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NORTHWESTERN UNIVERSITY REPORT NUMBER 20

RELICT DIAGENETIC TEXTURES AND STRUCTURES IN REGIONAL METAMORPHIC ROCKS, NORTHERN MICHIGAN

(NASA GEOLOGICAL TEST SITE NUMBER 126)

by

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EVANSTON, ILLINOIS 60201

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Statistical evaluation of the composition, physical properties, and surface configuration of terrestrial test sites and their correlation with remotely-sensed data.

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PREFACE

The Northwestern University team has had a continuing interest in remote sensing of Geological Test Site #126 (comprising the Marquette and Republic Troughs, Northern Michigan). The requested radar imagery has still not been obtained by NASA but photographic imagery was made by Mission 72 in May 1968. During academic year 1967-68 Dr. C. McA. Powell was working on our project (under a postdoctoral fellowship); he was in the field (test site #126) during Mission 72 to complete some general structural observations.

While in the field, Dr. Powell collected a lot of Siamo Slate samples. Study of these has shed considerable light on the general deformation and metamorphism of rocks within the Test Site. While not immediately relevant to the remote-sensing effort, this research has direct bearing on the development of the structures that were to be remotely-sensed. Also, the results are of sufficient general scientific interest to warrant presentation at this time. The work may be considered part of the scientific 'fall out' from our main NASA effort.

Some of this research was completed during the summer of 1969 after Dr. Powell was appointed to the faculty of the University of Cincinnati in September, 1968.

ABSTRACT

Relict diagenetic textures and structures in the Siamo Slate of Northern Michigan are preserved in regionally metamorphosed rocks along the northern flank of the Marquette Synclinorium. Essentially nonmetamorphosed, folded argillites and graywackes near Negaunee have a steeply inclined slaty cleavage produced by tectonic dewatering. The cleavage is defined by thin (0.01 mm) foliae of well-oriented phyllosilicates which separate thicker quartz-rich lenses in which phyllosilicates are more randomly oriented. In places, the layering produced by the cleavage foliae is accentuated owing to reconstitution of the intrafolial phyllosilicates and to migration of silica into the interfolial lenses where it forms quartz overgrowths. Rounded detrital quartz grains are distinguished from optically-continuous quartz overgrowths by fluid inclusions, iron-oxide "dust", and minute sericite crystals.

Subsequent to cleavage formation, the Siamo Slate was regionally metamorphosed in zones which center on a sillimanite-grade node near Republic, Northern Michigan (James, 1955). The cleavage foliae, rounded detrital quartz grains with the overgrowths, and thin bedding laminations persist in the Siamo Slate through all metamorphic facies up to the staurolite grade (near the western end of the Marquette Synclinorium). Some of the large, detrital quartz grains have polygonized into smaller equidimensional, non-strained subgrains. The metamorphism involved thermal recrystallization only, without producing preferred dimensional orientation of quartz. In contrast to classical Barrovian regional metamorphism, the Northern Michigan metamorphism involved no cataclasis, mineral orientation, or schistosity development.

INTRODUCTION

The Upper Peninsula of Northern Michigan has long been the source of inspiration for many important geological concepts. It was in Upper Michigan and adjacent parts of Wisconsin that Van Hise (1904) developed his classical concepts of katamorphism and anamorphism. Van Hise's work in collaboration with Bayley and Smyth (1897) and Leith (1911) is one of the finest and clearest expositions of the geology of Northern Michigan, and the concepts developed form the basis for structural geology in North America in the early part of this century. Leith (1905), working in northern Michigan and adjacent Wisconsin, produced his definitive paper on Rock Cleavage. Studies of the banded iron formation of northern Michigan and other areas in the Lake Superior region led to some of the most important conclusions on the origin of iron formations (Govett, 1966; James, 1954, 1966), and more generally on the composition of the primitive atmosphere (Abelson, 1966; Holland, 1962).

In 1955, James described the distinctive zonal arrangement of metamorphic minerals associated with regional thermal domes. More recently, Winkler (1967) characterized the regional zonations of James as examples of regional dynamothermal metamorphism, and Ernst (1969, p. 132) described the zonal arrangement of isograds as "a fairly typical example". Both Winkler and Ernst contended that the distinctive feature of regional dynamothermal metamorphism is that the rocks develop penetrative oriented mineral fabrics. It is the purpose of this paper to document relict diagenetic textures which can be traced from the lowest greenschist facies to the staurolite grade of metamorphism in Northern Michigan, and to present the thesis that oriented mineral fabrics are not necessarily developed during regional metamorphism.

ACKNOWLEDGEMENTS

I am indebted to Professor E. H. T. Whitten for his interest and encouragement throughout the work. Discussions with Drs. A. L. Howland and E. C. Dapples of Northwestern University contributed greatly to my understanding of particular problems. Drs. Wm. F. Jenks and H. C. Sunderman of the University of Cincinnati provided helpful criticisms of early drafts of this paper.

GENERAL GEOLOGY

The Marquette Synclinorium of Northern Michigan is an early Proterozoic trough elongate east-west. Rocks within the synclinorium have been divided (James, 1958, p. 35) into three groups separated from each other by unconformities. The middle group, the Menominee Group, is subdivided into three formations: the Ajibik Quartzite at the base grades conformably into the Siamo Slate formation which, by stratigraphic transition and interdigitation, passes upwards into the Negaunee Iron Formation. My interest in the Siamo Slate was initially generated because, as a ductile unit sandwiched between the more competent Ajibik Quartzite below and the Negaunee Iron Formation above, it might be expected to provide a reasonably complete and interpretable record of the structural history.

Structural analysis of the Siamo Slate revealed two periods of deformation (Powell, 1968a). The first deformation, F_1, was the more intense and produced the main folds observed in the outcrop pattern. F_1 was accompanied by development of a quasi-vertical slaty cleavage, S_1. The presence of intrusive sandstone dykes and thin pelitic foliae parallel to the cleavage indicate that S_1 was formed by tectonic dewatering when the sediments were only partially lithified (Maxwell, 1962; Moench, 1966; and Powell, 1968b, 1969a, b). The second deformation, F_2, is a brittle deformation about a steep axis, and is most commonly represented by a crenulation lineation, L_2, pitching steeply on S_1. Apart from a few broad, open, angular folds on the outcrop scale, no large F_2 folds have been identified.

One of the unique features of Northern Michigan and adjacent parts of Wisconsin is the presence of four nodes of regional thermal metamorphism with metamorphic zones cutting across the structure (James, 1955). One of these thermal nodes, the Republic node, lies a few kilometers south of the western part of the Marquette synclinorium.

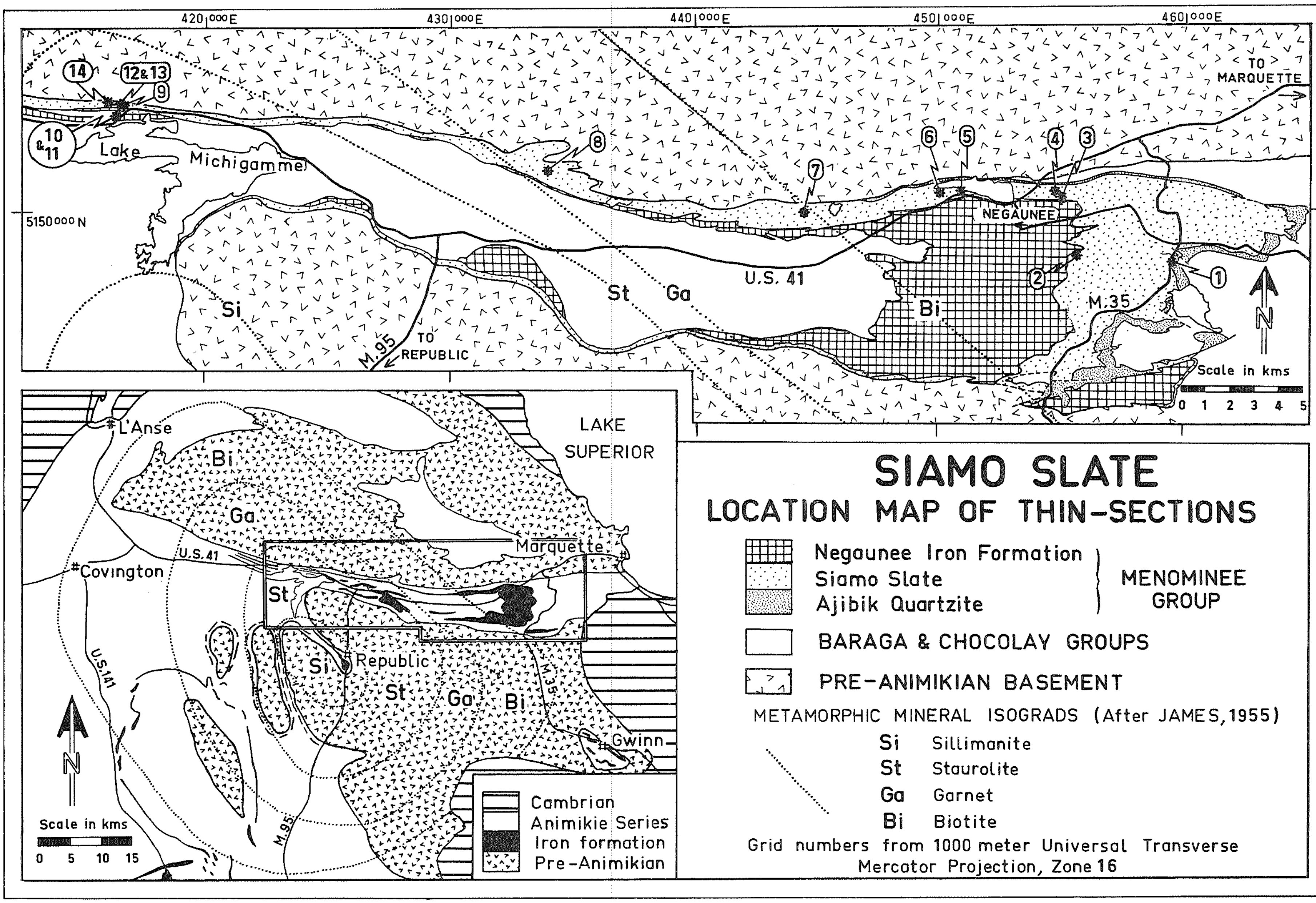

SIAMO SLATE
LOCATION MAP OF THIN-SECTIONS
Negaunee Iron Formation
Siamo Slate
Ajibik Quartzite
MENOMINEE GROUP
BARAGA & CHOCOLAY GROUPS
PRE-ANIMIKIAN BASEMENT
METAMORPHIC MINERAL ISOGRADS (After JAMES, 1955)
Si Sillimanite
St Staurolite
Ga Garnet
Bi Biotite
Grid numbers from 1000 meter Universal Transverse Mercator Projection, Zone 16
420|000E
430|000E
440|000E
450|000E
460|000E
5150000N
TO MARQUETTE
Lake Michigamme
NEGAUNEE
U.S. 41
M.35
M.95
TO REPUBLIC
Scale in kms
0 1 2 3 4 5
LAKE SUPERIOR
L'Anse
Covington
Marquette
Republic
Gwinn
U.S.41
U.S.141
Cambrian
Animikie Series
Iron formation
Pre-Animikian
Scale in kms
0 5 10 15

FIGURE 1

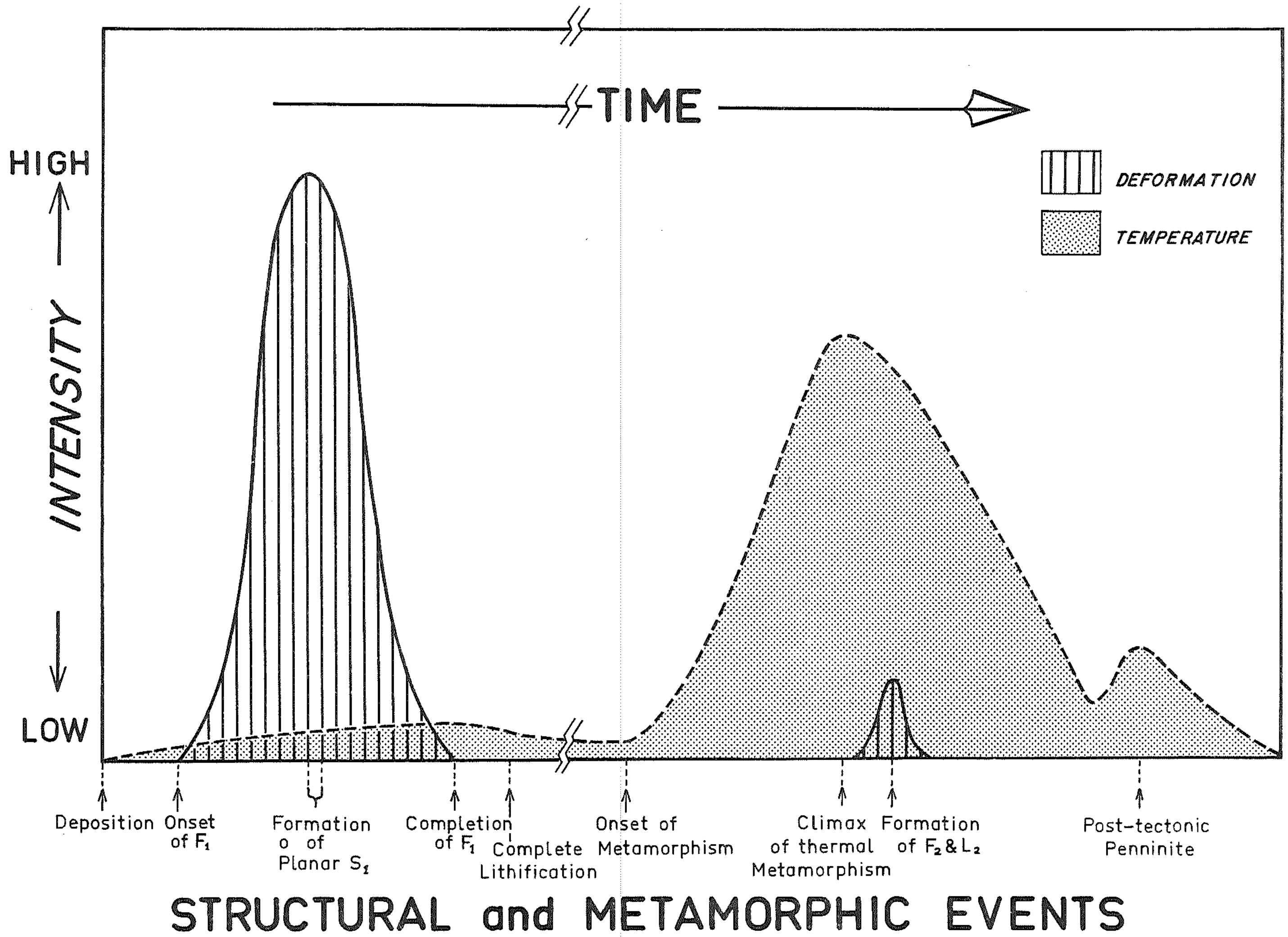

TIME
HIGH
INTENSITY
LOW
DEFORMATION
TEMPERATURE
Deposition
Onset of F1
Formation of Planar S1
Completion of F1
Complete Lithification
Onset of Metamorphism
Climax of thermal Metamorphism
Formation of F2 & L2
Post-tectonic Penninite
STRUCTURAL and METAMORPHIC EVENTS

FIGURE 2

The eastern part of the Marquette synclinorium is essentially non-metamorphosed but rocks of staurolite grade can be found near Michigamme. James (1955, p. 1482) noted that since the metamorphic isograds cut across the structure, metamorphism postdated deformation. Detailed structural analysis of the Siamo Slate (Powell, 1968a) confirmed this conclusion, and also provided an opportunity to examine the textural, mineralogical, and structural effects of the regional metamorphism on the early structures.

The most persistent F_1 structure in the Siamo Slate is cleavage, S_1, characterized by thin, anastomosing but essentially parallel, pelitic foliae that pervade all detrital rocks (Powell, 1969b). The spacing of the pelitic foliae varies with grain size, shape of detrital particles, and state of lithification at the time of cleavage formation. Rounded quartz grains (probably representing relict detrital grains) are separated by thin selvedges of fluid inclusions, minute sericite flakes, and iron-oxide "dust" from quartz overgrowths; these overgrowths are intergrown with neocrystallized sericite and chlorite flakes elongate parallel to S_1. The pelitic foliae and quartz overgrowths can be recognized in successively-higher grades of metamorphism up to the staurolite zone near Michigamme. More than 140 thin sections have been examined, and photomicrographs selected from thirteen of these (Fig. 1 and Table 1) form the documentation of the processes described in this report. Hand-specimens and thin sections are catalogued and filed at the Department of Geological Sciences, Northwestern University, Evanston, Illinois 60201.

STRUCTURES AND TEXTURES BELOW THE BIOTITE ISOGRAD

(a) Field Outcrop.

Outcrops of Siamo Slate are quite common in the eastern part of the Marquette Synclinorium and sedimentary structures are preserved with little or no distortion. Apart from cleavage in the pelitic beds and the tough, indurated nature of the sandstones, there is no indication

TABLE 1:- LOCATION AND DESCRIPTION OF ROCKS FIGURED IN PLATES

Rock Number in Figure 1	Location	Co-ordinates*	Northwestern University Catalogue Number	Field Description
1	In the south end of a prominent road cut on M35. Ajibik quartzite at the base grades upwards into interbedded sandstones and pelites	459430E 5148190N	X102-62D	Quartzose sandstone interbedded with thin layers of argillite
2	In the southeast branch of a rail cut at the junction between C&NW and DSS&A railroads	455380E 5148130N	X102-40B	Medium-grained, cleaved sandstone with some coarse lenses of labile clastics. Soft-sediment deformation in some beds
3	Almost 2 kms east of Teal Lake on the north side of LS&I railroad	454910E 5150760N	X102-39	Thin slate bands interbedded with massive, medium-grained, quartzose sandstone
4	In low ridges midway between County Road 492 and the LS&I railroad about $1\frac{1}{2}$ kms east of Teal Lake	454640E 5150920N	X102-37	Interbedded sandstone and slate with well-developed cleavage that is refracted as it passes from sandstone into slate
5	On the north side of US 41 about 50 meters east of an intersection with a side street	450520E 5150780N	X102-5	Interbedded sandstone and laminated slates with a well-developed cleavage parallel to which there are some intrusive sandstone dykes
6	In the Siamo Hills midway between Teal Lake and US 41	449850E 5150790N	X102-98	Finely laminated, dark slate

7	At a bend in a small farm road that runs alongside the LS&I railroad immediately north of North Lake Township	444050E 5150130N	X102-11B	Dark slate of low biotite grade. Thermal metamorphism has partially annealed slaty cleavage
8	About 200 meters northwest of a small gneissic hill in otherwise flat, swampy country	434070E 5151850N	X102-22	Dark laminated slate in which cleavage has been almost completely annealed
9	Small hillock of white quartzite just south of a major power line	416530E 5154820N	X102-90C	Clean, white quartzite
10	On the west side of US 41 in a prominent outcrop just east of a junction with a small side road	416410E 5154560N	X102-89A	Dark, pelitic hornfels with conformable lenses of coarsely crystallized hornblende and plagioclase sweated out of rock *in situ*
11	About 100 meters southwest of Outcrop 10	416320E 5154510N	X102-102	Laminated, grey, siliceous hornfels adjacent to a basic intrusive
12	Prominent outcrop on the south side of a major power line	416230E 5154870N	X102-104B	Quartzose schist containing garnets overlying an almost pure, white quartzite. Relict cross-bedding visible
13	Same location as 12	416230E 5154870N	X102-104C	Same outcrop as 12
14	Isolated outcrop in a glacial boulder field just north of a swamp	415930E 5154750N	X102-96	Laminated, dark, siliceous slate

*Co-ordinates accurate ± 20 meters and expressed to the nearest 10 meters on the 1000 meter Universal Transverse Mercator Projection, Zone 16.

PLATE 1. CHARACTERISTIC CLEAVAGE FOLIAE

Bar scales marked on photographs. All photographs in plane-polarized light.

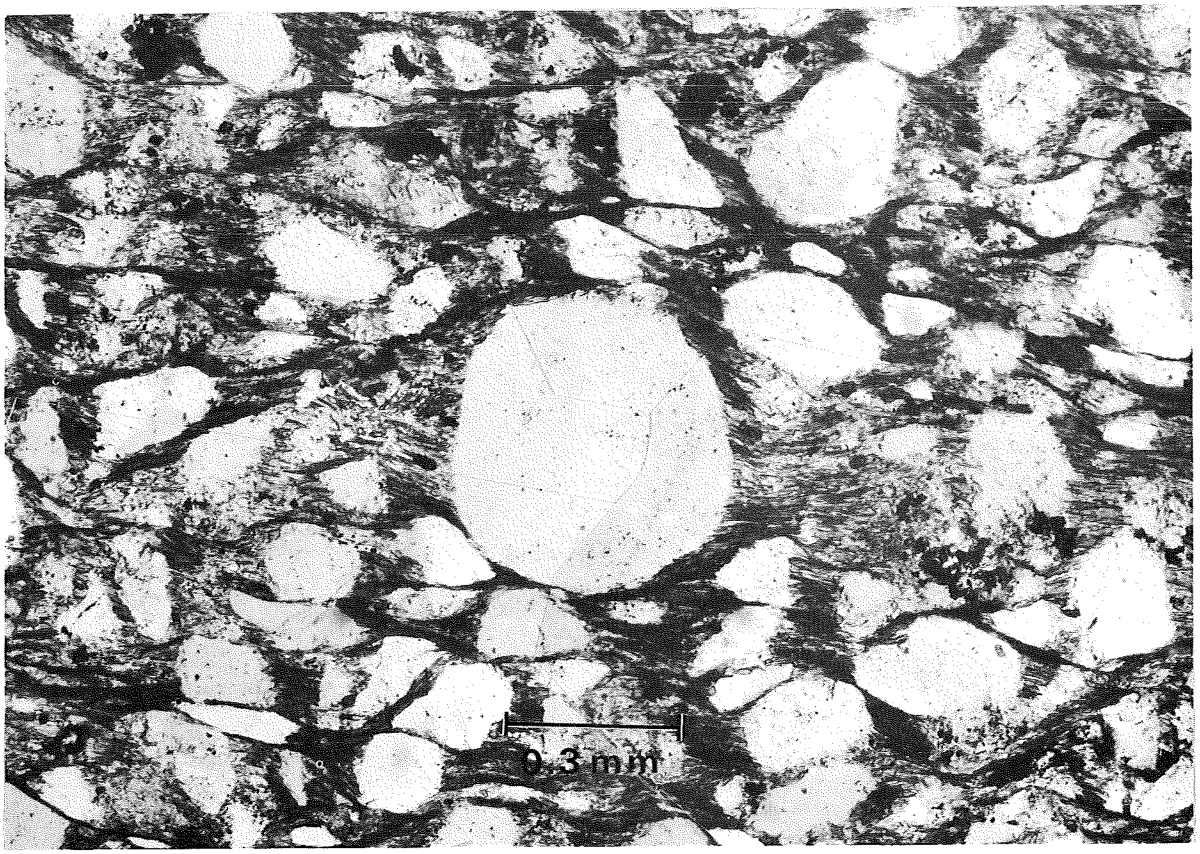
A. Rock 5. Mosaic illustrating typical cleavage foliae transecting a medium-grained sandstone. Shapes of white grains (predominantly quartz) appear little changed from detrital condition.

B. Rock 5. Dark cleavage foliae composed of finely crystalline phyllosilicates, iron oxide and possibly hydrated silica, envelop detrital quartz grains to form augen-like structures. Rounded shape of detrital quartz grains is outlined by thin selvedges of fluid inclusions, small sericite flakes and iron oxide "dust." The detrital core can be distinguished from the quartz overgrowths (Q_o) where neocrystallized sericite and chlorite (colorless to pale green in thin section) are intergrown with quartz.

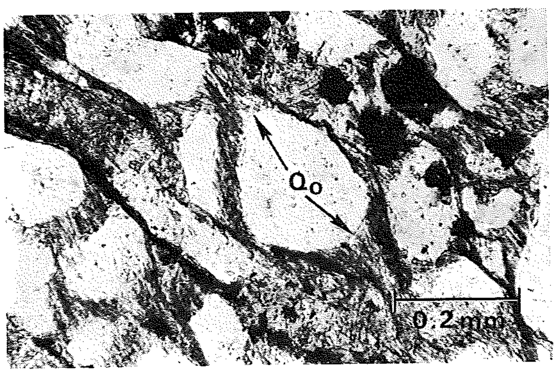
C. Rock 4. Dark, pleochroic chlorite in cleavage foliae in fine-grained sandstone, is distinct from light-colored, faintly pleochroic sericite and chlorite in interfolial lenses.

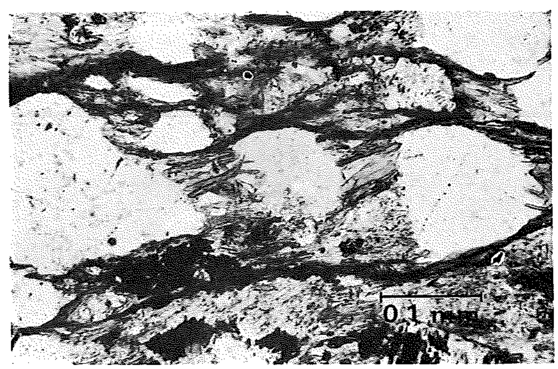
D. Rock 6. Cleavage foliae (S_1) in originally silt-sized material disrupt fabric of sediment and cut across a thin, sandy bedding lamination (S_0). Large diagenetic chlorite grains (Ch) parallel to S_0 appear to have formed before the cleavage.

E. Rock 6. S_1 cleavage characteristic of the fine-grained pelitic rocks. Anastomosing cleavage foliae envelop detrital quartz grains (Qd) with essentially the same structure as in the interbedded coarser grained sandstones. Chloritic phyllosilicates in the cleavage foliae are dark and strongly oriented, but in the interfolial lenses colorless to pale green chlorite and sericite is intergrown with quartz in a more random orientation (Q_i). Only the largest detrital quartz grains (recognized by quartz overgrowths) have been preserved, the smaller grains having recrystallized or migrated to form overgrowths on the larger grains.



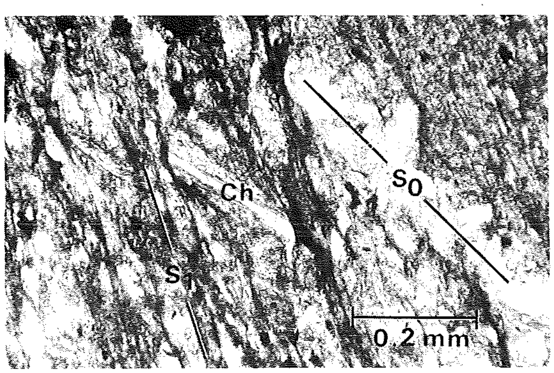
A

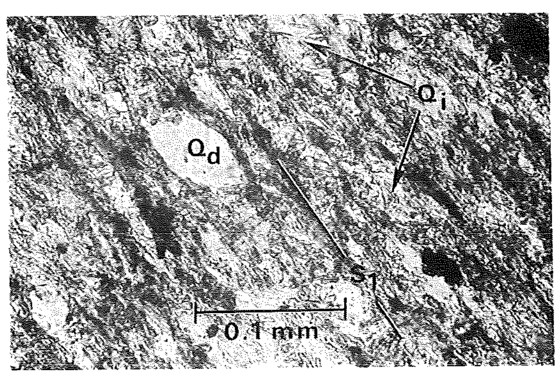




B

C





D

E

PLATE 1

PLATE 2. STRUCTURES AND TEXTURES IN SLATY CLEAVAGE

Bar scale on all photographs is 0.1 mm. All photographs are in plane-polarized light.

A. Rock 2. Characteristic cleavage foliae in a fine-grained silt. Strongly oriented, dark, chloritic phyllosilicates in cleavage foliae contrast with randomly oriented sericite and light-colored chlorite in interfolial lenses (arrowed in photograph).

B. Rock 2. Cleavage foliae in fine-grained silt have essentially the same structure as cleavage foliae in sandstone and slate. The proportion of platy particles to equidimensional grains, rather than the average grain size, determines the structure and spacing of the cleavage foliae.

C. Rock 6. Cleavage foliae in slate typically wrap around quartz grains (Q) and diagenetic pennine chlorite (Ch). Interfolial lenses are composed of intergrowths of finely crystallized sericite, chlorite and quartz.

D. Rock 6. Planar cleavage foliae transecting a folded, quartzose, bedding lamination (S_o). Pelitic material in the cleavage foliae appears to have been intruded throughout the rock, and commonly an individual folia can be traced for several cms in thin section. Interfolial lenses (arrowed in photograph) are commonly enriched in quartz due to migration of silica out of the cleavage foliae. A rudimentary compositional banding parallel to cleavage is thereby produced.

E. Rock 4. Characteristic cleavage foliae enveloping detrital quartz grains in a fine-grained sandstone.

F. Rock 8. Relict cleavage foliae in a cleaved sandstone metamorphosed to the biotite grade. Cleavage foliae orginally similar to those in rock 4 are recrystallized into well-formed biotite crystals oriented parallel to the pre-existing cleavage (arrowed in photograph). A rounded detrital quartz grain (Qd) distinguished from its quartz overgrowth by a selvedge of fluid inclusions and sericite crystals is sharply terminated against biotite in the cleavage foliae owing to "pressure solution." The sericite and chlorite characteristic of interfolial lenses in the slaty cleavage, have recrystallized into muscovite.

G. Rock 3. A group of cleavage foliae transecting a quartzose bedding lamination (S_o). Cleavage foliae which are evenly distributed throughout the body of pelitic layers characteristically converge at the margins of quartzose laminations, and transect the sandy bands at spacings of several mms or cms.

H. Rock 63N 48E loaned by W. Puffet, U. S. G. S., Marquette, Michigan - Location:-In Siamo Slate, east of Teal Lake. Refraction of cleavage through a sandy lamination in which some of the detrital quartz grains (Qd) have diameters as wide as the lamination.

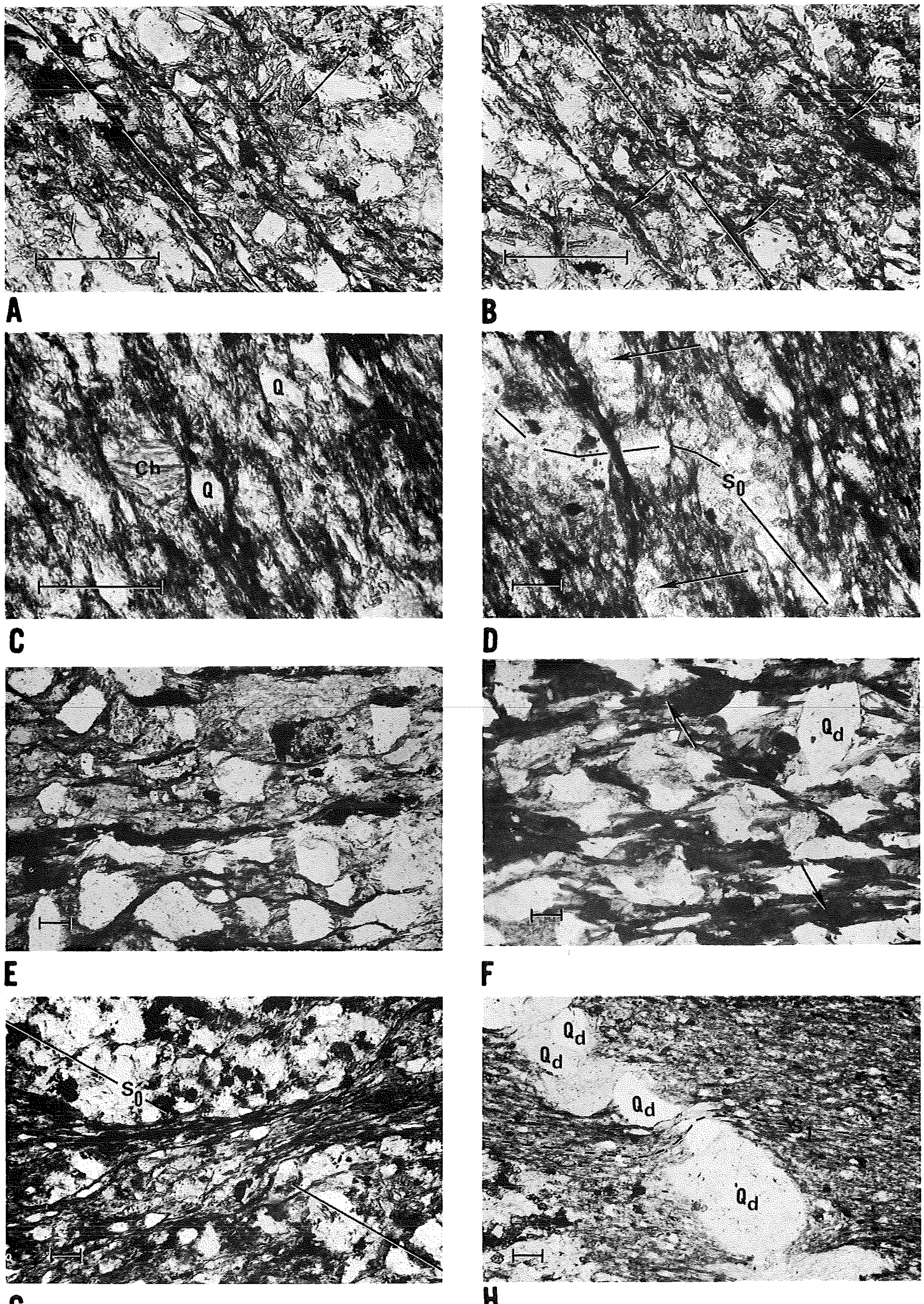


PLATE 2

PLATE 3. OVERGROWTHS ON ROUNDED QUARTZ GRAINS IN THE LOWEST METAMORPHIC GRADES

Bar scale in A, B, C, and D is 0.1 mm; in E, F, G, and H is 0.2 mm.

A. Rock 5. (plane-polarized light). Quartz overgrowth on a rounded, detrital, quartz grain outlined by a selvedge of fluid inclusions, sericite crystals and iron-oxide "dust." Small chlorite and sericite crystals parallel to the slaty cleavage are intergrown with the quartz overgrowth, but in no place do the new phyllosilicates indent the rounded detrital core.

B. Rock 5. (Crossed polarizers). Quartz overgrowth on a rounded, detrital quartz grain. Overgrowth has extended in all directions and is partially intergrown with chlorite (dark in photograph) and sericite parallel to the cleavage.

C. Rock 5. (Plane-polarized light). Quartz overgrowth on a rounded, detrital quartz grain. Dark cleavage folia lies adjacent to the right-hand side of grain; there may have been some "pressure solution" of the quartz grain along the contact with the cleavage folia.

D. Rock 4. (Plane-polarized light). Vermiculite overgrowth (Ve) on a rounded, detrital, quartz grain (Q) which has been plucked out of the thin-section during grinding. Vermiculite commonly appears as an alteration of detrital biotite, but in a few thin-sections the vermiculite has pseudo-hexagonal outlines and forms overgrowth on some quartz grains.

E. Rock 1. (Plane-polarized light). Coalescence of quartz overgrowths on two adjacent, well rounded, detrital, quartz grains.

F. Rock 1. (Plane-polarized light). Rounded detrital quartz grains clearly distinguishable from the quartz overgrowths which have coalesced thereby binding all grains firmly together. These quartz overgrowths developed before the cleavage. Differing degrees of cementation by quartz overgrowth throughout the sedimentary succession caused some beds to be completely lithified, others partially lithified and some not lithified at all when the cleavage developed.

G. Rock 1. (Plane-polarized light). Quartz overgrowth on a rounded detrital quartz grain outlined by a selvedge of fluid inclusions and small sericite flakes (arrows).

H. Rock 1. (Crossed polarizers). Strain in the quartz grain in G caused subdivision into smaller, non-strained, straight-sided, polygonal subgrains (arrowed in photograph) that transect the original quartz-grain boundary.

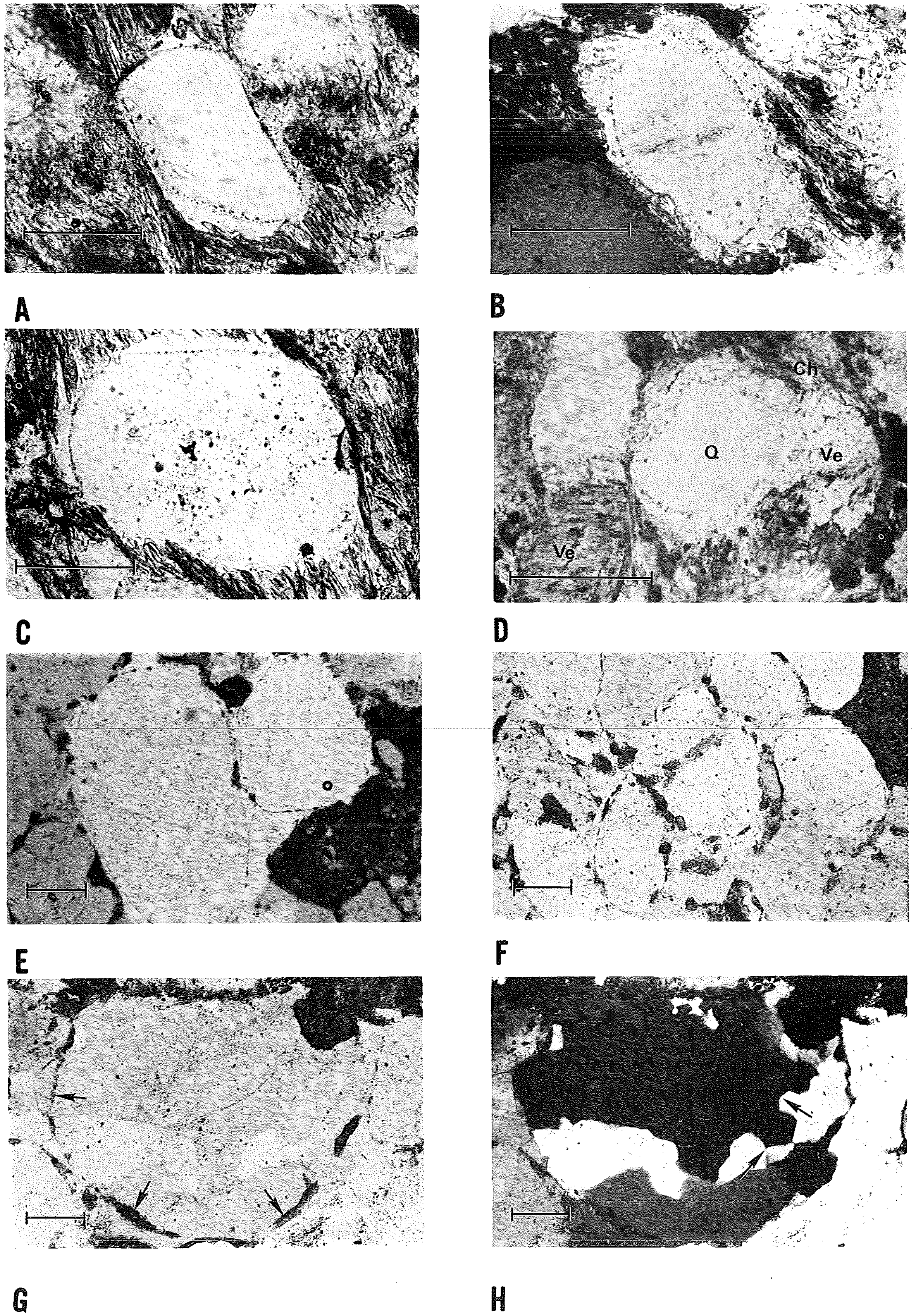


PLATE 3

in outcrop that the rocks have been metamorphosed.

The thickness of sandstone beds is quite variable ranging from only a few centimeters to 3 meters in thickness. Bedding is generally well-defined in the slate by sandy laminations (a few mms thick) that are composed of medium- or fine-grained quartz grains. In places, the sandy laminations in the slate are no thicker than the diameter of the largest detrital quartz grains (Plate 2H).

(b) Thin Section.

(i) Cleavage Foliae

A steeply-dipping, east-west striking cleavage parallel to the axial planes of the major folds in the Marquette Synclinorium, is present in most outcrops of the Siamo Slate. Cleavage is most prominently developed in the slate on the northern flank of the synclinorium, and commonly it traverses both the slate and interbedded sandstones. Because the cleavage in the sandstone has a different orientation and appearance in outcrop from the slaty cleavage, it is common practice among structural geologists to classify such cleavages separately. The cleavage in sandstones is referred to as "fracture" cleavage, and the cleavage in slates as "flow" cleavage; generally the cleavages are ascribed to totally different modes of origin. However, in the Siamo Slate, as indeed in many other successions of cleaved sandstones and argillites deformed before the rocks were lithified, it can be shown that the "fracture" cleavage in the sandstone and the "flow" cleavage in the slate are essentially the same phenomenon, and were produced during tectonic dewatering (Powell, 1968b, 1969a, b).

In thin-section the cleavage is seen to be a set of anastomosing pelitic foliae that transect the bedding and wrap around the detrital grains (Plate 1). In many places, the pelitic foliae which were intruded throughout the rocks during tectonic dewatering, have recrystallized into dark chlorite that is distinct from the pale green sericite and chlorite which occupy the interfolial lenses (Plate 1C). Where the foliae wrap around detrital grains, augen-like structures are produced (Plate 1B).

The spacing of the cleavage foliae in both the sandstones and the argillites (Plate 1) appears to depend on the proportion of approximately equidimensional grains (mainly quartz) to platy particles (phyllosilicates). Cleavage foliae are more abundant, spaced closer together, and less well defined in those rocks with the lowest proportion of equidimensional grains. In rocks with 40% to 70% of equidimensional grains, the cleavage foliae are spaced at distances approximately equal to the diameter of the equidimensional grains. In some of the quartz-rich sandstones--particularly those toward the base of the formation where considerable quartz cementation occurred before tectonic dewatering--the average distance between the main cleavage foliae may be greater than a centimeter.

The identification of the spacing in the argillites is more difficult than in the interbedded sandstones. The argillites have recrystallized more than the adjacent sandstones making identification of detrital grain shapes difficult (Plates 1E and 2A, B, and C). No argillites have been found with more than 80% quartz or more than 80% platy particles. A representative "slate" from the formation has approximately equal proportions of phyllosilicates and equidimensional particles (mainly quartz).

(ii) Quartz Overgrowths

Overgrowths of quartz on rounded quartz grains are separated from the relict cores by selvedges of fluid inclusions, small sericite crystals, and iron-oxide "dust". These overgrowths which are optically continuous with the relict core are very common in some rocks, and have been found in almost all thin sections. In the well-cleaved sandstones, the overgrowths are intergrown with pale green sericite and chlorite* strongly oriented parallel to the cleavage (Plates 3A, B, and C). In the quartz-rich sediments--particularly those near the base of the formation--quartz overgrowths form an interlocking texture completely

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*Identification of all minerals has been made with optical microscope only. Whereas many minerals are readily identified by optical microscope, only preliminary identification of the fine-grained phyllosilicates can be made. Hopefully, x-ray and electron microscope identifications will be made in the future.

PLATE 4. OVERGROWTHS ON ROUNDED QUARTZ GRAINS IN THE BIOTITE ZONE

Bar scale on all photographs is 0.1 mm. All photographs are in plane-polarized light.

A. Rock 7. Quartz overgrowth on rounded quartz grain (arrowed in photograph). Chlorite is intergrown with the quartz overgrowth but does not indent the rounded grain. Dark patches of carbonate [C_d - iron-rich dolomite (?)] are elongate parallel to cleavage.

B. Rock 7. Chlorite (Ch) intergrown with quartz overgrowth on rounded quartz grain.

C. Rock 7. Two adjacent quartz grains cemented by quartz overgrowth. Chlorite interdigitated with quartz overgrowth is strongly oriented parallel to slaty cleavage direction. Dolomitic carbonate grains (C_d) are elongate parallel to the cleavage.

D. Rock 7. Rounded quartz grain elongate oblique to cleavage. Dark dolomitic carbonate grain in upper right-hand corner is bent around quartz grain and elongate parallel to the cleavage.

E. Rock 8. Recrystallized cleavage foliae enveloping a rounded quartz grain whose long axis is oblique to the cleavage. Biotite (Bi) which, at a slightly lower grade of metamorphism occurs only in the cleavage foliae, has almost completely replaced the chlorite (Ch) interdigitated with the quartz overgrowth.

F. Rock 8. Characteristic texture in cleaved sandstones metamorphosed to the biotite grade. Rounded quartz grains (Q_d) can be distinguished from quartz overgrowths by selvedges of fluid inclusions and small sericite crystals. Cleavage foliae have recrystallized to well-formed biotite flakes which are parallel to the cleavage direction. Chlorite in interfolial lenses has been replaced by muscovite (M) or, in some places, by biotite. "Pressure solution" of rounded quartz grains is common where the quartz adjoins biotite crystals. The relict cleavage foliae, though easily identifiable, are not as prominent as in lower grades of metamorphism.

G. Rock 8. Overgrowth on a rounded quartz grain with tabular crystals of quartz interdigitated with biotite. The tabular quartz crystals (arrowed) are in optical continuity with the rounded quartz core, and elongate parallel to the basal plates of the biotite. The overgrowth of intergrown quartz and biotite is several times longer in the direction of the cleavage than the original quartz grain.

H. Rock 8. Rounded quartz grain (Q_d) with "pressure solution" adjacent to a large biotite crystal that has crystallized in an earlier formed cleavage folia. The overgrowth on the quartz grain is several times larger than the rounded core, and has developed by solution of smaller quartz grains and precipitation on the overgrowth.

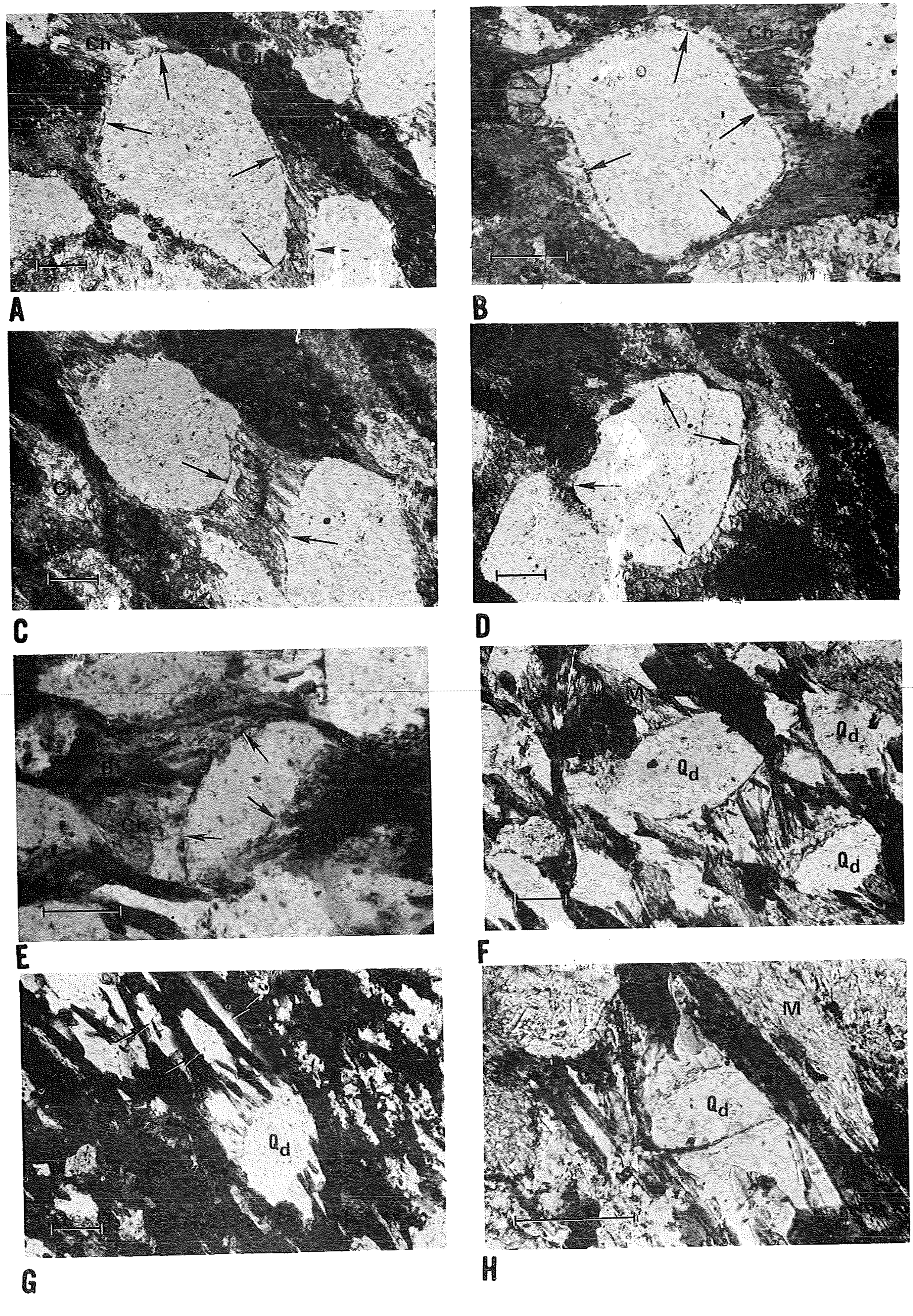

PLATE 4

PLATE 5. OVERGROWTHS ON ROUNDED QUARTZ GRAINS IN GARNET AND STAUROLITE ZONES

Bar scale in all photographs is 0.1 mm.

A. Rock 10. (Plane-polarized light). Thin selvedges of fluid inclusions and small sericite crystals outline quartz overgrowths (arrowed) on rounded, detrital quartz grains (Q_d). Inclusions of biotite and muscovite in the quartz overgrowth recrystallized during thermal metamorphism, and are randomly oriented.

B. Rock 9. (Crossed polarizers). Group of rounded, detrital quartz grains cemented together by quartz overgrowths (arrowed in photograph) that developed during diagenesis. Sericite and muscovite recrystallized later during either the thermal or retrograde metamorphisms and have replaced the quartz in places, leaving a disconnected fabric of quartz-cemented grains separated by irregular patches of sericite.

C. Rock 13. (Plane-polarized light). Quartz overgrowth on rounded detrital quartz grain (Q_d) envelops small, well-crystallized, randomly oriented muscovite and biotite crystals. Small quartz crystals in adjacent areas have interlocking polygonal outlines and appear dimensionally non-oriented.

D. Rock 12. (Crossed polarizers). Quartz overgrowth on well-rounded, detrital quartz grain (Q_d).

E. Rock 9. (Crossed polarizers). Two rounded, detrital grains - one K-feldspar (Fe - cleavage traces marked by white lines in photograph) and the other quartz (Q_d). Quartz overgrowth has developed on the rounded quartz grain but not on the feldspar.

F. Rock 9. (Crossed polarizers). Rounded, detrital quartz grain (Q_d) with quartz overgrowth sharply terminated along a contact with a feldspar grain (Fe). Rounded end of quartz grain appears to have been removed by "pressure solution."

G. Rock 10. (Crossed polarizers). Large, rounded, detrital quartz grain (outlined in white) has been broken down into small, non-strained, polygonal subgrains. Adjacent quartz grain (at extinction in photograph) has retained its crystallographic unity.

H. Rock 10. (Crossed polarizers). Two adjacent, rounded, detrital quartz grains (outlined in white) one of which has been polygonized into small, non-strained subgrains. The other quartz grain has strained extinction except for a small, straight-sided, non-strained, polygonal subgrain (arrowed in photograph). The polygonization of large detrital grains is interpreted as caused by readjustment of the quartz to impressed strains. Thus the large quartz grains - most stable in the diagenetic environment where the finely crystalline quartz is dissolved and precipitated as overgrowths on the large quartz grains - become unstable when subjected to strain, and polygonize to form smaller, equidimensional grains stable in the new environment.

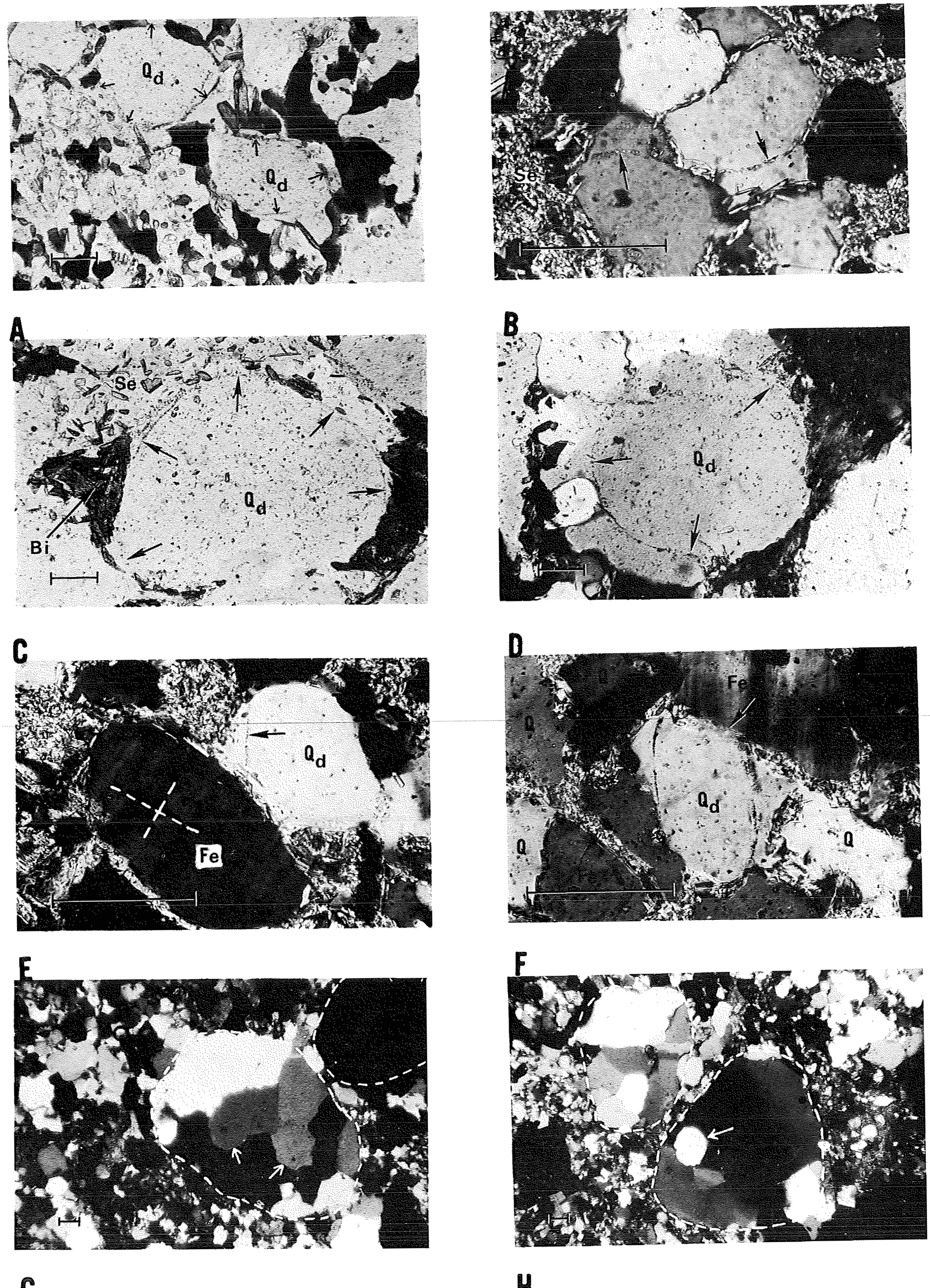

PLATE 5

PLATE 6. METAMORPHIC AND STRUCTURAL HISTORY REVEALED BY TEXTURAL FABRIC

Bar Scale in all photographs is 0.1 mm.

A. Rock 14. (Plane-polarized light). Pre-tectonic garnet with margins altered to chlorite and a planar internal foliation (S_i) oblique to the external foliation (S_1 - mimetically recrystallized parallel to the slaty cleavage formed earlier). S_1 is 16° oblique to S_o - represented by thin, quartzose bedding laminations.

B. Rock 14. (Plane-polarized light). Magnified view of pre-tectonic garnet in A. Garnet crystallized under static conditions across early-formed S_1 cleavage during regional thermal metamorphism. Subsequently, the garnet was rotated approximately 60° accompanied by some recrystallization of the phyllosilicates parallel to S_1, and development of mesoscopic lineation L_2 plunging steeply along the S_1 cleavage. The margins of the garnet were altered to chlorite (Ch) during later regional retrogressive metamorphism.

C. Rock 14. (Plane-polarized light). Syntectonic garnet with continuous curvature of internal foliation. S_o, represented by thin quartzose laminations, contains a small fold (on the right-hand side of the garnet) sympathetic to the sense of rotation implied by the curvature of S_i.

D. Rock 14. (Plane-polarized light). Magnified view of syntectonic garnet which has a maximum rotation of 85° between S_i and S_e. The outer rim of the garnet, at least, has crystallized during deformation which produced the magascopic lineation, L_2.

E. Rock 11. (Plane-polarized light). Relict cleavage foliae (S_1) transecting bedding (S_o) have recrystallized to a muscovite-biotite foliation during regional thermal metamorphism. The large, well-formed penninite crystals grew randomly across the foliation during later regional retrogressive metamorphism.

F. Rock 11. (Crossed polarizers of E).

G. Rock 11. (Crossed polarizers). Post-tectonic, well-crystallized penninite cutting across the moscovite-biotite foliation recrystallized during the regional thermal metamorphism.

H. Rock 12. (Crossed polarizers). Large, post-tectonic penninite cutting across bedding (S_o) and recrystallized cleavage foliae (S_1). Penninite crystallized after the deformation which produced the mesoscopic crenulation lineation, L_2.

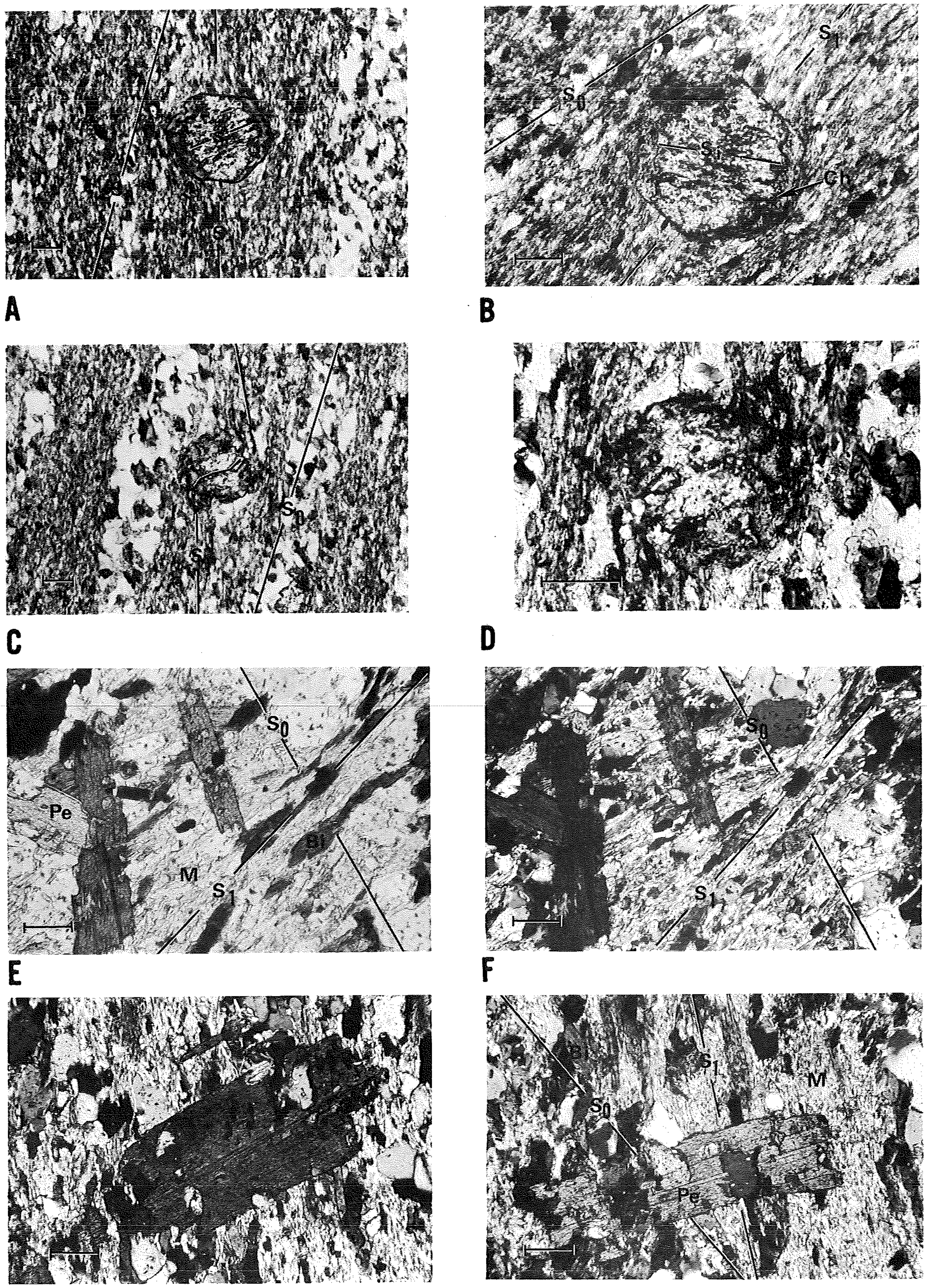

PLATE 6

cementing the rounded detrital grains together (Plate 3E to G).

(iii) Other Diagenetic Textures

Notwithstanding the prominence of the cleavage in the fabric of most of the detrital rocks, several other diagenetic minerals and textures can be recognized (Powell, 1969b). Very thin, plate-like flakes of muscovite up to 1 mm long and generally lying parallel to the bedding have overgrowths of fibrous chalcedony in which the siliceous fibers are oriented perpendicular to the mica flakes. Small crystal aggregates of magnetite have grown across the bedding and cleavage, and finely crystalline chalcedony in "pressure shadows" is oriented with siliceous fibers parallel to the slaty cleavage.

Crystals of penninite occur both as tabular crystals parallel to the cleavage (Plate 1D) and as ovate granules enveloped by the cleavage foliae (Plate 1C). Prochlorite forms small granules up to 0.1 mm diameter which are commonly rimmed by a selvedge of colorless sericite. Vermiculite occurs in a number of rocks on the northern flank of the Marquette Synclinorium near Negaunee, and appears to be an alteration product of detrital biotite. In a few places vermiculite forms overgrowths on detrital quartz (Plate 3D).

STRUCTURES AND TEXTURES IN THE BIOTITE ZONE

(a) Field Outcrop

Outcrops in the Siamo Slate are scarce between Negaunee and Lake Michigamme, but sufficient are present to trace the changes in mineralogy and texture. In the lower part of the biotite zone, the pelitic rocks cleave along S_1 with equal facility as the pelites farther east. The steep lineation, L_2, though still weak, is more prominent than in the eastern part of the Marquette Synclinorium. Towards the upper part of the biotite zone, the facility to cleave along S_1 is considerably less, and the rocks commonly break irregularly.

(b) Thin Section

The increased intensity of metamorphism has recrystallized the cleavage foliae into well-formed, strongly pleochroic biotite. All excess silica originally in the cleavage foliae appears to have migrated to quartz overgrowths on the rounded detrital grains in the interfolial areas. The finely crystalline, pale chlorite or sericite is reconstituted as well-formed flakes of muscovite or chlorite oriented parallel to the early S_1 cleavage (Plate 4A to D). Microscopic banding is probably best developed in the lower part of the biotite zone.

Towards the garnet isograd the microscopic foliation is less distinct. Cleavage foliae (Plate 4E to H) have recrystallized as large sheaves of biotite, but are not as distinct from the interfolial zones as at lower grades. Chlorite which is common in the interfolial areas in the lower part of the biotite zone is partially or completely replaced by biotite (Plate 4E). Quartz overgrowths on rounded detrital grains are readily identified in the originally coarser-grained rocks. Lenticular quartz grains, elongate parallel to the basal plates of biotite (Plate 4G), form large overgrowths optically continuous with the rounded detrital cores. Pressure solution of quartz perpendicular to the cleavage foliae--particularly obvious where rounded quartz grains are in contact with basal plates of biotite (Plate 4F and H)--has supplied silica to enhance the elongate quartz overgrowths. In a few places the neocrystallized biotite and muscovite have cut across the microscopic S_1 foliation.

STRUCTURES AND TEXTURES IN GARNET AND STAUROLITE ZONES

(a) Field Outcrop

The main outcrops are located just northeast of the town of Michigamme between the prominent ridge of gneissic basement and Lake Michigamme. Commonly bedding laminations are easily seen, but the early S_1 cleavage is very rarely identifiable. The rocks have a hornfels appearance and fracture irregularly. L_2 is well developed in some places but is not uniformly present in all outcrops. Locally, coarse lenses of hornblende, epidote and quartz develop parallel to the bedding. The rocks appear to have been annealed.

(b) Thin Section

S_0 can be identified by alternating micaceous and siliceous laminations. S_1 is visible, but it is not nearly as prominent as in lower metamorphic grades, and individual cleavage foliae can be identified only with difficulty. Quartz overgrowths on rounded detrital cores, however, are easily recognized (Plate 5A)--particularly in the originally coarser-grained, quartz-rich laminations. Muscovite and biotite have recrystallized with much less well-developed preferred orientation than at lower grades, and in many specimens appear to be randomly oriented.

In the finer-grained rocks, quartz has recrystallized so completely that it is not possible to recognize original rounded, detrital grains. In many thin-sections, the typical texture involves pools of interlocking, equidimensional, non-strained, small, polygonal quartz grains with patches of randomly oriented, well-crystallized muscovite and biotite. Magnetite, epidote, garnet, plagioclase, and hornblende are minor constituents in most rocks, and cut across all earlier formed structures. There is no evidence of pervasive shearing, granulation, or growth of oriented crystals associated with this grade of metamorphism.

The various stages in breakdown of large quartz grains into pools of small polygonal subgrains can be seen in thin-section. Quartz overgrowths on rounded detrital quartz grains provide the control necessary for recognition of textural changes. It appears that where large quartz grains were deformed, they developed strain lamellae and variable, but continuous, extinction. Small, nonstrained, polygonal subgrains developed in the areas of high strain (Plate 5H), and show no control by the original, rounded, quartz-grain boundary. Polygonal subgrains cut right across, and include the fluid inclusions and small mica crystals delineating the round core. Where the process is complete, the old fluid inclusions are empty and the original rounded quartz grains cannot be identified, except as oval areas of quartz concentration. The process of polygonization is not restricted to the highest grades of metamorphism and can be observed in all grades (Plate 3H).

INTERPRETATION OF METAMORPHIC AND STRUCTURAL HISTORY

The sequence of metamorphic and structural events in the Siamo Slate is represented qualitatively in Figure 2. The main deformation F_1 was initiated before the beds were completely lithified. The steeply dipping, quasi-planar slaty cleavage appears to have been formed as a planar structure during tectonic dewatering accompanying F_1. By rotating the refracted cleavage back to planarity in the psammitic beds on the planar limbs of folds (Powell, 1967, 1969b), it can be shown that tectonic dewatering occurred during the middle of the F_1 deformation. Although many sandy beds were partially cemented by quartz overgrowths, and thus were capable of withstanding some tensile forces on the rock fabric, some layers were subject to liquifaction and intrusion along the cleavage direction as sandstone dykes when excessive water pressures developed.

F_1 deformation before cleavage initiation was predominantly by bedding-surface slip producing essentially concentric folds. The slaty cleavage provided a second mechanical heterogeneity in the rocks, so that continuing F_1 deformation involved movements along both bedding and cleavage surfaces. Movements along cleavage foliae, particularly in the pelites, enhanced recrystallization and chemical segregation, and premitted thickening and thinning of layers approximating a similar-fold style where demanded by the geometry of the encompassing, competent psammitic layers. Thus, the preserved fold style is a product of initially concentric-style deformation that changed to a more similar-style deformation as the influence of the bedding as a mechanical inhomogeneity was reduced.

Temperatures were very low throughout F_1 deformation, and commonly chemical equilibrium was reached only in very small domains (Powell, 1969b). Heat may have been generated by movements along the cleavage in the latter part of F_1, and this energy, together with the inherent thermodynamic instability of finely divided particles, enabled the pelites to recrystallize to a greater extent than interbedded psammites.

The regional metamorphism centered on the Republic node was predominantly a thermal event. Minerals appear to have crystallized statically, although in the lower part of the biotite and in the chlorite grade the anisotropy inherited from F_1 has largely controlled the development of the new phyllosilicates. Cleavage foliae recrystallized into dark-colored chlorite or, at a slightly higher grade, into biotite, and the orientation of the phyllosilicates already existing determined the orientation of the new chlorite and biotite. Thus, the rudimentary chemical differentiation in the F_1 cleavage was initially enhanced during the thermal metamorphism and thereby produced a good microscopic foliation in the upper greenschist facies.

At higher grades, the biotite, while still partially mimicking the orientation of the early phyllosilicates, tends to be more randomly oriented throughout the rock. The interfolial areas characterized at low grades by rounded quartz grains with overgrowths intergrown with strongly oriented sericite, recrystallize as less well-oriented grains in quartz-muscovite-biotite lenses. Quartz grains adjacent to biotite flakes undergo solution and redeposition as the quartz grains flatten parallel to the basal plates of the biotite flakes. This type of "pressure solution" is probably controlled by the energy relationships of crystal interfaces between quartz and biotite.

In the higher metamorphic grades most of the garnets grow across, and include the mimetically recrystallized S_1 fabric. However, a few garnets show either rotation after growth (Plate 6A) or, in rare cases, some growth during rotation (Plate 6C). These rare rotations are the only evidence of movement in the Siamo Slate during the thermal metamorphism, and are related to the sporadically developed lineation.

The weak deformation, F_2, is considered to have occurred after the climax of metamorphism when some plastic adjustments and growth of garnet were possible without causing cataclasis of the rock fabric.

A widespread retrogressive metamorphism occurred after the regional thermal metamorphism and was characterized by growth of large, well-crystallized pennine chlorite crystals across all earlier fabric elements (Plate 6E to H). This retrogressive event was noted by James (1955) to be present in most of the surrounding rocks as well as the Siamo Slate.

SIGNIFICANCE OF TEXTURES IN RELATION TO THE CONTROLS OF METAMORPHISM

Concepts of the controls of metamorphism have changed considerably since Van Hise (1904) proposed that metamorphism was of two fundemental types, katamorphism and anamorphism, which could be correlated roughly with levels in the earth's crust. Harker (1932) considered metamorphism to be either thermal or dynamic in nature, or a combination thereof. In considering dynamic metamorphism, Harker made an important distinction between the hydrostatic state of stress and shearing stress. He pointed out that the mean stress and the stress difference are independent variables, but concluded that the maximum stress difference a rock could sustain is inversely proportional to the temperature (ibid. p. 183). Harker contended that, in most conditions, the maximum stress difference was attained during metamorphism, and thus the normal case of regional metamorphism was of large stress differences at low temperatures and low stress differences at high temperatures. Cases where deficient shearing stress appear to have existed were set aside as exceptional.

Harker (1932) also contended that shearing stress was an important control on the fields of stability of various minerals, and he developed the stress-antistress mineral concept (ibid. p. 147-151). This view is discounted today (e.g., Pitcher and Flinn, 1965, p. 11), and it is generally upheld that temperature is the most important control on the mineral assemblages developed (e.g., Winkler, 1967) with confining pressure a subordinate factor. Shearing stress is thought to have no influence on the kinds of mineral reactions that occur, although rates of reaction are increased by deformation (Dachille and Roy, 1964).

Until recently, it had been customary to regard regional metamorphism as occurring at moderate to high confining pressures with variable temperatures, and the Barrovian progression of zones was regarded as typical. Miyashiro (1961) introduced the concept of metamorphic facies series, and pointed out that the Barrovian zonation is merely a high-pressure member of a whole family of possible metamorphic facies series; the Abukuma Series in Japan formed at much lower confining pressures. Winkler (1967) pointed out that pressure should be considered in terms of both the pressures exerted on the rock by the overlying rocks (P_1-- the lithostatic pressure), and the pressure borne by the fluids within the rock (P_f). Winkler did not consider its role in metamorphic rocks. Nevertheless, Winkler (ibid., p. 2) recognized two types of regional metamorphism

(1) regional dynamothermal metamorphism, and

(2) regional burial metamorphism,

and erected a criterion based on texture for the recognition of regional dynamothermal metamorphism (p. 85): -

> In contradistinction to the nearly isotropic, well-crystallized fabric of the hornfeles of contact metamorphism, regional metamorphic rocks bearing platy or prismatic minerals like micas, chlorite or amphibole therefore exhibit strong schistosity.

In his section on regional dynamothermal metamorphism, Winkler considered (p. 86-7) the "thermal domes" of metamorphism in northern Michigan to be "a zonal succession very similar to that in the Grampian Highlands". This view was supported by Ernst (1969, p. 133). While the isograds are indeed well developed and simple in outline, the lack of both cataclasis and oriented mineral growth in the metamorphic zones of Northern Michigan clearly contradict the criteria set up for regional metamorphism by Winkler and Ernst.

Harker (1932, p. 183) argued that in "normal regional metamorphism" the stress difference developed was equal to the maximum the rocks could support at a given temperature. In Harker's frame of reference, the Northern Michigan metamorphism would be regarded as developed under "deficient shearing stress". Whether or not oriented fabrics are indeed characteristic of "normal" regional metamorphism appears to be in question. Many recent metamorphic studies show that the metamorphic minerals grew in a "static" period between episodes of deformation (e.g., Zwart, 1963; Pitcher and Flinn, 1965) and, as shown in this study, the orientation of micas may be strongly inherited from pre-existing fabrics. Harker's sketches (1932, Chapter IV) also support this important mimetic crystallization in the development of textures.

On the basis of mineral assemblages, Winkler (1967, p. 127) considered the Northern Michigan metamorphism to have developed at confining pressures similar to those of the northern New Hampshire facies series (Green, 1963). However, texturally the anisotropic fabrics in northern New Hampshire are quite distinct from the annealed, isotropic textures in Northern Michigan.

Strongly preferred orientation may be caused by a high degree of plasticity as much as by large stress differences (Thompson, 1955). As Rutland (1965, p. 129) suggested, and as in the Northern Michigan metamorphism, a considerable degree of preferred orientation may develop by mimetic crystallization after movement has ceased. Rast (1965) supported this view in comparing regional metamorphism to annealing recrystallization in metals. Indeed, the conclusion of Sutton (1965, p. 22) that

> ...regional metamorphism is essentially a thermal phenomenon, and that contact and dislocation metamorphism are merely special cases...

may well be the key to understanding both the fabrics and the mineral assemblages developed in regional metamorphism.

BIBLIOGRAPHY

ABELSON, P. H., 1966. Chemical events on the primitive earth: Nat. Acad. of Sciences Pr., 55, no. 6, p. 1365-1372.

DACHILLE, F. and ROY, R., 1964. Effectiveness of shearing stresses in accelerating solid phase reactions at low temperatures and high pressures. J. Geol., 72, p. 243-247.

ERNST, W. G., 1969. Earth Materials. Prentice-Hall, New Jersey, 149 p.

GOVETT, G. J. S., 1966. Origin of banded iron formations: Geol. Soc. Amer. Bull., 77, p. 1191-1212.

GREEN, J. C., 1963. High-level metamorphism of pelitic rocks in Northern New Hampshire. Amer. Miner., 48, p. 991-1023.

HARKER, A., 1932. Metamorphism. Methuen, London, 360 p.

HOLLAND, H. D., 1962. Model for the evolution of the earth's atmosphere: p. 447-477, in Engel, A. E. J., et al, Editors, Petrologic studies: a volume in honor of A. F. Buddington, Geol. Soc. Amer., 660 p.

JAMES, H. L., 1954. Sedimentary facies of iron formation: Econ. Geol., 49, p. 235-91.

-----, 1955. Zones of regional metamorphism in the Precambrian of northern Michigan. Geol. Soc. Amer. Bull., 66, p. 1455-1488.

-----, 1958. Stratigraphy of pre-Keweenawan rocks in parts of northern Michigan. U. S. Geol. Surv. Prof. Paper 314-C, 44 p.

-----, 1966. Chapter W: Chemistry of the iron-rich sedimentary rocks: in Data of Geochemistry (6th ed.), U. S. Geol. Surv. Prof. Paper 440-W, 61 p.

LEITH, C. K., 1905. Rock cleavage: Bull. U. S. Geol. Surv. 239, 216 p.

MAXWELL, J. C., 1962. Origin of slaty and fracture cleavage in the Delaware Water Gap area, New Jersey and Pennsylvania, p. 281-311. in Engel, A. E. J., et al, Editors, Petrologic studies: A volume in honor of A. F. Buddington. Geol. Soc. Amer., 660 p.

MIYASHIRO, A., 1961. Evolution of metamorphic belts. J. Petrology, 2, p. 277-311.

MOENCH, R. S., 1966. Relation of S_2 schistosity to metamorphosed clastic dikes, Rangeley-Phillips area, Maine. Bull. Geol. Soc. Amer., 77, p. 1449-1462.

PITCHER, W. S., and Flinn, G. W., 1965. Controls of Metamorphism. Symposium L'pool Geol. Soc. Oliver and Boyd, London, 368 p.

POWELL, C. McA., 1967. Studies in the geometry of folding and its mechanical interpretation. Unpub. Ph.D. thesis, Univ. of Tasm., 282 p.

-----, 1968a. Structural Analysis of the Siamo Slate, Marquette Trough, Michigan. Northwestern University Report Number 18. NASA Research Grant NGR 14-007-027, p. 15-45.

-----, 1968b. Structure and significance of intrusive sandstone dykes in the Siamo Slate of the Marquette Trough, Upper Peninsula, Michigan: Abstract in 14th Annual Institute on Lake Superior Geology, meeting at Superior, Wisconsin, p. 54.

-----, 1969a. Structures in tectonically dewatered slates. Abstract in Southeastern Section G.S.A. 18th Annual Meeting, South Carolina, p. 64.

-----, 1969b. Intrusive sandstone dykes in the Siamo Slate near Negaunee, Michigan. Bull. Geol. Soc. Amer., 80, p. 2585-2594.

RAST, N., 1965. Nucleation and growth of metamorphic minerals. in Pitcher, W. S. and Flinn, G. W., Editors, Controls of Metamorphism. Symposium L'pool. Geol. Soc. Oliver and Boyd, London, 368 p.

RUTLAND, R. W. R., 1965. Tectonic Overpressures, p. 119-139, in Pitcher, W. S. and Flinn, G. W., Editors, Controls of Metamorphism. Symposium L'pool Geol. Soc. Oliver and Boyd, London, 368 p.

THOMPSON, J. B., 1955. The thermodynamic basis for the mineral facies concept. Amer. Jour. Sci., 253, p. 65-103.

VAN HISE, C. R., 1904. A treatise on metamorphism: U. S. Geol. Surv. Monogr. 47, 1286 p.

VAN HISE, C. R., BAYLEY, W. S., and SMYTH, H. L., 1897. The Marquette Iron-Bearing District of Michigan. U. S. Geol. Surv. Monogr. 52, 641 p.

WINKLER, H. G. F., 1967. Petrogenesis of Metamorphic Rocks. 2nd edition. Springer-Verlag, New York, 237 p.

ZWART, H. J., 1963. Some examples of the relations between deformation and metamorphism from the Central Pyrenees: Geologie Mijnh., 42, p. 143-154.

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