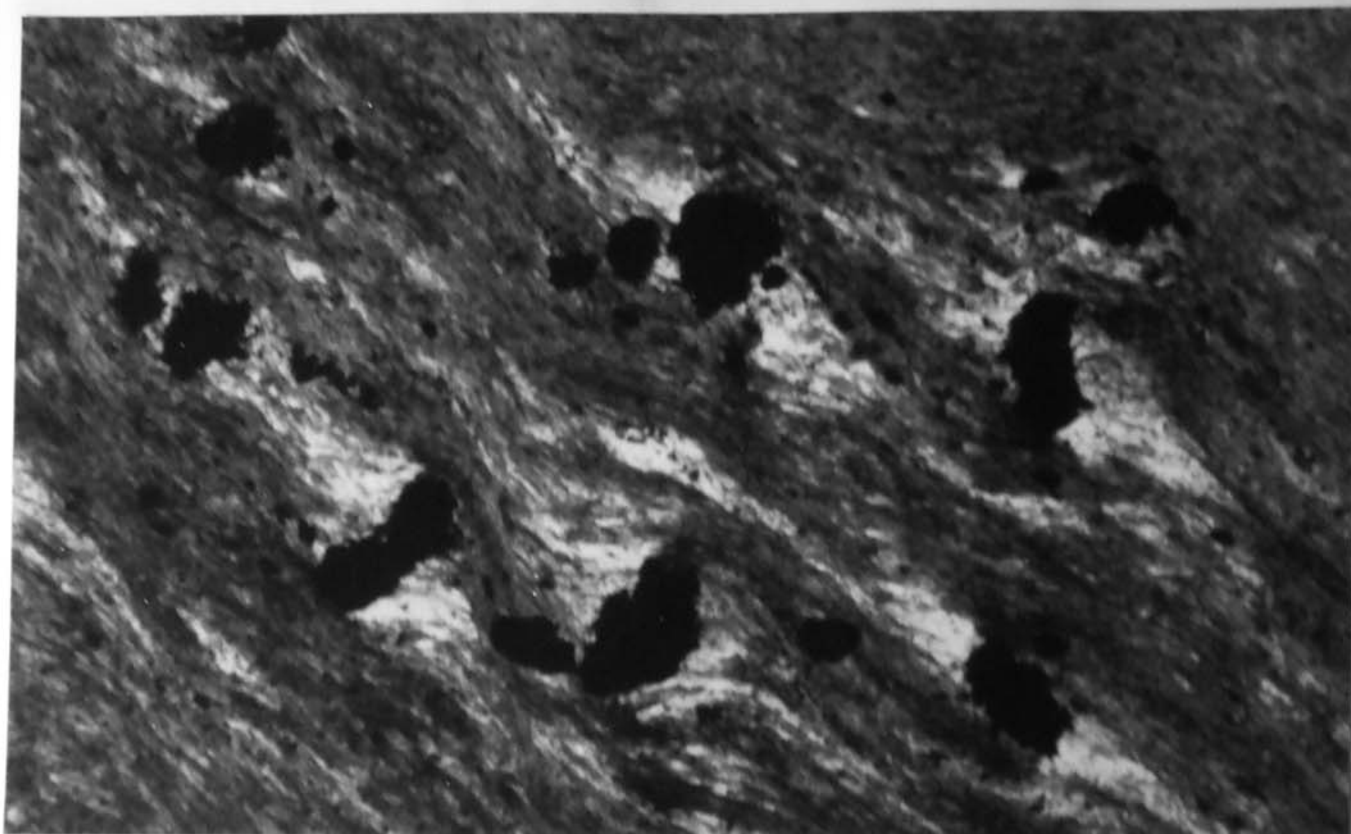

Figure 27. B_2-deformed strain shadows (field of view is approx. 1.7 mm.; plane-polarized light).

pelitic units, while blasts approaching 1 mm in length are frequently observed in the graded siltstone-greywacke units. They appear to be absent in the coarse greywackes located in the central part of the field area.

A combination of factors indicates that the chlorites predate the culmination of B_1 deformation. The long axes of the porphyroblasts are parallel to S_1 slaty cleavage. They possess S_1-parallel strain shadows (see above). Those with (001) traces essentially perpendicular to S_1 commonly display pull-apart textures, while those with (001) at intermediate angles to S_1 show displacement along those crystallographic planes. Fig 26 displays the general appearance of a chlorite porphyroblast.

Non-penetrative Features

Faults

A system of low-angle S_1-parallel faults is observed in the field area (Plates I through III). They are most commonly located near large B_1 fold hinges. The appearance of these fault zones is widely variable. Most are simple planar features that have been mineralized with white milky quartz (Fig. 28). The thickness of the quartz mineralization varies from a few inches to several feet. Joint systems in the immediate vicinity of some fault zones have been mineralized with quartz as well. Others consist of cataclastized sections of slate that have been

Figure 28. Quartz-mineralized fault zone near survey station 18, looking west; prominent surfaces in the outcrop are parallel bedding and slaty cleavage (S_0 and S_1).

Figure 29. Microscopic appearance of carbonate-mineralized fault material in slates (field of view is approx. 6 mm.; plane-polarized light).

mineralized primarily with carbonate (Fig. 29). A few faults are unmineralized, their presence being indicated by the truncation of bedding planes. Slickensides lineations are commonly observed near faulted areas. The upper plates (hanging walls) often form small bluffs, waterfalls or similar areas of local relief along the stream bank (Fig. 18a and Plates I through III). Faults in areas affected by B_2 deformation are often overturned or possess severely convoluted fault surfaces (Plates I through III).

The symmetry observed between B_1 structures and the fault system, combined with the localized refolding of fault zones by B_2 folds (Fig. 18a and Plates I through III), indicates that faulting predates B_2 deformation, and may have been partly contemporaneous with B_1 deformation. The amount of offset is indeterminate due to a lack of marker horizons, but a reverse (thrusting) sense of movement is inferred from the overall mechanics of the B_1 deformational system.

Joints

A pervasive, complex system of joints exists in the field area, forming spaced planar fractures in all of the metamorphosed sediments. Appearance in outcrop is similar throughout the field area (Figs. 30a and 30b). The interbedded sequences of slates and coarse greywackes often display preferential joint patterns within individual beds. Joint planes are steeply dipping to vertical. Strikes are

Fig. 30a

Figures 30a and 30b. Mesoscopic appearance of joints in a) slates, and b) greywackes.

Fig. 30b

Figures 30a and 30b. Mesoscopic appearance of joints in a) slates, and b) greywackes.

widely variable. Spacing varies from a few inches to a few feet. Quartz mineralization sometimes occurs along joint planes that are proximal to fault zones (see above). Small seams of carbonate and chlorite mineralization along joint planes are restricted in occurence. For the most part they are unmineralized. Discoloration along joint planes as a result of weathering is common.

GEOMETRIC ANALYSIS OF FABRIC ELEMENTS

Introduction

The geometric analysis of various structural elements assists in the quantitative description and interpretation of the dynamics of deformational events. As part of this study, all pertinent features of rock fabric were directly measured and recorded in the field, and presented on equal-area (Schmidt) stereographic projections, according to the methodology of Turner and Weiss (1963). The stereographic projections used in this report illustrate planar features (bedding, cleavage, faults and joints) as S-poles, whereas foliation intersections are plotted as lineations. Data is contoured according to the method of Braun (1967). The fabric elements that are most useful in the delineation of structural domains are S_1 slaty cleavage and S_2 crenulation cleavage.

General Trends and Selection of Domains

Stereographic projections for all orientations of S_0, S_1, S_2 and S_3 throughout the field area are given in Fig. 31. As can be seen, the first three S-surfaces display strong evidence for deformation subsequent to development of the surface. Predictably, the best analysis of deformational style for each system (B_1, B_2 and B_3) is

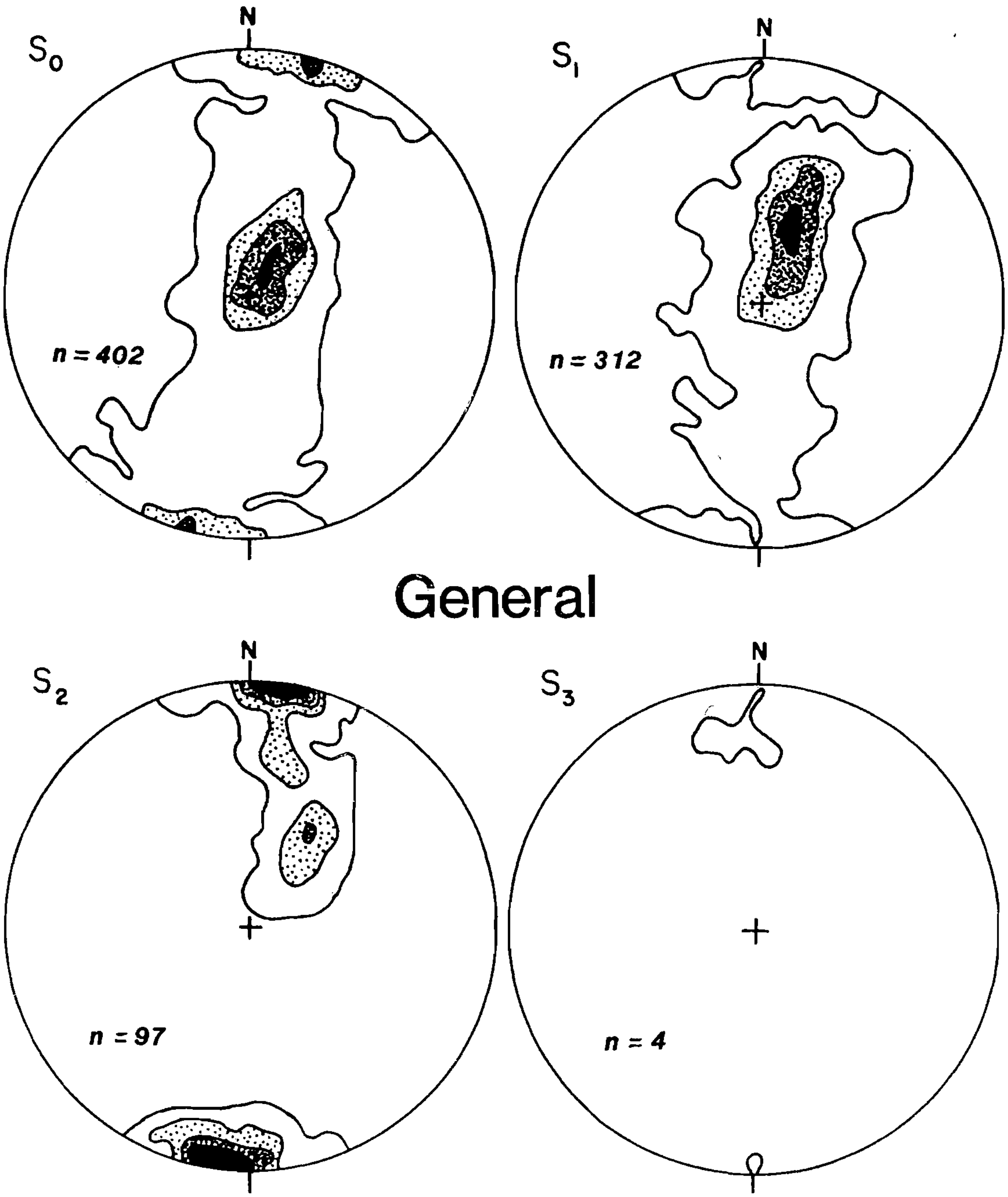

Figure 31. Stereographic projections of S-poles for all penetrative foliations throughout the field area (contours are at 1 pt., 5%, 10% and 15% per 1% area

provided by the foliation whose development immediately preceeded it (i.e., S_0, S_1 and S_2). Style group B_1 resulted in deformed S_0 bedding surfaces and the formation of an axial planar S_1 slaty cleavage (or psammitic equivalent). The ubiquity of B_1 is reflected by the bimodal character of S_0 stereonet data and by the large number of S_1 attitudes available for plotting. B_2's comparatively weak development can be seen in the limited rotation of S_1 surfaces and the moderate elongation of the S_1 maximum. A more limited development of S_2 cleavage is shown by the smaller number of S_2 data points. B_3 is even more restricted in occurrence, with only a small number of S_3 data points available from the southern end of the survey line. The B_3-related rotation of S_2 appears more prominent on the stereonet as a result of the initially smaller sample population.

The definition of a structural domain followed in this investigation is the one stated by Turner and Weiss (1963): "any finite three-dimensional portion of a rock body that is statistically homogeneous on the scale of the domains. Domains are usually outlined by boundaries that are natural surfaces of major discontinuity in structure or composition." Within the field area, the number of deformational events is the criterion used in distinguishing structural domains. Domain I contains mesoscopic evidence for B_1 deformation alone. Domain II has been subjected to B_1 and B_2 deformation. Domain III has been affected by B_1, B_2 and B_3 deformation. The latter has been further subdivided into three subdomains. The locations of domain boundaries within the field area are shown on the inset map on Plate II.

Description of Domain I

Domain I has been affected by B_1 deformation only, and therefore preserves the original attitudes of the fabric elements related to that style group. In the field, it is situated in the northern two-thirds of the field area (north of station 24 on Plates I through III and inset map on Plate II) and consists of all areas that possess no mesoscopic evidence of later deformational events (see following section regarding Domain II). Mesoscopic expression of B_1 deformation occurs as folds in S_0 bedding surfaces, with associated S_1 axial planar cleavages and L_1 bedding-slaty cleavage intersection lineations. However, the frequency of B_2 overprinting in the vicinity of B_1 fold hinges limits the number of meaningful S_0 values available for the quantitative description of Domain I. Therefore, the only fabric elements suited for defining Domain I are S_1 and L_1. Stereographic projections for Domain I are given in Fig. 32.

Description of Domain II

Within Domain II, B_2 deformation overprints prexisting B_1 structural features. This domain is also situated in the

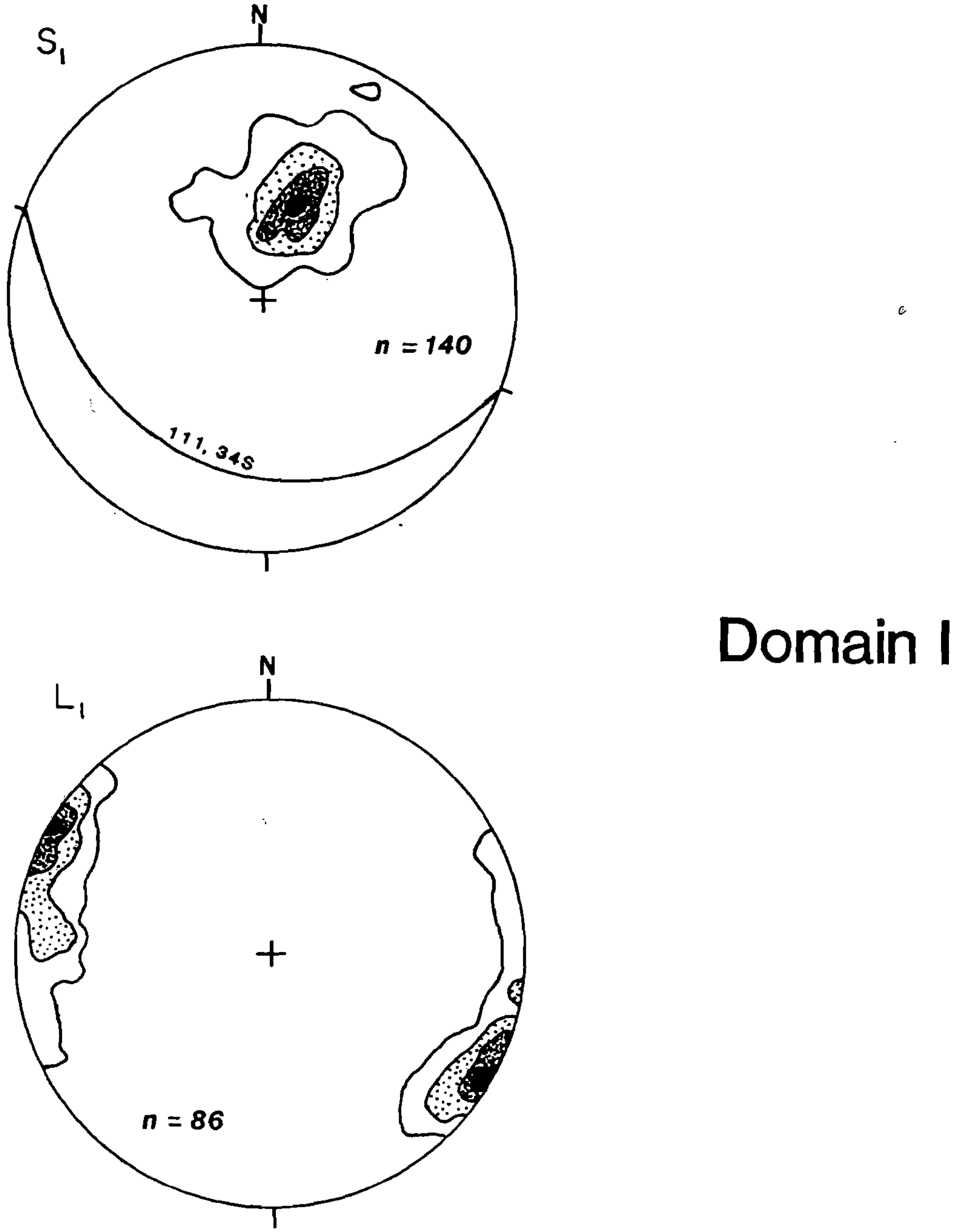

Figure 32. Stereographic projections of S-poles for penetrative structures from Domain I (contours are at 1 pt., 10%, 20% and 30% per 1% area).

northern two-thirds of the field area (north of station 24 on Plates I through III and inset map on Plate II), and consists of deformed zones bounded by the axes of open B_2 folds and asymmetric flexures. S_1 cleavage surfaces within these deformed zones have been systematically rotated from their Domain I positions. Fold hinges usually display a localized S_2 crenulation cleavage (see preceeding section on local geologic setting and structural features). The B_2 axial surface (as represented by S_2) remains vertical or nearly so. Three consistent, although minor, changes in the attitudes of B_2 fold axial surfaces may be seen by separating Domain II into three areas (Figs. 33 through 35). These slight variations result in systematic differences in both the strike of S_2, and the trend of the S_1 rotational axis. The fluctuation most likely reflects a natural variation within the mechanics of the B_2 fold system, and was probably not caused by later-stage deformation. It should be noted that L_2 indicates only the trend of the B_2 axis. Plunge is indeterminate from this fabric element due to the fact that S_1 was not horizontal prior to the development of the B_2 fold system. Horizontal to gently west-plunging B_2 axes are inferred from the rotational axes of S_1 poles.

Description of Domain III

Domain III is located in the southern third of the

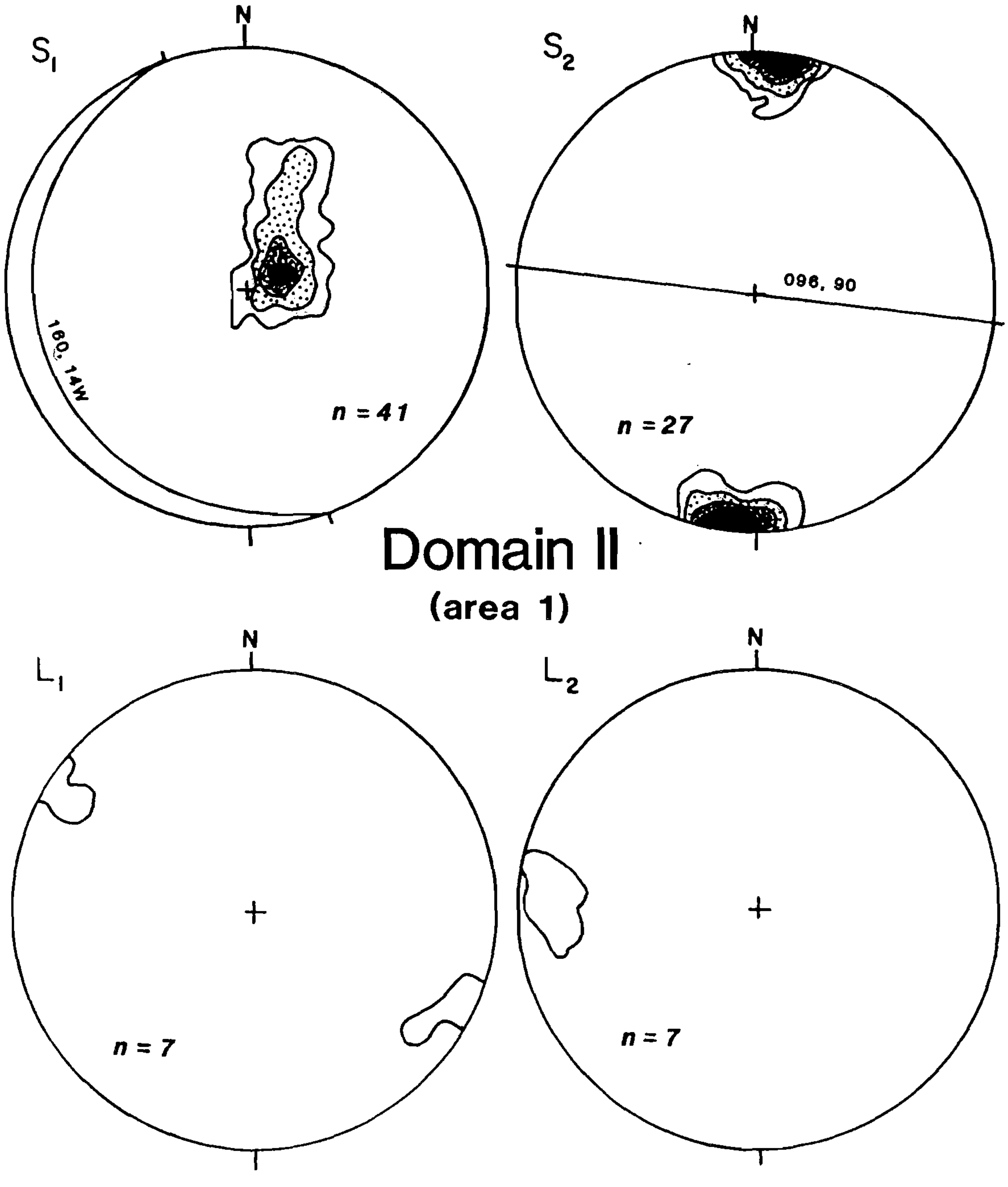

Figure 33. Stereographic projections of S-poles for penetrative structures from Domain II, area 1 (contours are at 1 pt., 10%, 20% and 30% per 1% area).

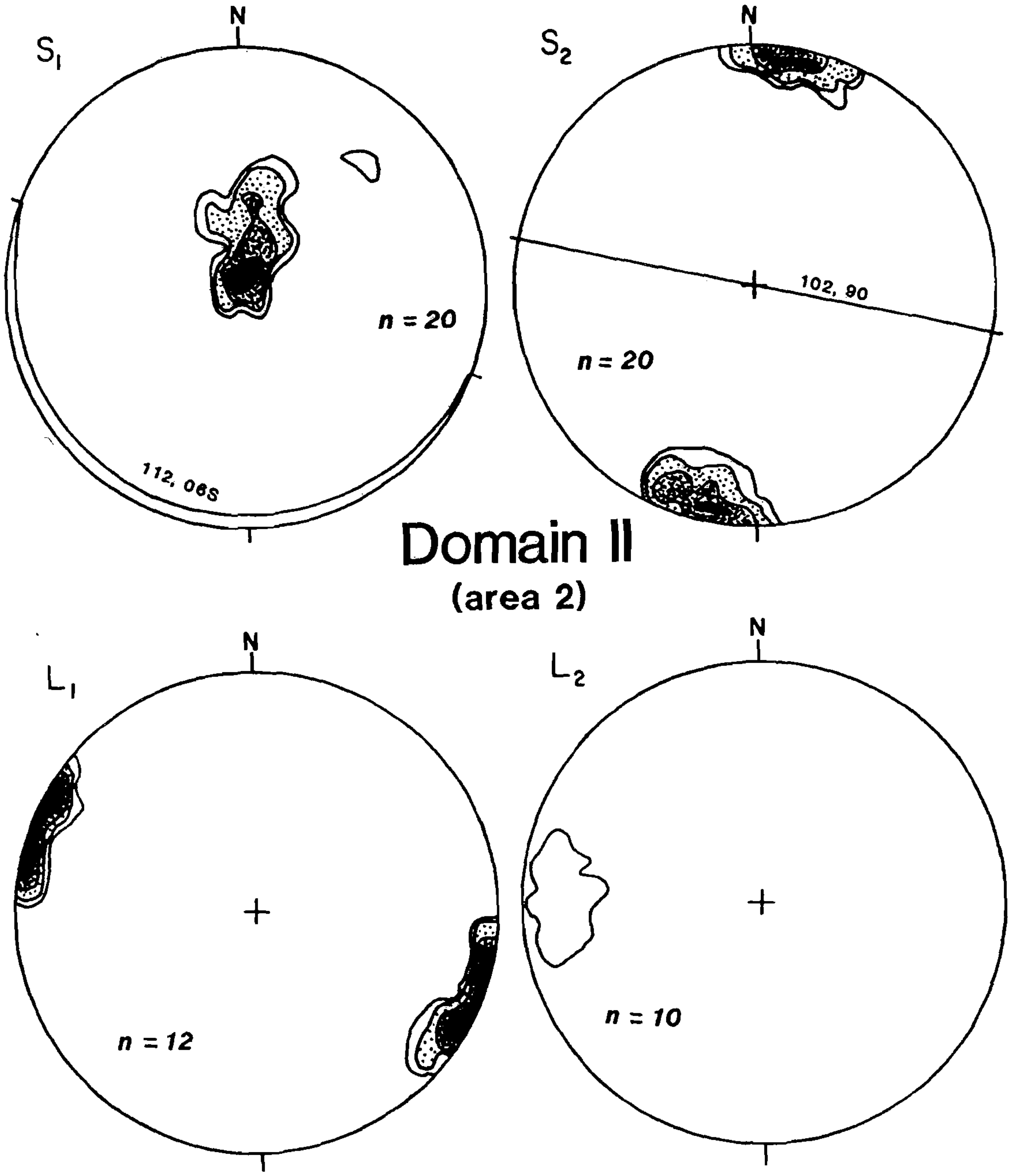

Figure 34. Stereographic projections of S-poles for penetrative structures from Domain II, area 2 (contours are at 1 pt., 10%, 20% and 30% per 1 % area).

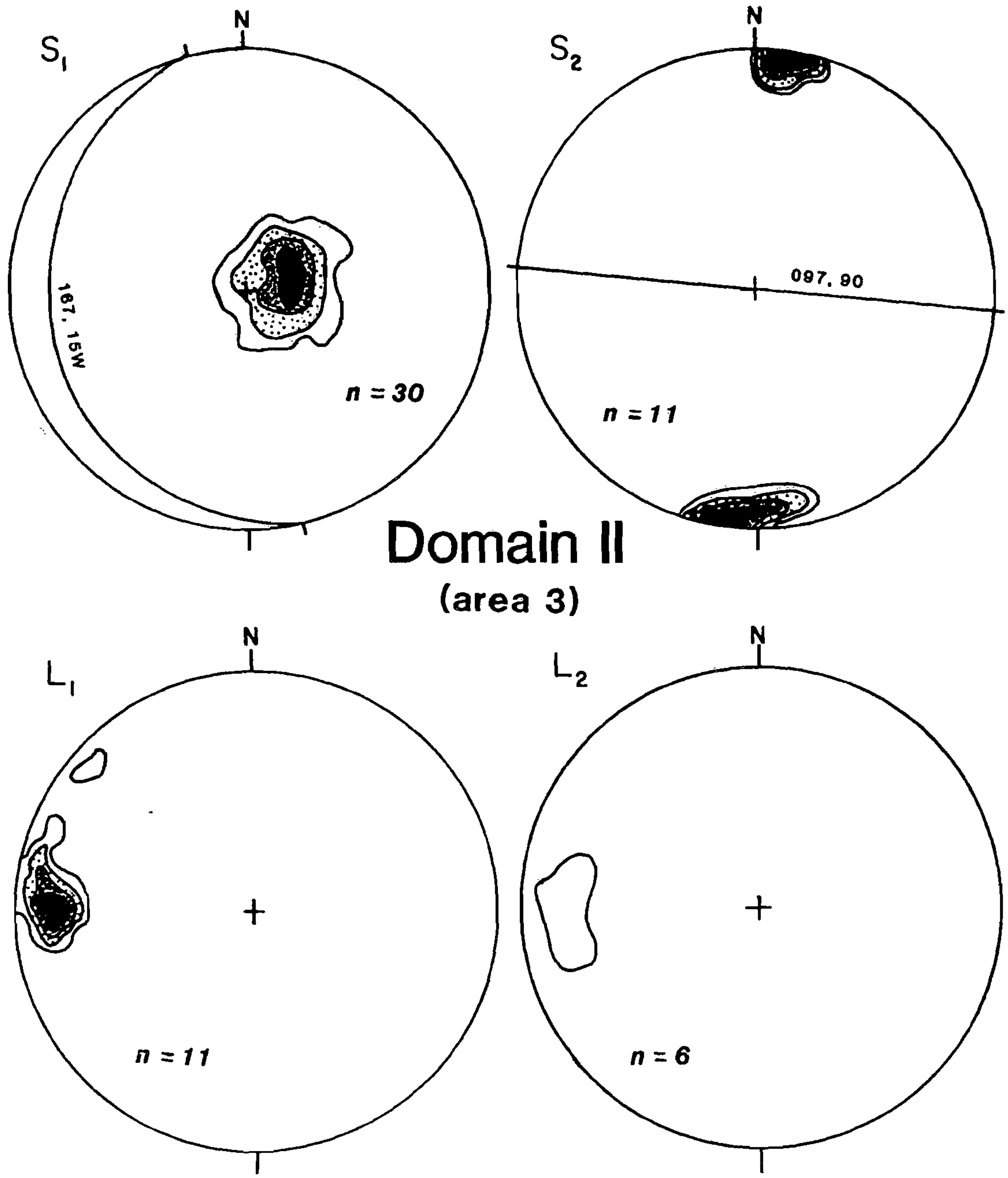

Figure 35. Stereographic projections of S-poles for penetrative structures from Domain II, area 3 (contours are at 1 pt., 10%, 20% and 30% per 1% area).

field area (south of station 24 on Plate III and inset map on Plate II). The distinguishing characteristic of this domain is the presence of a third deformational component, B_3. However, dramatic changes in the style of B_2 folding within the boundaries of the domain (see previous chapter on local geologic setting and structural features) requires the division into three subdomains. Figs. 36 through 38 present stereographic projections of S_1, L_1 (where available), S_2, L_2 (where available) and S_3 (where available) for Domains IIIa, IIIb and IIIc.

Two aspects of B_3 deformation are observed in the field. The most obvious evidence is seen in the reorientation of S_2 crenulation cleavage attitudes. From the end of Domain II at station 24 to the southern terminus of the survey line at station 30, S_2 has undergone a rotation of approximately 70 degrees about a horizontal axis that trends east-northeast (Fig. 39).

The only mesoscopic expression of B_3 fabric occurs as a spaced S_3 cleavage that is restricted to a few siltstone outcrops within Domain IIIc (see previous chapter on local geologic setting and structural features for a description of this fabric). Stereonet data for S_3 is presented in Fig. 38 and Fig. 31. As can be seen, the strike of S_3 is coincident with the axis of rotation for S_2 presented in Fig. 39.

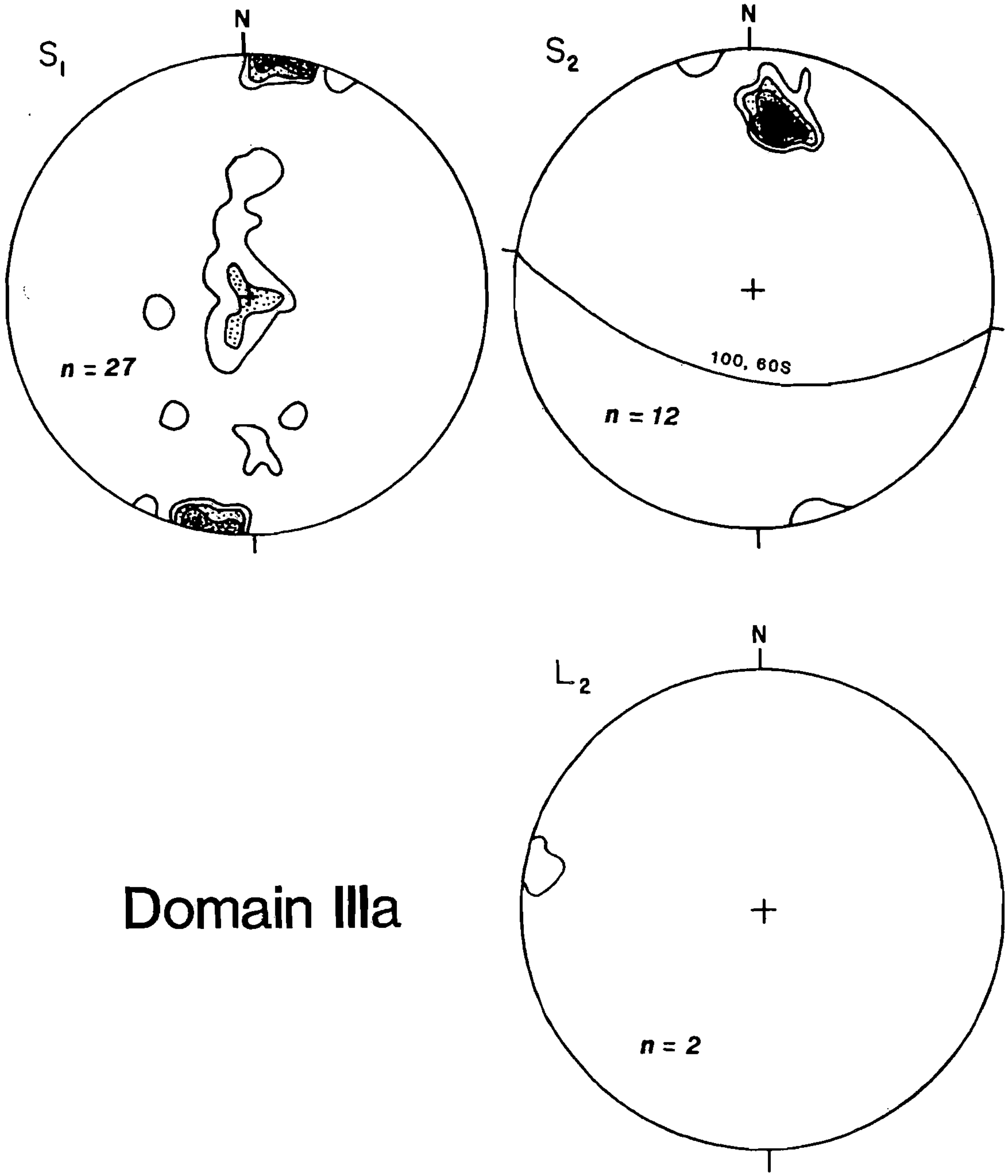

Figure 36. Stereographic projections of S-poles for penetrative structures from Domain IIIa (contours are at 1 pt., 10%, 20% and 30% per 1% area).

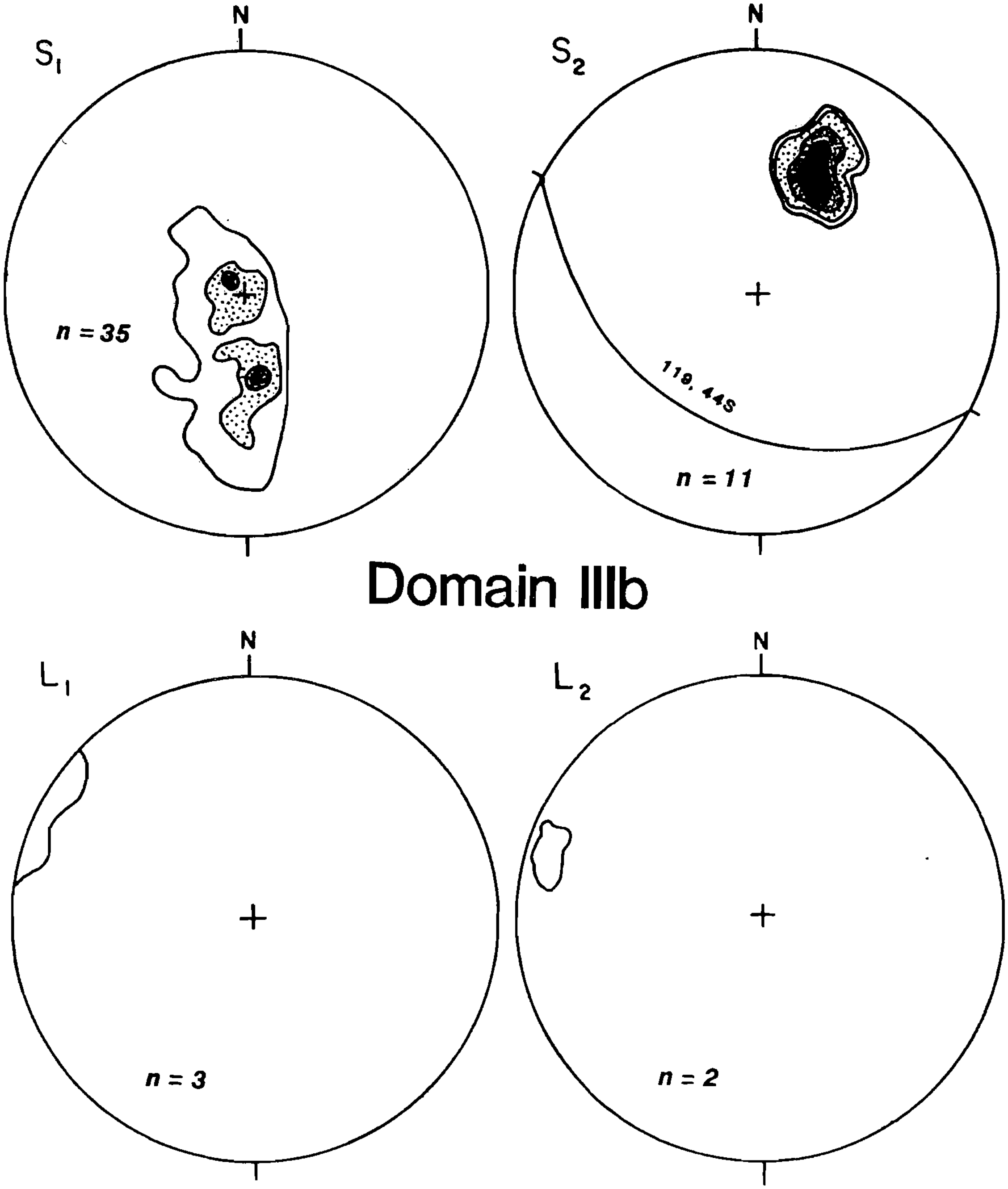

Figure 37. Stereographic projections of S-poles for penetrative structures from Domain IIIb (contours are at 1 pt., 10%, 20% and 30% per 1% area).

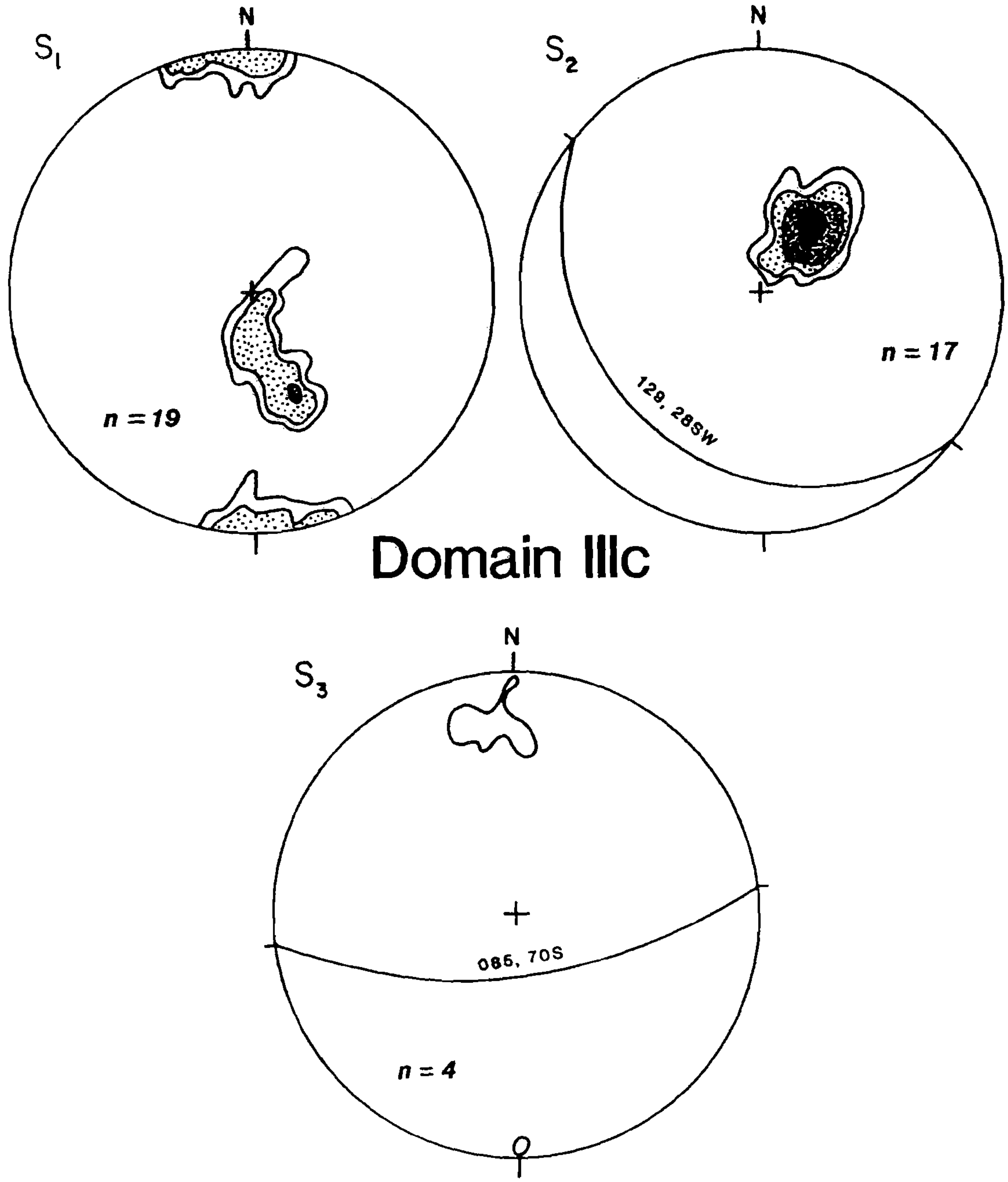

Figure 38. Stereographic projections of S-poles for penetrative foliations from Domain IIIc (contours are at 1 pt., 10%, 20% and 30% per 1% area).

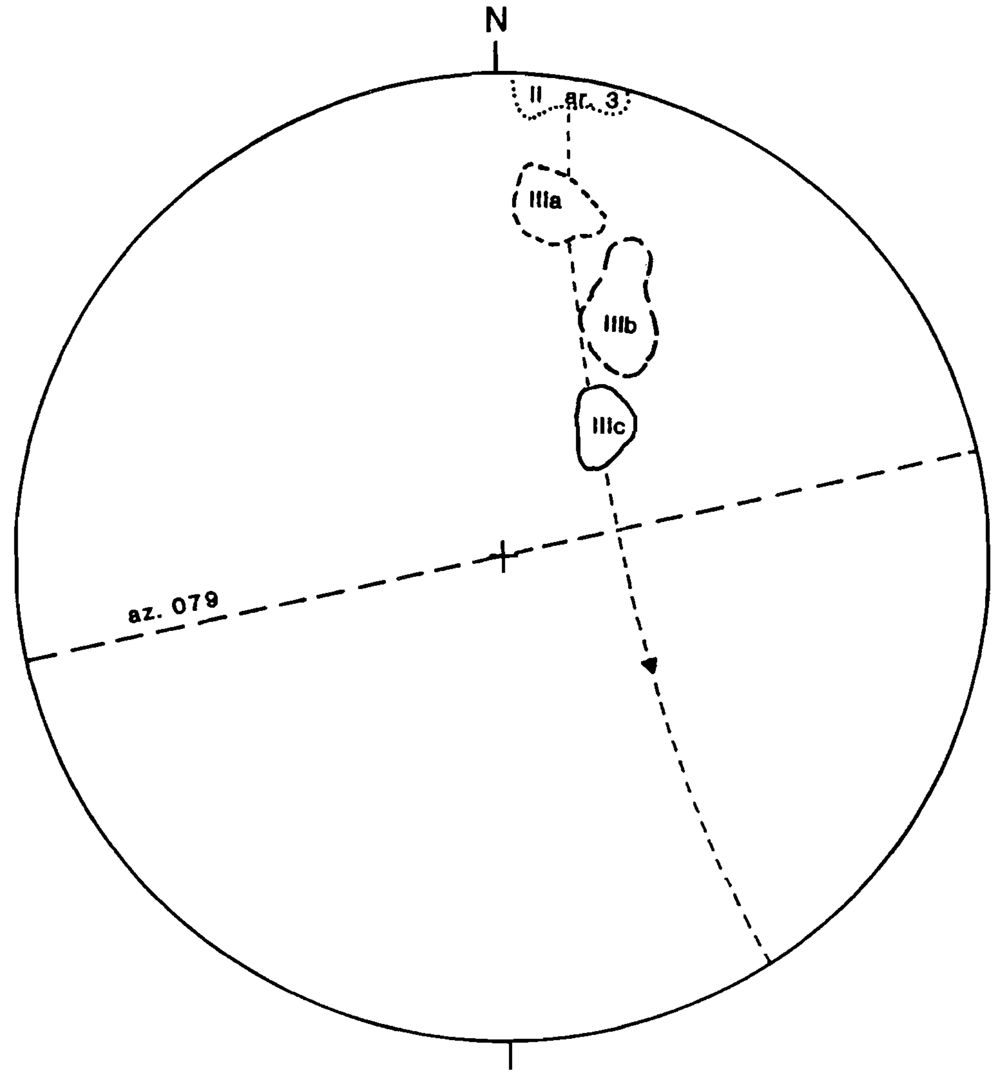

Figure 39. Stereographic projection displaying progressive rotation of the 30% contour interval for S_2 crenulation cleavage S-poles, Domains II (area 3) through IIIc.

Relationship of Non-penetrative Features to Deformational Events

Faults

Fig. 40 represents the orientations of thrust fault surfaces located within Domain I. The S_1-parallel relationship of the fault system in the field area is immediately obvious when this stereonet is compared with the S_1 stereonet presented in Fig. 32. Although stereonet data from B_2-deformed areas are not presented here, field evidence (see previous section on local geologic setting and structural features) indicates that fault surfaces and S_1 cleavages were synchronously deformed by the B_2 event.

Joints

The orientations of joints over the entire field area are presented in Fig. 41. As can be seen, most joints are steeply dipping to vertical, with highly variable strikes. Domainal separation of joint data reveals no discernable relationships. For the most part, the multiplicity of deformational events eliminates the possibility of quantitatively analyzing joint patterns. A notable exception to this case occurs with those joint systems that display localized quartz mineralization (Fig. 42). Hobbs and others (1976) have developed a diagram of typical joint

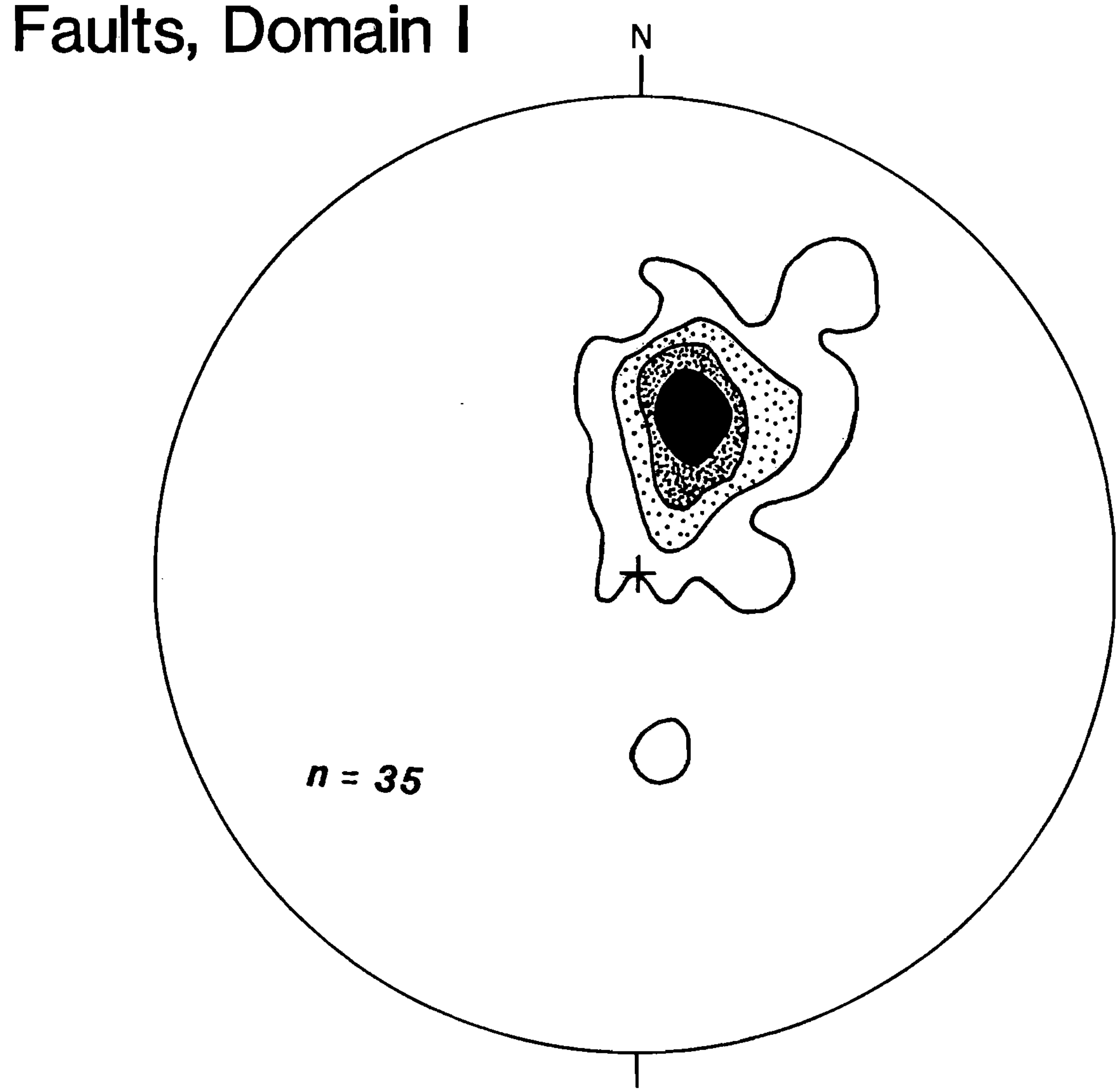

Figure 40. Stereographic projection of S-poles for fault surfaces within Domain I (contours are at 1 pt., 10%, 20% and 30% per 1% area).

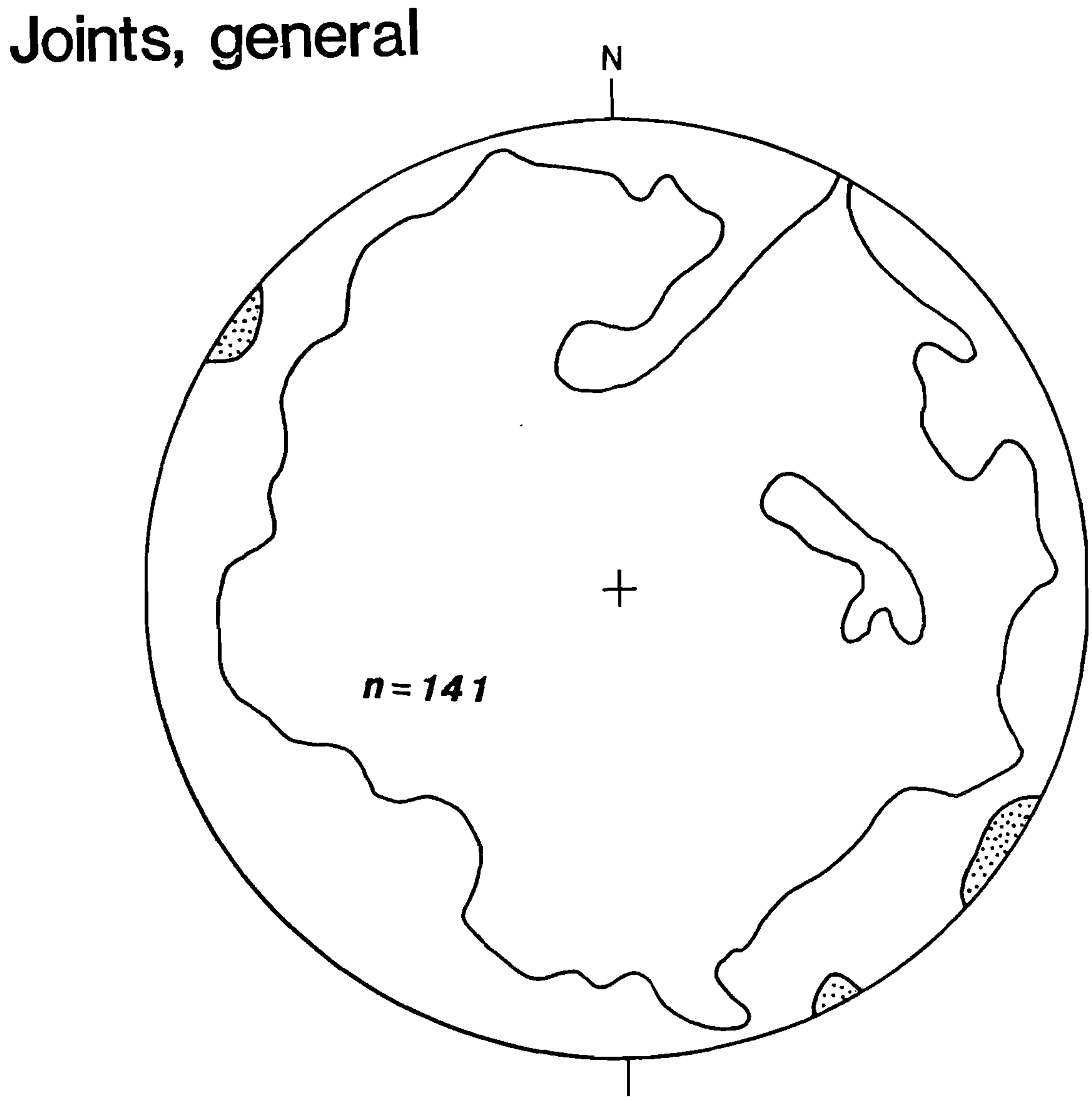

Figure 41. Stereographic projection of S-poles for joint surfaces throughout the entire field area (contours are at 1 pt. and 10% per 1% area).

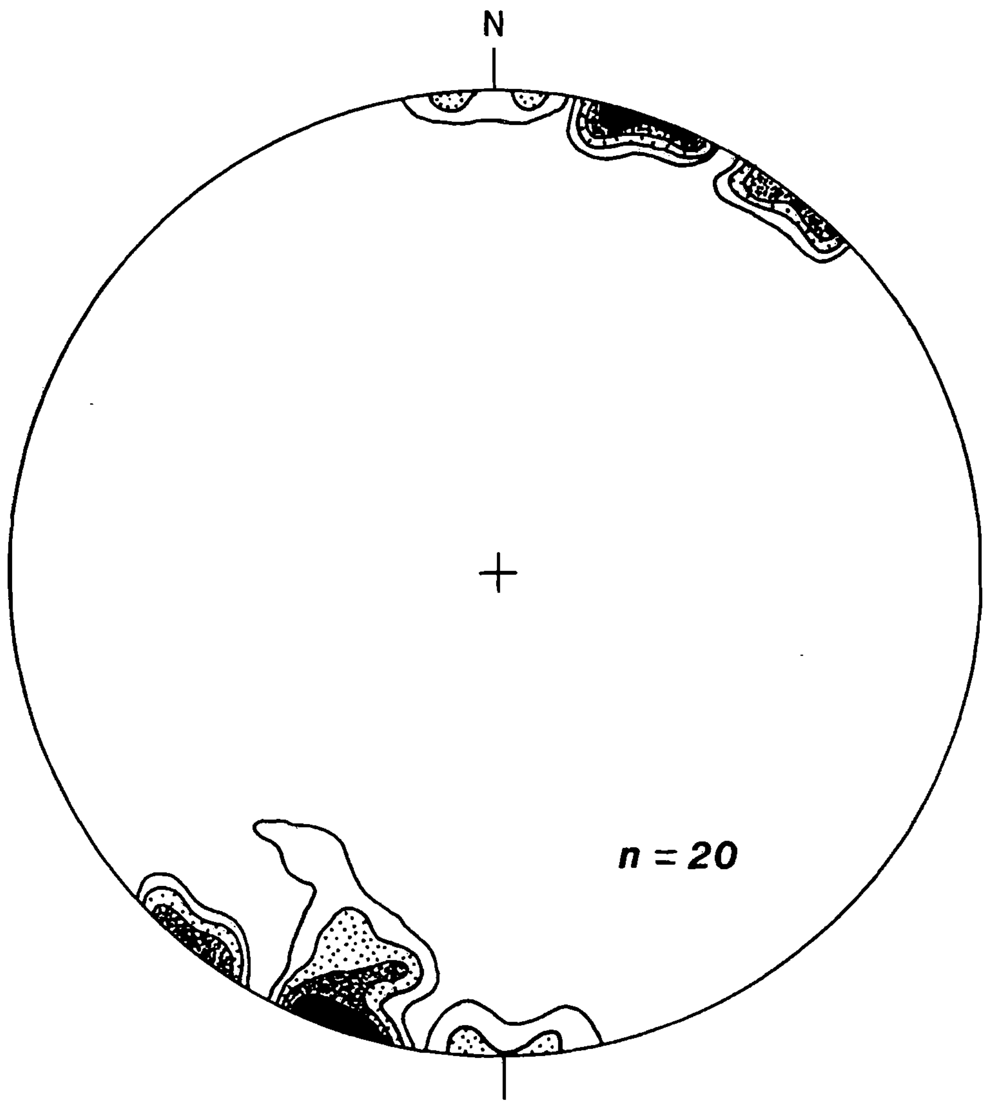

Figure 42. Stereographic projection of S-poles for joint surfaces displaying quartz mineralization (contours are at 1 pt., 10%, 20% and 30% per 1% area).

patterns in a simple fold system (Fig. 43). When compared to this diagram, the quartz-mineralized joints observed in the field area appear consistent in orientation with the expected patterns for B_2-related radial joints (no. 3 in Fig. 43). However, the proximity of these mineralized joints to known fault zones suggests the alternate possibility that they may be representative of some fault-related tensional (tearing?) forces.

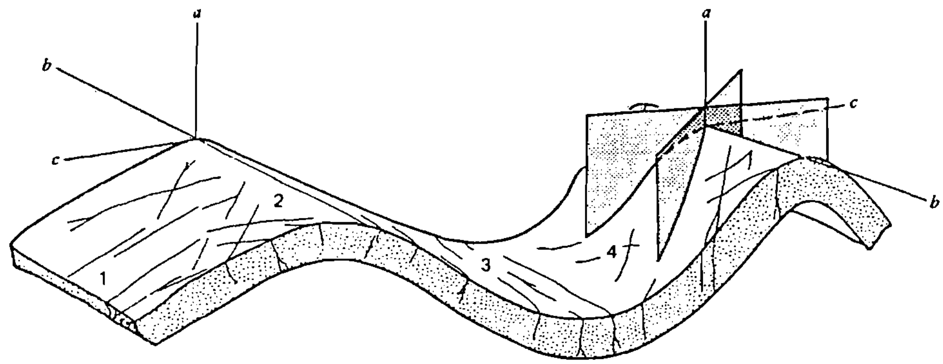

Figure 43. Common joint patterns in folded rocks (Hobbs et. al., 1976).

DISCUSSION

Slates are a common rock type in orogenic belts throughout the world. The usefulness of slates in the analysis of the mechanics of orogenic events is considerable, as they are generally only mildly metamorphosed (greenschist facies), contain abundant layer-silicate minerals, and preserve much of their primary sedimentary structures, even after multiple deformation.

The morphology of slate terranes is variable, but they are commonly seen as narrow, elongate belts of outcrop oriented parallel to the regional strike of the orogenic front; hence the use of "slate belt" as a general descriptive term of this structural association (Hobbs et. al., 1976). Classic Phanerozoic examples of such terranes include the Cambrian slates of North Wales and the deformed Ordovician flysch sequences of the Taconic Allochthon in eastern New York. Although the above term has never been specifically applied to this region, the deformed Lower Proterozoic sedimentary sequence of the northern Great Lakes region could be considered as a similar type of terrane related to Penokean orogenesis.

A series of stylized cross-sections representative of the possible sequence of events leading to the deformational features seen in the Falls River area is given in Figure 44. A description of this figure is given below.

Deposition and lithification of the sediments ("A" in

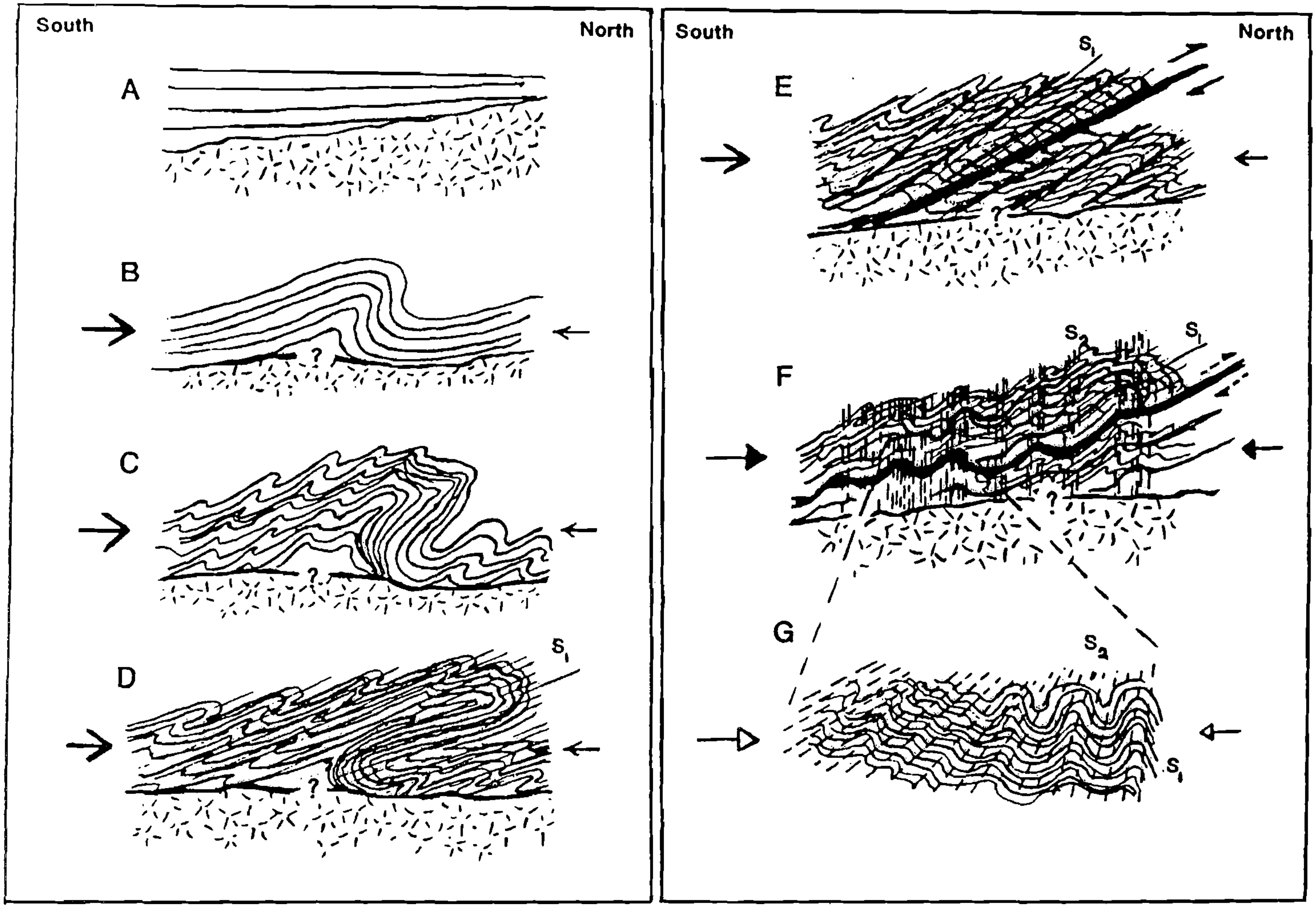

Figure 44. Sequence of events proposed as an explanation of the major structural features observed in the deformed rocks of the Falls River area (see text for description).

Fig. 44) probably occurred synorogenically in a rapidly subsiding eugeosynclinal environment (see chapter on regional geology and tectonic setting). North-south compressional forces resulted in the onset of deformation and the initiation of a fold system (B_1) in the sedimentary rocks ("B" in Fig. 44), possibly facilitated by a large-scale detachment surface at the Lower Proterozoic-Archean interface (see chapter on regional geology and tectonic setting). The development of a northward-directed shear couple resulted in an enhancement of the asymmetry of regional folds, overturning them towards recumbency ("C" and "D" in Fig. 44). At some time a regional slaty cleavage developed perpendicular to the direction of maximum shortening strain ("D" in Fig. 44). Localized variations of the stress field accentuated the development of smaller-scale parasitic asymmetric folds on the long limbs of regional folds (i.e., the first-order B_1 fold system in the Falls River area) and precluded extensive development of such fold systems on the short limbs. Instead, it is possible that large-scale thrust faults eventually developed along the short limbs of these regionals, resulting in various degrees of lateral displacement ("E" in Fig. 44). The smaller-scale thrust faults in the field area may be reflections of this regional overthrusting.

Evolution of the northward-directed regional compressional stress field resulted in a cessation of the development of B_1 folds and the thrust faulting, and resulted in a series of comparatively gentle second-generation folds (B_2) that overprinted preexisting features ("F" in Fig. 44). S_2 crenulation cleavage is the axial planar foliation associated with these folds, as the mechanical homogeneity induced in the rocks by the pervasive S_1 fabric prevents the later development of a similar (slaty) B_2 fabric (W. Gregg, personal communication).

Mechanisms responsible for the development of B_3, the third period of deformation ("G" in Fig. 44), are somewhat cryptic. The orientation of the macroscopic fold axis is roughly coaxial to those for the previous fold systems, inferring the continued presence of a general north-south compressional force. Therefore, it is possible that the B_3 system is a late-stage expression of Penokean deformational activity. Fold systems appear to be large in scope and are not immediately visible at outcrop scale. The proposed axial-planar foliation for this system (S_3) is very restricted in occurrence and does not resemble either of the two previous tectonically-induced rock fabrics. The morphology in thin-section consists of a series of widely spaced simple fractures and discolored seams, with no associated reorientation of layer-silicate minerals. In short, its appearance resembles a closely spaced set of joints. It should be noted that a large vertical Keweenawan diabase dike in the vicinity of the occurrence of S_3 has a strike coincident with the strike of S_3 and the trend direction of the proposed B_3 rotational axis (see previous chapter on geometrical analysis). However, the idea that Keweenawan-age processes are responsible for such a significant rotation of Penokean features is speculative.

There are several factors that suggest that the structural features (B_1-related features in particular) observed in the Falls River area and other locations in the western Marquette Range could be explained by a mechanism of allochthonous displacement of the Lower Proterozoic sequence via large-scale thrusts and nappe-style folding:

1) Observations of vergence sense for regional B_1 fold systems in the Michigamme Formation all indicate positions on the long limb of an asymmetric overturned B_1 regional fold system. Vergences indicative of a position along the short limb are not seen.

2) The development of a system of S_1 parallel thrust faults may reflect the existence of a large-scale system of overthrusting.

3) A very large B_1 synclinal axis at Little Mountain, approximately 1 mile south of the field area, may be representative of the hinge region of a B_1 regional nappe fold.

4) A lateral progression along strike of regional structure from intense folding (the Falls River area) to fault-dominated deformation (the east branch of the Huron River, as described by Van Roosendaal, 1985) is a feature observed in many fold-and-thrust situations (Hobbs et. al., 1976)

5) A noticable change in the style and orientation of B_1 deformational features several miles south of the field area (the Taylor Mine area, as described by Klasner, 1972) might be explained by the presence of a major structural discontinuity (a thrust fault?).

6) The existence of large-scale fault contacts between the Archean basement and the overlying sedimentary pile (Klasner, 1972; Cannon, 1973) may indicate the presence of a decollement surface, which is consistent with the idea of large-scale allochthonous movement.

7) The marked similarities between deformational features in the Lower Proterozoic of the western Marquette Range and many of those in Phanerozoic allochthonous terranes, particularily the Ordovician-age Taconic Allochthon (Bosworth and Vollmer, 1981; W. Gregg, personal communication) suggest that similar processes may have been operating during the Penokean Orogeny.

SUMMARY

This study consisted of an intensive descriptive analysis of the structural features present in the Lower Proterozoic sequences of the northernmost mile of the Falls River. A general overview of observations is given below.

Three folding events, roughly coaxial in nature, are recognized. The first (style group B_1) is characterized within the field area by a ubiquitous set of tight to isoclinal asymmetric overturned folds in S_0 bedding surfaces. Small-scale (second-order) parasitic folds are commonly associated with these larger (first-order) folds. Axes are either subhorizontal or plunging gently in west-northwestly and east-southeastly directions. S_1 slaty cleavage (or its domainal equivalent in psammitic units) is the axial planar foliation associated with this fold system. The average dips of S_1 in areas unaffected by later-stage deformational events indicates that the B_1 axial surface strikes west-northwest and dips moderately to the south-southwest. Vergence of the first-order folds is indicative of a position on the long limb of a regional B_1 fold system, with a large-scale synclinal axis somewhere to the south of the field area.

The second folding event (style group B_2) visibly overprints B_1 structural features. The most common expression of B_2 deformation occurs as an irregular series of gentle to moderate asymmetric folds and flexures in S_1

cleavage surfaces throughout the northern two-thirds of the field area. The orientation of S_2 crenulation cleavage surfaces in areas unaffected by later (B_3) deformation reflects the roughly east-west trending, vertical to steeply dipping orientation of the B_2 axial surface. The appearance of tight, often symmetrical B_2 folds and strongly developed S_2 cleavage towards the southern third of the field area indicates an increase of B_2 deformational intensity towards the south, and the possible existence of a B_2 regional hinge.

The most visible expression of the third folding event (style group B_3) is seen as a substantial progressive reorientation of B_2 fabric elements over the approximate distance of a third of a mile near the southern end of the survey line. The fold system is macroscopic (i.e., no mesoscopic B_3 hinge regions are identified), and probably simple in morphology. The trend of the fold axis (see chapter on geometric analysis) is approximately coaxial to the axes of the two earlier fold systems. The appearance of an axial planar S_3 spaced cleavage is restricted to the southern terminus of the survey line.

The most important set of non-penetrative structural features within the field area is a system of small-scale faults that possess an inferred reverse (thrusting) sense of movement. Fault surfaces generally display a parallel relationship with S_1 cleavage. Quartz and carbonate mineralization is associated with some fault zones. Fault surfaces are visibly folded in those areas affected by second-generation (B_2) deformation. This indicates that the development of the fault system (and subsequent mineralization of some fault zones) postdates the onset of B_1 deformation and the formation of S_1 cleavage, and predates the onset of B_2 deformation.

Joint systems are extensive and complex. The number of deformational events makes determination of the origin of specific joint sets difficult. A possible exception to the above occurs in the case of quartz-mineralized joints, which display a consistent orientation reflective of a crude symmetry with respect to either B_2 fold axes or the thrust fault system. The proximity of these mineralized joints to fault zones appears to suggest the latter.

Structural domains in the field area are delineated by the progressive appearance of physical evidence for each particular fold system. Domain I contains elements of style group B_1 alone. Domain II occurs as localized zones within the Domain I boundary and is characterized by aspects of B_1 and B_2 deformation. Domain III is distinguished by the introduction of B_3 deformation, which overprints all previously existing fabric elements.

The styles of deformation observed in the Falls River area are consistent with a hypothetical model involving early-stage nappe-style tectonics and overthrusting. Continued, though subdued, compressional forces resulted in an overprinting by relatively moderate later-stage structures. In general, structural features are remarkably similar to those seen in other terranes where allochthonous displacement processes have been recognized.

REFERENCES

Barrett, L.P., 1927, Huronian slate areas of northeastern Baraga County, Michigan (abs.). Geol. Soc. Am. Bull., v. 38, p. 117.

Beutner, E.C., 1978a, Slaty cleavage and related strain in Martinsburg Slate, Delaware Water Gap, New Jersey. Am. J. Sci., v. 278, p. 1-23.

Beutner, E.C., 1978b, Clastic dikes, tectonic dewatering and slaty cleavage: an unrelated trio (abs.). Geol. Soc. Am. annual meeting South-Central Section 12th Ann. Mtg., abs., p. 2.

Beutner, E.C. 1980, Slaty cleavage unrelated to tectonic dewatering: The Siamo and Michigamme slates revisited. Geol. Soc. Am. Bull., v. 91, p. 171-178

Beutner, E.C., Jancin, M.D. and Simon, R.W., 1977, Dewatering origin of cleavage in light of deformed calcite veins and clastic dikes in Martinsburg slate, Delaware Water Gap, New Jersey. Geology, v. 5, p.118-122.

Bodwell, W.A., 1972, Geologic compilation and non-ferrous metal potential, Precambrian section, northern Michigan (unpub. M.S. thesis). Michigan Technological University, Houghton, Mich., 106 p.

Bosworth, W. and Vollmer, F. W., 1981, Structures of the medial Ordovician flysch of eastern New York: deformation of synorogenic deposits in an overthrust environment. J. Geology, v. 89, p.551,568.

Boulter, C.A., 1974, Tectonic deformation of soft sedimentary clastic dikes from the Precambrian rocks of Tasmania, Australia, with particular reference to their relations with cleavages. Geol. Soc. Am. Bull., v. 85, p. 1413-1420.

Braun, G., 1967, Neus Jahrbuch Fur Mineralogie, Monats., Heft 11, p. 469-476

Brown, B.A. and Greenberg, J.K., 1984, Early Proterozoic structures of northeastern Wisconsin as constraints on the Penokean tectonic models (abs.). 30th Institute on Lake Superior Geology, Wausau, Wisc., p. 4

Burns, G.K., 1975, Middle Precambrian black slate of the Baraga Basin, Baraga County, Michigan (unpub. M.S. thesis). Bowling Green University, Bowling Green, Ohio, 129 p.

Cambray, F.W., 1978, Plate tectonics as a model for the environment of deposition and deformation of the early Proterozoic (Precambrian X) of northern Michigan (abs.). Geol. Soc. Am. Abstracts with Programs, v. 10, p. 376.

Cannon, W.F., 1973, The Penokean orogeny of northern Michigan. Geol. Assoc. Can. Special Paper 12 (Huronian Stratigraphy and Sedimentation; G.M. Young, ed.), p. 251-271.

Cannon, W.F. and Gair, J., 1970, A revision of stratigraphic nomenclature for Middle Precambrian rocks in northern Michigan. Geol. Soc. Am. Bull., v. 81, p. 2843-2846.

Cannon, W.F. and Klasner, J.S., 1972, Guide to Penokean deformational style and regional metamorphism of the western Marquette Range, Michigan. Field Trip Descriptions and Road Logs (W.I. Rose, ed.), 18th Institute on Lake Superior Geology, Houghton, Mich., p. B1-B38.

Faure, G. and Kovach, J., 1969, The age of the Gunflint Iron Formation of the Animikie Series in Ontario, Canada. Geol. Soc. Am. Bull., v. 80, p. 1725-1736.

Fleuty, M.J., 1964, The description of folds. Geologists' Assoc. Proceedings, v. 75, p. 461-492.

Geiser, P.A., 1974, Cleavage in some sedimentary rocks of the central Valley and Ridge province, Maryland. Geol. Soc. Am. Bull., v. 85, p. 1399-1412.

Geiser, P.A., 1975, Slaty cleavage and the dewatering hypothesis--an examination of some critical evidence. Geology, v. 3, p. 717-720.

Goldich, S.S., 1972, The Penokean Orogeny (abs.). 18th Institute on Lake Superior Geology, Houghton, Mich., paper 25.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H. and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota. Minn. Geol. Surv. Bull. 41, 193 p.

Gray, D.R., 1977, Morphologic classification of crenulation cleavage. J. Geology, v. 85, p. 229-235.

Gray, D.R., 1978, Cleavages in deformed psammitic rocks from southeastern Australia: their nature and origin. Geol. Soc. Am. Bull., v. 89, p. 577-590.

Gray, D.R., 1979, Microstructure of crenulation cleavages: an indicator of cleavage origin. Am. J. Sci., v. 279, p. 97-128.

Greenberg, J.K. and Brown, B.A., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district. Geol. Soc. Am. Mem. 160 (Early Proterozoic Geology of the Great Lakes Region, L.G. Medaris, ed.), p. 67-84.

Gregg, W.J., 1979, The redistribution of pre-cleavage clastic dikes by folding at New Paltz, New York. J. Geol., v. 87, p. 99-104.

Gregg, W.J., 1986, Deformation of chlorite-mica aggregates in cleaved psammitic and pelitic rocks from Isleboro, Maine, U.S.A. J. Structural Geol., v. 8, no.1, p. 59-68.

Hobbs, B.E., Means, W.D. and Williams, P.F., 1976, An Outline of Structural Geology. John Wiley and Sons, pub., New York, 571 p.

Hoffman, J., 1983, The occurrence and character of the graphitic slate within the Michigamme Formation. Geol. Surv. Div., Michigan Department of Natural Resources, Box 30028 Lansing, Michigan 48909, unpub. open-file report.

Holst, T.B., 1982, Evidence for multiple deformation during the Penokean Orogeny in the Middle Precambrian Thomson Formation, Minnesota. Can. J. Earth Sci., v. 19, p. 2043-2047.

Holst, T.B., 1984, Evidence for nappe development during the Early Proterozoic Penokean orogeny, Minnesota. Geology, v. 12, p. 135-138.

James, H.L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan. Geol. Soc. Am. Bull., v. 66, p. 1455-1488

James, H.L., 1958, Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan. U.S. Geol. Surv. Professional Paper 314-C, p. 27-44.

Klasner, J.S., 1972, Style and sequence of deformation and associated metamorphism due to the Penokean orogeny in the western Marquette Range, northern Michigan (unpub. Ph.D. thesis). Michigan Technological University, Houghton, Mich., 132 p.

Klasner, J.S., 1978, Penokean deformation and associated metamorphism in the western Marquette Range, northern Michigan. Geol. Soc. Am. Bull., v. 89, p.711-722.

Laberge, G.L., Schultz, K.J. and Myers, P.E., 1984, The plate tectonic history of north-central Wisconsin (abs.). 30th Institute on Lake Superior Geology, Wausau, Wisc., p. 25-27.

Larue, D.K., 1981, The Chocolay Group, Lake Superior region, U.S.A.: sedimentological evidence for deposition in basinal and platform setttings on an Early Proterozoic craton.

Geol. Soc. Am. Bull., Part I, v. 92, p.417-435.

Larue, D.K., 1983, Early Proterozoic tectonics of the Lake Superior region: tectonostratigraphic terranes near the purported collision zone. Geol. Soc. Am. Mem. 160 (Early Proterozoic Geology of the Great Lakes Region, L.G. Medaris, ed), p. 33-47.

Larue, D.K., and Sloss, L.L., 1980, Early Proterozoic sedimentary basins of the Lake Superior region. Geol. Soc. Am. Bull., part I, v. 91, p. 450-457.

Leith, C.K., Lund, R.J. and Leith, A., 1935, Pre-Cambrian rocks of the Lake Superior region. U.S. Geol. Surv. Professional Paper 184, 34 p.

Maharidge, A.D., Mancuso, J.J. and Onasch, C.M., 1986, Tectonic evolution of the Felch Trough (abs.). 32nd Institute on Lake Superior Geology, Wisconsin Rapids. Wisc., p. 53-54

Mancuso, J., Laugheed, M., Seavoy, R. and Shaw, R., 1975, The significance of the cherty iron formation, Baraga Basin, Michigan (abs.). 21st Institute on Lake Superior Geology, Marquette, Mich., p. 25.

Mancuso, J., Laugheed, M. and Shaw, R., 1975, Carbonate-apatite in Precambrian cherty iron formation, Baraga County, Michigan. Econ. Geol., v. 70, p. 583-586.

Maxwell, J.C., 1962, Origin of slaty and fracture cleavage in the Delaware Water Gap area, New Jersey and Pennsylvania. Geol. Soc. Am. Buddington volume, p. 281-311

Morey, G.B., 1983, Lower Proterozoic stratified rocks and the Penokean Orogeny in east-central Minnesota. Geol. Soc. Am. Mem. 160 (Early Proterozoic Geology of the Great Lakes Region, L.G. Medaris, ed.), p.97-112.

Powell, C.McA., 1972, Tectonic dewatering and strain in the Michigamme slate, Michigan. Geol. Soc. Am. Bull., v. 83, p. 2149-2158.

Schultz, K.J., 1984, Early Proterozoic igneous rocks of the Lake Superior region: geochemistry and tectonic implications (abs.). 30th Institute on Lake Superior Geology, Wausau, Wisc., p. 65-66.

Sims, P.K., Card, K.D., Morey, G.B. and Peterman, Z.E., 1980, The Great Lakes tectonic zone--a major crustal structure in North America. Geol. Soc. Am. Bull., Part I, v. 91, p.690-698.

Sims, P.K. and Peterman, Z.E., 1983, Evolution of Penokean fold-belt, Lake Superior region, and its tectonic environment. Geol. Soc. Am. Mem. 160 (Early Proterozoic Geology of the Great Lakes Region, L.G. Medaris, ed.), p. 3-14

Spiroff, K., 1964, Arvon slate deposits, Baraga County, Michigan (abs.). 10th Institute on Lake Superior Geology, Ishpeming, Mich., p. 33.

Stauffer, M.R., 1970, Deformation textures in tectonites. Can. J. Earth Sci., v. 7, p. 498-511.

Trow, J., 1979, Final report diamond drilling for geologic information in the middle Precambrian basins in the western portion of northern Michigan. Geol. Surv. Div., Michigan Department of Natural Resources, Box 30028 Lansing, Michigan 48909, Open-File Report UDOE OFR GJBX-162(79), 44 p.

Turner, F.J. and Weiss, L.E., 1963, Structural Analysis of Metamorphic Tectonites. McGraw-Hill, pub., New York, 545 p.

Tyler, S.A. and Twenhofel, W.H., 1952, Sedimentation and stratigraphy of the Huronian of upper Michigan. Am. J. Sci., v. 250, p. 1-27, 118-151.

Van Roosendaal, D.J., 1985, An analysis of rock structures and strain in cleaved pelitic rocks, East Branch of the Huron River, Baraga County, Michigan (unpub. M.S. thesis). Michigan Technological University, Houghton, Mich., 82 p.

Van Schmus, W.R., 1976, Early and Middle Proterozoic history of the Great Lakes area, North America. Royal Soc. London Philosophical Transactions, ser. A, v. 280, p. 605-628.

Williams, P.F., 1972, Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia. Am. J. Sci., v. 272, p. 1-47.

Wood, D.S., 1974, My current views of the development of slaty cleavage. Ann. Rev. Earth and Planetary Sci., v. 2, p. 1-35.

Young, G.M., 1983, Tectono-sedimentary history of Early Proterozoic rocks of the northern Great Lakes area. Geol. Soc. Mem. 160 (Early Proterozoic Geology of the Great Lakes Region, L.G. Medaris, ed.), p.15-32.

Zen, E-An, 1974, Origin of the slaty cleavage in the Taconic Allochthon and age of metamorphism. U.S. Geol. Surv. Professional Paper 900, p. 24.


STRUCTURAL GEOLOGY OF THE FALLS RIVER,
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EXPLANATION
location and number of survey station
location of outcrop; hachures point towards downhill side of steep to vertical exposures
unconsolidated stream bank
cultural features, labeled as to type
location of oriented samples
CP-2
Jacobsville Sandstone
Keweenawan diabase dikes
pre-Keweenawan mafic dikes
turbidite—silty, frequently with visible laminations
turbidite—medium- to fine-grained, massive greywacke
coarse-grained greywacke
gray, green-gray, black and minor red slates
contact, general; gradational contact
contact, projected; approximate attitudes given for intrusive contacts
ang. unconf.
angular unconformable contact, approximately located
strike and dip of bedding (S_0)
strike and dip of overturned bedding (S_0)
horizontal bedding; strike of vertical bedding (S_0)
strike and dip of slaty cleavage (S_1)
horizontal slaty cleavage; strike of vertical slaty cleavage (S_1)
strike and dip of parallel bedding and slaty cleavage (S_0 and S_1)
horizontal parallel bedding and slaty cleavage; strike of vertical parallel bedding and slaty cleavage (S_0 and S_1)
strike and dip of crenulation cleavage; strike of vertical crenulation cleavage (S_2)
strike and dip of spaced cleavage (S_3)
strike and dip of joints; strike of vertical joints
strike and dip of quartz veins; strike of vertical veins
strike and dip of S_1-parallel carbonate mineralization
trend and plunge of bedding-slaty cleavage intersection lineation; trend of horizontal lineation (L_1)
trend and plunge of slaty cleavage—crenulation cleavage intersection lineation (L_2)
direction of younging
thrust fault, showing approximate dip, sawteeth on upper plate
overturned thrust fault, showing approximate dip, sawteeth pointing towards upper plate
thrust fault, approximately located
thrust fault, conjectural (existence uncertain)
thrust fault, projected under mapped units
quartz-mineralized fault zone, showing approximate dip
trend and plunge direction of fault-associated lineations
axis of major B_1 overturned anticline, showing plunge
axis of major B_1 overturned syncline, showing plunge
horizontal axis of major B_1 overturned anticline
horizontal axis of major B_1 overturned syncline
recumbent and moderately reclined major B_1 folds, showing sense of closure
axis of major B_1 overturned antiformal syncline
axis of major B_1 overturned synformal anticline
small-scale B_1 overturned folds
small-scale B_1 anticlines and synclines
small-scale asymmetric B_1 anticlines and synclines
approximate location of B_1 fold axis
conjectural B_1 fold axis (existence uncertain)
B_1 fold axis, projected under mapped units
strike and dip of B_2 fold axial surface; horizontal axial surface
approximate location of B_2 fold axial hinge, conjectural B_2 fold axial hinge
trend and plunge direction of B_2 folds too small to be plotted individually, outline of folds seen in profile
inferred location of B_2 fold axial hinge
PLATE I
N
PLATE 1
Domain II (area I)
S_1
S_2
N
Domain I
contour intervals, in % per 1% area
30 %
20 %
10 %
1 pt. (not %)
SCALE: 1:240
1 inch = 20 feet
UPPCO water outlet
bridge to Celotex
Celotex Inc. haul bridge
PLATE I
(reference map)


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1986
PLATE 2
REFERENCE MAP SHOWING DOMAIN BOUNDARIES
PLATE 1 | PLATE 2
PLATE 2 | PLATE 3
N
SCALE: 1:1200
1 inch = 100 feet
100 0 100 200 300 400
Domain II (area 2)
Domain II (area 3)
Domain I
S_1
S_2
N
contour intervals, in %
per 1% area
30%
20%
10%
1 pt. (not %)
SCALE: 1:240
1 inch = 20 feet
20 0 20 40 60 80 100 200
(see Plate I for explanation of map symbols)
pre-Keweenawan mafic dike

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PLATE 3
N
Domain IIIa
Domain IIIb
SCALE: 1:240
1 inch = 20 feet
20 0 20 40 60 80 100 200
(see Plate 1 for explanation of map symbols)
(see Plate 2 for small-scale reference map)
PLATE 3