Cataclastic Rocks

GEOLOGICAL SURVEY PROFESSIONAL PAPER 687

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By MICHAEL W. HIGGINS

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Includes field and microscope criteria for recognition of cataclastic rock zones, petrogenesis of rocks in these zones, and description of occurrences in the United States, Scotland, and New Zealand

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CATACLASTIC ROCKS

By Michael W. Higgins

ABSTRACT

Cataclastic rock is a general term for all rocks produced by cataclasis. Cataclastic rocks can be divided into two main types: (1) those without primary cohesion; and (2) those with primary cohesion. Cataclastic rocks without primary cohesion are *fault breccia* and *fault gouge*. Cataclastic rocks with primary cohesion are basically metamorphic rocks and owe their cohesion to a combination of crystalloblastic and cataclastic processes. They can be divided into two main categories on the basis of whether cataclasis was dominant over neomineralization-recrystallization (crystalloblastic processes) in their formation, or vice versa. Rocks in which cataclasis was dominant over neomineralization-recrystallization can be further divided on the basis of whether or not they possess fluxion structure, a cataclastic foliation. Rocks without fluxion structure are *microbreccia* and *cataclasite*. Rocks with fluxion structure are *protomylonite*, *mylonite*, and *ultramylonite*. *Phyllonite* is a variety of mylonite or ultramylonite. Rocks in which neomineralization-recrystallization was dominant over cataclasis also have fluxion structure. They are *mylonite gneiss* or *mylonite schist* and *blastomylonite*. All terms in italics are defined in this paper.

Protoclastic rocks are rocks produced by *protoclasis*, a variety of cataclasis. *Protoclasis* applies to cataclasis of an igneous body or parts of an igneous body, resulting from late intrusive movements of or within that body, generally before it has completely crystallized.

Diaphthoresis or retrograde metamorphism is a process which is not necessarily related to or associated with cataclasis. *Diaphthorites* are retrograde metamorphic rocks.

Pseudotachylite is a rock formed by melting of already-hot rocks because of frictional fusion during faulting near igneous intrusions.

Rocks which record a history of two or more separate periods of metamorphism are *polymetamorphic rocks*. Rocks which have been subjected to two or more periods or episodes of cataclasis are *polycataclastic rocks*.

Cataclastic rocks can best be classified quantitatively by using approximate size of most of the porphyroclasts or fragments combined with approximate percentage of these features.

In outcrop and hand sample cataclastic rocks may be easily mistaken for metasedimentary, metavolcanic, volcanic, or fine-grained intrusive rocks. In many cases, overlooking the presence of cataclastic rocks has led to erroneous interpretations of structure, stratigraphy, and geologic history.

Recognition of cataclastic rocks in the field is often closely tied with recognition of fault zones, and vice versa. Criteria are given for recognition of fault zones and cataclastic rocks and for distinguishing cataclastic rocks from some of the rocks with which they are easily confused. Any rock suspected of being cataclastic should be examined in thin section.

Cataclastic rocks are commonly felsic and (or) silicic in composition because the majority of rocks in mobile metamorphic terranes are of this composition, and because mafic rocks commonly recrystallize so readily that they seldom preserve cataclastic textures. Felsic and (or) silicic intrusive rocks commonly utilize faults and fault zones as pathways of easy intrusion; there is a remarkable coincidence of cataclasis and small felsic and silicic intrusive rocks. Late mineralization is also common along fault zones, and many cataclastic rocks show secondary mineralization.

Examples of cataclastic rock zones are the San Andreas fault system, California-Nevada (particularly the San Andreas fault and zones in the San Gabriel Mountains), the Alpine fault zone, New Zealand; the Towaliga, Goat Rock, and Bartletts Ferry fault zones, Georgia and Alabama; the Brevard zone, southeastern United States, the Moine Thrust zone, Scotland, and the border of Colville batholith, Washington. Brief descriptions of these zones and their rocks are given in this paper. A hypothetical zone can be constructed using these zones and others as a basis.

Associations of various rocks with fluxion structure, but with varying degrees of neomineralization-recrystallization are tentatively interpreted as indicating concurrent formation under differing physical and (or) chemical conditions. Rocks without fluxion structure commonly formed later than the fluxion structured rocks with which they are associated.

Cataclastic texture develops progressively with increase of comminution and shearing and can be demonstrated by different rocks in the same zone. Different minerals react differently, and a crude "cataclastic reaction series" can be constructed based on empirical observations.

Fluxion structure should be considered separate from color lamination and (or) compositional layering. Fluxion structure refers only to cataclastic foliation, developed by shear and flowage. Compositional layering and color lamination probably develop in various ways: by preferred comminution due to original grain-size differences, by varying degrees of comminution, by original compositional layering, by glide-fold schistosity, and by cataclastic metamorphic differentiation.

Cataclastic metamorphic differentiation is a process by which minerals react differently to shearing and tend to segregate on this basis. It has been proven in a number of cases, where compositionally layered cataclastic rocks have been produced from unlayered parent rocks.

Folds in cataclastic rocks have been described and illustrated by many workers. Most of the cataclastic rocks with folds can

be shown to be blastomylonites or mylonite schists or gneisses.

Cataclastic rocks at the thin section or hand sample scale may reflect structural patterns at map scale.

Conditions of cataclastic rock formation are largely speculative. Fluid content and pressure may be quite important to the formation of cataclastic rocks and to determining the types of rocks formed. Experimental data can, at this time, only be applied in a very general way when attempting to determine the conditions of cataclastic rock formation.

INTRODUCTION

Since Lapworth (1885, p. 559) first used and defined the term mylonite (from the Greek "mylon"—a mill), the terminology of cataclastic rocks has been considered by many workers. Three papers in particular—Waters and Campbell, 1935; Christie, 1960; and Reed, 1964—have been valuable in reducing the confusion resulting from misuse and lack of awareness of terms. Despite these papers, a geologist studying cataclastic rocks for the first time still finds many confusing terms. He is hampered by multiple terms for the same type of rock and by single terms for rocks of widely varying characteristics and origins. Even those experienced in cataclastic rock nomenclature find the classifications and terms confusing and difficult to apply. There is no single article in the literature where the uninitiated can learn cataclastic rock nomenclature, theory, and characteristics or where the more experienced worker can turn for reference and comparison. The purpose here is to provide such a paper.

Few new terms are introduced, but terms already in use are selected on the basis of applicability, general usage, and historical precedence. In some cases my own preferences and prejudices are unavoidably applied.

Probably the greatest source of confusion in geologic literature concerning cataclastic rocks (as implied by Knopf (1931), and stated by Waters and Campbell (1935) and Christie (1960)) is the use of the term *mylonite* in a general or genetic way to include almost any cataclastic rock.

Lapworth (1885, p. 559) defined *mylonites* as "microscopic pressure-breccias with fluxion structure, in which the interstitial dusty, siliceous, and kaolinitic paste has only crystallized in part." He elaborated on the formation and characteristics of mylonites and made a distinction between this *restricted* type of cataclastic rock and others of general similarity but with different characteristics and origins. Thus Lapworth intended, and most later workers have agreed, that the term *mylonite* should be restricted to one particular type of cataclastic rock. As Waters and Campbell (1935, p. 476) stated, although other terms are available for general or tectonic usage, "no other term adequately fills the place Lapworth assigned to mylonite." The use of this term to include all superficially similar rocks probably results chiefly from lack of a good general term.

Waters and Campbell (1935, p. 476) suggested *cataclastic rock* as a general term for all rocks produced by cataclasis. Many workers have used this term (including Knopf (1931), Hsu (1955a), Reed and Bryant (1964)), sometimes without emphasis. Only Holmquist (1910) used it in a more restricted sense. The term has disadvantages in that it includes fault breccias and gouge formed under conditions generally not considered applicable to mylonites, mylonite gneisses, blastomylonites, cataclasites, and other cataclastic rocks with primary coherence. However, usage and the advantage of a generally understood term which includes the various rock types under consideration seem to outweigh the disadvantages. Definitions of *cataclastic* vary slightly, but the following is typical: "Rock deformation accomplished by fracture and rotation of mineral grains or aggregates; granulation." (Am. Geol. Inst, 1957). I propose that *cataclastic rock* be used as a general term for all rocks produced by cataclasis including mylonites, protomylonites, blastomylonites, fault breccias, etc., and that the term *mylonite* be restricted, as originally intended, to rocks with the characteristics enumerated by Lapworth (1885, p. 559), restated by Waters and Campbell (1935, p. 474–475, 478), and described and defined in this paper.

ACKNOWLEDGMENTS

Willard H. Grant of Emory University introduced me to cataclastic rocks and guided me in their study along part of the Brevard zone. It was Grant who first suggested that work was needed on their nomenclature and classification. I am also indebted to the U.S. Geological Survey for support during my study of the Brevard zone, particularly to Jarvis B. Hadley who visited me in the field and with whom I discussed many aspects of cataclastic rocks.

I am especially indebted to Aaron C. Waters of the University of California at Santa Cruz, who furthered my interest in cataclastic rocks, made his collection from many fault zones available to me, and was always available for discussions during the years 1965–67, when I was a graduate student at the University of California, Santa Barbara.

Excellent suites of cataclastic rocks were provided by C. B. Sclar, A. R. Philpotts, W. H. Grant, and K. J. Hsu. Grant and Hsu guided me on trips to the Towaliga fault zone in Georgia and the Cucamonga Canyon fault zone in California, respectively; and R. D. Bently guided me along the Goat Rock, Towaliga, Bartletts Ferry, and Brevard zones in Alabama.

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valuable suggestions. I wish to express special thanks to David A. Brew, whose critical review of the manuscript was so complete and constructive that it resulted in a complete revision incorporating many of his suggestions. Finally, many geologists provided me with reprints of their papers—in some cases their last copy.

CLASSIFICATION AND NOMENCLATURE

My classification of cataclastic rocks is outlined in table 1.

These terms are all that are necessary to name and classify the known types of cataclastic rocks. The following definitions and discussions are keyed to this classification. Terms that I have chosen to eliminate from the classification are defined and discussed in the glossary.

Most of the basic "structural" terms used in this paper are defined by Turner and Weiss (1963). Other terms are defined in the glossary. Because the term *fluxion structure* is such an integral part of the classification and definitions, it is defined first.

FLUXION STRUCTURE

Definition.—Fluxion structure (fluxion texture): Cataclastically produced directed penetrative texture or structure commonly involving a family or set of *s*-surfaces; cataclastic foliation. May be visible megascopically or only microscopically. Does not necessarily involve compositional layering or lamination, although many examples do show such layering.

Discussion.—Lapworth (1885, p. 559) first used the term "*fluxion structure*" in the original definition of *mylonite*. He gave no definition of the structure or texture other than that incidental to his description of mylonite:

> * * * a finely-laminated schist * * * the lamination being defined in minute inosculating lines (fluxion lines) of kaolin or chloritic material and secondary crystals of mica.

Later geologists have used the term without defining it, although nearly all have given illustrations showing the texture. There is, and has been, confusion as to whether or not *fluxion structure* requires compositional layering or color lamination. As discussed in a later section, many mylonites, ultramylonites, and blastomylonites do have such layering, but many protomylonites and mylonite gneisses clearly transitional from undeformed, and in many cases unlayered, parent rocks into layered cataclastic rocks have only a cataclastic foliation or, in their finer grades, an incipient layering. Many mylonites, ultramylonites, blastomylonites, and phyllonites have no compositional layering either, but the "tectonic" significance of their cataclastic foliation is identical to that of the layered varieties.

Technically, *fluxion* is a synonym for *flow*, and indeed the fluxion structure of cataclastic rocks commonly resembles the flow structure or flow texture common to silicic and felsic volcanic rocks. Lapworth's choice of the term reflects his idea that the comminuted matrix of mylonites "flowed" around the porphyroclasts in differentially-moving layers perhaps separated by the thin "inosculating lines" marked by concentrations of fine micaceous minerals.

Because a definition of *fluxion structure* that requires the presence of color or compositional lamination would necessitate an unnatural separation between rocks such as protomylonite and mylonite, where there is ample evidence of a gradual transition, and between rocks such as layered and unlayered mylonites whose fabrics are otherwise identical, and because I consider

TABLE 1.—*Classification of cataclastic rocks*

[Porphyroclastic, protoclastic, diaphthoritic, pseudotachylitic, polymetamorphic, polycataclastic, phyllitic, and other terms are used as modifiers. See text and glossary]

Approximate volume percent porphyroclasts in rocks *with* fluxion structure. or Approximate volume percent fragments in rocks *without* fluxion structure.	Rocks *without* primary cohesion	Rocks *with* primary cohesion				Approximate size of *most* porphyroclasts in rocks *with* fluxion structure. or Approximate size of *most* fragments in rocks *without* fluxion structure.
		Cataclasis dominant over neomineralization-recrystallization			Neomineralization-recrystallization dominant over cataclasis	
		Rocks *without* fluxion structure	Rocks *with* fluxion structure		Rocks *with* fluxion structure	
>50	Fault breccia	Microbreccia	Protomylonite		Mylonite gneiss (mylonite schist)	Visible to naked eye
<50 / 30	Fault breccia	Microbreccia	Mylonite	Phyllonite (variety)	Mylonite gneiss (mylonite schist)	
>10	Fault gouge	Cataclasite	Mylonite	Phyllonite (variety)	Blastomylonite	>0.2mm
<10	Fault gouge	Cataclasite	Ultramylonite	Phyllonite (variety)	Blastomylonite	<0.2mm

All rocks are gradational

fluxion structure or cataclastic foliation to have a different significance from color or compositional layering or lamination, the two features are separated in this paper and the definition above is proposed for *fluxion structure.*

CATACLASTIC ROCKS WITHOUT PRIMARY COHESION

Near-surface faulting is generally associated with low confining pressures and low temperatures and may produce rocks of varying degrees of granulation and brecciation. The degree or fineness of the granulation depends on the confining pressure, original character of the rock(s) involved, amount of movement, and duration of movement. The resulting disrupted rocks range from coarse breccias, in which the original rock is only slightly disrupted, to fine gouge, in which the rock is reduced to a paste. All of these rocks have one main feature in common: they lack *primary* cohesion. Except for the effects of secondary processes, which may cement the disrupted fragments into unified rock they would be without cohesion. The rocks involved may be sedimentary, igneous, or metamorphic, but the disruption or granulation occurred at low temperatures and pressures. Gouge and breccias have been reported along all types of faults (*see* Hill, 1959) and have been mentioned in many publications since the early days of geologic science.

Such rocks have generally been considered separately from mylonites, mylonite gneisses, cataclasites, ultramylonites, etc., because of their lack of primary cohesion and their implied low pressure-low temperature origins (*see* Knopf, 1931; Waters and Campbell, 1935; Christie, 1960). They are briefly considered here only because there probably exists a complete transition from noncohesive to cohesive cataclastic rocks.

FAULT BRECCIA

Definition.—Fault breccia: A rock composed of angular to rounded fragments, formed by crushing or grinding along a fault. Most fragments are large enough to be visible to the naked eye, and they make up more than 30 percent of the rock. Coherence, if present, is due to secondary processes.

FAULT GOUGE

Definition.—Fault gouge: Pastelike rock material formed by crushing or grinding along a fault. Most individual fragments are too small to be visible to the naked eye, and fragments larger than the average groundmass grains make up less than 30 percent of the rock. Coherence, if present, is due to secondary processes.

CATACLASTIC ROCKS WITH PRIMARY COHESION

Deep-seated faulting occurs with generally high confining pressures. The rocks produced in the fault zones, though extremely granulated, have remained cohesive, As with the noncohesive fault gouges and breccias, confining pressure, original character of the rock(s), and amount and duration of movement are important determinants of the product, but with the cohesive cataclastic rocks the effects of temperature, fluids, and other variables must also be considered. Regardless of the theoretical possibilities and implications of origin, the rocks produced have in common a *primary* coherence—they needed no secondary cementation to become indurated. Cataclastic rocks with primary cohesion are really metamorphic rocks.

In contrast to the noncohesive gouges and breccias which occur in all kinds of terranes, cohesive cataclastic rocks are commonly associated with plutonic and metamorphic rocks because of the environment necessary for their formation.

Cataclastic rocks with primary cohesion can be divided into three gradational categories (table 1): (1) those in which neomineralization-recrystallization (constructive processes), though present, is subordinate to cataclasis (destructive processes); (2) those in which neomineralization-recrystallization is dominant over cataclasis; (3) retrograde cataclastic rocks. In addition, there is a special category of rock that has been melted, formed by cataclasis of rock that was hot before faulting. This type is not gradational to the others.

CATACLASIS DOMINANT

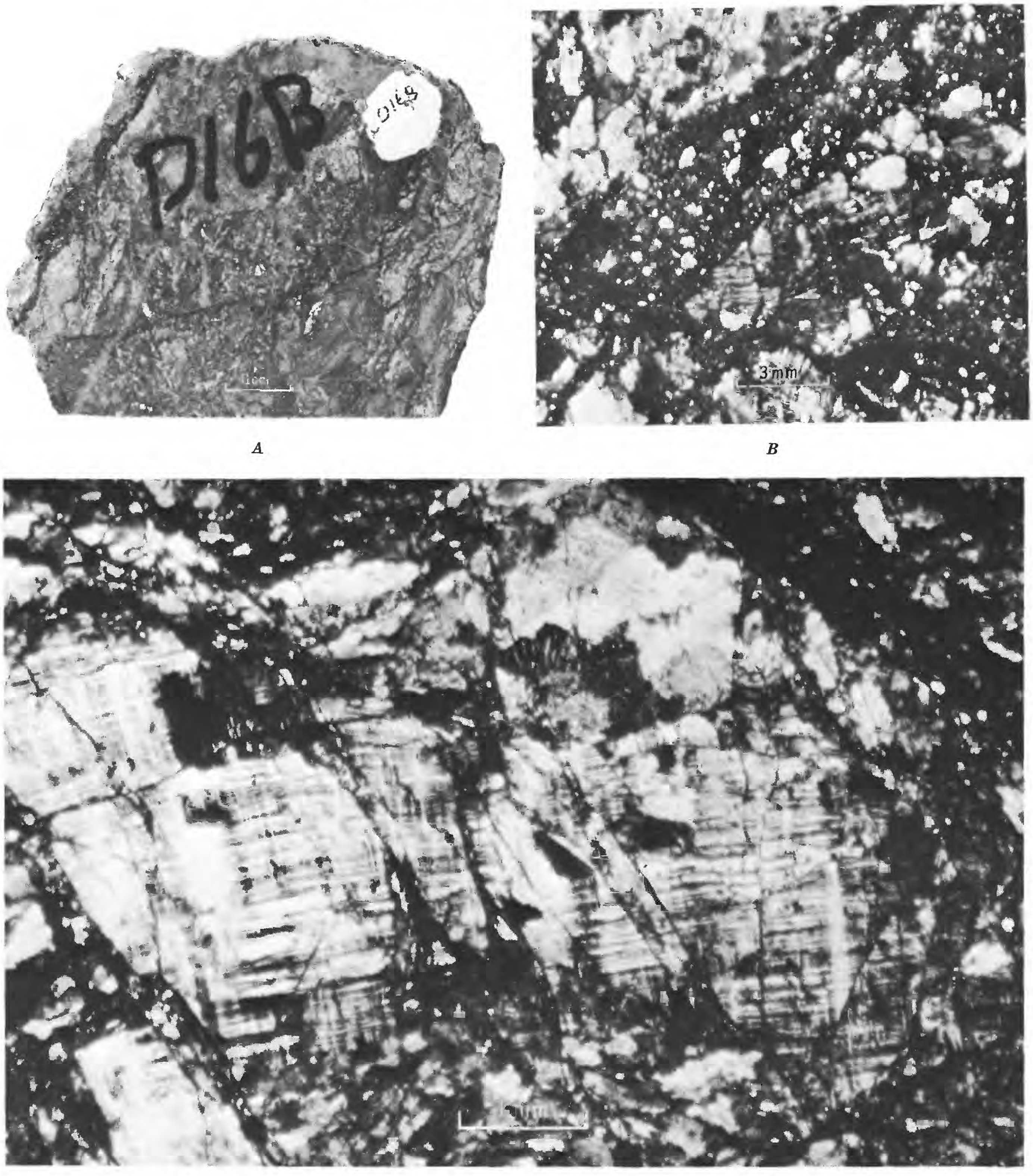
ROCKS WITHOUT FLUXION STRUCTURE

SERIES: MICROBRECCIA-CATACLASITE

MICROBRECCIA

Definition.—Microbreccia: An intensively fractured but unground (fragments have not rolled) cohesive breccia in which the grains and fragments are without form orientation. Fragments may range from megascopic to about 0.2 mm and are separated by finer grained material. Fragments larger than 0.2 mm make up more than about 30 percent of the rock.

Figure 1 shows typical microbreccias.



A B

C

FIGURE 1.—Microbreccias. *A*, From a dikelike fault zone in the North Carolina Piedmont, collected by J. F. Conley, Virginia Div. Mineral Resources. *B*, Photomicrograph of a microbreccia from the Brevard zone near Atlanta, Ga.; crossed polarizers. Parent rock was probably a "granite." C, Photomicrograph of a large microfaulted microcline grain in a microbreccia from the northwest edge of the Brevard zone near Atlanta, Ga.; crossed polarizers. Note the undirected nature of the cataclasis in *A* and *C*.

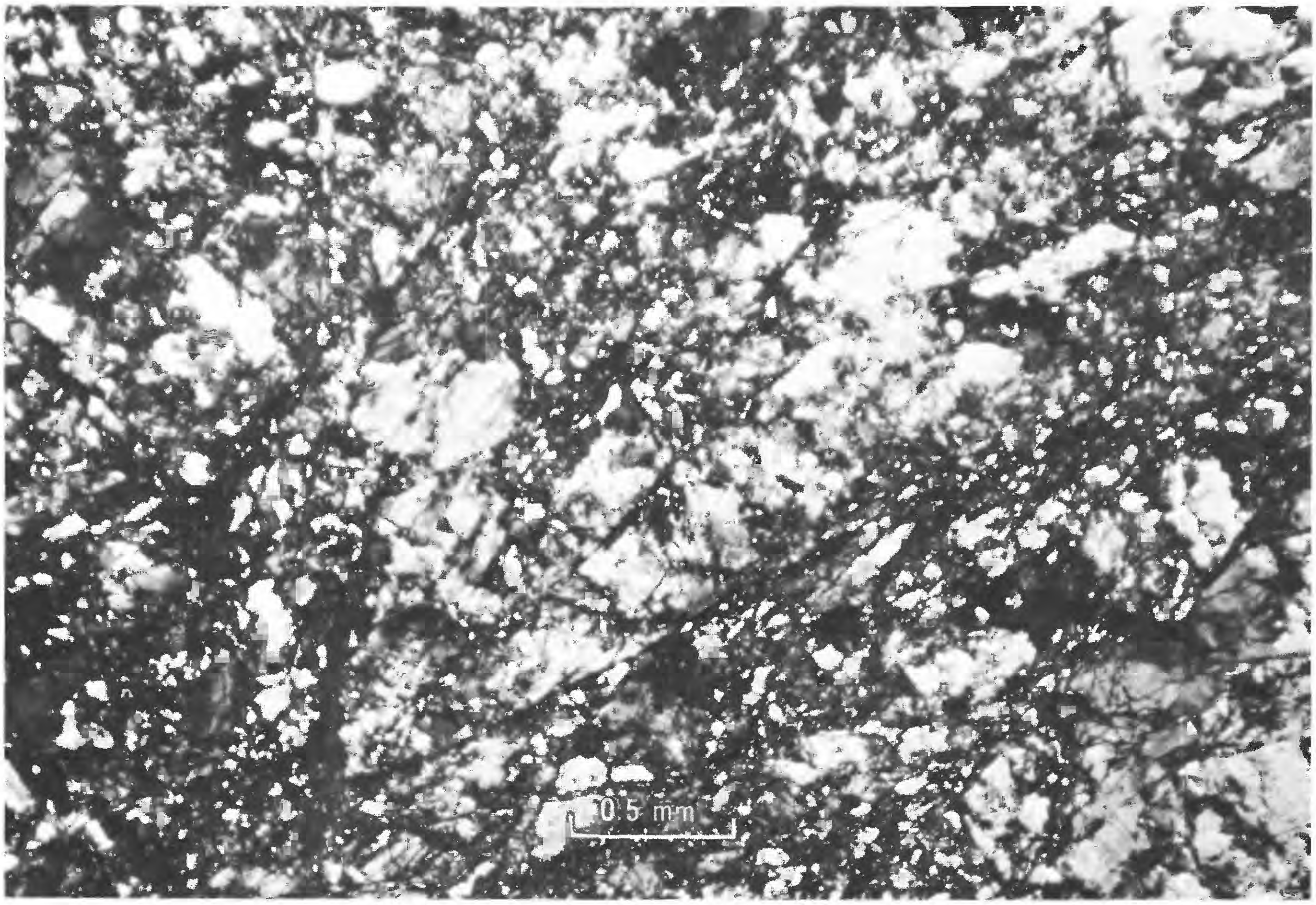


FIGURE 2.—Photomicrograph of a cataclasite from the Brevard zone near Atlanta, Ga.; crossed polarizers. Note the undirected nature of the cataclasis. Grain or fragment size about the same as in mylonites. Parent rock probably a "granite."

Discussion.—The term *microbreccia* was originally used by Tyrrell (1926, p. 281–285; he used *micro-breccia*). Tyrrell (1926) also used *crush-breccia* for essentially the same rocks. Microbreccias might fit into Quensel's (1916) definition of *kakirite* (although microbreccias generally lack lenticularity), but Holmquist (1910) used *kakirite* almost synonymously with *mylonite*. *Microbreccia* is an adequate term for the rock described and is less exotic than similar terms. The size grade has been introduced into the definition in order to distinguish *microbreccia* from *cataclasite*.

CATACLASITE

Definition.—*Cataclasite:* An aphanitic, structureless cohesive cataclastic rock in which most of the fragments are less than 0.2 mm, and make up less than about 30 percent of the rock. Essentially like a mylonite but lacks fluxion structure.

Figure 2 shows a typical cataclasite.

Discussion.—*Cataclasite* was first defined by Grubenmann and Niggli (1924). Tyrrell (1926, p. 285), following Grubenmann and Niggli (1924), stated:

> * * * when the product is a structureless rock powder, in which a few porphyroclasts may have survived, the term *cataclasite* is used in preference to mylonite, as the latter connotes a rolling out or milling of the material with resulting parallel structure.

The definition given in this paper is essentially that of Waters and Campbell (1935, p. 477); a size grade has been added to differentiate the rock from microbreccia. *Cataclasite* has been used in this sense by most workers (Grubenmann and Niggli, 1924; Tyrrell, 1926; Knopf, 1931; Waters and Campbell, 1935; Christie, 1960, 1963; Hsu, 1955b; Reed, 1964; Higgins, 1966). Schoch (1962) has used *cataclasite* both in the sense of this paper and as a general term for all cataclastic rocks.

ROCKS WITH FLUXION STRUCTURE

SERIES: PROTOMYLONITE-MYLONITE-ULTRAMYLONITE

Protomylonite

Definition.—Protomylonite: A coherent crush-breccia composed of megascopically visible fragments that are generally lenticular and are separated by megascopic gliding surfaces filled with finely ground material. The fragments, or "megaporphyroclasts," make up more than about 50 percent of the rock. Protomylonite commonly resembles conglomerate or arkose on weathered surfaces. Features of the original rock, such as stratification and schistosity, may be preserved in the larger fragments.

Figures 3 and 4 show typical protomylonites.

Discussion.—Backlund (1918, p. 195–199) created the term *protomylonite* to describe rocks from Cape Chelyuskin-Sarya on the northern tip of Asia. Neither Lapworth (1885) nor Teall (1918, see following section on mylonite, this paper) mentions any names for this type of rock, but from Teall's descriptions and photomicrographs, the rocks transitional from Lewisian gneiss to mylonite can be recognized as protomylonites (fig. 9). With one exception (Holmes, 1928, p. 190), there has been little disagreement over the definition and characteristics of protomylonite. However, some geologists were not aware of the term and created new names for the same type of rock. Thus, protomylonite is roughly equivalent to *kakirite* as defined by Quensel (1916), to the "*nodular mylonite*" of Raguin (1926), and to the "*fissured and brecciated granite*" of Termier and Boussac (1911). *Protomylonite* is preferable to the other terms because it fits into the series *mylonite-ultramylonite* best and is more concisely descriptive of the rock represented.

Mylonite

Definition.—*Mylonite*: A coherent microscopic pressure-breccia with fluxion structure that may be megascopic or visible only in thin section and with porphyroclasts generally larger than 0.2 mm. These porphyroclasts make up from about 10 to about 50 percent of the rock. Mylonites generally show recrystallization and even new mineral formation (neomineralization) to a limited degree, but the dominant texture is cataclastic.

Figures 5, 6, 7, 8, 9 show typical mylonites.

Discussion.—The above definition is essentially that of Lapworth (1885, p. 559), with modifications based on papers by Staub (1928), Knopf (1931), Waters and Campbell (1935), and Christie (1960), and on my own work. The parts of Lapworth's paper dealing specifically with mylonite and related cataclastic rocks are quoted below:

> The most intense mechanical metamorphism occurs along the grand dislocation (thrust) planes, where the gneisses and pegmatites resting on those planes are crushed, dragged, and ground out into a finely-laminated schist (*Mylonite*, Gr. *mylon*, a mill) composed of shattered fragments of the original crystals of the rock set in a cement of secondary quartz, the lamination being defined by minute inosculating lines (fluxion lines) of kaolin or chloritic material and secondary crystals of mica. Whatever rock rests immediately upon the thrust-plane, whether Archean, igneous, or Paleozoic, etc., is similarly treated, the resulting mylonite varying in colour and composition according to the material from which it is formed.
>
> * * * While the *mylonites* may be described as microscopic pressure-breccias with fluxion-structure, in which the interstitial dusty, siliceous, and kaolinitic paste has only crystallized in part; the *augen-schists* are pressure-breccias, with fluxion-structure, in which the whole of the interstitial paste has crystallized out. The *mylonites* were formed along the thrust-planes, where the two superposed rock-systems moved over each other as solid masses; the *augen-schists* were probably formed in the more central parts of the moving system, where the all-surrounding weight and pressure forced the rock to yield somewhat like a plastic body. Between these augen-schists there appears to be every gradation, on the one hand to the mylonites, and on the other to the typical mica-schists composed of quartz and mica.

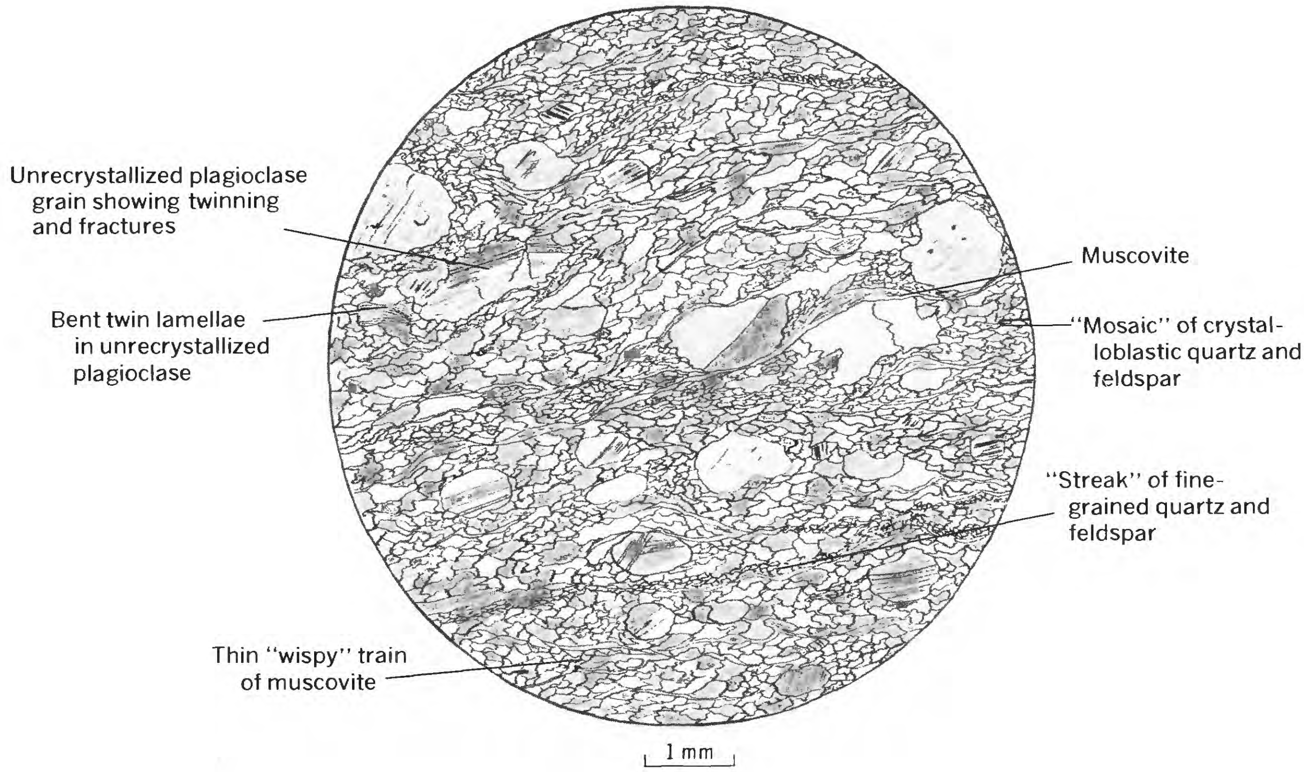
Lapworth made no attempt to illustrate mylonites or mylonite texture, but Teall (1918, p. 2) published photomicrographs of what might be called the "type mylonite," with the following statement:

> During our first day's excursion [in 1883] in the Eribol district he [Lapworth] led us to Arnabol Hill, showed us Archean gneiss resting almost horizontally on Cambrian quartzite, explained that this was due to an overthrust fault, and, pointing to the lower portion of the gneiss, used words to this effect: If you want to study the microscopic structure of rolled out gneiss take a specimen from there. That was my first introduction to a special type of dynamic metamorphism, and here is the specimen I collected on that occasion. . . . This is the kind of rock for which Prof. Lapworth subsequently proposed the term *mylonite*.

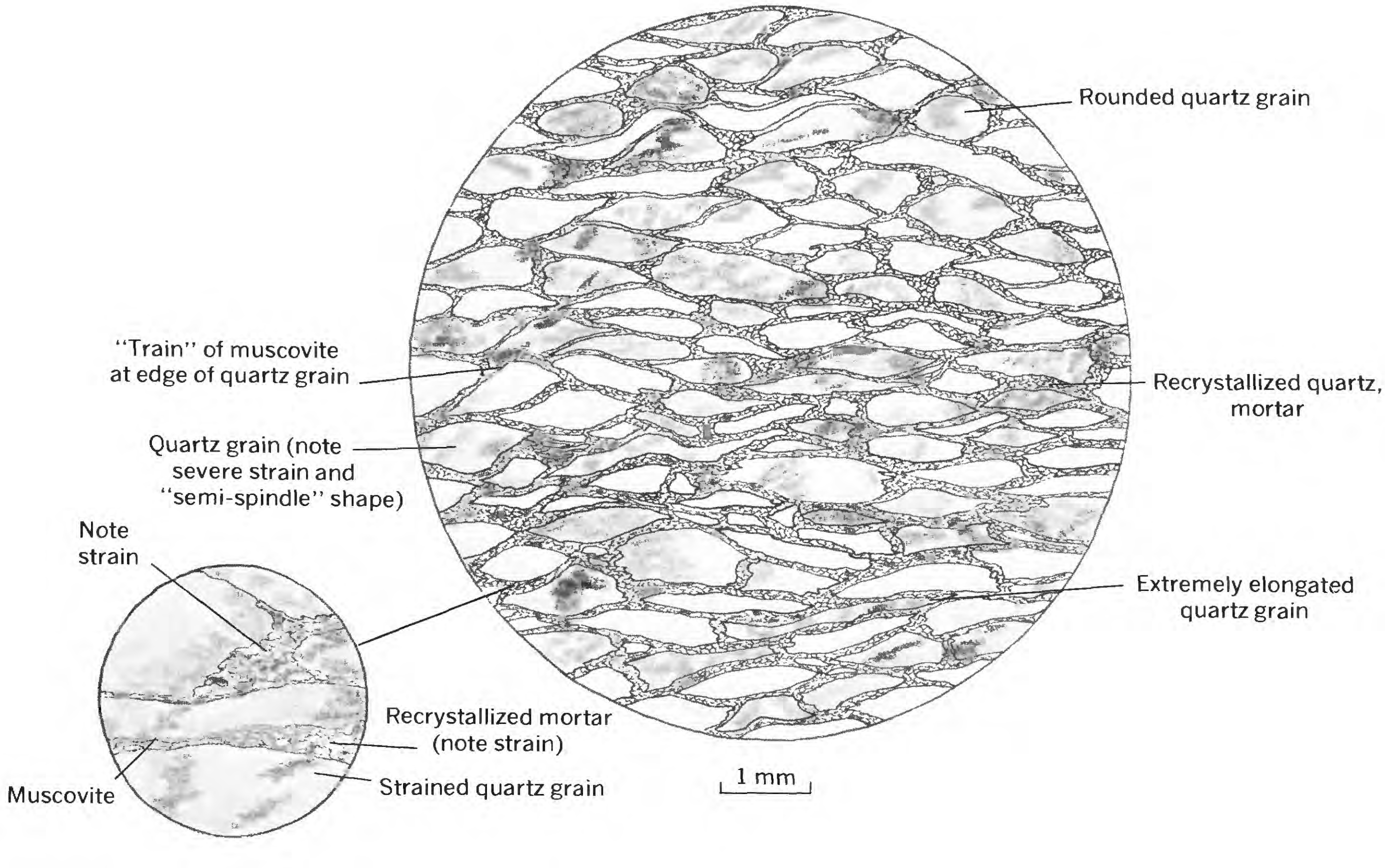
Teall's (1918, p. 2) photomicrographs are reproduced here as figure 9. He also illustrated and described rocks from Lapworth's Eribol district showing the transition from Lewisian gneiss to mylonite. Other cataclastic rocks from the Eribol district have been sketched by Harker (1950, p. 168–169). Harker's illustrations also show the complete transition from Lewisian gneiss to mylonite.

From Lapworth's (1885) descriptions, Teall's (1918) photomicrographs, and Harker's (1950) sketches we get a good picture of the rock the original term *mylonite* was intended to describe.

A


Unrecrystallized plagioclase grain showing twinning and fractures
Bent twin lamellae in unrecrystallized plagioclase
Muscovite
"Mosaic" of crystal- loblastic quartz and feldspar
"Streak" of fine- grained quartz and feldspar
Thin "wispy" train of muscovite
1 mm

B


Rounded quartz grain
"Train" of muscovite at edge of quartz grain
Recrystallized quartz, mortar
Quartz grain (note severe strain and "semi-spindle" shape)
Note strain
Extremely elongated quartz grain
Recrystallized mortar (note strain)
Muscovite
Strained quartz grain
1 mm

The definition of *mylonite* suggested in this paper differs slightly from those of earlier papers (Knopf, 1931; Waters and Campbell, 1935; Christie, 1960) in stressing the presence of neomineralization-recrystallization, in stating that fluxion structure may be visible only in thin section, and in addition of a size grade. The neomineralization-recrystallization aspect will be discussed in detail in a later section of this paper. The fluxion-structure aspect represents a source of possible contention. Was it Lapworth's intention that *mylonite* be restricted to rocks showing fluxion structure in outcrop, or may this feature be visible only in thin section? Lapworth did not make a clear point of this, and later geologists have also neglected to do so (Lapworth, 1885, p. 559; Knopf, 1931, p. 9–14; Waters and Campbell, 1935, p. 474–476, 478; Christie, 1960, p. 80–85; Reed, 1964, p. 648). The "type mylonites" are laminated and show fluxion structure in outcrop (Lapworth, 1885; Teall, 1918; Christie, 1960). However, although mylonite structure is correctly identifiable in many cases without thin section work, it is definitely identifiable only in thin section. Rocks with megascopic fluxion structure almost invariably have microscopic fluxion structure, and fluxion structure that is only visible in thin section has the same significance as megascopically visible fluxion structure. It is clear from Lapworth's and most subsequent definitions that fluxion structure in thin section is a requisite for a rock to be called *mylonite*. Therefore, I propose that possessing microscopic fluxion structure qualifies a rock to be called *mylonite*.

Ultramylonite

Definition.—Ultramylonite: A coherent, aphanitic, ultra-crushed pressure breccia with fluxion structure, in which most of the porphyroclasts have been reduced to breccia streaks and the few remaining porphyroclasts are smaller than 0.2 mm. These porphyroclasts make up less than about 10 percent of the rock. As in protomylonite and mylonite, recrystallization-neomineralization is present but is subordinate to cataclastic texture. In hand specimen and outcrop ultramylonites are commonly homogeneous-appearing rocks (although many have compositional layering), easily confused with chert, quartzite, or felsic volcanic rock. Ultramylonite represents the highest stage in intensity of mylonitization in the series *protomylonite-mylonite-ultramylonite*.

Figure 10 shows typical ultramylonites.

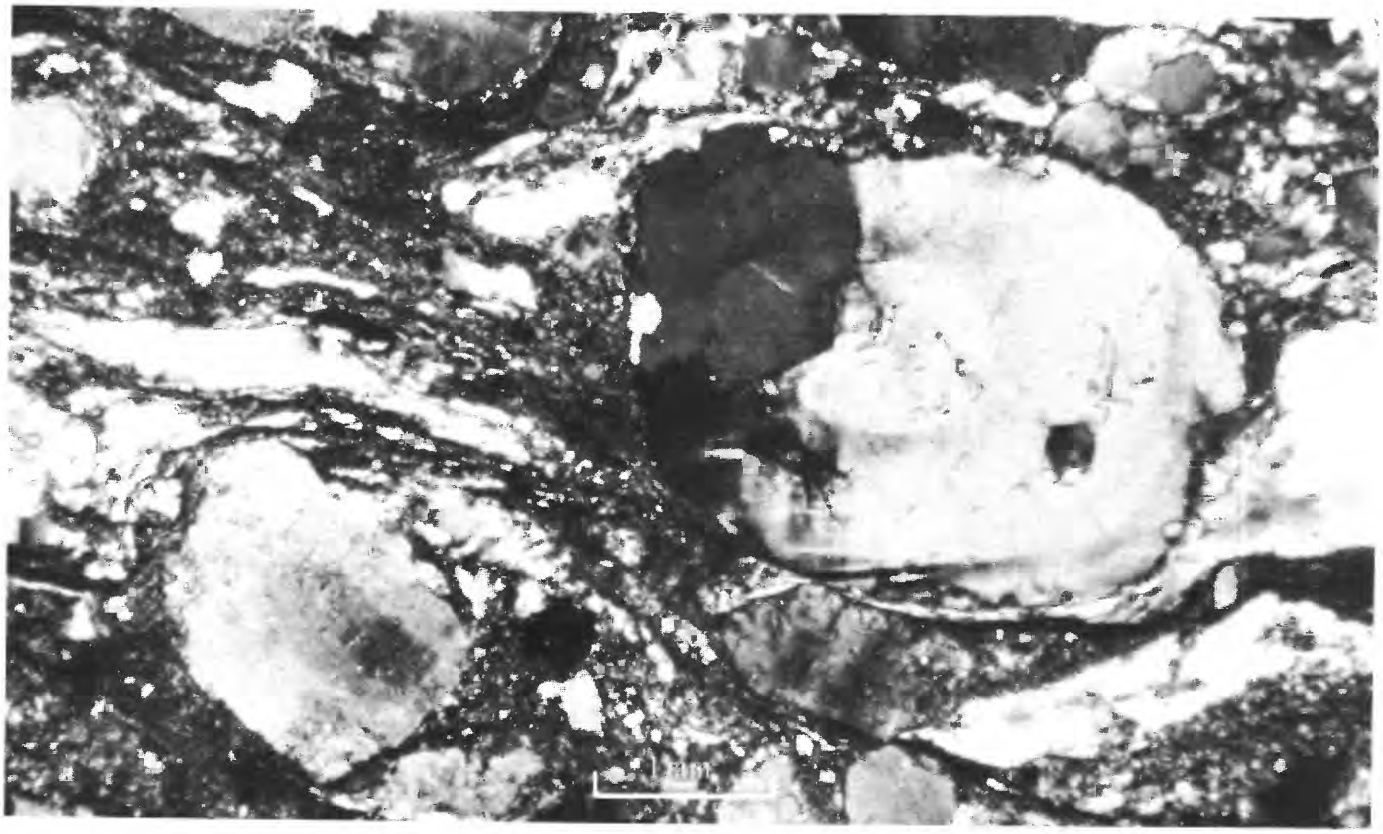
FIGURE 3.—Microdrawings of protomylonite. *A*, From Moscow Mountain, Wash. Parent rock was a "granite." *B*, Developed from micaceous quartzite of the Weaverton Formation in the Virginia Blue Ridge. Note lensoid shape of quartz grains and the finely comminuted "mortar" in the interstices. Both drawings with polarizers crossed.

Discussion.—Ultramylonite was first defined by Staub (1915) and subsequently elaborated upon by Quensel (1916). Both authors defined *ultramylonite* as a rock in which all porphyroclasts have been entirely reduced to breccia streaks. Staub (1928), however, later reconsidered and refined his definition, stating: "the extreme form of ultramylonitization has been reached when the matrix appears as a glass-like substance and the porphyroclasts have diminished to a diameter less than 0.02 mm." (translation). Waters and Campbell (1935, p. 481) followed the earlier definitions almost *verbatim*, but their photomicrographs of ultramylonites (p. 489, fig. 6; p. 490, fig. 7; p. 492, fig. 8) all show easily identifiable porphyroclasts (see fig. 17C). In fact, Quensel's (1916, Pl. 5, fig. 2) photomicrographs (also used by Knopf, 1931, p. 11, fig. 3) also show porphyroclasts. Perhaps the fact that Staub's (1928) refined definition using the 0.02 mm. limit refers to the "*extreme* form of ultramylonitization" has been overlooked. In the ultramylonites that I have studied and in photomicrographs of ultramylonites in the literature, the division between *mylonite* and *ultramylonite* occurs when the porphyroclasts have reached a diameter of about 0.2 mm. I propose that rocks in which *most* of the porphyroclasts are greater than 0.2 mm in diameter should be called *mylonite*, and those in which *most* of the porphyroclasts are less than 0.2 mm in diameter should be called *ultramylonite*.

In addition to the size of the porphyroclasts there is the problem of their relative abundance. Hsu (1955b, p. 251–252) modified Waters' and Campbell's (1935) definitions of *protomylonite*, *mylonite*, and *ultramylonite* to include percentage of "aphanitic paste" relative to the bulk of the rock. Under his definitions:

> Mylonite is a microbreccia produced by the milling down of the original rock material into an aphanitic paste which constitutes more than 50 percent, and less than 95 percent, of the bulk of the rock."
>
> * * * * *
>
> *Protomylonite* is a mylonitic rock in which the aphanitic paste constitutes less than 50 percent of the bulk of the rock, and *ultramylonite* is a mylonitic rock in which the aphanitic paste constitutes more than 95 percent of the bulk of the rock.

However, given the same original rock type, a cataclastic product with only a few percent porphyroclasts 0.21 mm in diameter in a very finely granulated matrix has probably been milled more than one with a large percentage of porphyroclasts 0.15 mm in diameter, and, using Hsu's definitions, a rock with only 10 percent "aphanitic paste" or matrix, in which the porphyroclasts were all ground down to less than 0.2 mm, has probably been milled more than one with 55 percent



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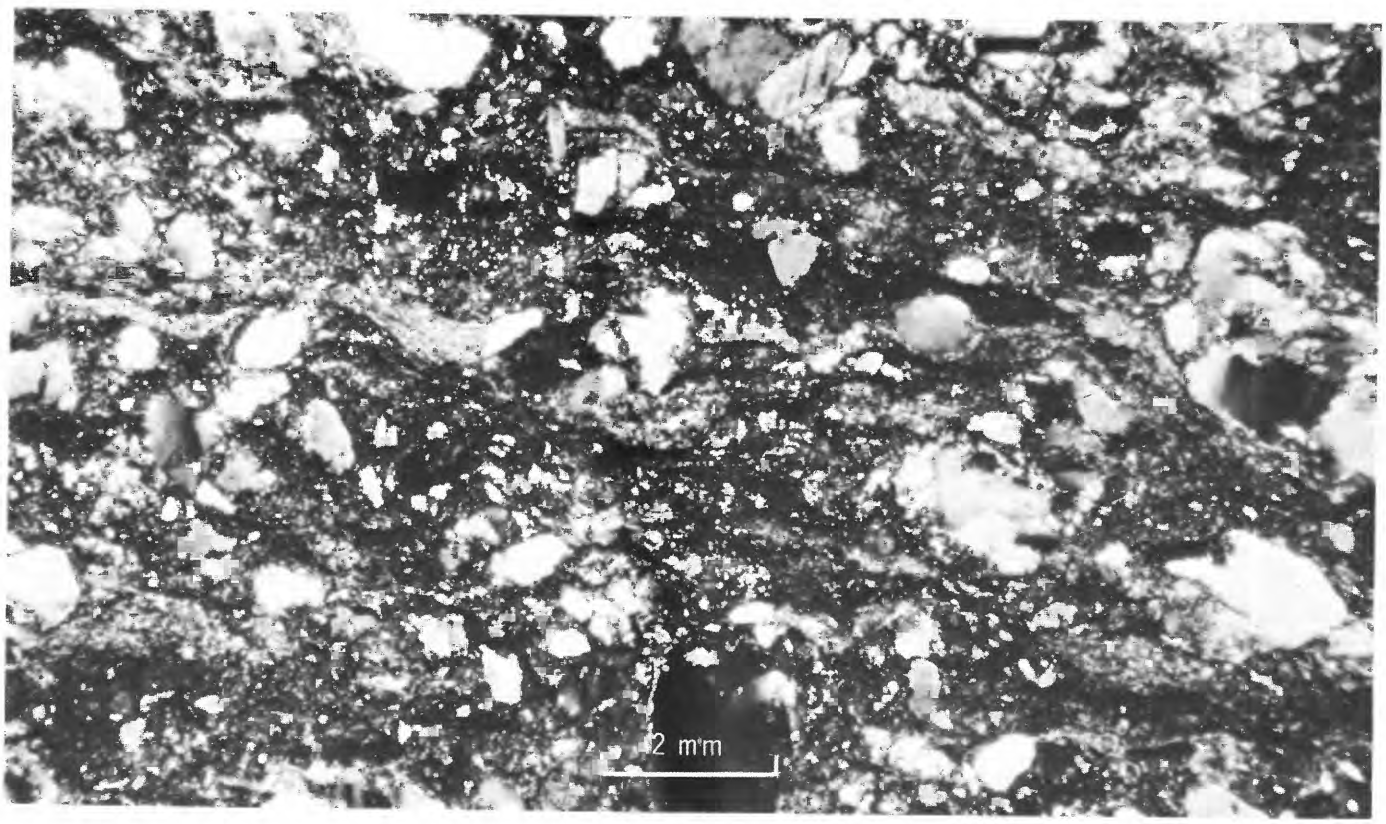

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matrix and large porphyroclasts. The relative percentage of porphyroclasts, or the percentage of matrix, to the bulk of the rock, is extremely important in defining *mylonite* and *ultramylonite*. The percentages added to the definitions of all of the rocks are based on my empirical observations.

Neither Staub (1915, 1928) nor Quensel (1916) made a real point of the presence or absence of lamination or fluxion structure in ultramylonites, but all photomicrographs of "typical" ultramylonites show fluxion structure (Quensel, 1916, Pl. 5, fig. 2; Knopf, 1931, fig. 3; Waters and Campbell, 1935, figs. 6, 7, and 8; see fig. 10 of this paper).

PHYLLONITE: A VARIETY OF MYLONITE AND ULTRAMYLONITE

Definition.—Phyllonite (phyllite-mylonite): A rock of phyllitic appearance formed by mylonitization of an originally coarser grained rock.

Figure 11 shows typical phyllonites. Because of confusion between the terms *phyllonite* and *diaphthorite*, *phyllonite* is discussed after *diaphthorite*, in a later section.

NEOMINERALIZATION-RECRYSTALLIZATION DOMINANT

SERIES: MYLONITE GNEISS (MYLONITE SCHIST)-BLASTOMYLONITE

MYLONITE GNEISS (MYLONITE SCHIST)

Definition.—Mylonite gneiss (*mylonite schist*): A coherent rock intermediate between a protomylonite or coarse mylonite and a crystalline gneiss or schist because its texture is the result of combined cataclastic and crystalloblastic processes. Augen structure is characteristic, the augen generally being porphyroclasts or crushed aggregates of felsic minerals. The augen, although commonly recrystallized, preserve evidence of cataclastic texture by their shapes and by the crush trails commonly associated with them; the surrounding groundmass has been recrystallized and (or) neomineralized, although it also may show palimpsest cataclastic texture. Most of the porphyroclasts are larger than about 0.5 mm, and they make up more than about 30 percent of the rock.

Figure 12 shows typical mylonite gneisses and mylonite schists.

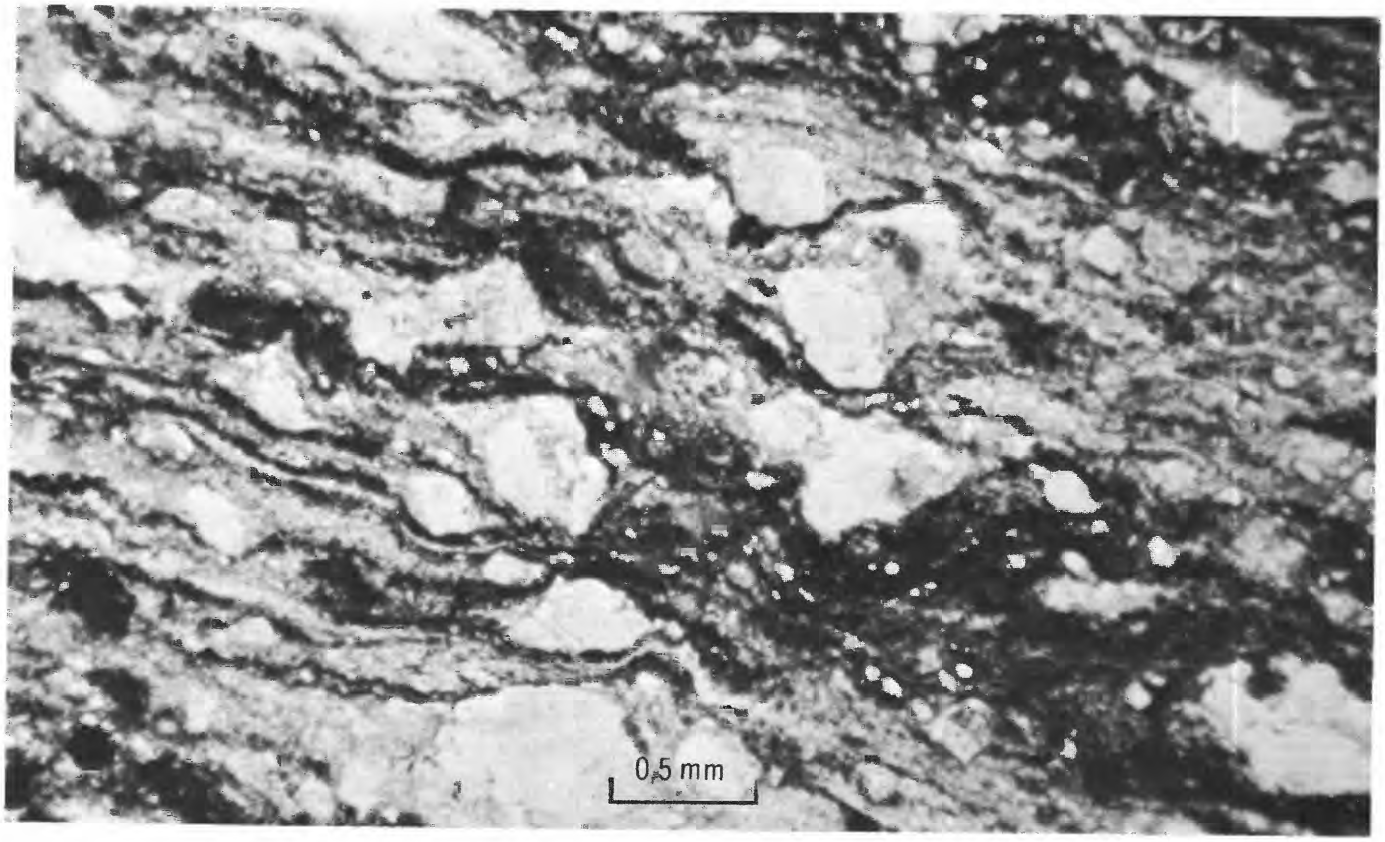
Discussion.—Quensel (1916, p. 99, 101–102) introduced the term *mylonite gneiss*. The term is equivalent to Lapworth's (1885, p. 559) *augen schist* (Knopf, 1931, p. 12; Waters and Campbell, 1935, p. 477, 479; Christie, 1960, p. 82; Reed, 1964, p. 650). Lapworth described and defined *augen schists* and contrasted them with mylonites. He indicated that there is complete gradation between the two rock types. Lapworth's term takes historical precedence over *mylonite gneiss*, but the use of the term *augen gneiss* might lead to confusion with ordinary products of progressive regional metamorphism in which the augen are commonly porphyroblasts.

There is no common agreement among geologists as to what kind of rock should be called *gneiss* and what kind should be called *schist*, despite admirable efforts to standardize these terms (see Dietrich and Mehnert, 1961). Moreover, some rocks would be transitional between gneiss and schist, no matter how strict the definition of these terms. What is termed *mylonite gneiss* may in some cases resemble *schist*, as most geologists use the term more than *gneiss*. Therefore, *mylonite schist* is proposed here as an alternate term for *mylonite gneiss* where the rock is more schistose than gneissic.

Mylonite schist, as defined here is a new term. Quensel (1916) used the term *mylonitschiefer*, which translates roughly as mylonite schist, to distinguish laminated mylonites with fluxion structure (his mylonitschiefer) from unlaminated cataclastic rocks without fluxion-structure (cataclasites) which he considered "true mylonites" or "mylonites in the strictest sense" (see discussion of *mylonite*). Therefore, Quensel's *mylonitschiefer* is essentially synonymous with *mylonite* as defined and used in this paper.

In terms of porphyroclast size and abundance *mylonite schist* and *mylonite gneiss* are equivalent to *protomylonite*, but they also include rocks equivalent to coarse grained *mylonite* with porphyroclasts larger than 0.5 mm. However, this may be strictly a textural comparison, because there is a problem regarding the origin of mylonite gneisses and mylonite schists. Some of these rocks may actually be equivalent to protomylonite;

FIGURE 4.—Photomicrographs of protomylonite. *A*, From Cucamonga Canyon, San Gabriel Mountains, Calif. Large subhedral, zoned feldspars are surrounded by a matrix consisting chiefly of quartz and micas, with some finely ground feldspar. See Examples section of text (p. 42). Also note "flamboyant" quartz, and degree of recrystallization. This rock is fairly well recrystallized for a protomylonite. *B*, From the San Andreas fault zone near Crystal Springs Lakes, Calif. (collected by A. C. Waters). This rock is relatively fine grained for a protomylonite, and when compared with *A*, it illustrates the range in grain size covered by the term *protomylonite*. Parent rock was a meta-arkose. Both with crossed polarizers.



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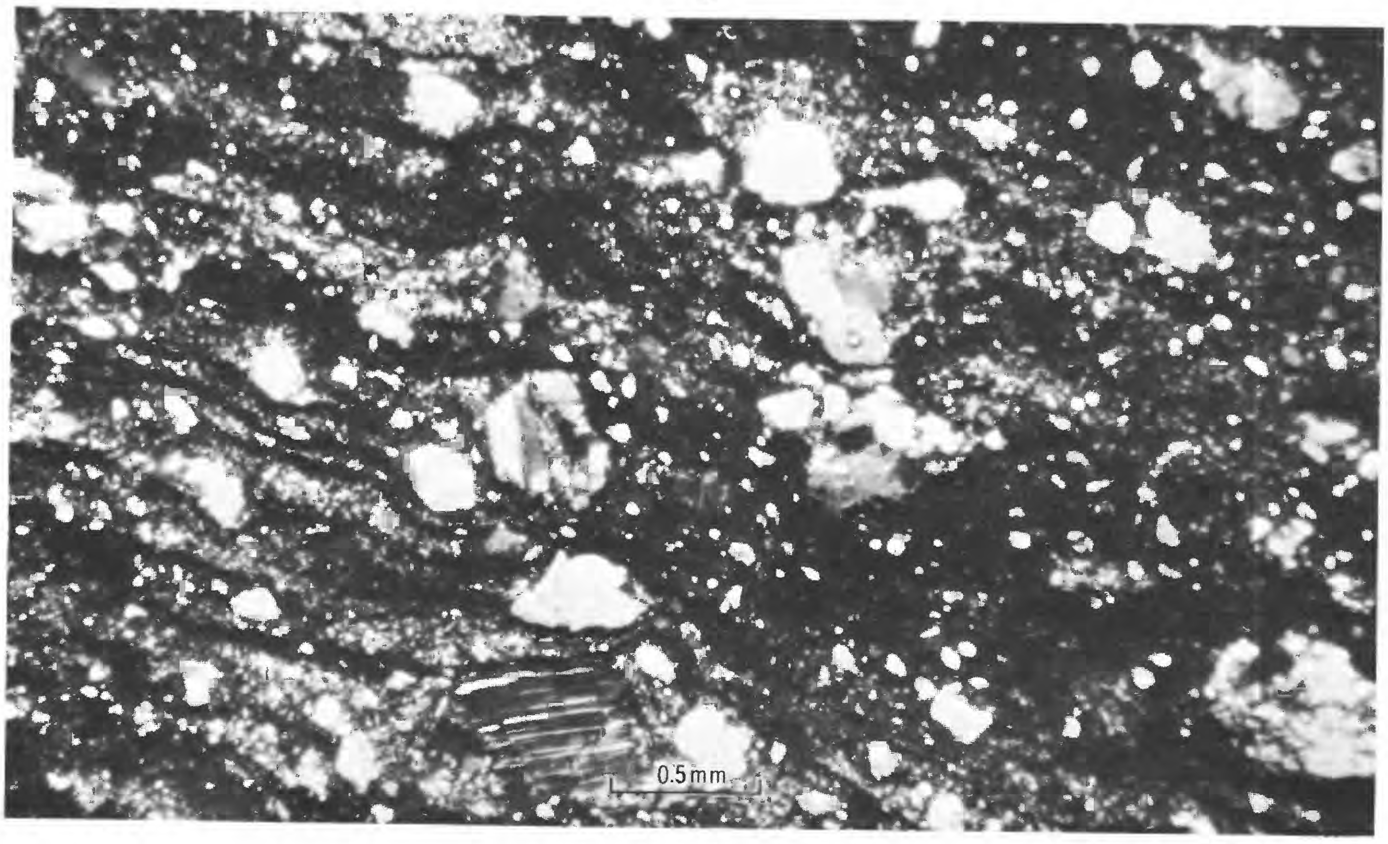

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they may represent the early stages of mylonitization with concomitant recrystallization and neomineralization, just as protomylonite represents the early stages of the same process, but with less recrystallization and neomineralization. Other identical rocks, however, may represent more intense stages, somewhat equivalent to mylonite or ultramylonite as far as mylonitization or comminution is concerned, but in which recrystallization and neomineralization have been sufficiently intense to produce a coarse-grained rock. In other words, some mylonite gneisses or mylonite schists may represent rocks "on their way down" to blastomylonite, while others may represent rocks "on their way up" to crystalline schists because neomineralization-recrystallization has "overpowered" or "outdistanced" the cataclasis, so to speak. Thus a more accurate representation on a classification chart would be somewhat like that shown diagrammatically in figure 13.

BLASTOMYLONITE

Definition.—Blastomylonite: A coherent rock intermediate between medium- to fine-grained mylonite or ultramylonite and a crystalline schist or gneiss because its texture is the result of combined cataclastic and crystalloblastic processes. It is *not* produced by later recrystallization or neomineralization of a previously mylonitized rock; cataclasis and neomineralization-recrystallization are concurrent, which produces a rock in which crystalloblastic texture appears to have overprinted the basic mylonite texture. Porphyroclasts in blastomylonite are generally smaller than about 0.5 mm and may show recrystallization. They make up less than about 30 percent of the rock.

Figure 14 shows typical blastomylonites.

Discussion.—Sander (1912, p. 250) first used the term *blastomylonite* to describe rocks from the Tauernwestend, Austria. Knopf (1931, p. 12) introduced the term to English-speaking geologists. The definition above is essentially a rewording of Knopf's definition. Her definition (which most later papers follow) includes the phrase: "Neomineralization is so far advanced that the mylonitization can only be recognized with difficulty." This phrase has been removed from the definition because the degree of difficulty obviously depends on the observer and his knowledge of the rock and its field relations. In fact, Knopf (1931, p. 14) states in a later sentence: "The characteristic feature wherein mylonites differ from cataclastic rocks in general is in their ultracataclasis or intensive rolling out, so that even where much neomineralization accompanies the process as in blastomylonites the texture is still characteristic."

The size grade for porphyroclasts is based on my data. *Blastomylonite* is equivalent in terms of porphyroclast size to medium- and fine-grained *mylonite* and *ultramylonite;* it thus includes all rocks with porphyroclasts less than 0.5 mm. where neomineralization-recrystallization dominates over cataclasis.

FIGURE 5.—Photomicrographs of a mylonite (collected by A. C. Waters), from the San Andreas fault zone near Crystal Springs Lakes, Calif., in plane-polarized light (*A*) and with crossed polarizers (*B*). Note the fluxion structure and the trails of crushed particles in the pressure shadows of porphyroclasts. The porphyroclasts are chiefly feldspar. Also note how the trails of finely comminuted dark minerals (much of this is magnetite) help define the fluxion structure. The parent rock was a meta-arkose.

PROTOCLASTIC ROCKS

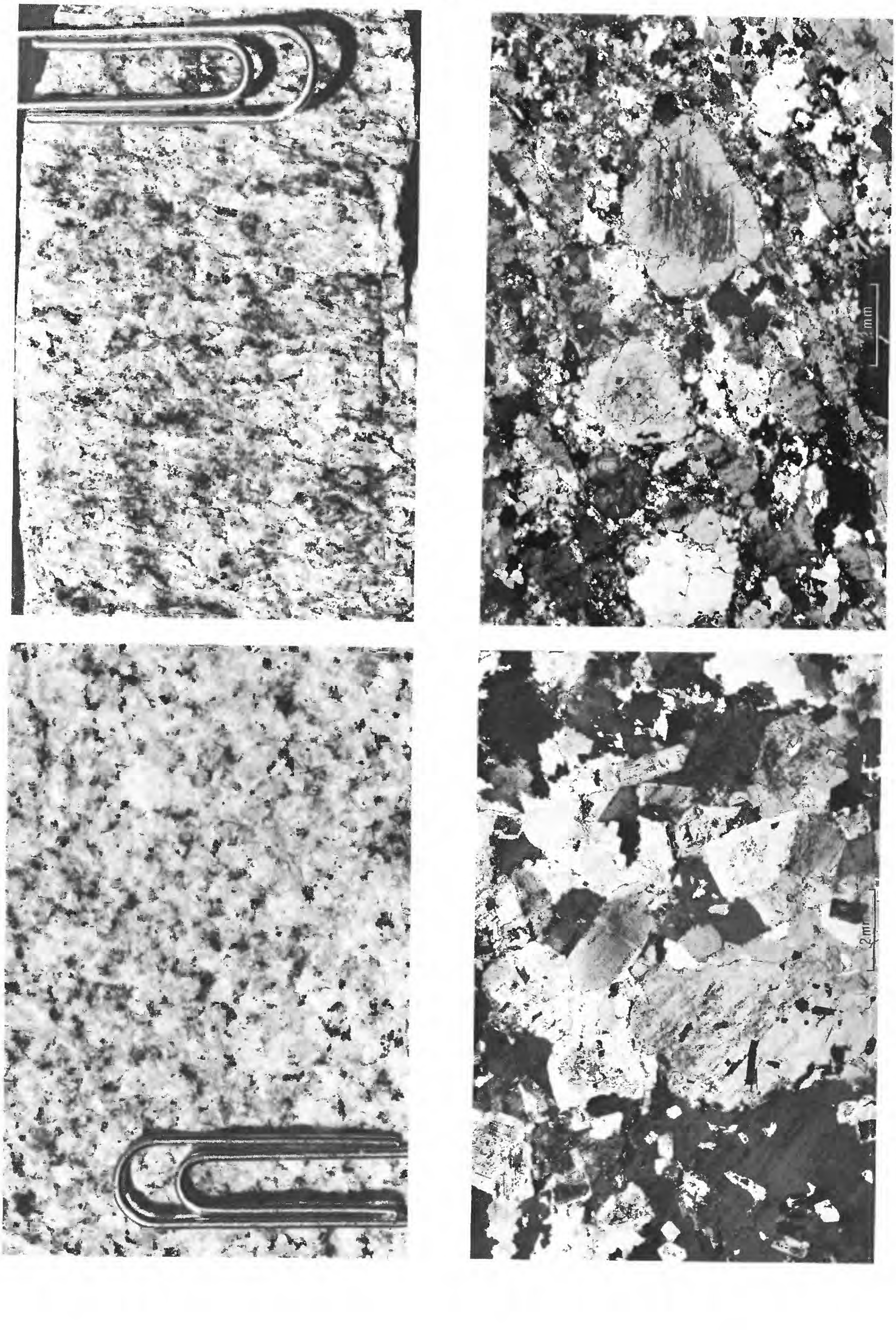
Protoclastic deformation, or *protoclasis*, is a type of cataclastic deformation. It applies to cataclasis of an igneous body, or parts of an igneous body, due to late intrusive movements of, or within, that body, generally before it has completely crystallized. The products of protoclasis are called *protoclastic rocks*, and may be indistinguishable texturally from other cataclastic rocks, except for their intimate association with, or localization within, the parent igneous body.

Brögger (1890, p. 105) was apparently the first to use the term *protoclastic* (protoklastisch). The meaning and use of the term has changed little since it was first defined. Thus, my definition above is essentially the original translated into modern terms.

Protoclastic rocks can be considered special varieties of cataclastic rocks; thus, there seems no need for separate nomenclature. However, the term *protoclastic* should be used as a prefix to the cataclastic rock name, (for example: *protoclastic mylonite*).

Despite the fact that protoclastic rocks are cataclastic rocks, they differ from the latter in one important respect; protoclastic rocks are formed by deformation of magmatic rocks which are not completely solidified at the time of deformation, although the percentage of unsolidified material may be extremely small. Some crystallization must therefore occur during, or even slightly after the protoclastic deformation. This crystallization is reflected in the textures of the protoclastic rocks, and consequently most of these rocks fit best into the series *mylonite gneiss* (*mylonite schist*)-*blastomylonite.*

Waters and Krauskopf (1941) have given perhaps the best and most detailed description of an occurrence of protoclastic rocks at the Colville batholith, Washington. The protoclastic rocks of the Colville batholith are discussed in this paper at the end of the section, Examples of cataclastic rock zones and their interpretation, (p. 53–56).



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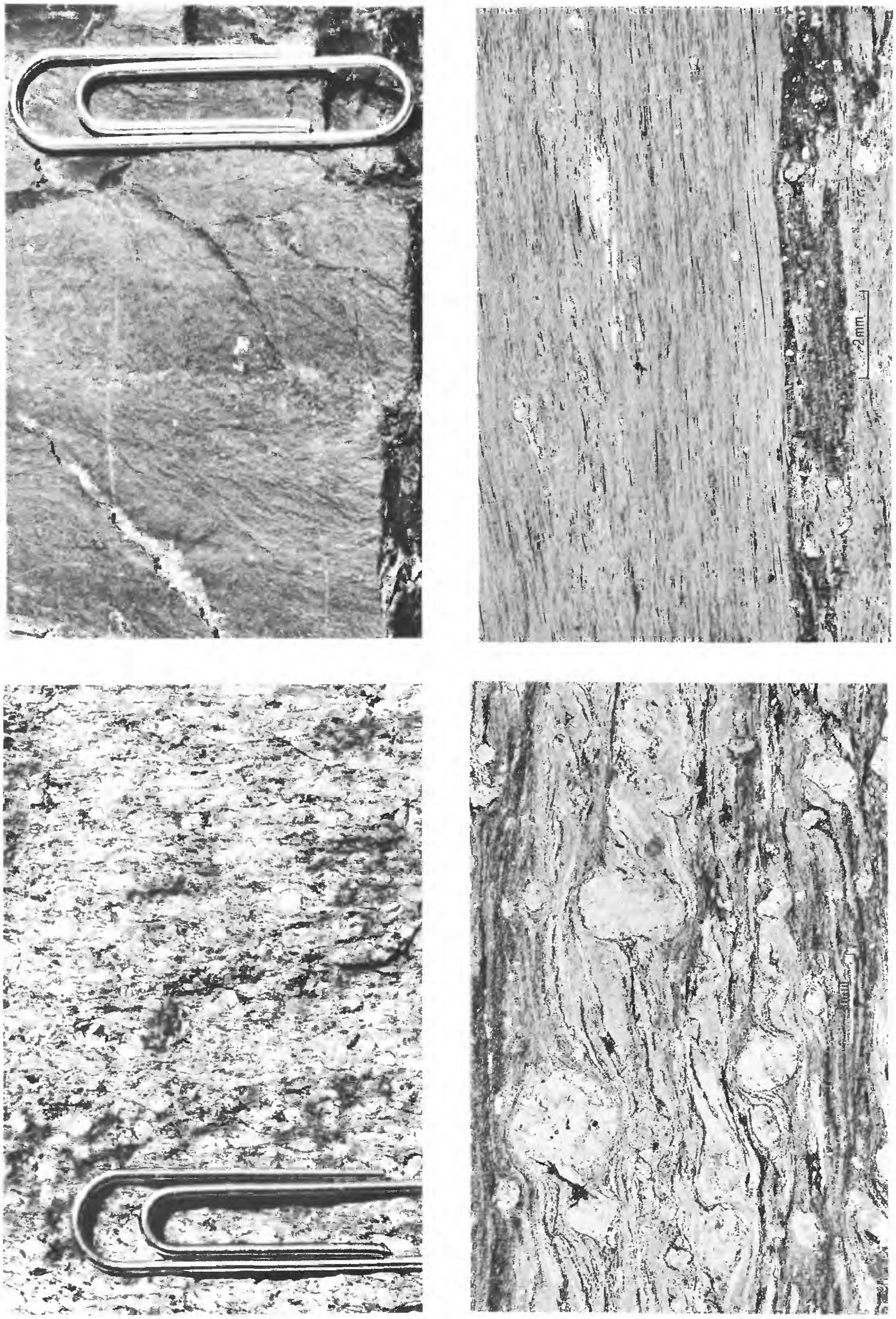


FIGURE 6.—Suite of four specimens and corresponding photomicrographs showing progressive mylonitization of granitic rock in the southeastern San Gabriel Mountains, Calif. Photographs courtesy J. S. Shelton; reproduced with permission of H. W. Freeman and Company, publishers of "Geology Illustrated" (Shelton, 1966). *A*, Parent granitic rock. *B*, Protomylonite. *C*, Mylonite; relatively coarse grained; porphyroclastic. *D*, Ultramylonite; relatively fine grained.

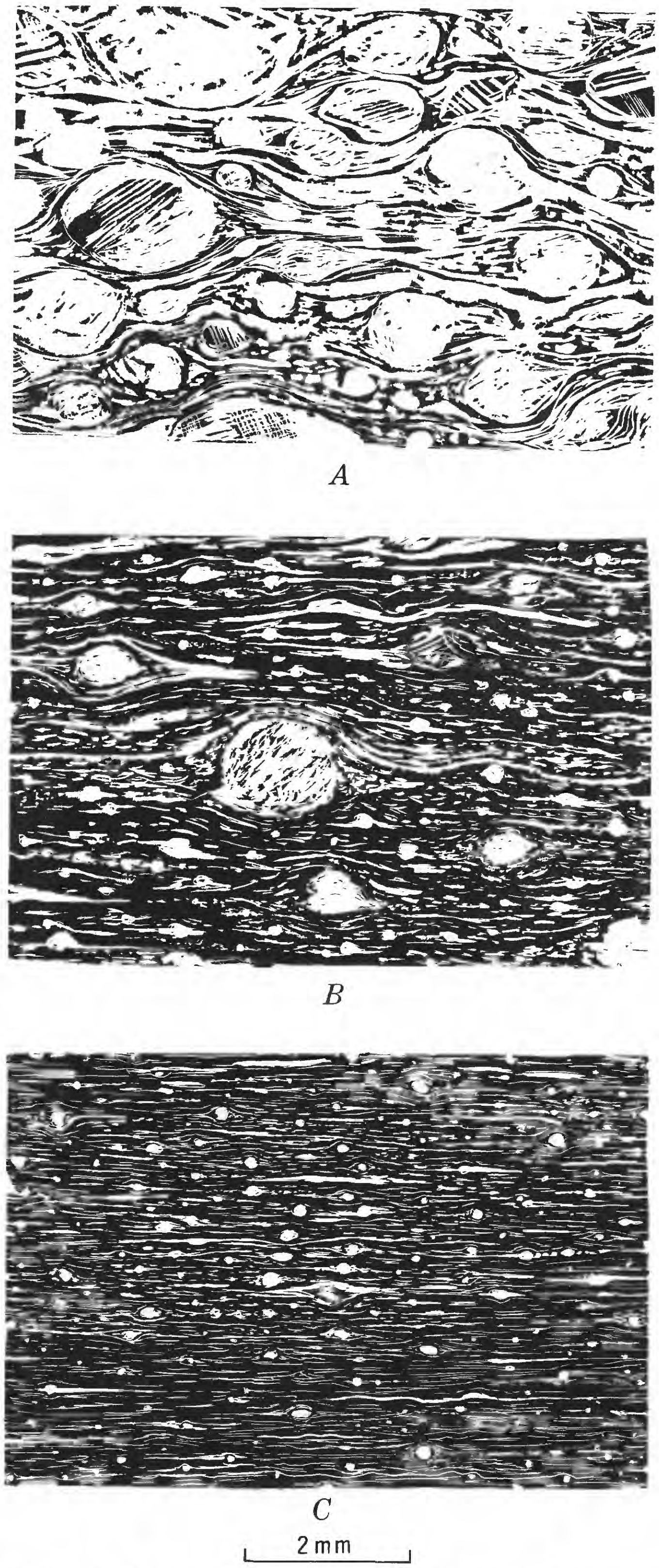


FIGURE 7.—Schematic sketches showing textures of protomylonite (*A*), mylonite (*B*), and ultramylonite (*C*). The white represents porphyroclasts and "breccia streaks" or trails from porphyroclastic material; the black represents finely comminuted material and dark minerals. All three represent rocks produced from the same parent, coarse-grained "granite."

RETROGRADE CATACLASTIC ROCKS

Retrograde or diaphthoritic cataclastic rocks are the products of retrograde metamorphism (diaphthoresis) occurring concurrently with cataclasis. They are in a sense simply variations of the basic cataclastic rocks already defined. However, their common occurrence in major fault zones (see bibliography) makes it desirable to include them in any general classification of cataclastic rocks.

Diaphthoresis is a process not necessarily related to or associated with cataclasis. A diaphthoritic rock or diaphthorite has relict minerals of a higher grade or facies of metamorphism which have been elsewhere in the rock changed or partially changed by retrogressive metamorphism (diaphthoresis) to minerals of a lower grade or facies of metamorphism. Such rocks are commonly but not necessarily phyllitic in appearance, which has led to confusion and misuse of the terms *phyllonite* and *diaphthorite*.

The concept of diaphthoresis was first introduced by Becke (1909) to account for relict high-grade minerals in low-grade rocks of the High Tauern Alps of the Austrian Tyrol. E. B. Knopf (1931) introduced the concept of diaphthoresis, the concept of phyllonitization, and the terms *diaphthorite* and *phyllonite* (originally defined by Sanders, 1911, p. 301) into English geological literature. She emphasized the distinction between phyllonites (which may or may not be retrogressive) and diaphthorities (which may or may not be cataclastic). She listed (1931, p. 19) the following criteria for the recognition of phyllonites:

(1) Phyllitic appearance accompanied by the characteristic lenticular structure, either megascopic or microscopic.

(2) A completely phyllonitized rock does not show cleavage that cuts the old S-planes because its phyllitic texture is the result of a refolding and transportation of the old S-planes of the rock.

(3) Adjacent lenses are of different sizes but the individuals in each lens are of similar grain size.

(4) All the individuals in one lens show subparallel optical orientation.

Knopf (1931, p. 14) defined *phyllonite* as follows:

> * * * a rock of phyllitic appearance that as a rule is indistinguishable from a normal phyllite. Unlike normal phyllites, however, it has been formed not by the crystallization of new mineral constituents, progressively increasing in grain size, but by the mylonitic degradation of an originally coarser-grained rock.

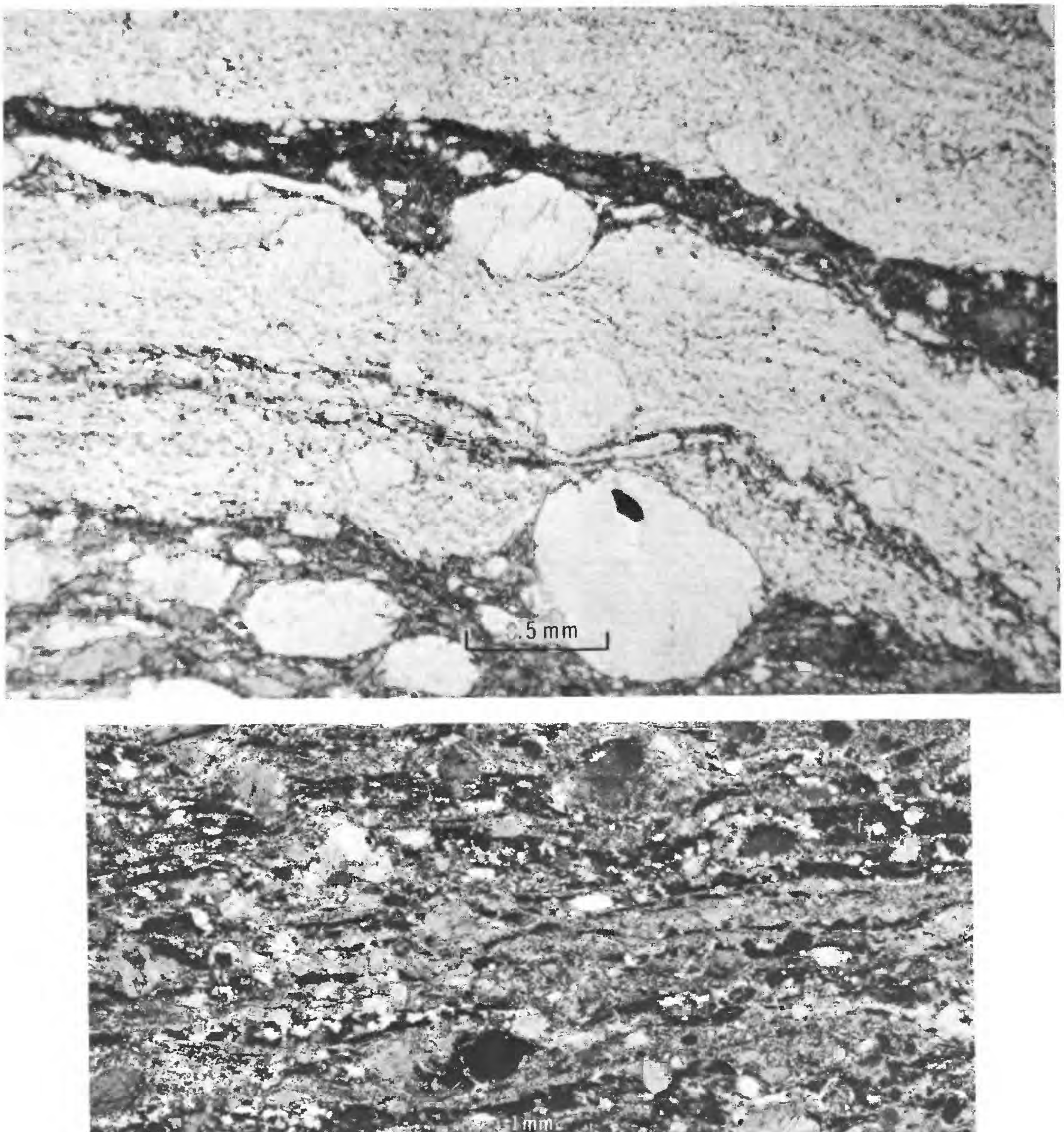


FIGURE 8.—Photomicrographs of mylonite. *Above:* From Scotland (collected by A. C. Waters); plane light. The porphyroclasts are chiefly plagioclase. Note the "flow" of the finely comminuted matrix around them. This photomicrograph also illustrates compositional layering, probably due to cataclastic metamorphic differentiation. Effects of recrystallization-neomineralization can be seen in the matrix, but the dominant texture is cataclastic. Parent rock was a gneiss. *Below:* From the San Andreas fault zone near Crystal Springs Lakes, Calif. (collected by A. C. Waters); crossed polarizers. Note fluxion structure. Parent rock was probably a meta-arkose.

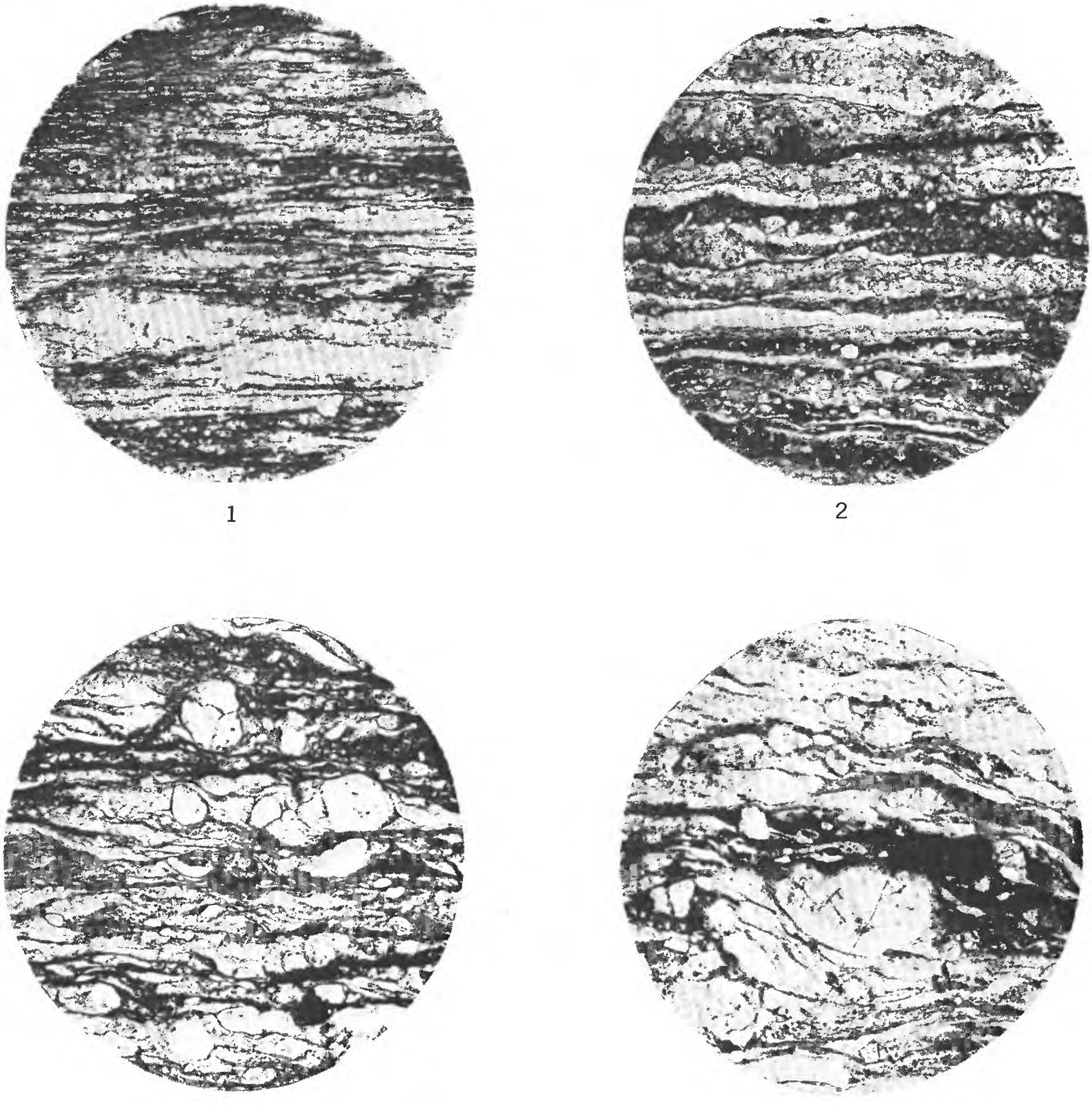
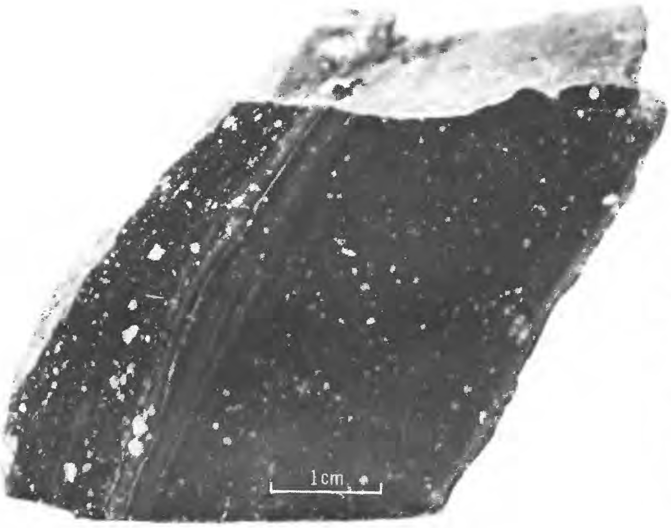


FIGURE 9.—Teall's (1918, pl. 1) photomicrographs of Lapworth's original "mylonites" and "augen gneisses" from the Eribol district of northwest Scotland. Presumably under plane-polarized light. No scale given. According to Teall (1918, p. 2), 3 is least mylonitized Lewisian gneiss, 2 is more mylonitized Lewisian gneiss, and 1 is typical of mylonite produced from Lewisian gneiss. Four is a mylonitized metasediment which Teall presented to show that the effects of mylonitization were the same regardless of the rock type.



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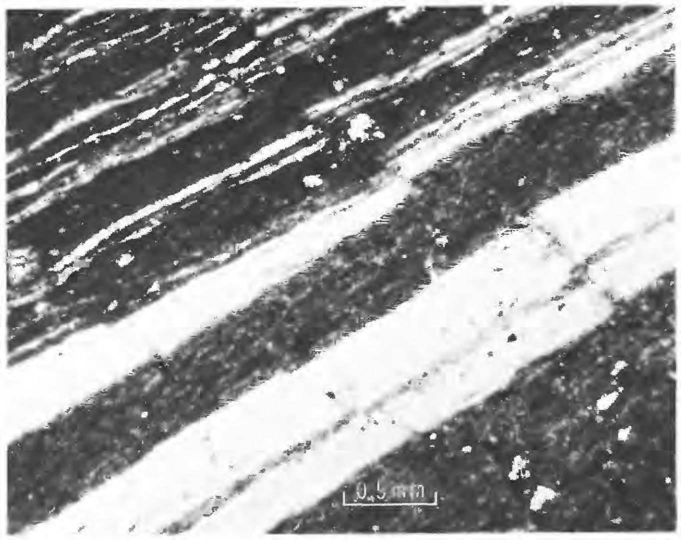

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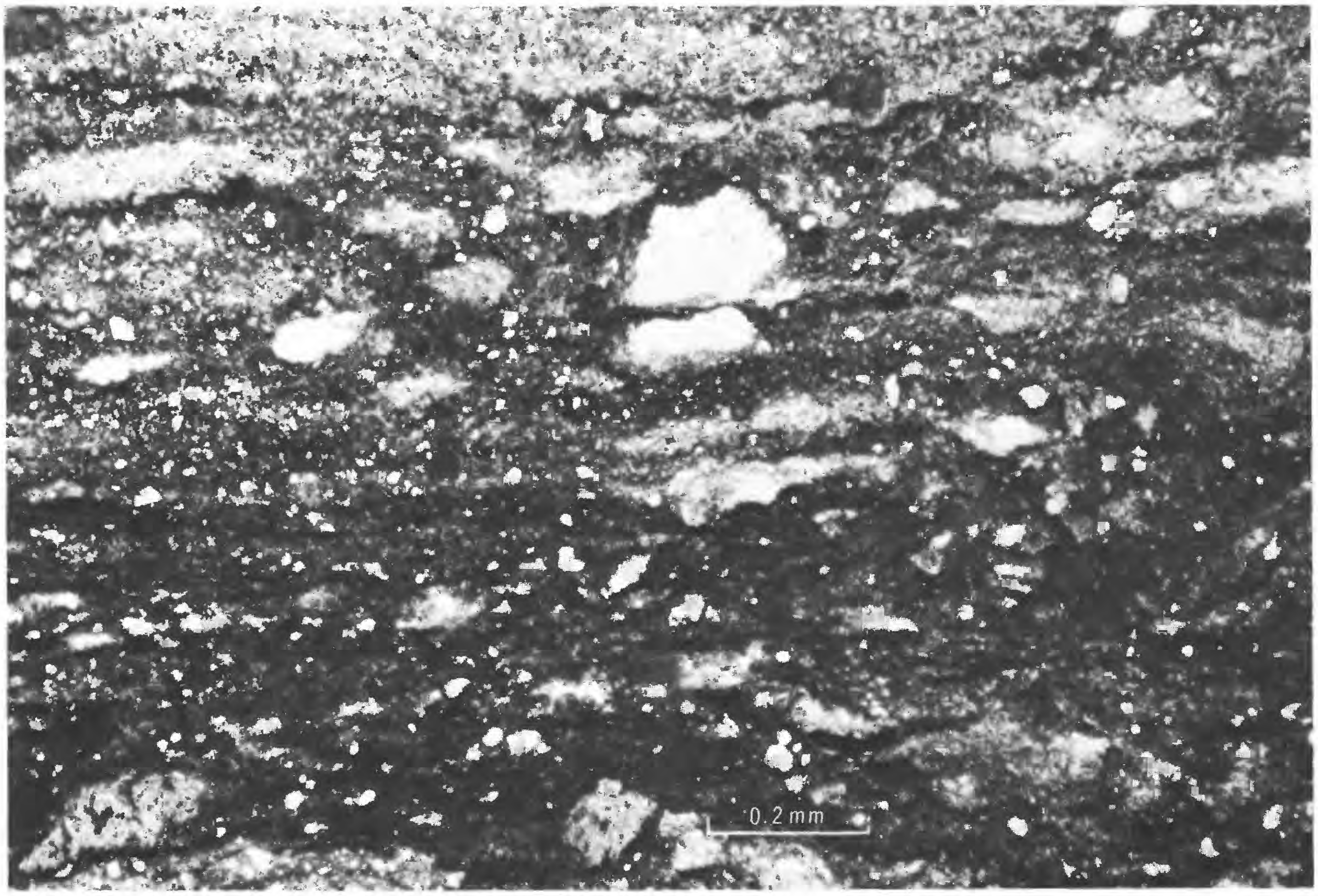

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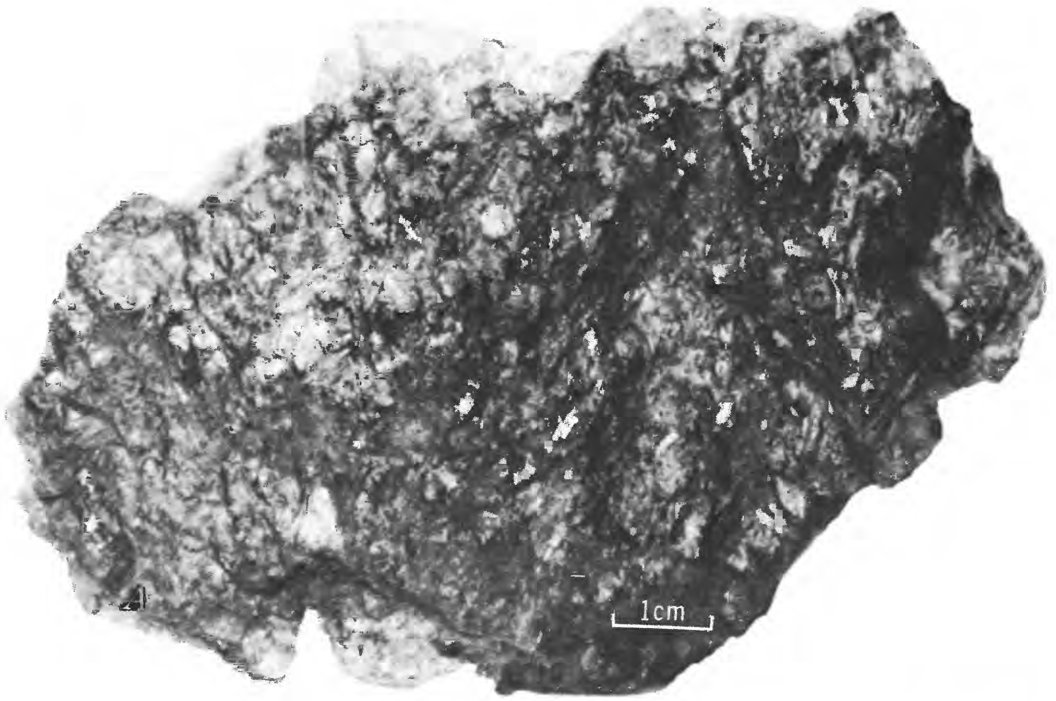
FIGURE 10.—Ultramylonites. *A*, From a fault zone in Cucamonga Canyon, San Gabriel Mountains, Calif. Note layering separating coarser ultramylonite at left from fine variety at right. *B*, From New London County, Conn. (collected by C. B. Sclar, Battelle Memorial Institute); photomicrograph with polarizers crossed. Well-developed compositional layering resulted from cataclastic metamorphic differentiation. The parent rock is a nonlayered biotite-cummingtonite-hornblende gneiss. *C*, From Scotland (collected by A. C. Waters); photomicrograph taken in plane-polarized light. The blurring is partly due to the high magnification. Note lack of compositional layering. Parent rock probably a gneiss.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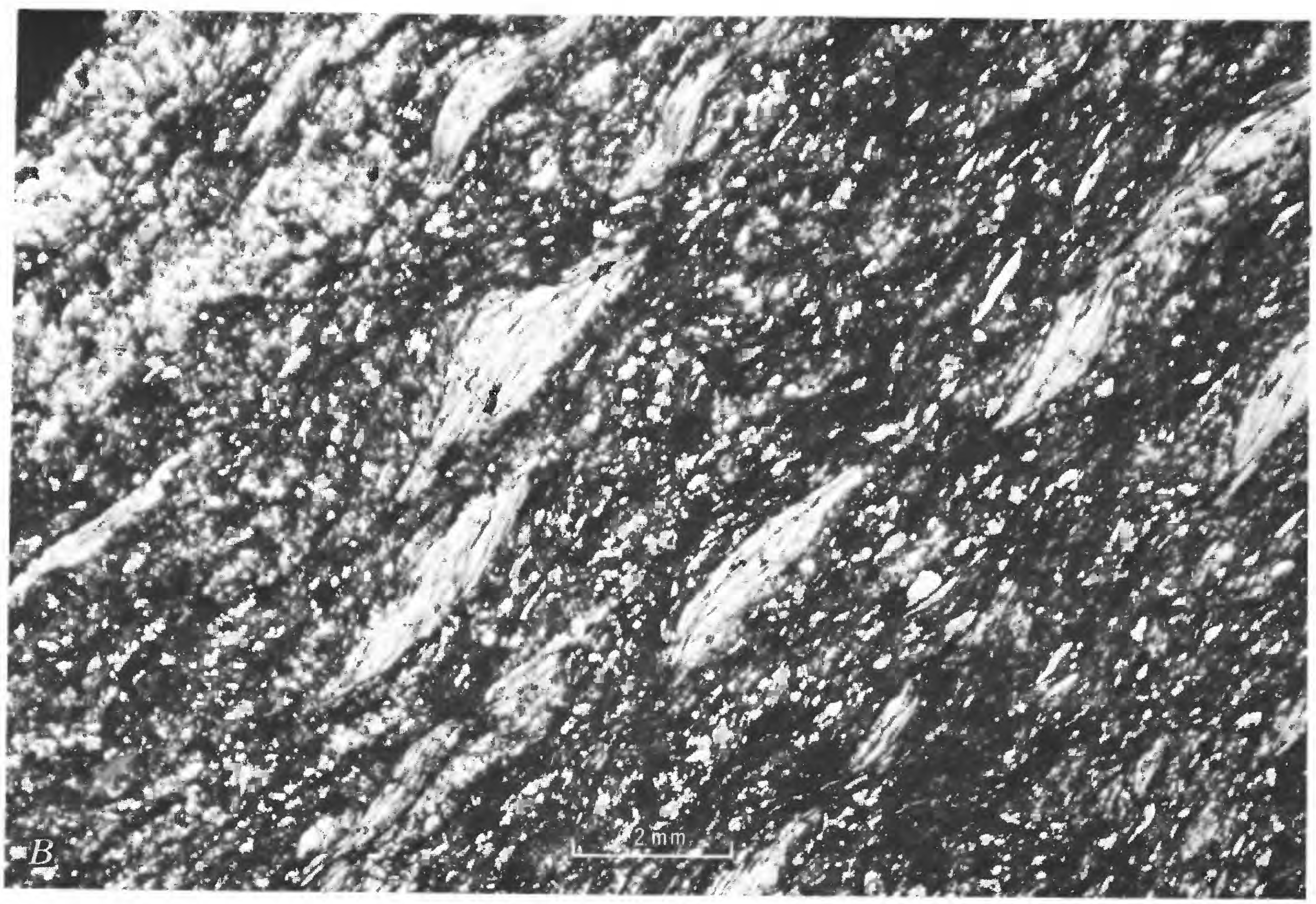
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She also stated (1931, p. 19–20):

Unfortunately the term phyllonite is often used in the literature without a clear distinction as to what it implies, and it is a common error among writers on metamorphism to make phyllonite synonymous with diaphthorite even where no evidence is produced to show the retrogressive metamorphism in the mylonitized rock. Unless the correct meaning of phyllonitization is appreciated, a misinterpretation of tectonic history is likely to result, because phyllonitization does not necessarily mean retrogressive metamorphism, although many phyllonites are also diaphthoritic. For example, a phyllonite may be derived by the mylonitization of a porphyritic granite or conglomerate. Obviously the resultant rock has not been produced by retrogressive metamorphism because the original rock was unmetamorphosed to begin with. Moreover, a phyllonite may be formed by the degradation of a highly crystalloblastic schist and yet not be, as tacitly assumed by some geologic writers, diaphthoritic. * * * Thus a biotite phyllonite derived from a biotite schist or a chlorite phyllonite derived from a chlorite-sericite schist is not diaphthoritic, but a chlorite-sericite phyllonite produced from a garnetiferous biotite schist does show a retrogression in metamorphism. In general a diaphthorite must be sufficiently crystalloblastic to show mineral retrogression, while a phyllonite must be sufficiently cataclastic to reveal its mylonitic origin.

Knopf (1931) made two important points regarding *diaphthorites:* (1) they *must* have relict minerals of a higher grade or facies of metamorphism; (2) they commonly have a phyllitic appearance and a "diseased look" in outcrop. She also stated that most diaphthorites are in fact tectonites. Knopf did not emphasize one important point strongly enough—that any retrogressively metamorphosed rock can be a *diaphthorite* even though it is not cataclastic. For example, *diaphthorite* can be produced where igneous intrusions cause retrogressive contact metamorphism of previously metamorphosed rocks.

From the above it is seen that *phyllonite* should be used for phyllitic mylonitic cataclastic rocks (those with fluxion structure as defined in the glossary); *diaphthorite* for retrograde rocks (phyllitic or not; cataclastic or not); *phyllitic diaphthorite* for noncataclastic retrogressive rocks that have the appearance of phyllites; and *diaphthoritic phyllonite* for retrogressive mylonitic cataclastic rocks with the appearance of phyllites. *Diaphthoritic* can be used as a modifier of any of the other cataclastic rock names (see table 1). Figure 15 shows some diaphthoritic rocks.

FIGURE 11.—Phyllonite from the Brevard zone near Atlanta, Ga. *A*, Hand specimen with "eyes" of porphyroclastic muscovite. *B*, Photomicrograph of same rock. The spindle-shaped, bent, and twisted porphyroclasts of muscovite give the phyllonite the appearance of having fish scales on its cataclastic foliation planes. The rock is not a diaphthorite. Parent rock was probably a gneiss. Plane-polarized light.

CATACLASTIC ROCKS IN WHICH FUSION OR MELTING WAS IMPORTANT

In addition to the more common types of cataclastic rocks already defined, there are some in which fusion or melting played an important role. In some cases, melting has virtually erased most of the cataclastic texture, and other criteria must be used to identify and classify the rocks.

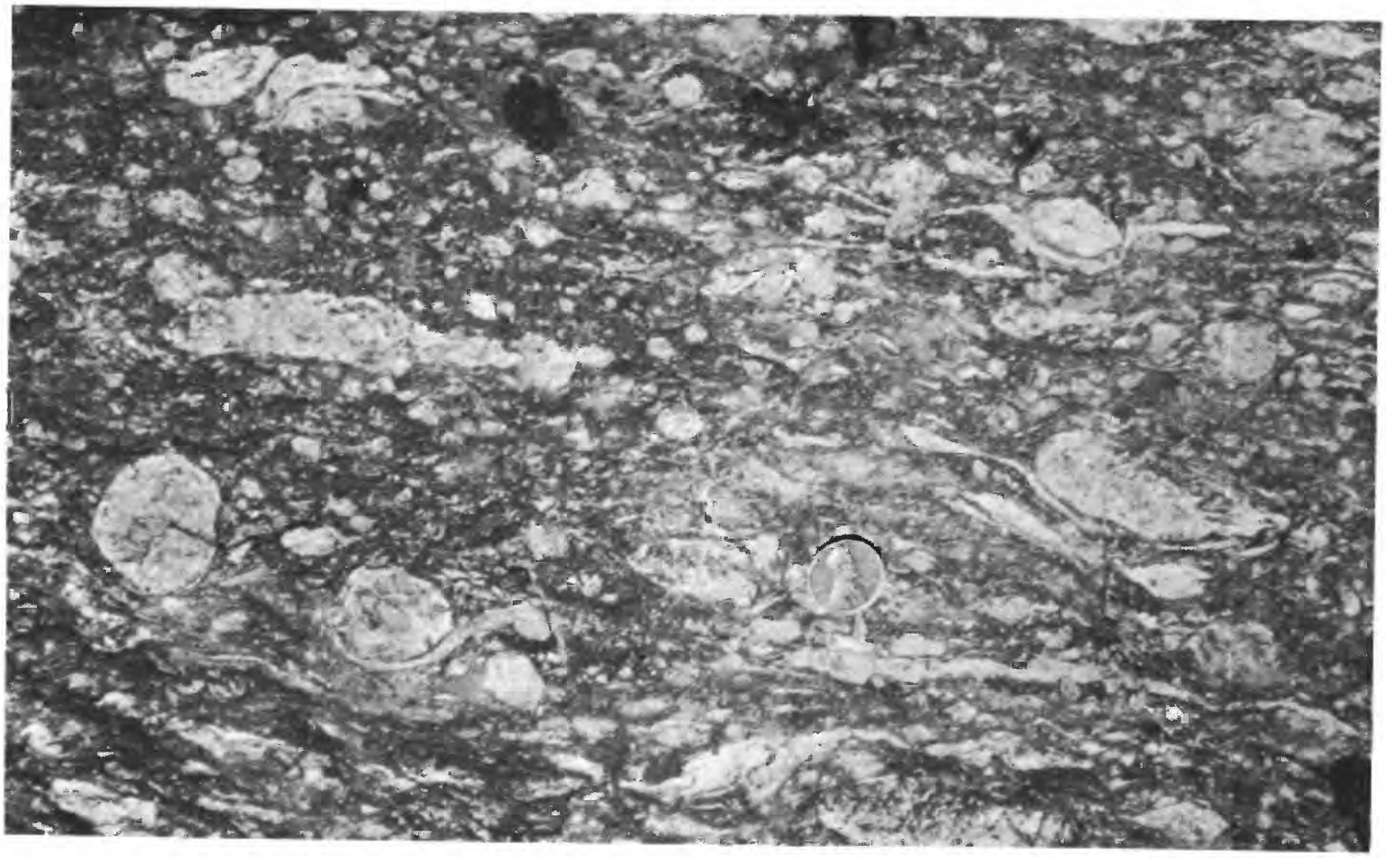
PSEUDOTACHYLITE

Definition.—Pseudotachylite: A glassy rock generally resembling tachylite, commonly of intrusive habit, and closely associated with faults or fault zones. The groundmass of the rock is composed mainly of glass, which in some cases contains microlites of feldspar, vesicles, spherulites, amygdules, or partially melted rock and mineral fragments. The rock fragments may be cataclastic or undeformed. Pseudotachylite probably forms by melting resulting from frictional fusion during faulting of already-hot rocks.

Figure 16 shows typical pseudotachylite.

Discussion.—Dark, glassy rocks of intrusive habit occur in many fault zones, particularly those closely associated in time and space with plutonic activity. Commonly, these rocks have the aspects of thin basaltic (dolerite) dikes: they are definitely of intrusive habit (fig. 16*B*); they are glassy; they may have finer-grained margins; they may contain microlites (chiefly of feldspar), skeletal crystals, vesicles, spherulites, amygdules, and partly melted (embayed) or corroded minerals and mineral fragments (fig. 16*A*, *B*). However, they also have aspects of cataclastic rocks: they are invariably closely associated with faults or fault zones; many are gradational to mylonites, ultramylonites, cataclasites, or other types of cataclastic rock; some have recognizable porphyroclasts; in most, the mineral fragments are chiefly quartz and feldspar, and the rock fragments are from the host rock (fig. 16*C*); commonly, the plagioclase microlites are more sodic than andesine; and, where chemical analyses have been made, almost all of the glassy rocks have the approximate chemistry of their intermediate to felsic host rocks (Shand, 1917; Hall and Molengraaff, 1925; Salop, 1949; Philpotts, 1964). These glassy rocks have been called by several names, and various origins have been proposed for them.

Shand (1917, p. 199) introduced the term *pseudotachylite* for branching, glassy, dikelike rocks associated



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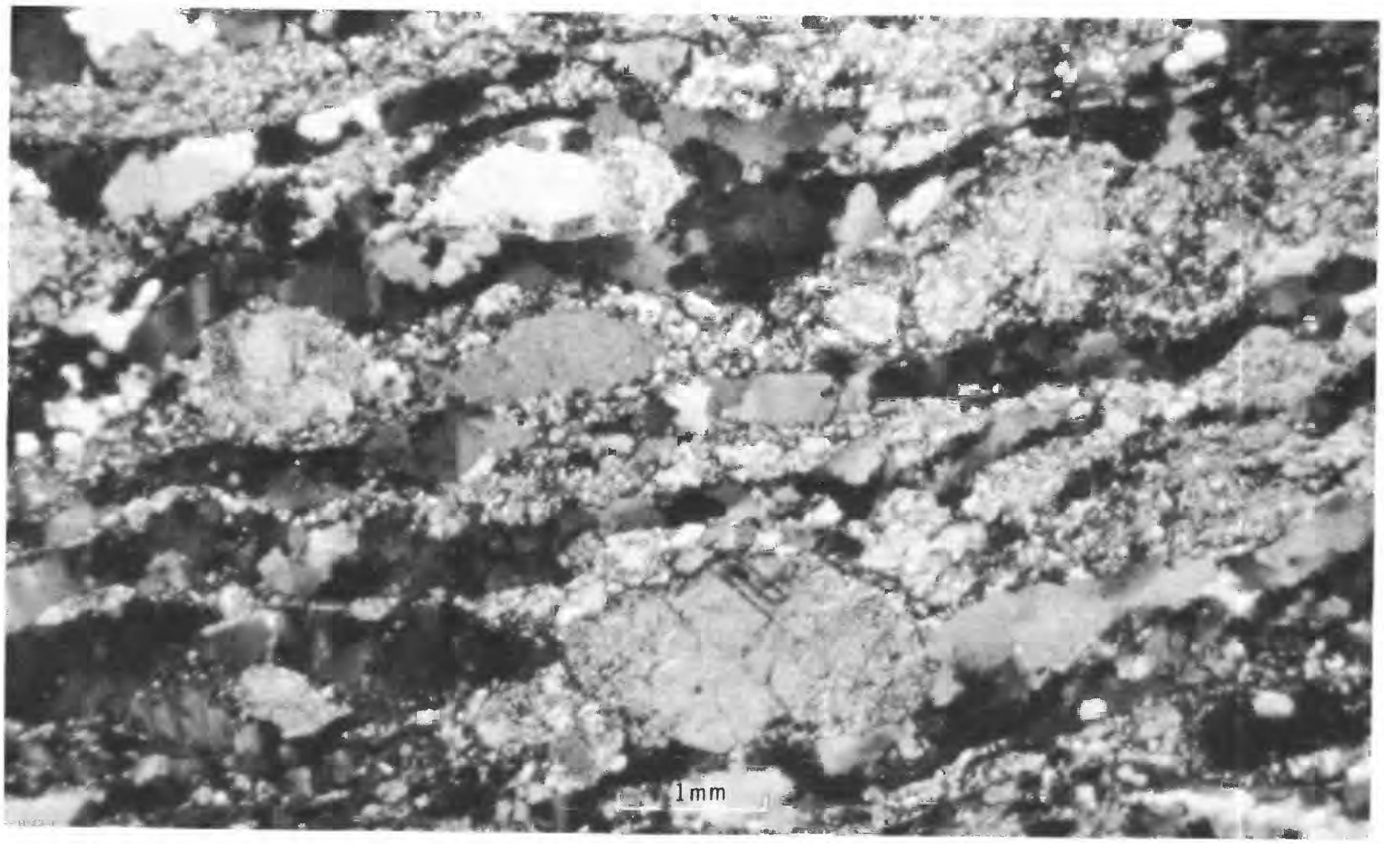

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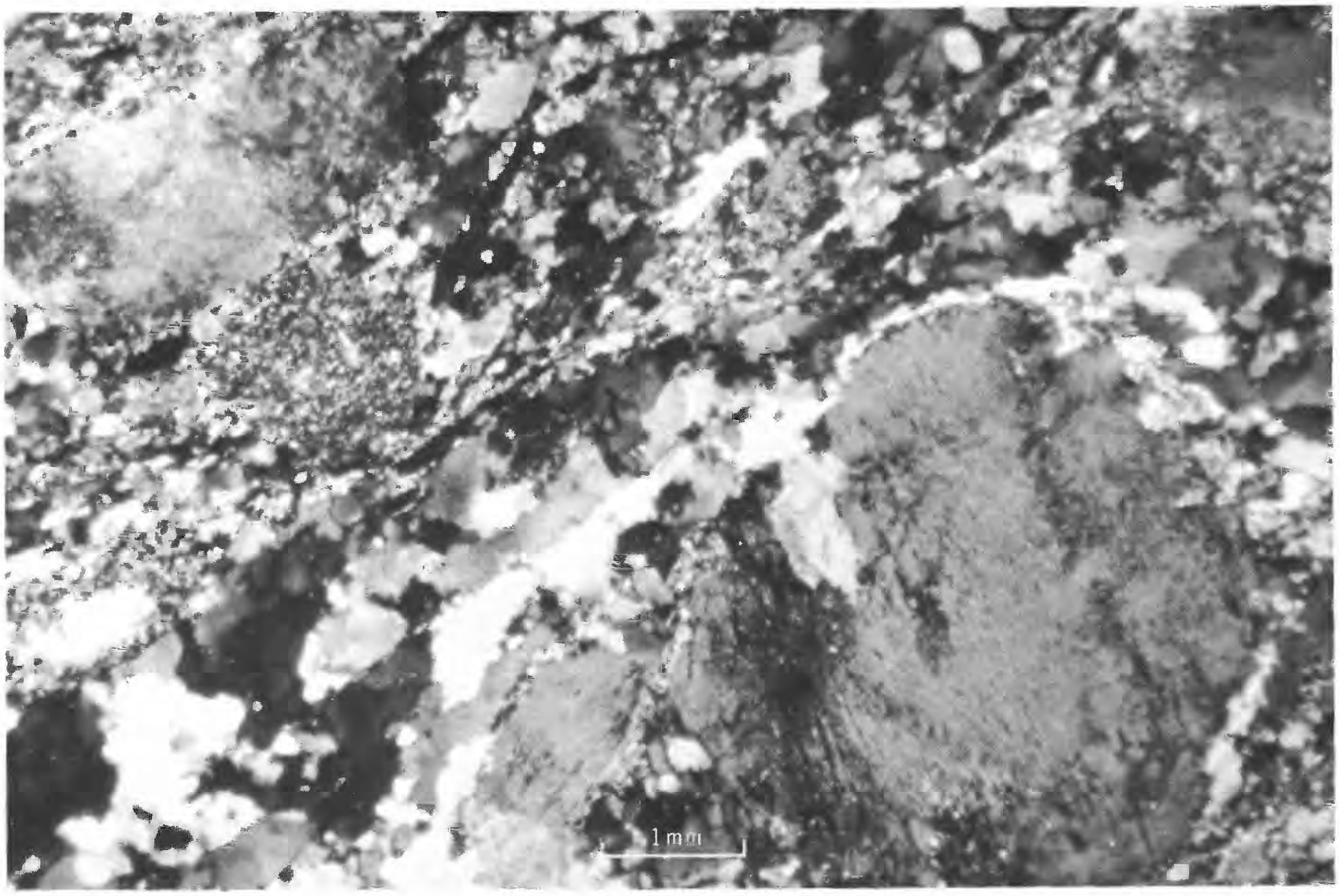

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FIGURE 12.—Mylonite gneisses. *A*, Outcrop of coarse-grained mylonite gneiss in the Towaliga fault zone near Auburn, Ala. (coin is 1.9 cm in diam.). The structure in this outcrop is strikingly like the texture of a mylonite in thin section (compare with fig. 7*B*). The giant porphyroclasts are feldspar. *B*, Photomicrograph of specimen from northwest edge of the Brevard zone near Atlanta, Ga.; crossed polarizers. Note high degree of neomineralization-recrystallization. Despite this, the fluxion structure is still visible. This rock is finer grained than the one shown in *C*, illustrating the range in grain size covered by the term "mylonite gneiss." The range is about the same as that of protomylonites. Parent rock was probably a coarse-grained "granite." *C*, Photomicrograph of specimen from the northwest edge of the Brevard zone near Atlanta, Ga.; crossed polarizers. Note relatively high degree of neomineralization-recrystallization of the matrix. This is a fairly coarse-grained mylonite gneiss, comparable in grain size with coarser protomylonites. Note the "roundness" of the large feldspar porphyroclast (lower right). Fuzzy grain boundaries in photomicrograph are natural and not due to poor photographic focus.

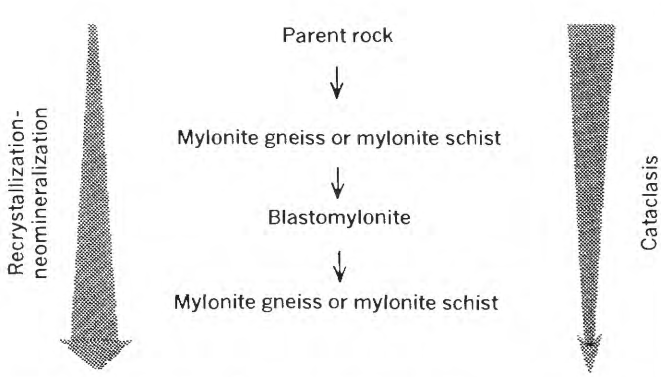


FIGURE 13.—Diagram showing relations between some mylonite gneisses or mylonite schists and blastomylonite.

with granitic rocks in the Vredefort dome of the Parijs (Parys) region of South Africa. He came to the tentative conclusion (1917, p. 219) that "* * * the pseudotachylite has originated from the granite itself through melting, caused not by shearing but by shock, or, alternatively, by gas-fluxing." Several geologists at that time agreed with Shand; others offered different explanations (see Shand, 1917, p. 220–221, discussion). Similar rocks had been described earlier (King and Foote, 1864, p. 271; Holland, 1900, p. 198–248) from southern India, where they were called *trap-shotten gneiss*, and from Scotland (Clough, 1888; Clough and others, 1909; Peach and others, 1907), where they were called *flinty crush-rock*.

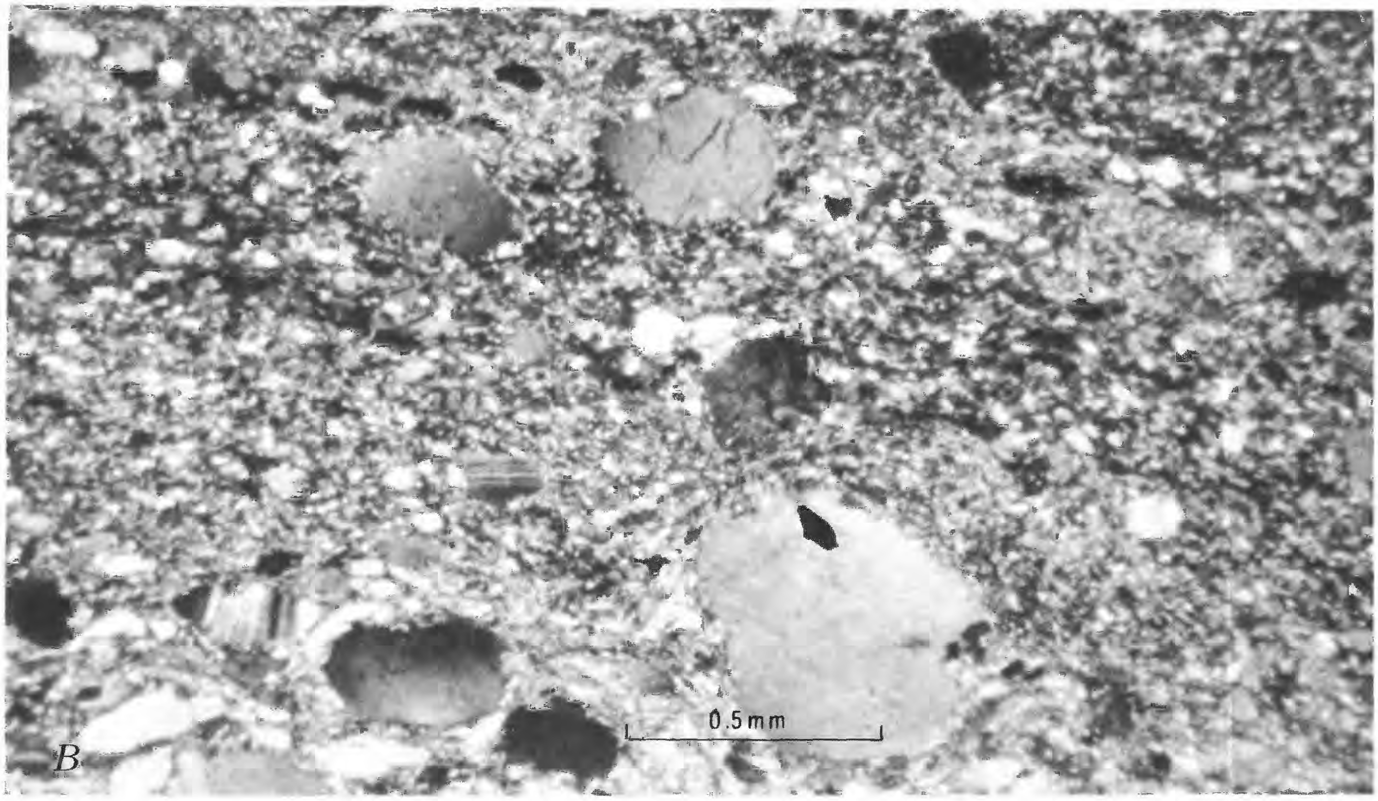
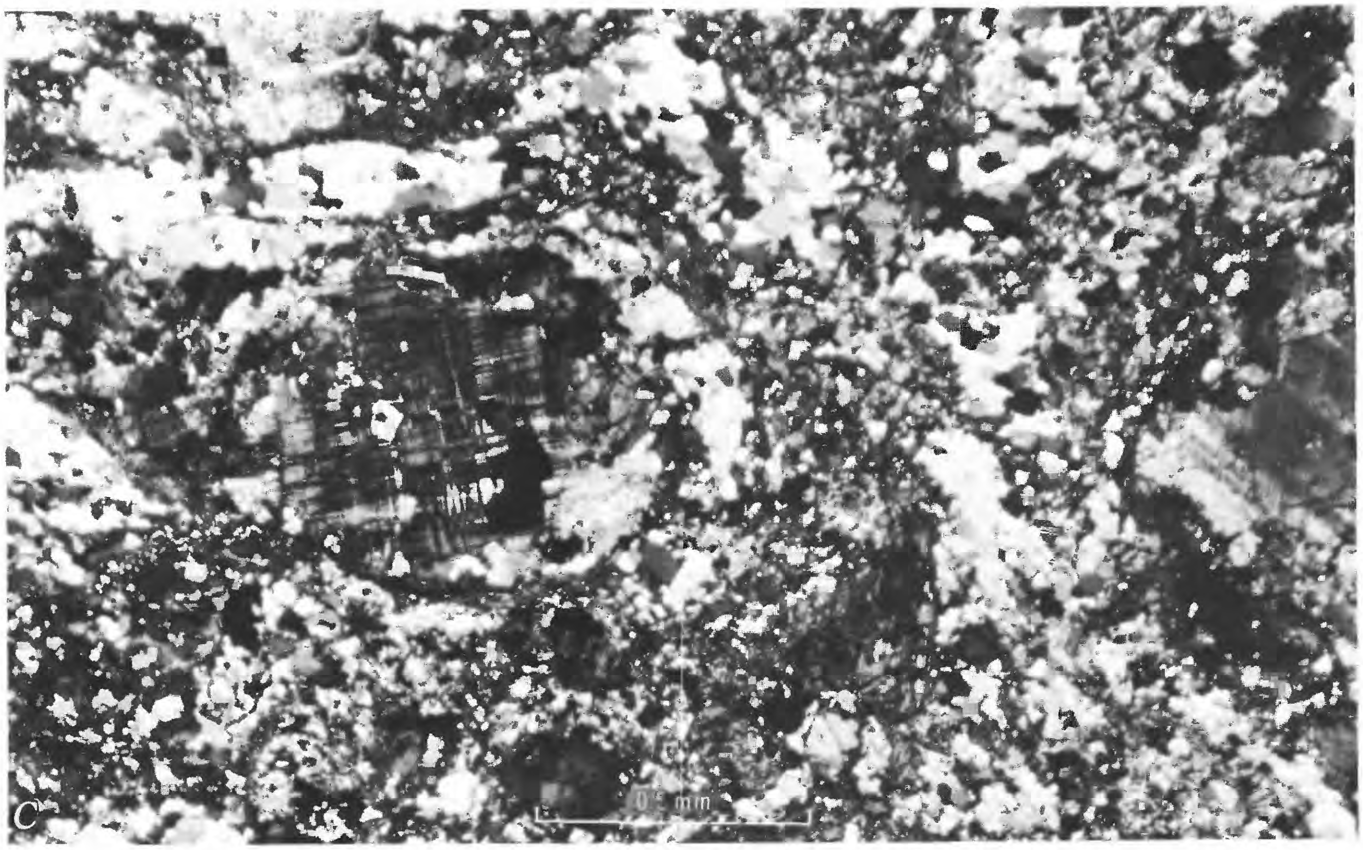


FIGURE 14.—Blastomylonites. (All photomicrographs with crossed polarizers.) *A*, Porphyroclastic, crudely laminated blastomylonite from the Towaliga fault zone in Alabama. The large porphyroclasts are K-feldspar. *B*, Photomicrograph of a blastomylonite from the Brevard zone near Atlanta, Ga. Note high degree of neomineralization-recrystallization of the matrix. The fuzziness is natural and is not due to poor focus; it is common in blastomylonites, and probably results from the fine-grained neomineralization. The porphyroclasts are feldspars. Parent rock was possibly a micaceous gneiss. *C*, Photomicrograph of a blastomylonite from the Brevard zone near Atlanta, Ga. Note the relatively high degree of neomineralization-recrystallization of the matrix. Despite this, the fluxion structure and "flow" of trails of recrystallized material around the rounded porphyroclast are visible. Parent rock was a "granite." *D*, Photomicrograph of a porphyroclast and surrounding matrix in a blastomylonite from the Brevard zone near Atlanta, Ga. This view shows the neomineralized-recrystallized character of the matrix; note particularly the small micas. Fuzziness in photomicrograph is due to high magnification. Parent rock was probably a "granite."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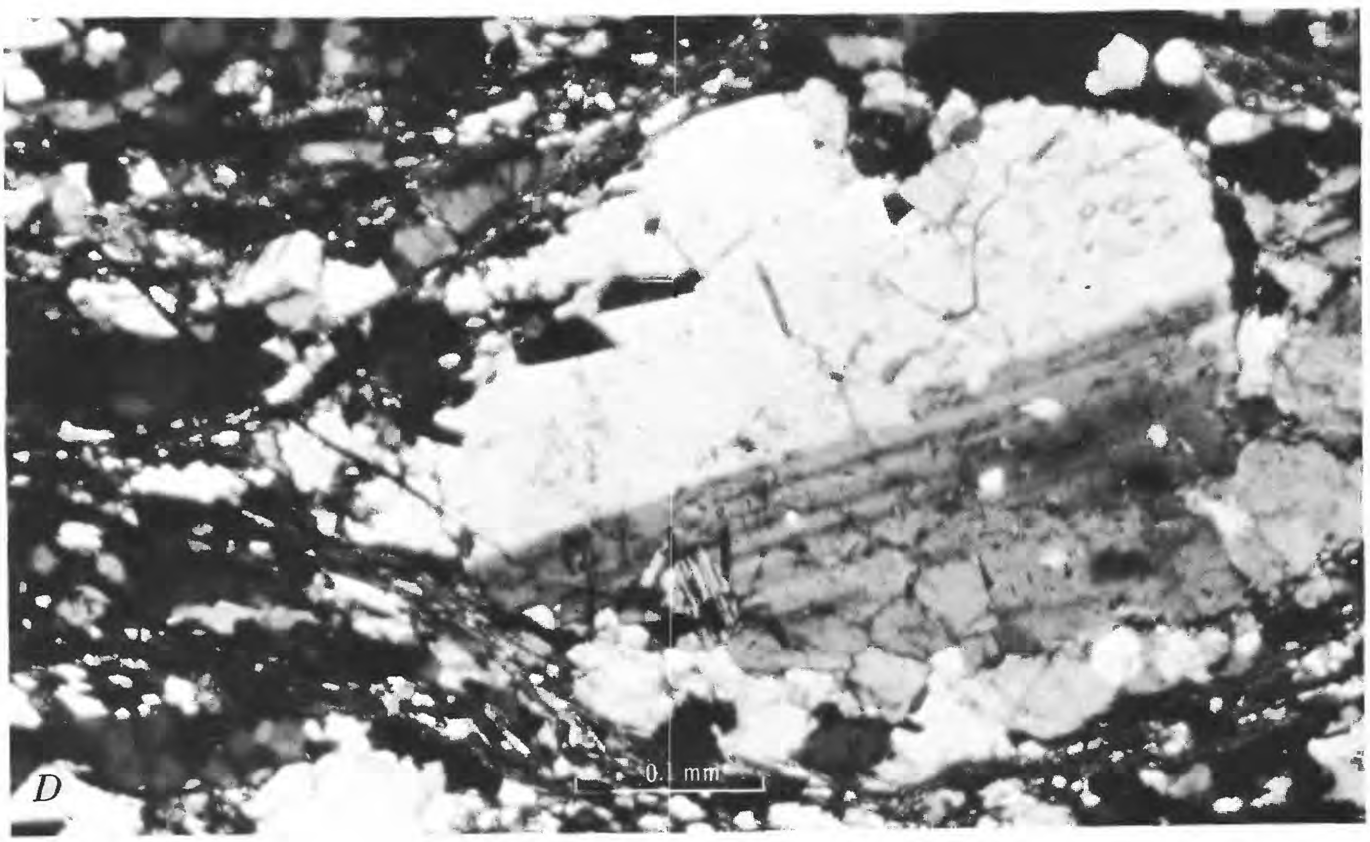
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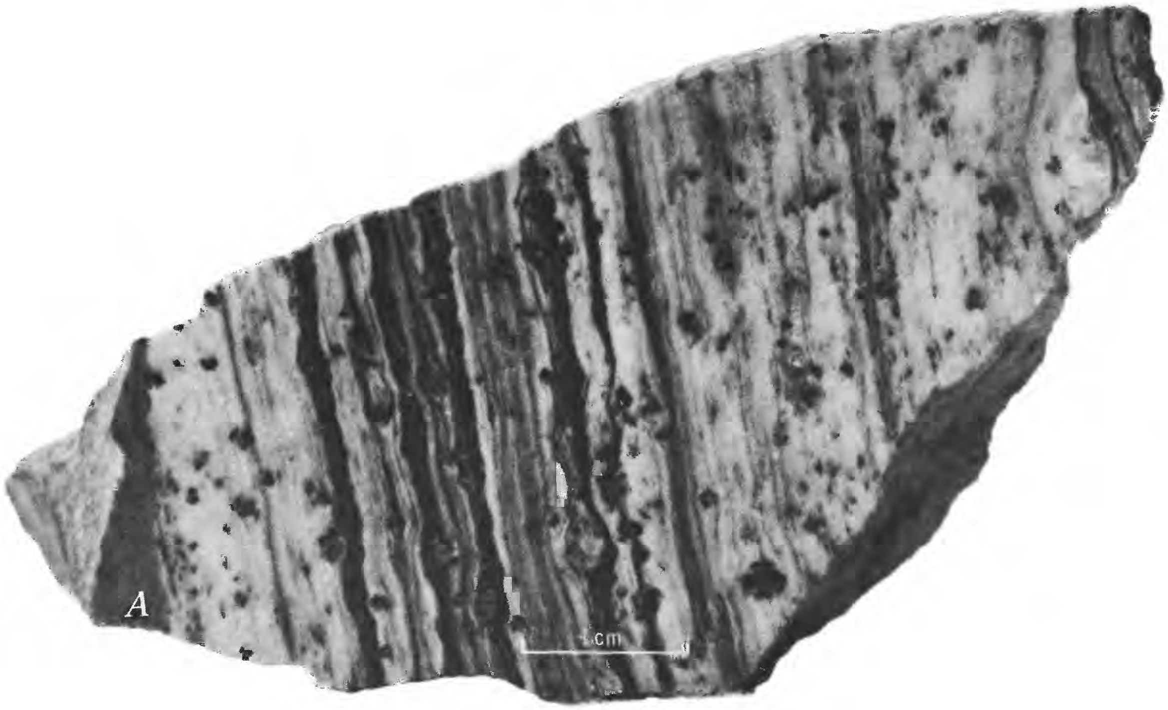


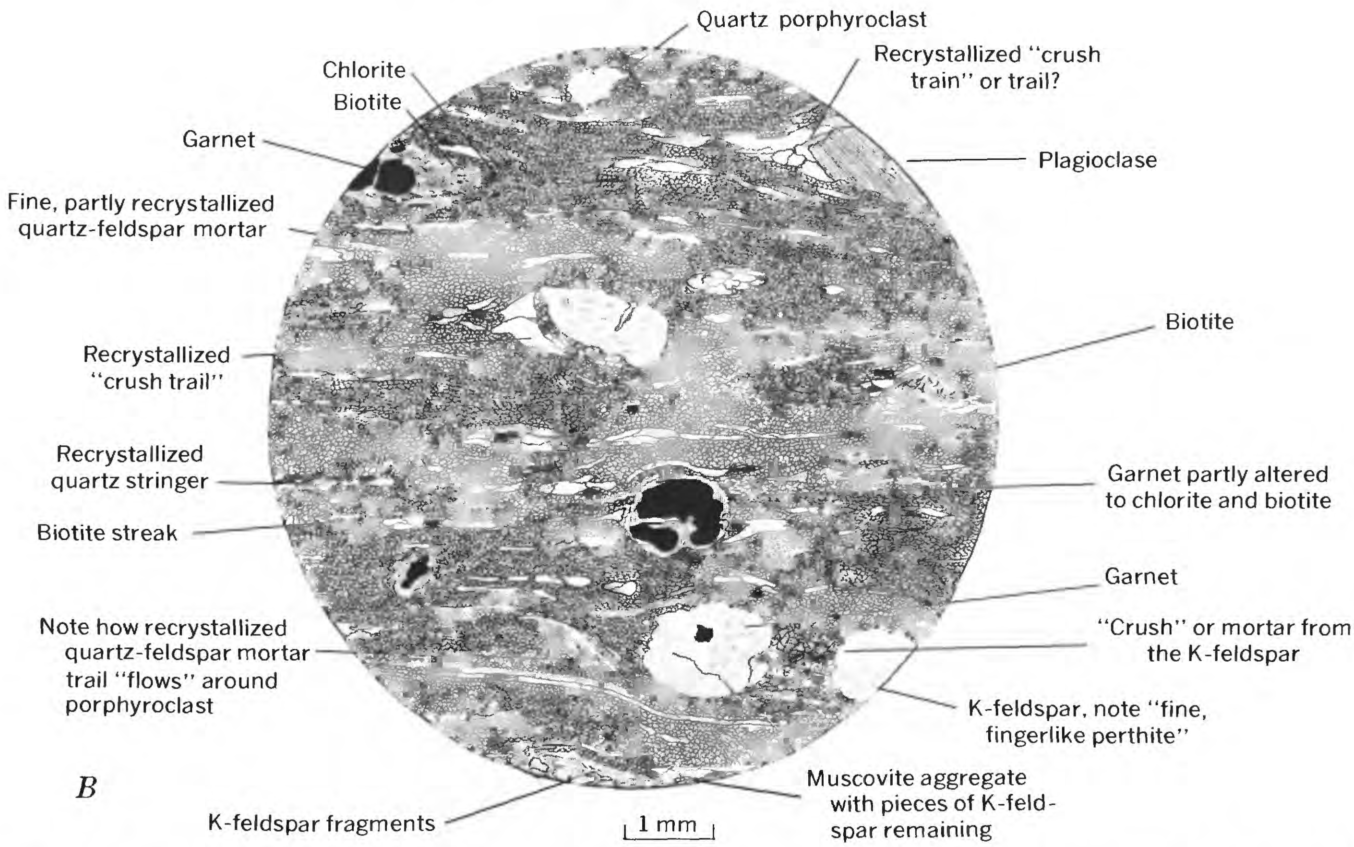
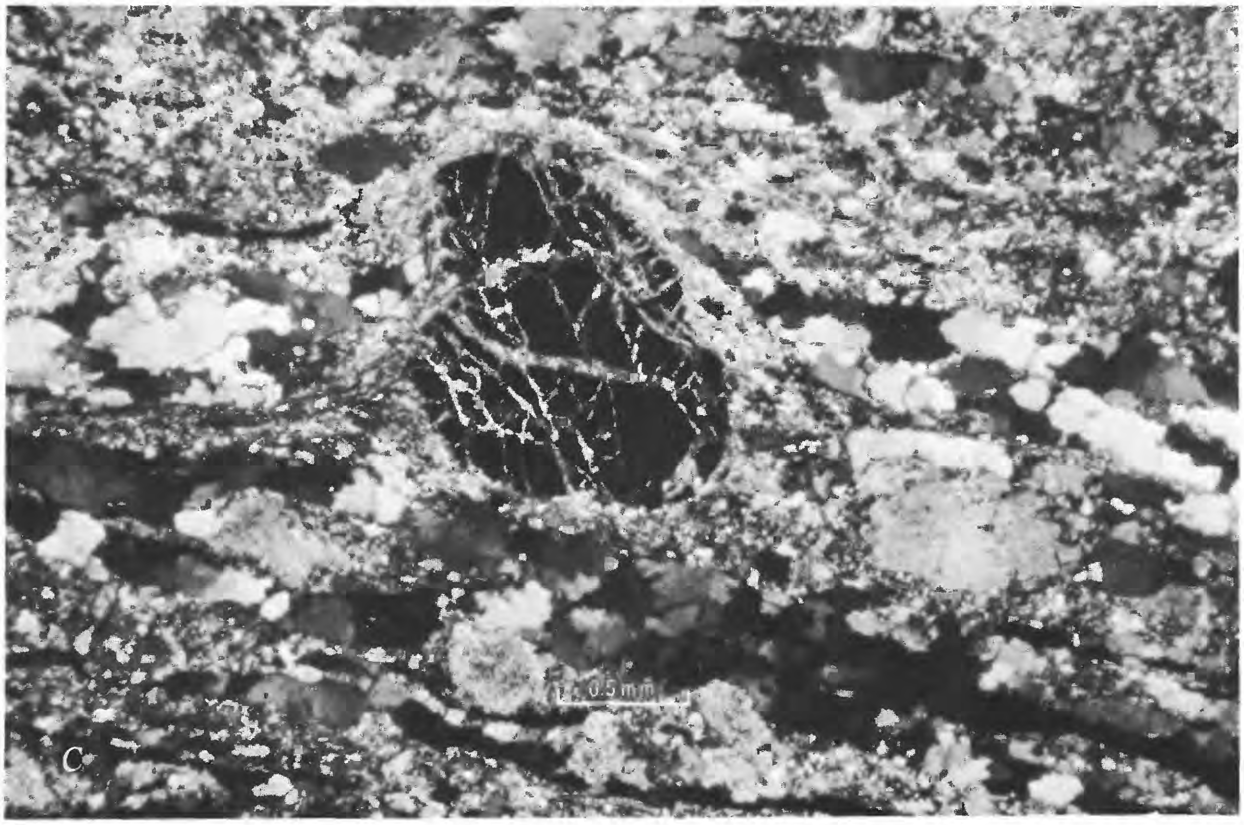
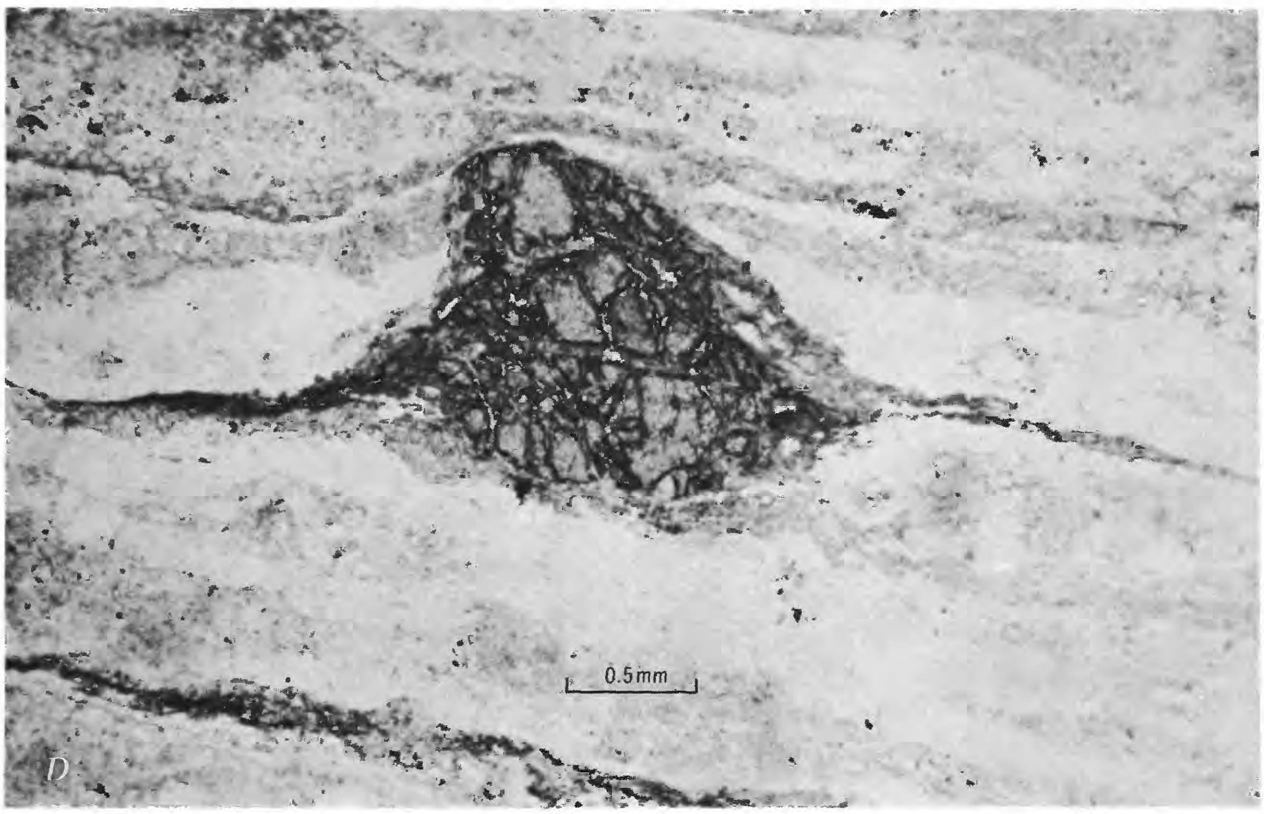


FIGURE 15.—Diaphthoritic blastomylonites. *A*, *B*, Layered, diaphthoritic blastomylonite from near Tirschneim, Germany. *A* shows texture common in mylonites and blastomylonites, as well as compositional layering. In the microdrawing (*B*), note the garnets partly altered to biotite and chlorite, and the K-feldspar partly altered to muscovite. The background mosaic, while still preserving the cataclastic flow texture, is thoroughly recrystallized. Drawing with crossed polarizers. *C*, Photomicrograph of a diaphthoritic blastomylonite from New London County, Conn. (collected by C. B. Sclar), crossed polarizers. Note the general neomineralization-recrystallization of the matrix.





Despite this, the cataclastic texture and fluxion structure are well preserved. *D*, Photomicrograph of a diaphthoritic blastomylonite from New London County, Conn. (collected by C. B. Sclar), plane-polarized light. The large garnet porphyroclast in the center has been retrogressively altered to chlorite at its borders and along fractures. The fluxion structure of the groundmass and the trails of retrogressively altered and crushed particles of garnet extending from either side of the porphyroclast help define the fluxion structure. Parent rock was a gneiss.

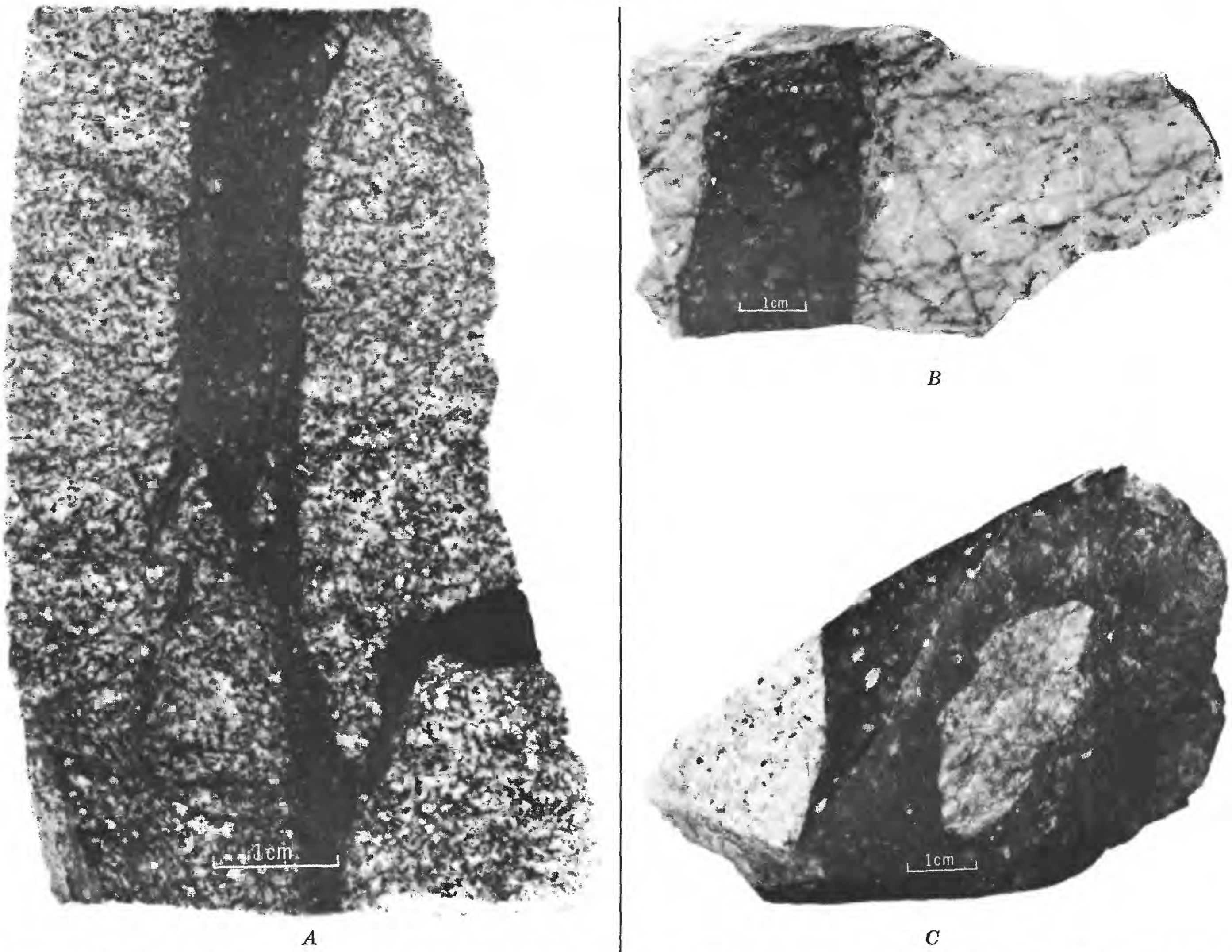


FIGURE 16.—Pseudotachylites. *A–C* from Vredefort dome in South Africa, collected by Bailey Willis, and furnished by A. C. Waters. *A*, Pseudotachylite dike and stringers in "granitic" host. Note thin stringers of pseudotachylite in the country rock. *B*, Pseudotachylite dike cutting "granitic" host rock. Note the sharp contacts of the dike, and the inclusions of "granitic" host rock in it. Many of these inclusions are corroded quartz grains. *C*, Pseudotachylite and "granitic" host rock. Note inclusion of fractured "granitic" host rock in the black pseudotachylite. *D*, Photomicrograph of pseudotachylite from the Belleau-Desaulniers area, Quebec (collected by A. R. Philpotts, McGill Univ.); plane-polarized light. Note the branching intrusive nature of the material, and its isotropic character.

The term *flinty crush-rock* was first used by Clough (1888, p. 22) for dark veinlike rocks along fault zones in the Cheviot Hills of Scotland. It was subsequently used by Peach and others (1907, p. 124, 141, 151–153, 190, 196, 214–216, 244–250) for rocks associated with thrust faults in the Northwest Highlands of Scotland; by Clough and others (1909, p. 629–631) for rocks associated with the ring fault at Glen Coe, Scotland; by Backlund (1913) for glassy rocks associated with fault zones in Argentina; by Jehu and Craig (1923, p. 430–436; 1925, p. 629–630) and Dougal (1928) for rocks associated with thrust faults in the Outer Hebrides; and by Scott and Drever (1953) for rocks associated with a Himalayan thrust fault.

In most of the early papers *flinty crush-rock* was used as a field name for many varieties of cataclastic rock. Thus, as Shand (1917, p. 209–210) noted, Clough's (1888) *flinty crush-rocks* include dark, flinty mylonites, ultramylonites, and cataclasites, as well as rocks that show evidence of fusion and melting, and the same is true of most of the *flinty crush-rocks* of later geologists.

Pseudotachylite (by name) has been described by Hall and Molengraaff (1925), Hammer (1930), Bearth (1933), Nockolds (1940), Goldschmidt (1943), Salop

D

(1949), Dietrichson (1953), Bryn (1959), Park (1961), and Philpotts (1962, 1964).

Holland (1900) was perhaps the first to give serious consideration to the origin of fused, intrusive cataclastic rocks.[1] He crushed a sample of the charnokite host rock from one of the pseudotachylite localities in southern India and heated it until fusion took place. He stated (1900, p. 200):

> The result was a fritted black cake having the lustre of a tachylite and showing in thin section a black structureless matrix including angular fragments of quartz; in fact, the fritted charnokite powder very closely resembled the so called strings of trap in these breccia bands.

Knopf (1931, p. 13) thought pseudotachylite was "possibly produced by fritting or by fusion under local development of intense heat." She presented a photomicrograph (1931, fig. 5) showing its "pseudoeruptive" nature. Crickmay (1933, p. 166–170) described intrusive "mylonites" (dike-mylonites) which he considered to be pseudotachylites, but which showed no fusion. Waters and Campbell (1935) gave an excellent summary of the various theories for the origin of pseudotachylite and compared pseudotachylites with mylonites and ultramylonites from the San Andreas fault zone. They tentatively concluded that pseudotachylite formed not by fusion but by extreme crushing of the rock material. However, in their definition (1935, p. 479–480) they retained the prerequisite of fusion as a distinctive property of pseudotachylite. Dietrichson (1953) and Bryn (1959) described and analyzed pseudotachylites from Norway and concluded that they formed by fusion at local hot spots produced by friction. Scott and Drever (1953) were the first to give convincing evidence of frictional fusion in the rocks they called *flinty crush-rocks*, *cryptomylonites*, and *hyalomylonites*. They described a glassy rock which is vesicular and has a refractive index of 1.5. The rock occurs in a thrust fault, where complete gradation can be traced from the glassy rock through mylonite into undeformed rock. This was the first convincing evidence that sufficient frictional heat could be produced in a fault zone to cause the rock to

[1] King and Foote (1864) thought that the rocks studied by Holland were basaltic dikes. Hence their terminology—*trap-shotten gneiss*.

melt, though Bowden and others (1947) and Bowden and Thomas (1954) had shown experimentally that two polished surfaces rubbed together at speeds as low as 1 to 2 feet per second under a load of 1,000 grams can develop visible hot spots.

Reynolds (1954, p. 591–595) suggested fluidized solid-gas systems (fluidization) as an explanation for the origin of pseudotachylite. After studying the South African pseudotachylites (also studied by Shand and by Hall and Molengraaff), she concluded that they were originally composed of finely ground particles transported in suspension by rapidly moving gases from the underlying magma to their present locations. Christie (1960, p. 84) accepted Reynolds' "fluidization hypothesis" for the origin of pseudotachylite. Fluidization as a major process producing such large features as the Vredefort dome (and thereby the pseudotachylite also) was subsequently discounted by McBirney (1963, p. 227–231), who showed by calculations the improbability of rapid release of the huge volumes of gases required.

The most satisfactory explanation for the origin of pseudotachylite resulted from Philpotts' (1964) complete study of Canadian and South African pseudotachylites. He carefully considered and eliminated most of the existing hypotheses of origin and gave good field, petrographic, X-ray, chemical, and petrologic evidence to support the interpretation that pseudotachylite forms by melting due to frictional heating during faulting of rocks already at temperatures above 400° C. Generally, these rocks are near igneous intrusions, and commonly the time of intrusion of the igneous mass can be shown to be quite close to the time of faulting and formation of pseudotachylite. According to Philpotts, the melted material is forced into fractures where it begins to cool. As the melt moves along the fractures, it differentiates, becoming progressively (though only slightly) enriched in the low-melting fractions. This is shown by chemical analyses along a single dike.

The definition of *pseudotachylite* used in this paper is based on the work of Philpotts (1964). Because it has so often been used as a general field term for various kinds of cataclastic rocks and because there is confusion regarding its meaning, even in the strictest sense, *flinty crush-rock* is not used in my classification (table 1). However, all gradations probably exist from pseudotachylite in which a large proportion of the rock has been melted, through partially melted cataclastic rock, to only slightly fused cataclastic rock, and some way to designate such rocks is desirable. Naming these rocks can be accomplished by using *pseudotachylitic* as a modifier of the cataclastic rock names already defined (table 1).

HARTSCHIEFER

The term "hartschiefer" was popularized by Holmquist (1910, p. 945), but had previously been in general use by Scandinavian geologists. There has been much disagreement over the characteristics and especially the origin of hartschiefer. Holmquist first favored the idea that they are sedimentary, chiefly because of the unusually straight and regular lamination. Quensel (1916, p. 100, 113–116) favored a cataclastic origin. Knopf (1931, p. 10) considered hartschiefer equivalent to ultramylonite. Waters and Campbell (1935, p. 477–478, 480) favored a cataclastic origin, and stated:

> In the opinion of most Swedish geologists they differ from ultramylonite, which they resemble rather closely, in the remarkable banding, a feature that is regarded to be the result of metamorphic differentiation, and in the much more thorough recrystallization, crystalloblastic structures commonly predominating over cataclastic.

Christie (1960, p. 82) essentially concurred with Waters and Campbell. Reed (1964, p. 650–651) considered most hartschiefer to be well-banded blastomylonites.

Descriptions and illustrations of hartschiefer (Holmquist, 1910; Quensel, 1916; Knopf, 1931) and my study of samples, kindly furnished by A. C. Waters, from Scandinavian localities which include Holmquist's Törnetrask area, lead me to conclude that the term "*hartschiefer*" comprises a variety of coherent cataclastic rocks. Most of these are well-banded (layered), neomineralized or recrystallized blastomylonites, but some are only slightly neomineralized or recrystallized and should be called ultramylonite and mylonite. Other "*hartschiefer*" are very probably thinly bedded metasedimentary rocks. *Hartschiefer* is therefore not used in my classification (table 1); the rocks to which it pertains are considered covered by the other terms.

POLYCATACLASTIC AND POLYMETAMORPHIC CATACLASTIC ROCKS

Coherent cataclastic rocks are an integral part of the metamorphic terranes in which they occur, and the metamorphic and deformational histories of the metamorphic terranes generally apply in some manner to the cataclastic rocks as well. Many metamorphic terranes have been subjected to multiple metamorphic events and to multiple deformations, and polycataclastic rocks and polymetamorphic cataclastic rocks are relatively common.

Following Read (1949) and Hsu (1955a), *polymetamorphic* rocks are those that record a history of two or more *separate* periods of metamorphism; or as Hsu (1955a, p. 238) stated: ". . . periods of metamorphism that present no obvious genetic connection." Rocks remetamorphosed during different stages or episodes of one single period of metamorphism are *monometamorphic* (Read, 1949; Hsu, 1955a). However, modern studies (particularly those including radiometric age dating) of several metamorphic terraces that have undergone only one major period of metamorphism show that there are generally distinct *episodes* within the single metamorphic period (Johnson, 1961, 1963; Steiger, 1963; Sutton, 1963). Perhaps these monometamorphic rocks should be called *polyepisodic.* These terms can be used as modifiers to the cataclastic rock names; for example: *polymetamorphic mylonite* or *polymetamorphic ultramylonite.*

The term *blastomylonite* does not apply to polymetamorphic mylonites or even to polyepisodic monometamorphic mylonites; a *blastomylonite* is not a metamorphosed mylonite. *Blastomylonite* applies only to rocks in which the cataclasis and the neomineralization-recrystallization were essentially concurrent, though possibly also recurrent.

Polycataclastic rocks are those that have been subjected to two or more periods or episodes of cataclasis. Most major fault zones have long histories of repeated movements—for example, the Caledonian thrust belt (Johnson, 1961, 1963; Holgate, 1963; Christie, 1960); the Alpine fault zone (Reed, 1964; Suggate, 1963); the Brevard fault zone (Reed and Bryant, 1964; Higgins, 1966, 1968); the San Andreas fault zone (Hill and Dibblee, 1953; Crowell, 1962, 1966); the Cucamonga fault zone (Hsu, 1955b); the Great Glen fault zone (Kennedy, 1946); the Towaliga fault zone (Grant, 1967, 1968). Many of the rocks in these zones are polycataclastic. Generally, if the latest cataclasis was equal to or greater in intensity than the earlier episodes, then the earlier textures will have been obliterated and the rock will appear to be monocataclastic. However, if, as is often the case, the later cataclasis was weaker, then the resulting rock may have a polycataclastic texture.

Any of the rocks defined thus far could be affected by a second period or phase of cataclasis. For these polycataclastic rocks, combinations of terms can be used. For instance, a mylonite affected by a later, weaker cataclasis might result in a coherent breccia of mylonite fragments which should be called *brecciated mylonite* (fig. 17).

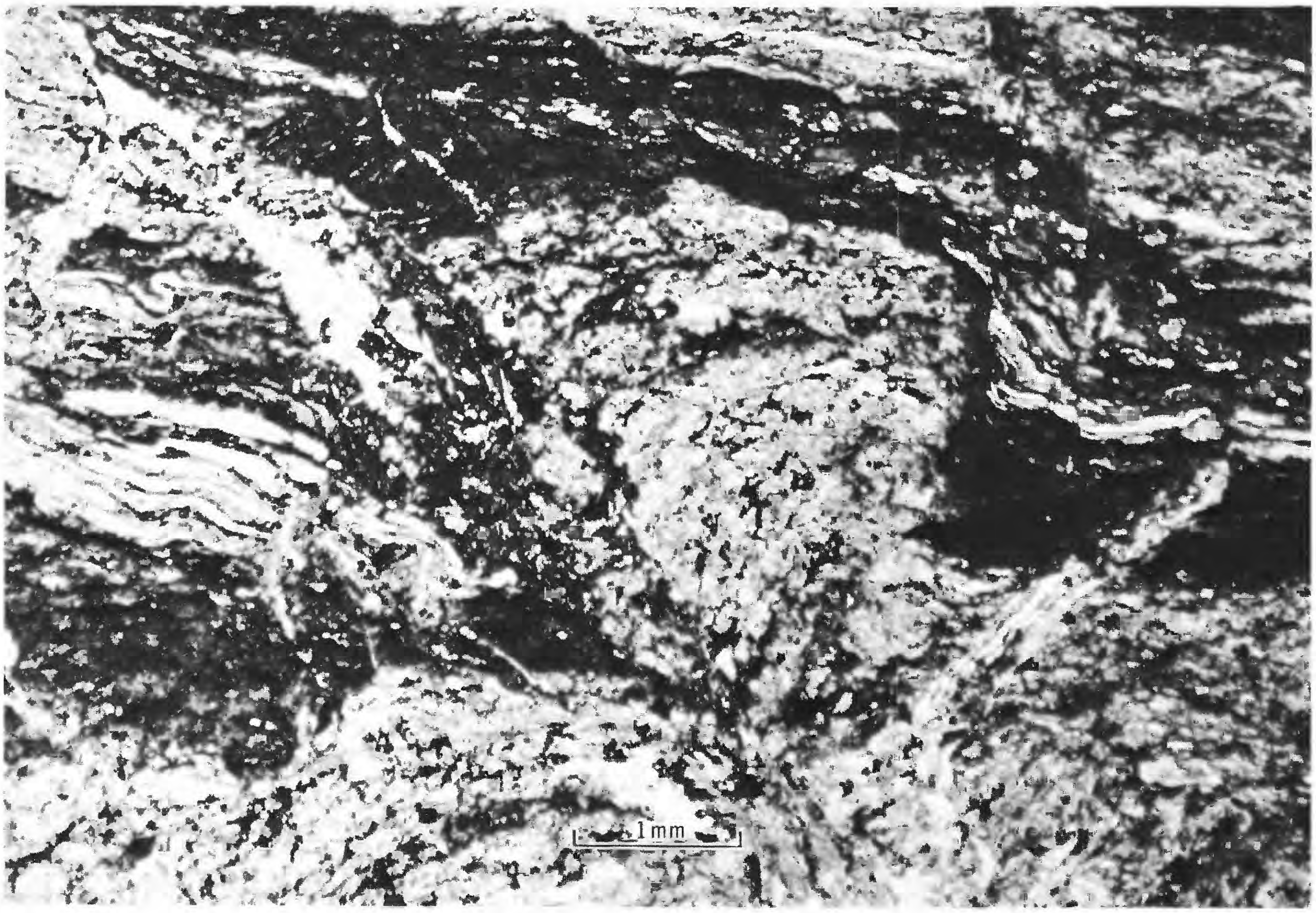


FIGURE 17.—Photomicrograph of a brecciated mylonite from the Brevard zone near Atlanta, Ga.; plane-polarized light. Note the "broken" fluxion structure.

PROBLEMS OF NOMENCLATURE AND CLASSIFICATION OF CATACLASTIC ROCKS

The definitions and classification proposed in this paper are for the most part qualitative. Texture, including degree of recrystallization-neomineralization, is the chief basis for classifying most cataclastic rocks. Approximate porphyroclast size combined with the approximate percentage of porphyroclasts, compared with photomicrographs of what may be called "standards," is the only quantitative parameter used. Because the various cataclastic rock types grade into one another, any classification is more or less arbitrary. Although coherent cataclastic rocks are really metamorphic rocks, problems of their nomenclature and classification have much in common with those of sedimentary rocks. Cataclastic rocks cannot be defined and classified by the parameters used to classify most other kinds of rocks.

MINERAL ASSEMBLAGE AND CHEMICAL COMPOSITION

We define and classify noncataclastic metamorphic rocks chiefly on the basis of their mineral assemblages and igneous rocks largely on the basis of their mineral assemblages, mineral compositions, and bulk chemical compositions. Cataclastic rocks are produced from rocks of diverse type; therefore mineral assemblages, mineral compositions, and bulk chemical compositions have little value in defining and classifying them. For example, a mylonite can be formed from granite, schist, conglomerate, gabbro, or almost any other rock. In fact, a mylonite can be formed from more than one parent rock. In this respect, cataclastic rocks are somewhat like sedimentary rocks.

PETROFABRICS

Petrofabric analysis has been made on many types of cataclastic rocks from many different areas. The results indicate that commonly all of the coherent cataclastic rocks of one deformation and the noncataclastic rocks of the same deformation within an area have essentially the same fabrics (Christie, 1963, p. 402–407 and fig. 23). Petrofabric analysis can be used in some cases to separate cataclastic rocks of different deformations in the same area (Grant, 1968), but not to develop general definitions and an overall classification of cataclastic rocks.

APPROXIMATE PERCENTAGE AND SIZE OF PORPHYROCLASTS AND ROCK FRAGMENTS (GRAIN SIZE)

In attempting to apply some quantitative criteria to definition and classification of cataclastic rocks, I measured porphyroclast and fragment size and determined the approximate percentage of porphyroclasts or fragments in eight or more thin sections of the cataclastic rock types in which grain size is a criterion.

DEFINING DEGREE OF NEOMINERALIZATION-RECRYSTALLIZATION

One of the chief problems in any classification of cataclastic rocks is that of defining the arbitrary separation between rocks of the sequence *protomylonite-mylonite-ultramylonite* and rocks of the sequence *mylonite gneiss* (*mylonite schist*)-*blastomylonite*. The problem is essentially one of recognizing degrees of recrystallization and (or) neomineralization. Most former workers have faced this problem by defining the two sequences of rock types as end members (Knopf, 1931; Waters and Campbell, 1935; Christie, 1960). Thus, mylonite and related rocks were defined as totally unrecrystallized or un-neomineralized, and blastomylonite and related rocks as nearly completely recrystallized and (or) neomineralized, so that their cataclastic texture was recognizable only with great difficulty. My study indicates that such end members are rare. Accordingly, I have chosen to define the two rock sequences so that the distinction between them depends on what has most influenced their present texture, the destructive process of cataclasis or the constructive process of neomineralization and (or) recrystallization, (table 1).

Thus defined, the separation must depend on some kind of standards to represent, as much as possible, the various degrees of neomineralization-recrystallization in natural cataclastic rocks. This is accomplished by means of photographs and photomicrographs of "typical" examples of the various rock types. It should be noted that the degree of neomineralization-recrystallization focuses attention primarily on the groundmass. There are numerous rocks for which a decision is extremely difficult, or even impossible, and a rock classified by one geologist as a *mylonite* might be classified by another as a *blastomylonite*. Therefore, detailed descriptions and photomicrographs are advisable, particularly when dealing with "borderline" rocks.

FIELD RELATIONS OF CATACLASTIC ROCKS

In outcrop and hand sample, cataclastic rocks may be easily mistaken for metasedimentary, metavolcanic, volcanic, or fine-grained intrusive rocks. In fact, many of the original definitions of cataclastic rocks include descriptive phrases such as "quartzite-like," "flinty," "felsitic," and "cherty."

In many cases, overlooking the presence of cataclastic rocks has led to erroneous interpretations of structure, stratigraphy, and geologic history. In other studies, the various types of cataclastic rocks have been "lumped" together, in mapping and in description, under one term such as *mylonite*. This too has led to oversimplified and erroneous interpretations in many areas.

Recognition of cataclastic rocks in the field is often difficult, and study of thin sections is the only positive method of recognizing them. Because cataclastic rocks are intimately associated with faults and fault zones, in many cases it is the suspicion of or recognition of the the existence of these structural breaks which leads one to suspect the presence of cataclastic rocks. The reverse is equally true; the recognition of cataclastic rocks has often led to recognition of major structural breaks.

In this section, criteria are given for the recognition of faults, fault zones, and cataclastic rocks, with examples described. Since this report is for the student as well as for the more experienced geologist, some of the more elementary aspects of field problems concerning cataclasis are considered.

RECOGNITION OF FAULTS AND FAULT ZONES

Faults or fault zones and belts of cataclastic rocks in crystalline terranes may be suspected where there are: (1) alinements of topographic features, springs, or marshy areas; (2) abrupt changes in attitude of bedding or foliation; (3) abrupt terminations of folds, dikes, faults, or other structural features; (4) changes in dips or in direction of joints or lineations; (5) offsets of map unit contacts; (6) repetition or omission of rock units; (7) blocks of float foreign to the underlying rock units; (8) lineaments in, or changes in the style of, magnetic or gravity anomalies; (9) steep gradients on magnetic or gravity maps; (10) anomalous changes in metamorphic zones or facies; (11) linear zones of mineralization, silicification, or alteration.

Steeply dipping fault zones are commonly marked by linear topographic alinements. Drainage may follow these lineaments because cataclastic rocks are commonly either less resistant or more resistant to weathering than the surrounding noncataclastic rocks. The more resistant varieties tend to block and divert small streams, so that these streams flow parallel to the cataclastic rock bands and then cross them at high angles when a zone of less resistant rock is reached. The less resistant cataclastic rocks tend to provide easily eroded streambeds, so that the streams follow the cataclastic rock bands. Marshy areas are relatively common on the upslope side of resistant cataclastic rock bands.

RECOGNITION OF CATACLASTIC ROCKS

Once the presence of fault zones or cataclastic rocks is suspected, there are certain general criteria which help to identify cataclastic rocks and to distinguish them from noncataclastic rocks.

(1) *Textural contrast.*—Cataclastic rocks are often recognizable in the field by their contrast with the noncataclastic rocks around them. This is especially true of phyllonites and of diaphthoritic cataclastic rocks, but it also applies to most of the other cataclastic rocks. For example, a fine-grained, laminated mylonite in medium-grained or coarse-grained schist or gneiss would be conspicuous.

(2) *Differential weathering.*—Weathering differences between cataclastic rocks and noncataclastic rocks can help in recognition of cataclastic rocks.

(3) *Gradational nature.*—The gradational nature into and out from crystalloblastic metamorphic rocks often helps to distinguish the cataclastic rocks (*see* Crickmay, 1933). Such gradation is especially useful in distinguishing cataclastic rocks from metavolcanic rocks.

(4) *Presence of porphyroclasts or visible fluxion structure.*—Except for microbreccias and cataclasites, coherent cataclastic rocks are commonly recognizable by the presence of porphyroclasts and streaking or other visible fluxion structure (fig. 18). They can be confused with porphyritic volcanic or metavolcanic rocks, but porphyroclasts tend to be rounded, whereas euhedral or subhedral shapes are more common for phenocrysts in volcanic and metavolcanic rocks (figs. 19 and 20). This criterion should be used with caution, however, because euhedral and subhedral porphyroclasts are not unknown (fig. 6; also see Hsu, 1955b), and rounded phenocrysts do occur in some volcanic and metavolcanic rocks (figs. 19*A*, *B* and 20), particularly in tuffaceous rocks and welded tuffs. Moreover, round or nearly round porphyro*blasts* are also known.

Cataclastic rocks may also be confused with flint, chert, slate, or fine-grained quartzite (figs. 21 and 22) (see Crickmay, 1933). Here again, the presence of porphyroclasts (fig. 22) may be the distinguishing feature, though rounded clastic grains may be mistaken for porphyroclasts.

Perhaps as important as the shapes of porphyroclasts in distinguishing them from most phenocrysts and porphyroblasts is their mineralogy. It is well-known that quartz is ground down more readily than feldspars during cataclasis and that most porphyroclasts are feldspar. Porphyroclasts of quartz are rare in cataclastic rocks, but quartz phenocrysts are fairly common in volcanic, metavolcanic, and intrusive igneous rocks.

FIGURE 18.—Blastomylonites from the Goat Rock fault zone in Alabama. *A*, Porphyroclastic blastomylonite with rounded feldspar porphyroclasts. *B*, Laminated blastomylonite. This rock is similar in appearance to some kinds of metamorphosed volcanic rocks with thin layering and phenocrysts. However, the rounded feldspars are porphyroclasts, and the streaking and layering are parallel to fluxion structure.

(5) *Zones of mineralization and alteration.*—Cataclastic rocks—particularly those in the sequence *microbreccia-cataclasite*—are commonly zones of mineralization and alteration. Consequently, they may be marked by discoloration and stains due to the mineralization or to weathering of the minerals. This is especially true where the mineralization involves sulfides.

(6) *Presence of mica masses.*— Micas in cataclastic rocks commonly occur in clotlike masses or in spindle-shaped lenses and generally are bent or smeared (fig. 11). On surfaces parallel to the fluxion structure or foliation, these mica masses commonly give the rock the peculiar appearance of having "eyes," or of being smeared with fish scales (fig. 11). The mica lenses have been called "buttons," "eyes," and "fish-scale structures," and the rocks "button schists," "eyed schists," "eyed phyllonites," "phyllonitic schists," and "curly schists" (see Crickmay, 1952; Reed and Bryant, 1964; Reed, 1964; Higgins, 1966). This feature is most common in phyllonites and blastomylonites.

(7) *Association with fault zones.*—Field relations (map relations) are most important in recognition of

cataclastic rocks. Although the kinds of rocks with which cataclastic rocks are commonly confused may be found in fault zones, they will generally also be found away from fault zones as well. Cataclastic rocks may thus be suspected simply by their intimate association with fault zones.

(8) *Catalastic texture in thin section.*—The primary rule for recognition of cataclastic rocks is that they are positively identifiable *only* in thin section. **Any rock suspected of being cataclastic should be examined in thin section.**

MAFIC CATACLASTIC ROCKS

It has long been recognized that most cataclastic rocks are felsic or silicic. This has been such a common observation that it was included in many of the definitions of cataclastic rocks. However, cataclastic rocks formed from mafic rocks are known and are not really rare. Waters and Campbell (1935, p. 484, 489) described basalt and diabase mylonites. Sclar (1958, p. 70–75) described mylonites and ultramylonites formed from mafic gneiss. Prinz and Poldervaart (1964) decribed mylonite formed from metadolerite. Dunite mylonites have been described from St. Paul's Rocks (Tilley, 1947), and from New Zealand (Turner and Verhoogen, 1960, p. 633; Williams and others, 1954, p. 77–78).

The fact that the greater proportion of cataclastic rocks are of "granitic" composition probably results from several factors. First, because cohesive cataclastic rocks form under conditions of relatively high confining pressure and moderate to high temperatures, they are mostly limited to metamorphic-plutonic terranes. "Granites" constitute 90 percent of the intrusive rocks in these terranes (Daly, 1933, chap. 3; Read, 1957, p. 70–82), and a large proportion of sedimentary and metasedimentary rocks in orogenic belts are felsic or silicic. Therefore, a large percentage of cataclastic rocks are necessarily "granitic." Secondly, as Waters and Campbell noted (1935, p. 489):

> * * * under the pressure-temperature conditions that result in the formation of a mylonite from quartzite or graywacke, basalts and diabases are partially recrystallized, and serpentine is entirely recrystallized and converted into schist.

ASSOCIATION OF CATACLASIS WITH FELSIC AND SILICIC INTRUSIVE ROCKS

Felsic and silicic dikes, veins, and thin sills are common features of most crystalline terranes. Faults coincident with these bodies are also common. In the Northwest Highlands of Scotland, minor fault zones and felsic and silicic dikes have a remarkable coincidence. In their classic memoir on this region, Peach and others (1907) describe no fewer than 18 cases of cataclastic zones in dikes (p. 116, 122, 124, 141, 145, 148–149, 152–153, 173, 202, 209, 213–214, 244, 248, 263, 470). The following two examples (1907, p. 153, 213) are typical:

> In the last two localities this type of deformation [mylonitization] occurs in dikes * * *. It is evident that the dikes formed lines of weakness along which movements were repeated.
>
> * * * * *
>
> Zones of mylonised pegmatite are common * * *. The pegmatites near Coppachy have more often been mylonised than the adjacent rocks * * *.

The association of dikes and lava-feeding fissures with faults is common in volcanic terranes (for example *see* Waters, 1962). Generally, repeated igneous activity has alternated with fault movement along these fissures. Dikes, veins, and sills in metamorphic terranes formed zones of easiest movement during directed stress, particularly if they were not quite completely solidified. In many cases, the intrusive bodies may have first been emplaced along fault planes, or in fault zones, only to be deformed by later fault movements. If confining pressures were great enough, cataclastic rocks might be produced preferentially in these igneous bodies. Alternatively, perhaps some of the cataclastic dikes are the result of protoclastic deformation.

Phillips (1945, p. 214–215) noted faulted and cataclastically deformed pegmatite dikes and veins in the Moine Schist. Read (1951) noted cataclastic zones which appear to be localized in "acidic dikes." Johnson (1961, p. 425) noted that: "Lewisian pegmatites have been selected for intense shearing during the Caledonian movements."

There are also examples from the United States. In his study of the Swakane Biotite Gneiss, Entiat Mountains, Wash., Waters (1932) noted preferential cataclasis of pegmatites. Alf (1948) has described preferential cataclasis (producing protomylonites, mylonites, and ultramylonites) of quartz monzonite sills and dikes in granulites of the San Gabriel Mountains, Calif. (*see* Hsu, 1955b, p. 256–258, 273–274, for an alternate hypothesis). Higgins (1966, p. 40–42) has described "blastomylonite dikes," which were probably originally pegmatite, in Georgia.

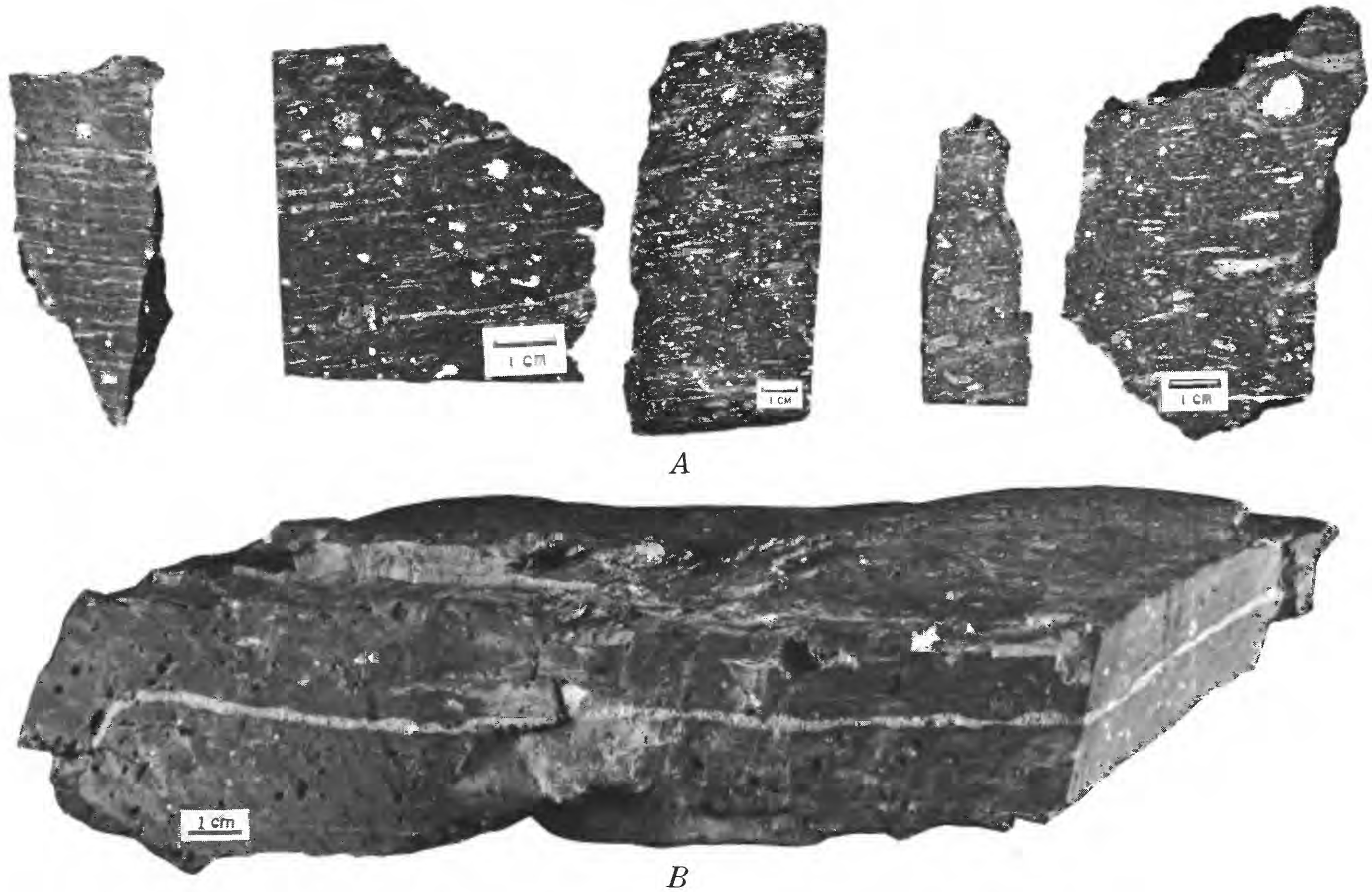
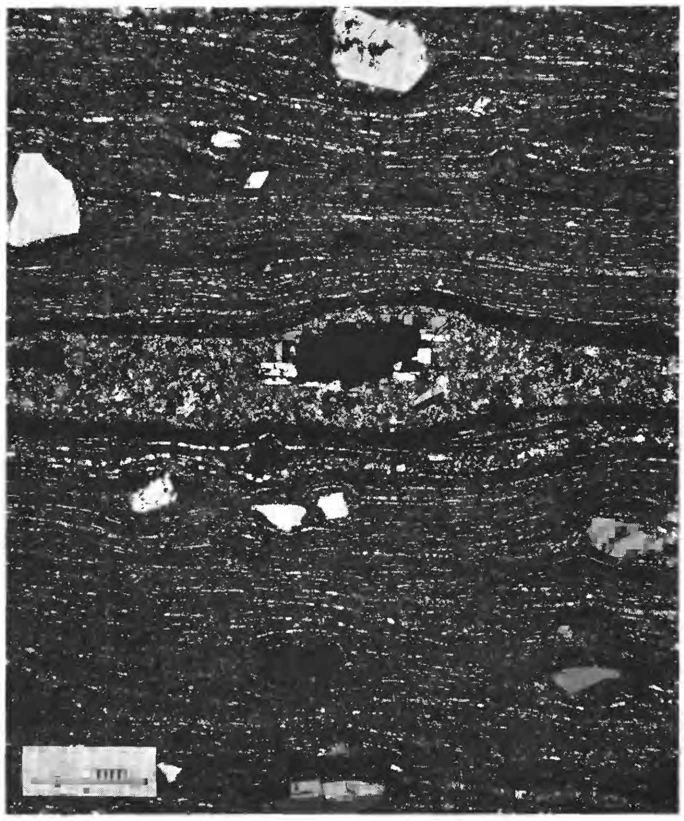


FIGURE 19.—Welded tuff from the San Juan Mountains, Colo. All photographs from Ratté and Steven, 1967 (*A*, fig. 4*A–C*; *B*, fig. 7; *C*, fig. 5*B*, *C*). *A*, Hand samples of welded tuff. Note similarity to some cataclastic rocks. Final forward creep of the welded tuff sheet produces structures resembling flow structure of some mylonites. Draping of flattened pumice lapilli around phenocrysts and rock fragments produces structures similar to those around porphyroclasts in fluxion-structured cataclastic rocks. *B*, Fluidal welded tuff. Note similarity to hand samples of some cataclastic rocks, and the rounded



C

phenocrysts visible on right end. *C*, Microscopic structures in welded tuff. *Left:* Eutaxitic structures showing weak fluidal characteristics, upper half of welded tuff member (Willow Creek Member of Bachelor Mountain Rhyolite). Note euhedral plagioclase phenocrysts and embayed quartz phenocrysts. *Right:* Fluidal structure in lower part of the welded tuff member. Note similarity to cataclastic texture. The euhedral and subhedral plagioclase phenocrysts and the angular quartz phenocrysts distinguish this rock from cataclastic rocks in thin section. Both with crossed polarizers.

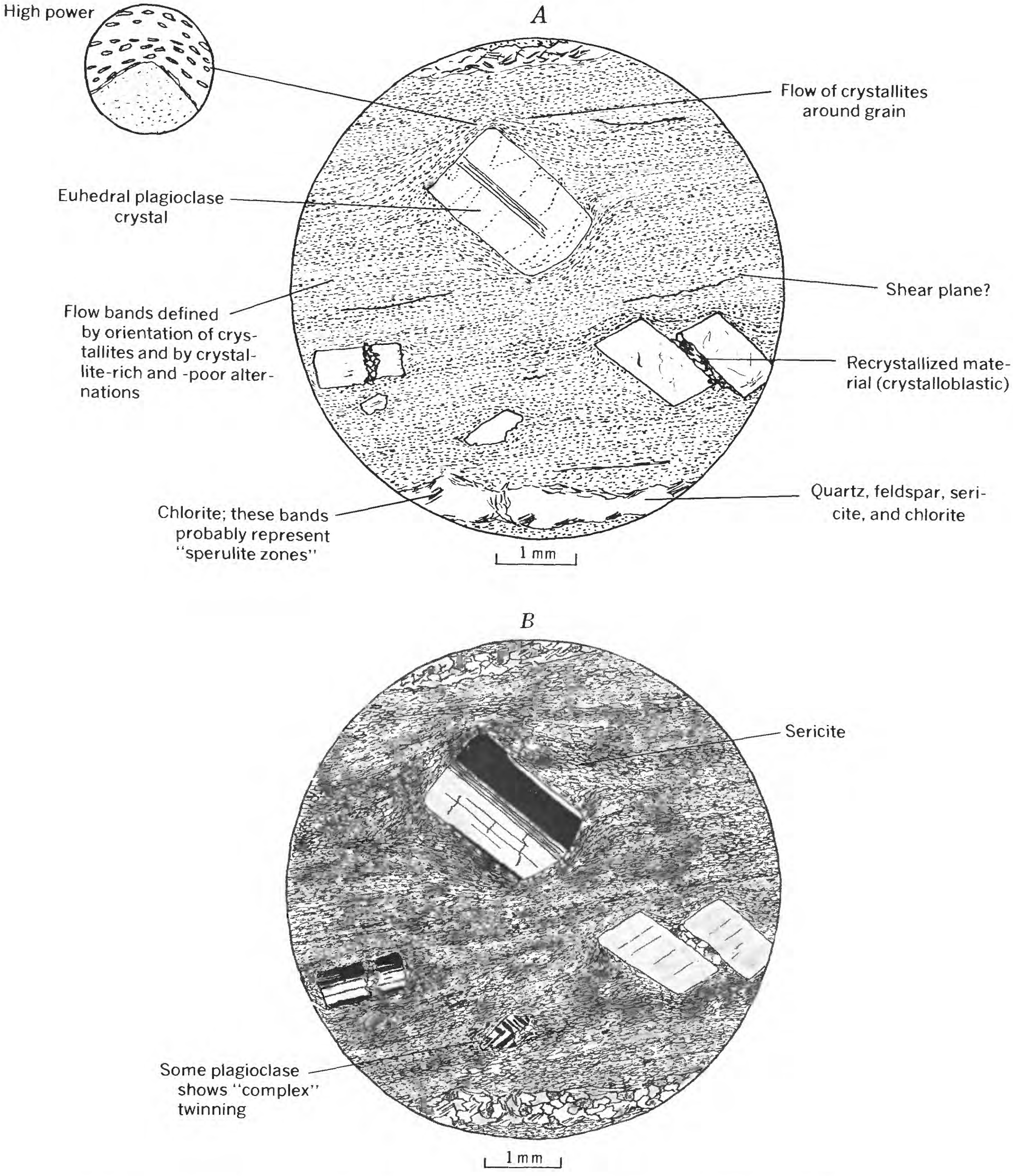


FIGURE 20.—Microdrawings of metarhyolite from near Waterville, Maine. *A*, Plane-polarized light; *B*, crossed polarizers. The rock superficially resembles a mylonite or blastomylonite, but the euhedral phenocrysts of plagioclase identify it as a metavolcanic rock. In *A*, crystallites (some are sericite) are shown in black which tends to exaggerate them. In *B*, note recrystallization follows same lines as crystallites (old flow lines). Sample from collection of A. C. Waters.

LATE MINERALIZATION OF CATACLASTIC ROCKS AND CATACLASTIC ROCK ZONES

Late mineralization is common along many fault zones and accounts for secondary minerals in many cataclastic rocks. The most common products of secondary mineralization in cataclastic rocks are sulfide minerals, carbonate minerals, silica minerals, magnetite, and hematite (Crickmay, 1933, p. 174–175; Waters and Campbell, 1935, p. 491–492; Hsu, 1955b, p. 307–308; Sclar, 1958, p. 66, 68, 76; Reed, 1964, p. 670, 672, 675; Conley and Drummond, 1965, p. 204–206; Higgins, 1966, p. 27–28). Secondary carbonate minerals and silica generally occur as veins cutting the cataclastic rocks. Magnetite and pyrite commonly occur as euhedral crystals unaffected by the cataclasis. Hematite may be produced still later from secondary magnetite.

Most geologists have proposed that the secondary mineralizations in cataclastic rocks are due to hydrothermal activity selectively concentrated in the fault zones.

FIGURE 21.—Banded chert from the Mojave Desert in California. Note the gross similarity to the banding of some cataclastic rocks.

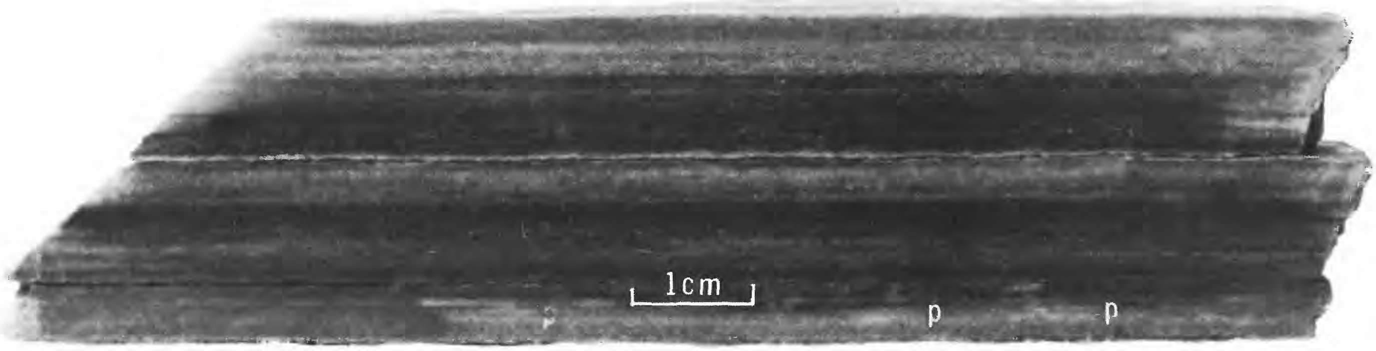


FIGURE 22.—Quartzo-feldspathic blastomylonite from the Goat Rock fault zone in Alabama. This rock strikingly resembles fine-grained metaquartzite, but the tiny porphyroclasts of feldspar (p) and the field relations indicate it is cataclastic. Thin sections show that it is a blastomylonite.

EXAMPLES OF CATACLASTIC ROCK ZONES AND THEIR INTERPRETATION

THE SAN ANDREAS FAULT SYSTEM, CALIFORNIA

The San Andreas fault system (Hill, 1966; Hamilton and Myers, 1966a) consists of thousands of anastomosing lateral faults in a belt approximately 600 miles long and 300 miles wide in California and western Nevada (fig. 23). Hamilton and Myers (1966b, p. 516) state:

> Some minor faults of the San Andreas system are single breaks, but most of the major faults are zones as much as a few kilometers wide of anastomosing nearly parallel breaks of varying age. Some breaks are moving now but others have been long inactive. Gouge and breccia are typically present along the faults, but mylonite and blastomylonite have been exposed along others.

According to Hill (1966, p. 240):

> The system appears to be typified by right-slip on northwest trending faults and by left-slip on some of the east-northeast trending faults.

The major faults of the system are shown by name on figure 23.

THE SAN ANDREAS FAULT

The San Andreas fault, the best known and largest fault of the San Andreas system in length and probable displacement, is continuous for more than 600 miles, from south of the Mexican border to the vicinity of

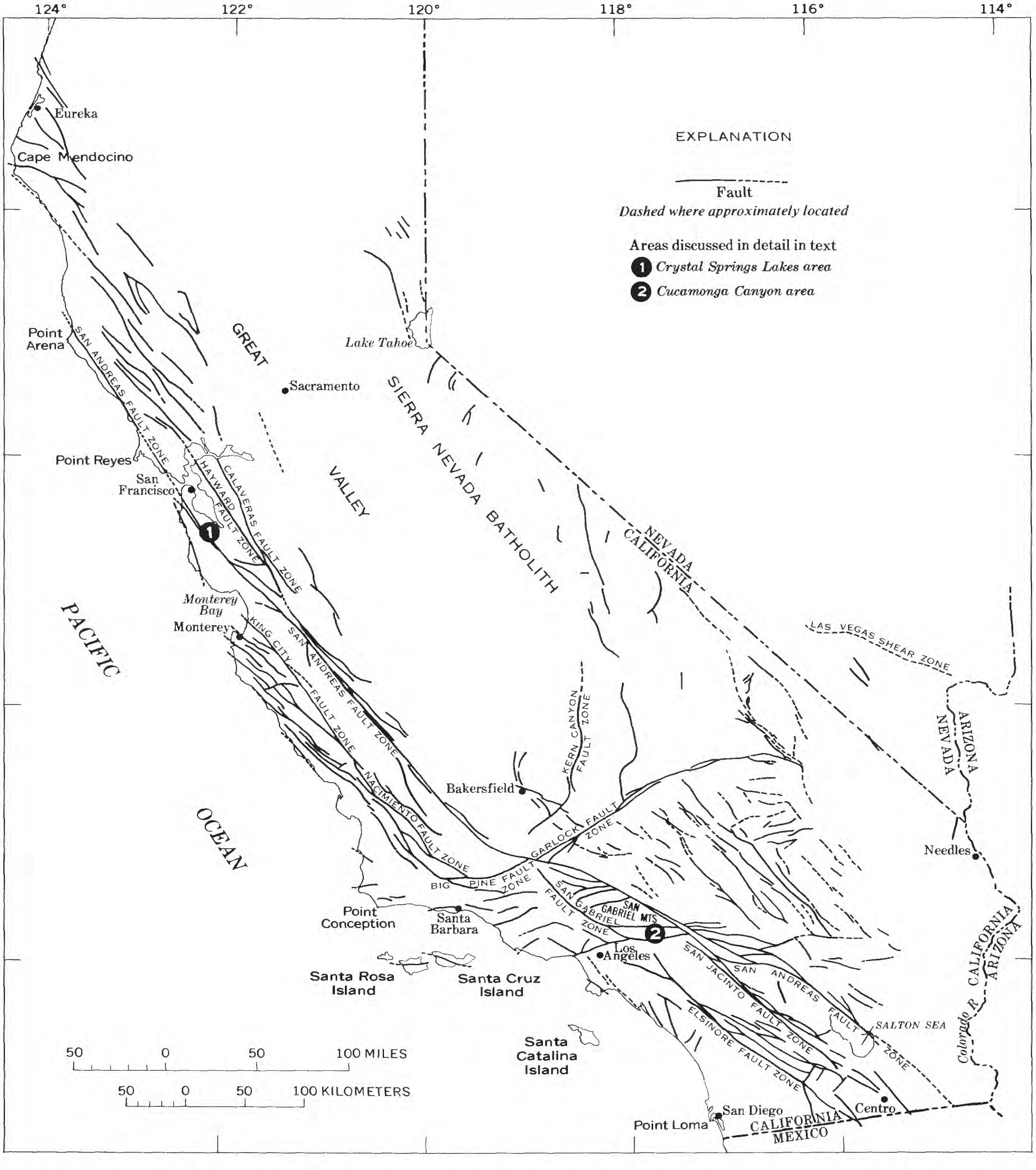


Figure 23.—Major fault zones of the San Andreas system. Modified from U.S. Geological Survey and American Association of Petroleum Geologists (1961).

Point Arena, north of San Francisco (fig. 23). It has been suggested that it extends for at least another 100 miles offshore to the north (Tocher, 1956; Shepard, 1957; Curray and Nason, 1967) and into and perhaps through the Gulf of California to the south (Hamilton, 1961). There are wide differences of opinion on both the sense and amount of movement on the San Andreas. Some workers contend that the main movement has been primarily vertical (Buwalda, 1937; Clark, 1929; Willis, 1929; Weaver, 1949; Oakeshott, 1966); others contend that the main sense is strike-slip (Noble, 1926; Waters and Campbell, 1935; Wallace, 1949; Hill and Dibblee, 1953; Moody and Hill, 1956; Hamilton, 1961; Dibblee, 1962; Crowell, 1962, 1966; Hamilton and Myers, 1966a, b; Hill, 1966). Vickery (1925), Noble (1926), Waters and Campbell (1935), and Wallace (1949) suggested strike-slip of 12 to 25 miles; Reed and Hollister (1936), Taliaferro (1943), and Oakeshott (1966) would restrict strike-slip to less than a mile; and Hill and Dibblee (1953), Moody and Hill (1956), Hamilton (1961), Dibblee (1962), Crowell (1962, 1966), Hill (1966), and Hamilton and Myers (1966a, b) suggest more than 200 miles of displacement. Most proponents of strike-slip movement agree on right-lateral displacement, with nearly 1 mile of right-lateral slip (based chiefly on stream offsets) having occurred since Pleistocene time. Historic displacements are right-lateral and measurable in tens of feet.

Lawson and others (1908), Noble (1926), Waters and Campbell (1935), Wallace (1949), Crowell (1962), and others have described the surface features of the San Andreas fault. In brief, it is commonly a *zone* more than half a mile wide marked by scarps, scarp lines, slice ridges, sag ponds, shutter ridges, irregular topography, and offset streams.

The fault zone cuts rocks of widely varying age and character along its course through California (U.S. Geol. Survey and California Div. Mines and Geology, 1966; Crowell, 1962). Depths of exposure resulting from erosion also vary greatly along the zone. Consequently, a great range of cataclastic rock types is found along the fault zone. In many places along the zone, movements have been distributed through unindurated or poorly-indurated rocks. These rocks are deformed and jumbled but are certainly not cataclastic. In other places, the zone is one of anastomosing shears filled with gouge or breccia. In still other places, the zone consists of coherent cataclastic rocks and is more than half a mile wide.

Waters and Campbell (1935, p. 482–484) have described the San Andreas fault zone and its cataclastic rocks in the vicinity of Crystal Springs Lakes, about 30 miles south of San Francisco:

The rocks along this zone are much sheared and broken, and fragments derived from every formation in the region from the oldest to the youngest have been brought together in a chaotic jumble. At some localities these blocks are sufficiently large to be mapped as separate fault slivers, but elsewhere they have been ground down until the entire zone can be designated only as a heterogeneous fault breccia. . . . A great number of different rock varieties are found in this breccia, but the most common ones are serpentine, feldspathic sandstone and siltstone, altered basalt or diabase, quartz diorite and diorite, quartzite, graywacke, impure calcareous rocks, and a well-laminated black rock with aphanitic texture which the microscope shows to be a true mylonite * * *.

Unlike the other rock varieties of the fault breccia, the mylonite occurs not in distinct blocks but as a sort of matrix which encloses the other rock varieties. Locally it forms great tabular masses many feet in thickness. It grades into all the other rock varieties and in this transition gradually takes on the properties and appearance of the rock with which it is in contact. Thus adjacent to the altered basalt the normally black color of the mylonite shades off into dark green until the rock is indistinguishable from schistose, chloritized basalt. Or it may grade into quartzite or feldspathic sandstone by a gradual increase in granularity and simultaneous decrease in the degree of lamination. Similar gradations are shown against quartz diorite, and at one place there is an even alternation of black mylonite with layers of antigorite schist, the individual layers locally averaging less than an inch in thickness. At some places minute veinlets of quartz ramify through the rock, some of them following the lamination, others cutting across it at all angles. The lamination is exceptionally well developed and produces a rock cleavage similar to that of slate or phyllite. The attitude of the lamination is highly variable. At Locality 2 it strikes parallel with the fault zone and dips vertically though local variations appear. At Locality 1 both strike and dip are highly variable, although the strike is prevailingly in the same direction as that of the fault, and the dip is commonly at a low angle. Although the lamination is straight at most places, it is locally highly contorted, the folds ranging in amplitude from microscopic dimensions to structures a few inches across. Many faults of small displacement are also visible in these plicated zones. At one place the rock shows two distinct banded structures, one dipping at a low angle, the other standing practically vertically. The rock splits readily into thin plates along either of these. Another curious feature of the lamination is the presence in the rock of minute elliptical spots pulled out parallel with the lamination. The true nature of these spots is seldom recognizable to the unaided eye, but with a hand lens one can see that they are eye-shaped mineral aggregates, or porphyroclasts, which have survived the complete pulverization of the groundmass, and which remind one on a minature scale of the 'augen' in a typical augen gneiss. Although the rock cleaves into thin plates as easily as schist or phyllite, the eye-shaped spots, local contortion, and other irregularities cause the lamination to resemble the flow structure of an acidic lava as much as it does the foliation of a metamorphic rock. The lustre of the rock may be like slate or may be subvitreous like chert or tachylyte.

They go on (p. 484–495) to describe and illustrate the mylonites, and ultramylonites in detail.

OTHER FAULT ZONES OF THE SAN ANDREAS SYSTEM

CUCAMONGA CANYON

Two major and several subsidiary fault zones pass through the San Gabriel Mountains, east of Los Angeles (fig. 23). Cataclastic zones are well exposed in the steep canyons that drain the western slopes of the San Gabriels (Alf, 1948; Hsu, 1955b). The cataclastic rocks of Cucamonga Canyon (fig. 24) are particularly interesting.

In the Cucamonga Canyon and Aurela Ridge groups [2] (fig. 24), cataclastic rocks are commonly associated with thrust faults on which the sense of movement is readily demonstrated by drag folds in the adjacent rocks. The zones or layers of cataclastic rocks attending the thrusts range from about a foot to several tens of feet in thickness. Thinner layers of cataclastic rock are also present in the country rocks away from the easily demarked thrust zones. The Sarac Ridge group (fig. 24), about 3,000 feet in apparent thickness, consists almost entirely of cataclastic rocks.

Protomylonite, mylonite, ultramylonite, mylonite gneiss, and blastomylonite are all represented in Cucamonga Canyon. There are also some polycataclastic rocks. Hsu (1955b, p. 281) stated:

> Mylonites in zones of later faulting are brecciated and recemented by secondary minerals, namely clinozoisite—penninite.

Some of the cataclastic rocks of the canyon are peculiar for several reasons: (1) Their modal and chemical compositions more closely match those of nearby plutons than they do those of the adjacent country rocks (see Alf, 1948); (2) Porphyroclasts of feldspars in some of these cataclastic rocks show the well-developed zoning common to igneous rocks, and some of the porphyroclasts are euhedral or subhedral (fig. 6B; also see Hsu, 1955b, p. 337); (3) The cataclastic rocks are interlayered with siliceous and felsic gneisses of the granulite facies of metamorphism, but also with rocks of the amphibolite facies.

Alf (1948) thought the cataclastic rocks were derived from the nearby intrusive rocks. He stated (1948, p. 1117):

> The thick, steeply north-dipping sheet of Black Belt mylonite [Hsu's Sarac Ridge group] suggests formation along a fault zone. If the 2000 feet of mylonite and mylonite gneiss were formed by crushing and milling of the formations now adjacent to the Belt, its chemical composition might be expected to be intermediate between that of the quartz diorite gneiss [Hsu's El Dorado Ridge gneissose quartz diorite] and that of the pyroxene dioritic gneiss [Hsu's Aurela Ridge group] (or locally the Cucamonga Complex) [Hsu's Cucamonga Canyon group]. But, as shown, chemical analyses and all other available information indicate that the Black Belt rocks have compositions close to that of the quartz diorite gneiss, and more siliceous than most of the pyroxene dioritic gneiss. Perhaps at depth the Black Belt is walled on both sides by quartz diorite gneiss, and was produced chiefly by the grinding up of a single rock type.
>
> The hypothesis of origin of the Black Belt from the crushing of solid, dark quartz diorite gneiss has two defects. First, the quartz diorite gneiss appears to intrude the Black Belt mylonite, and thus to have been at least locally semi-liquid after the mylonite had formed. Second, narrow dike-like streaks of pale analysed quartz monzonite mylonite cut the main mass of the Black Belt. This pale mylonite has neither the composition of the enveloping rock nor a simply related composition (e.g., merely more siliceous). The existence of two types of mingled mylonite, each with the composition of a plutonic rock present in the area, suggests that the main mass of mylonite may have been formed by the crushing of a barely consolidated upper layer of a quartz diorite batholith and that the bands of quartz monzonite mylonite may have resulted from the streaking out of plutonic dikes while they were more plastic than the surrounding rock, perhaps before crystallization was entirely completed.

Hsu (1955b) disagreed with Alf. He thought the cataclastic rocks were derived from the granulites and had been metasomatized (1955b, p. 256):

> * * * their composition is so varied that they could not have been derived from a homogeneous "igneous" body and probably not from the Stoddard Canyon quartz monzonite, which has a rather uniform composition over the area.
>
> The field occurrence suggests that cataclasis was synchronous with the thrusting of the Aurela Ridge granulites. If the cataclastic rocks were derived from "igneous" rocks, one has to assume that "igneous" rocks occurred as dikes where thrusting subsequently took place. Such a coincidence seems highly improbable, especially when one takes into consideration the remarkable preferred orientation of the cataclastic "dikes."
>
> The chemical and mineralogical compositions of the cataclastic rocks indicate that they are not simply mylonitized granulites; they are richer in potash feldspar and poorer in pyroxene than the granulites. Only in one or two specimens is a trace of relict pyroxene found. Such a discrepancy in composition, nevertheless, can be readily explained by assuming metasomatism accompanying cataclasis.

Of the feldspars Hsu stated (1955b, p. 256–257):

> The origin of the large plagioclase crystals in cataclastics is somewhat puzzling. Many of them are not severely strained. Their idiomorphic outline, straight twinning lamellae, and clear appearance are in remarkable contrast to the angular or lenticular outline, the bent and broken twinning lamellae, and the dusty apperance of the strained plagioclase crystals. Whether these little strained crystals are porphyroclasts or porphyroblasts is still debatable, although it seems highly improbable that any crystal a few millimeters long could survive cataclasis, with its

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[2] In the discussion of the Cucamonga Canyon that follows, all geologic names are informal and are from Hsu (1955b) unless otherwise noted. Pertaining to the use of the term "group," Hsu (1955b, p. 230) states:
"As the term 'zones' has been commonly used by petrologists to designate zones of different P–T–X conditions during progressive metamorphism * * * I choose to use the term group to designate bodies of polymetamorphic rocks whose differences in structures and textures resulted from localization of stress rather than from differences in temperature and pressure (hydrostatic) conditions. The term 'group' as applied to the polymetamorphic rocks of the area does not have the connotations commonly implied by stratigraphers * * *."

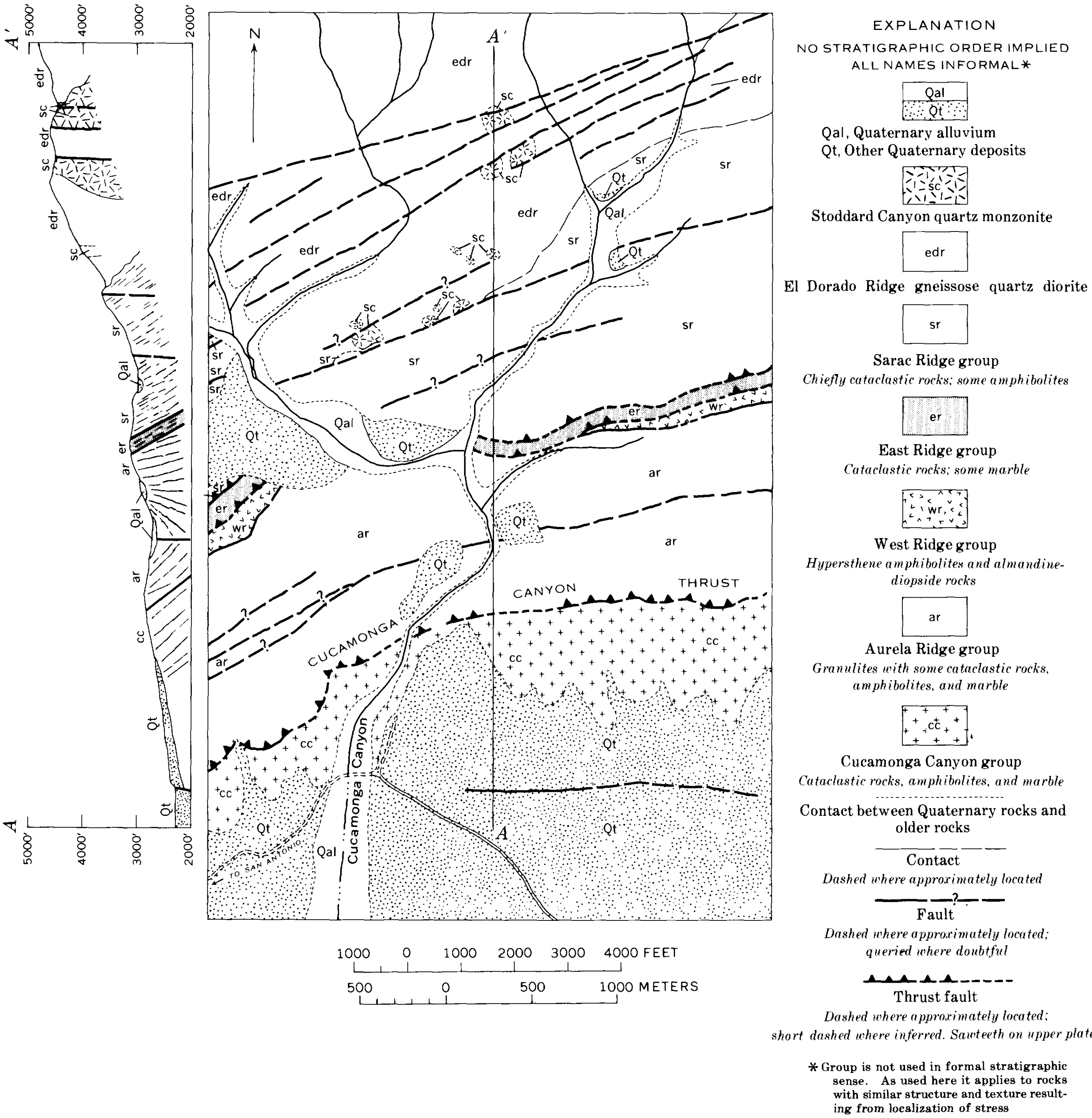

FIGURE 24.—Geologic map of the Cucamonga Canyon area, San Gabriel Mountains, Calif. (see fig. 23 for location). Generalized from Hsu (1955b).

idiomorphic outline preserved and showing little evidence of strain, while other crystals are broken into fragments 0.01 to 0.001 mm. in size. Broken porphyroclastic crystals are common. On the other hand, some crystals containing trains of inclusions, which may be relic foliation, are probably porphyroblasts. The fact that the relic foliation(?) in some plagioclase crystals is tilted at an angle to the foliation of the enclosing matrix and that the corners of some plagioclase porphyroblasts are sheared off indicate that some deformation occurred after the recrystallization of the plagioclase. It seems therefore that some crystals were pulverized by cataclastic deformation, others were recrystallized, and that recurrent movement caused repeated cataclasis. These observations and deductions indicate a synkinematic crystallization of plagioclase.

Potash feldspar probably crystallized from introduced ichors (hydrothermal or pegmatitic solutions). Textural criteria suggest a period of potash feldspar replacement subsequent to the crystallization of plagioclase. The filling-in of the cracks of broken plagioclase by aggregates of potash feldspar dates the metasomatic process as synkinematic. Myrmekite may have resulted from synkinematic or postkinematic metasomatic activities, and granoblastic quartz was probably formed in the waning phase of cataclasis.

I regard the origin of these cataclastic rocks as unsolved, but favor the hypothesis of Alf (1948). Hsu's point regarding the dikes is not convincing; as noted elsewhere in this paper (p. 35) the coincidence of cataclasis and dikes is common. It also seems that the feldspars can more simply be explained by cataclasis of incompletely crystallized dikes than by an exotic scheme of metasomatism; from what is known of protoclastic rocks the existence of euhedral porphyroclasts is not completely anomalous. Hsu does make a good point regarding Alf's scant chemical data, but his statement regarding the variation in composition is based on little evidence, because he presented no new analyses.

Regardless of arguments concerning ultimate origin, the rocks of Cucamonga Canyon are impressive because of their variety and good exposure and because it can be readily demonstrated that they formed by faulting under conditions of amphibolite facies metamorphism.

Other fault zones of the San Andreas system and the cataclastic rocks in them have been described by Noble 1954 (1954), Dibblee (1954, 1967), Mann (1955), Allen (1957), Ehlig (1959), Proctor (1962), Theodore (1966), and Sharp (1967).

THE ALPINE FAULT ZONE, NEW ZEALAND

The South Island of New Zealand is transected by a great fault zone (fig. 25) known as the Alpine fault (Wellman and Willett, 1942) or the Alpine fault zone (Reed, 1964). This fault zone has long been known to extend from Milford Sound on the southwest coast to near Lake Rotoroa, southeast Nelson, in the northern part of the island (Wellman and Willett, 1942). Recently, Suggate (1963) and Reed (1964) have shown that it is continuous with the Wairau fault, and by this connection reaches Cook Strait near the mouth of Wairau River (fig. 25). The fault zone probably continues into the North Island also (Wellman, 1956; Suggate, 1963; Reed, 1964).

Through most of its length the Alpine fault zone is marked by a conspicuous topographic and geologic lineament, according to Cotton (1947, p. 369), "the most remarkable lineament in the geology of New Zealand." Apparent stratigraphic offset along the fault zone is readily seen even on small scale geologic maps (fig. 25: also see New Zealand Geol. Survey, 1958). Suggate (1963) discussed alternative possibilities for the 280- to 300-mile right-lateral shift first proposed by Wellman (1955) but presented good evidence that the shift is probably real (also see Reed, 1964). As much as 60,000 feet of vertical movement has also taken place on the fault zone, but the amount probably varies considerably along its course (Suggate, 1963; Reed, 1964).

Reed (1964) has given an excellent description of the cataclastic rocks in the Alpine fault zone. He stated (pp. 645, 672):

> The cataclastic rocks along the Alpine Fault can be readily classified into three distinct groups: an incoherent group of fault pug [*fault gouge* in my classification—table 1], fault breccia, and shattered rock; a cataclasite group of brecciated rock, mortared rock, [both *microbreccia* in my classification] and cataclasite; and a mylonite group comprising augen mylonite [3], mylonite, ultramylonite, and blastomylonite.
>
> The first group is common along the line of Quaternary movement of the Alpine Fault, the fault pug and fault breccia being a few feet to more than 100 ft wide, and the zone of shattered schist several chains [4] or more in width.
>
> * * * The second group is conspicuous in the granitic rocks, the structureless cataclasite being 100–200 ft. thick, and the zone of brecciated and mortared granite a mile or more in width. The mylonite group is characterized by fluxion banding and forms a belt 1,000–2,500 ft. wide, largely within the granite.

And concerning the mylonite group (p. 675):

> The composite picture obtained from study of all the sections is of a mylonite belt 1,000–2,500 ft. in width, of which 600–2,000 ft. is augen mylonite and mylonite, 300–1,000 ft. blastomylonite, and 100–300 ft. schist derived mylonite.

Reed also describes specific sections of cataclastic rocks in the zone; the following is typical (1964, p. 672–673):

> * * * the passage between schist and mylonite is well displayed in a continuous section in the Saddle Creek tributary of Canada Creek; about 1,300 ft. of augen mylonite and mylonite passes eastward into about 600 ft. of blastomylonite, and this in turn into garnetiferous "curly" schist. These three rock types form distinct bands except for some minor interfingering of blastomylonite with augen mylonite and mylonite.

Reed (1964, p. 676) also notes cataclasites formed from mylonites (polycataclastic rocks). He describes all of the cataclastic rocks well, and his illustrations are particularly good. However, nothing would be gained here by quoting his descriptions, because the rocks are all similar to those defined, described, and illustrated elsewhere in this paper.

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[3] Reed (1964, p. 657–659) uses this term for mylonites with large porphyroclasts. It is not equivalent to *mylonite gneiss*. Perhaps porphyroclastic mylonite would serve better.

[4] 1 chain equals 66 feet.

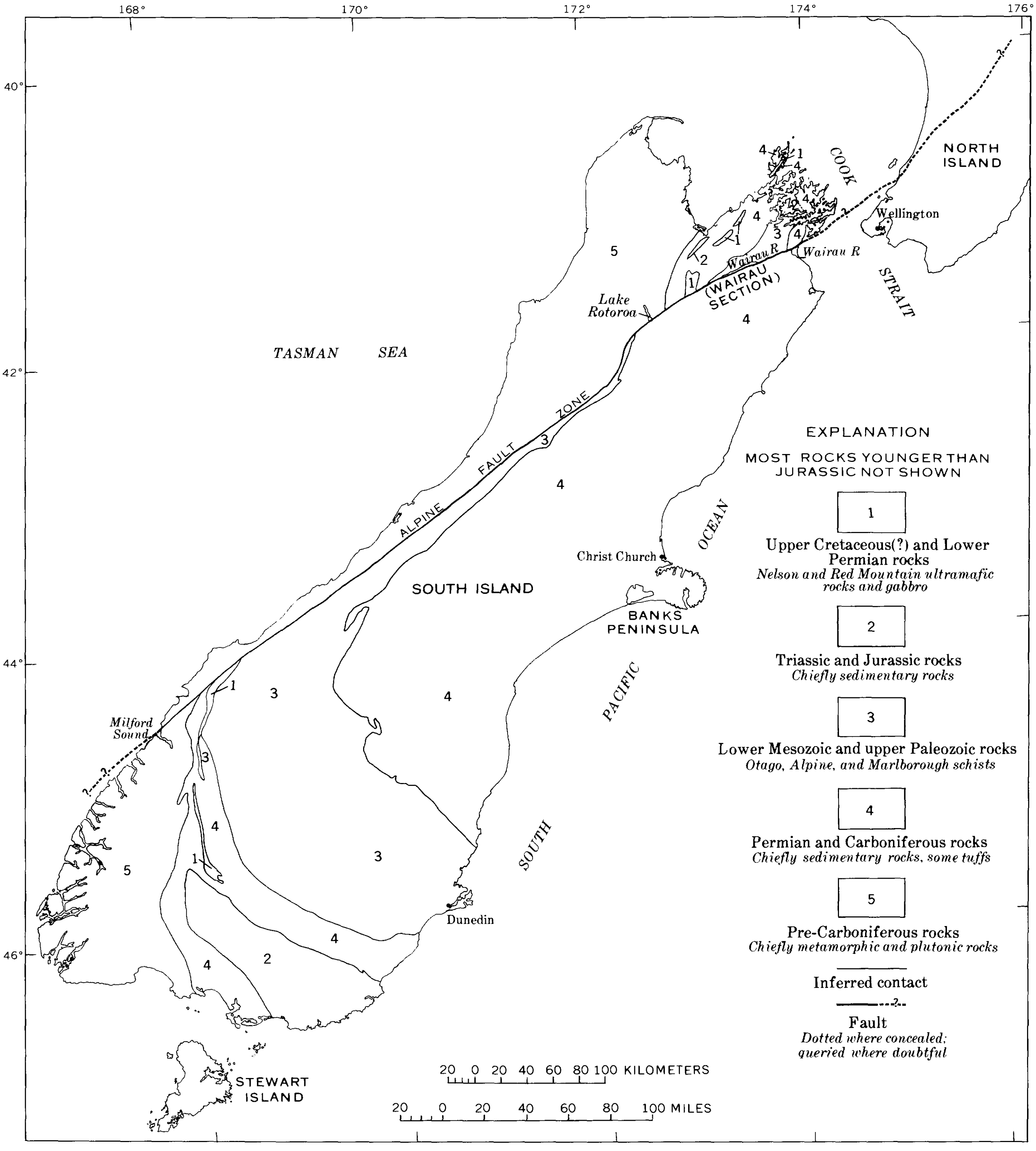


FIGURE 25.—Generalized geologic map showing the Alpine fault zone, New Zealand (modified from New Zealand Geol. Survey, 1958).

TOWALIGA, GOAT ROCK, AND BARTLETTS FERRY FAULT ZONES, GEORGIA AND ALABAMA

There are three major fault zones near the southern margin of exposed Piedmont crystalline rocks in Georgia and Alabama (fig. 26). Two of these, the Towaliga and Goat Rock zones, have been known since the early 1930's (Crickmay, 1933); the Bartletts Ferry has only recently been recognized (Bentley, 1969). The Towaliga and Goat Rock zones were long interpreted as thrust faults (Crickmay, 1933, 1939, 1952; Clarke, 1952), but recent work suggests that they probably have complicated movement histories involving thrust, normal, and strike-slip displacements (W. H. Grant, 1967, 1968, and oral commun., 1965–69; R. D. Bentley, oral commun., 1969). Bentley (1969) interprets displacement on the Bartletts Ferry zone as predominantly right lateral. All three zones are marked by thick assemblages of various types of cataclastic rocks.

Microscopic descriptions of various cataclastic rocks in the Towaliga and Goat Rock fault zones have been published by Crickmay (1933), Clarke (1952), and Grant (1968). They are not quoted or described here because the rocks are similar to those defined, described, and illustrated elsewhere in this paper.

TOWALIGA FAULT ZONE

The Towaliga zone (fig. 26) has been traced from Ocmulgee River, east of Barnesville, Ga., to near Auburn, Ala., where it disappears beneath Cretaceous rocks of the Gulf Coastal Plain (Crickmay, 1933, 1939; Bentley, 1969; W. H. Grant, oral commun., 1969). It probably extends farther east in Georgia (as dashed on fig. 26), and possibly into South Carolina.

Near Ocmulgee River, the main zone of the Towaliga is characterized by dense mylonite which Crickmay (1933, p. 172) described as follows:

> * * * the mylonite looks like a volcanic rock; it contains feldspar porphyroclasts in a dark gray to black, aphanitic groundmass that simulate phenocrysts in an extrusive, and it possesses a fluidal structure that is strongly reminiscent of the flow banding in certain rhyolites.

Near Barnesville, Ga., the main zone, about 100–400 feet thick, is marked by mylonite, blastomylonite, and microbreccia. According to Grant (1968), the mylonite and the microbreccias are relatively continuous, whereas the discontinuous blastomylonite recurs along the zone. Crickmay (1933, p. 171) described a mylonite in the zone near Barnesville as follows:

> The rock might easily be mistaken for the Hollis quartzite, which crosses the highway three-quarters of a mile south, but for the presence of rather characteristic banding and small porphyroclasts of feldspar. Through most of the mylonite the porphyroclasts are absent and the rock is aphanitic, but in certain thin layers, which have not been crushed to the same extent as the main mass, porphyroclasts are abundant and indicate at once the origin of the rock.

The rocks for several miles on either side of the main zone in the Barnesville area have been affected by intense penetrative deformation, and small en echelon fault zones, marked by mylonite or, more commonly, by microbreccia, are common within a mile or two of the main zone.

West of Barnesville the main zone gradually thickens, and polycataclastic rocks, chiefly brecciated mylonites, appear. Near the Alabama line the main zone is more than half a mile wide, and is occupied chiefly by "dense gray mylonites with abundant porphyroclasts" (Crickmay, 1933, p. 171), blastomylonites, and subordinate amounts of aphanitic ultramylonite. On either side of this main band are zones of mylonite gneiss up to three-quarters of a mile thick.

The whole zone continues to thicken to the west in Alabama, and near Auburn (fig. 26) it is a zone approximately 6 miles wide of blastomylonites and porphyroclastic mylonite gneisses interspersed with at least three mylonite bands and containing slices of metaquartzite, marble, and schist (Bentley, 1969).

GOAT ROCK FAULT ZONE

The Goat Rock zone (fig. 26) has been traced from near Talbotton, Ga., to southwest of Salem, Ala., where it is covered by Cretaceous rocks (Crickmay, 1933, 1939; Bentley, 1969; W. H. Grant, oral commun., 1969). On the Geologic Map of Georgia, Crickmay (1939) showed the fault curving northeast just east of Talbotton, and he extended it as a dashed line to Flint River. Actually, the Goat Rock zone extends east along Crickmay's contact between his biotite gneiss and schist unit and his augen gneiss unit at least as far as Flint River, and it may continue along this relatively straight contact for some distance to the east (fig. 26).

Through most of its known extent in Georgia, the Goat Rock is a zone, 2 to 4 miles wide, of mylonite, ultramylonite, blastomylonite, and mylonite gneiss. Microbreccias and polycataclastic rocks are also present but are subordinate in volume to the varieties listed above. Like the Towaliga, the Great Rock has a main, or central zone, as much as a mile thick, of mylonite, blastomylonite, and ultramylonite bordered on each side by zones of blastomylonite and mylonite gneiss. As Crickmay (1933, p. 173–174) recognized, these outer zones are gradational into crystalloblastic augen gneisses by decrease in cataclastic texture and increase in crystalloblastic texture.

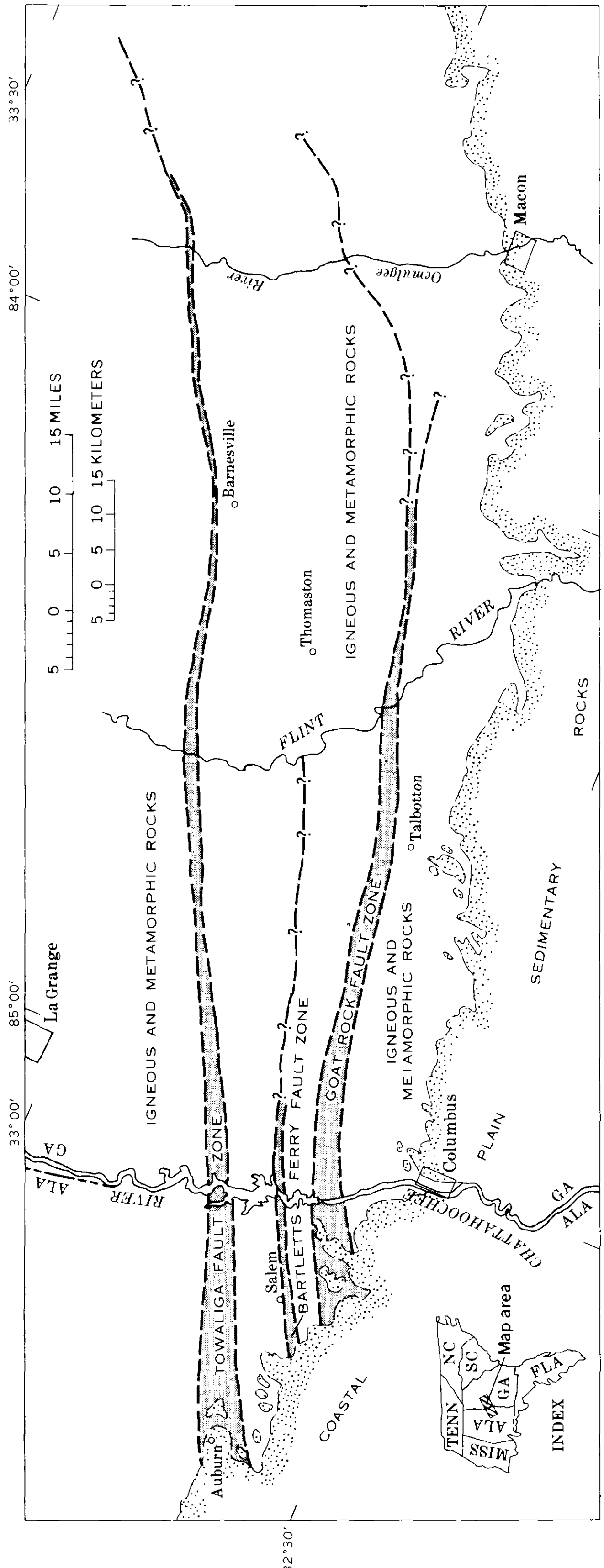


FIGURE 26.—Generalized geologic map showing the Towaliga, Goat Rock, and Bartletts Ferry fault zones, Georgia and Alabama. Also see fig. 27.

Crickmay (1933, p. 174) gave a good description of a mylonite (my classification, table 1; he refers to it as an ultra-mylonite) in the Goat Rock zone:

> The ultra-mylonite is well exposed near Piny Grove Church, about ten miles north-northwest of Columbus, near the center of the mylonitized zone. The rock has the apperance of a black argillite with a poorly developed slaty cleavage, which dips 35° southeast. The cleavage surfaces are dull, perfectly regular, and are commonly coated with a dendritic growth of manganese oxides. In the groundmass are embedded numerous rounded porphyroclasts of feldspar averaging .5 mm. and rarely more than 2.5 mm. in diameter.

Bentley (1969) has described the Goat Rock in Alabama as a vertical to steeply southeast dipping zone, at least three miles wide, with a central band about a mile wide, characterized by ultramylonite, mylonite, and blastomylonite, and marginal bands, each nearly a mile wide, of "flaser gneisses and augen gneisses." The latter are mostly mylonite gneiss.

BARTLETTS FERRY FAULT ZONE

The Bartletts Ferry zone (fig. 26) was recognized and mapped in Alabama by R. D. Bentley. It has not yet been mapped in Georgia, but it extends across the State line (R. D. Bentley, oral commun., 1969). Where the zone crosses the Chattahochee River into Georgia it approximates Crickmay's (1939) contact between his Manchester schist and Sparks schist unit and his augen gneiss unit. These units are similar to belts of rocks separated by the fault zone in Alabama (Bentley and Deininger, 1969). Possibly then, the Bartletts Ferry zone may follow Crickmay's contact, thus bounding the Pine Mountain sequence on the south as the Towaliga fault zone bounds it on the north (Crickmay, 1939). This would account for the cataclastic rocks near Flint River, east of Pleasant Hill, which caused Crickmay to curve the Goat Rock fault to the northeast on the Geologic Map of Georgia (Crickmay, 1939).

Bentley (1969) describes the Bartletts Ferry fault zone in Alabama as follows:

> The middle zone (Bartlets [sic] Ferry fault) trends N3OE N5OE and is nearly vertical throughout. This zone is characterized by 200 feet of ultramylonite, which is bordered on the southeast by several thousand feet of mixed mylonite, blastomylonite and porphyroclastic gneiss.

INTERPRETATION OF THE ZONES

The history of interpretation of the Towaliga and Goat Rock fault zones is particularly interesting because it illustrates how recognition and study of cataclastic rocks can influence geologic maps and interpretations of the geologic and tectonic history of an area.

Galpin (1915, p. 74–76) first recognized the peculiar nature of the rocks along the Towaliga fault zone with respect to the rocks on either side of the zone. He interpreted the rocks as volcanic. They do superficially resemble volcanic rocks (Crickmay, 1933, p. 171–173).

None of the fault zones are shown on the geologic map of Alabama (Smith, 1926).

Crickmay (1933, p. 171–175) recognized the rocks of the Towaliga and Goat Rock zones as cataclastic. Concerning the rocks in the Towaliga zone, he stated (p. 173):

> They are mylonites derived from a coarse biotite augen gneiss in which neomineralization is very minor or entirely absent. They might easily be mistaken for a quartzite or volcanic rock, from which they may be distinguished in the field by their mode of occurrence (e.g., they occur close to the Towaliga fault; they are gradational into cataclastic augen gneiss), and by the presence of feldspar porphyroclasts.

Because cataclastic rocks were then known to occur only in conjunction with thrust faults, or supposed thrust faults such as the "Brevard thrust" (Jonas, 1932), Crickmay (1933, 1939) interpreted the Towaliga and Goat Rock fault zones as thrusts.

Clarke (1952) studied the Towaliga and Goat Rock zones in the Thomaston, Ga., area. However, what Clarke mapped as the Goat Rock fault may be an extension of the Bartletts Ferry fault zone. He agreed with Crickmay, and interpreted both of the zones as thrusts. In addition, he expanded Crickmay's tectonic interpretations and postulated that the Towaliga, Goat Rock, and Brevard faults are the same folded thrust. This would make the whole Georgia and Alabama central Piedmont (Dadeville Belt of Crickmay, 1952) a klippe.

Since the early 1960's, the Towaliga fault zone has been studied by W. H. Grant of Emory University and his students. Grant (1968) stated:

> Three distinct periods of movement are recognized. The earliest is recognized by a blastomylonite in which considerable recrystallization is svident. These outcrops are very sparse hence reconstruction of the blastomylonite producing fault is not feasible. Recrystallization of biotite shows this movement overlaps with the later phases of metamorphism which raised the surrounding rocks to sillimanite and kyanite grade.
>
> The second movement period is seen in the main (strike N. 70° E.) mylonite zone. These mylonites are only slightly recrystallized. Dips on these easily traceable fault surfaces range up to 80° to the north. The major movement appears to have been strike slip as indicated by displacement of minor structures. This movement is also indicated by petrofabric data which show a strong maxima for quartz in the strike slip direction.
>
> Striations, at right angles to the fault and the rotation of joints formed in the mylonite, are evidence of the third movement. This indicates a dip slip movement, and appears to be the last.

Bentley (1969) reports evidence of lateral movement on all three fault zones in Alabama. Of the Goat Rock fault zone he states:

Most minor folds and local faults suggest a right lateral displacement along the zone.

Of the Bartletts Ferry fault zone:

Horizontal mineral lineations are only locally developed along this fault. Minor folds and faults and strained clasts all indicate a right lateral displacement.

And of the Towaliga fault zone:

Similar to the Goat Rock fault this zone shows a well developed, nearly horizontal mineral lineation. Drags of mapped units along the northern edge of the zone suggest right lateral regional displacements. The amount of displacement cannot be determined.

As I stated earlier, all three fault zones have probably had complicated movement histories with more than one sense of displacement.

THE BREVARD ZONE, SOUTHEASTERN UNITED STATES

The Brevard zone is a belt about 1 to 5 miles wide of cataclastic and low-grade metamorphic rocks that extends northeast in a nearly straight line from eastern Alabama nearly to Virginia (fig. 27). Throughout this course the zone is bordered on either side by plutonic and higher grade metamorphic rocks. Approximately coincident with the belt from near Wilkesboro, N.C., to about Tallapoosa River in Alabama is a marked topographic lineament (see U.S. Army Map Service plastic relief 1:250,000-scale series maps: Atlanta—NI 16–9; Greenville—NI 17–4; Knoxville—NI 17–1; Charlotte—NI 17–2; and Winston-Salem—NJ 17–11). A distinctive magnetic lineament is also coincident with the Brevard zone for at least part of its course (Philbin and others, 1964). The southern end of the Brevard zone in Alabama was assumed to bend to the south near Tallapoosa River to reach the edge of the Coastal Plain just northeast of Montgomery (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961; King, 1964; Reed and Bryant, 1964; Bayley and Muehlberger, 1968). However, recent work in that area shows that the zone probably splays southwest of Tallapoosa River; subsidiary zones bend gradually south, but the main zone continues on its southwest course to pass beneath the edge of the Coastal Plain near Central, Ala. (Bentley, 1969; Bentley and Deininger, 1969; Bentley, oral commun., 1969; fig. 27). A somewhat similar situation exists for the northern end of the Brevard zone, in North Carolina. On most maps (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961 King, 1964; Reed and Bryant, 1964), the Brevard zone is shown continuing along a straight northeast course past Mount Airy and into Virginia, but recent work (Dunn and others, 1966; Espenshade, 1967; Butler and Dunn, 1968; Centini, 1968) indicates that the zone begins to splay near Wilkesboro. One branch bends east to become the Stony Ridge fault zone; another branch bends eastward toward Pilot Mountain; and still another branch bends slightly eastward and follows a conspicuous topographic lineament through Ararat, between Mount Airy and Pilot Mountain (fig. 27).

From near Wilkesboro, to near Fletcher, N.C. (fig. 27) the Brevard zone is a belt of phyllonite, blastomylonite, and mylonite gneiss, about a mile wide, near the northwest edge of a zone of shearing and retrogressive metamorphism about 5 miles wide (*see* Reed and Bryant, 1964). Rocks quite similar to those in the segment from Wilkesboro to Fletcher occupy the two westernmost branches or splays northeast of Wilkesboro; the easternmost branch, the Stony Ridge fault zone, is characterized chiefly by microbreccia. The description of the Wilkesboro to Fletcher segment of the zone also fits the segment from Fletcher southeast to near Flowery Branch, Ga., except that this segment also contains discontinuous lenses of dolomitic marble, which Reed and Bryant (1964) consider "exotic tectonic lenses." Southwest of Flowery Branch, at least to Tallapoosa River in Alabama, phyllonites, blastomylonites, and mylonite gneisses identical to those in the zone to the northeast are joined by thin, discontinuous, and commonly en echelon bands of mylonite, protomylonite, ultramylonite, microbreccia, and cataclasite. Polycataclastic rocks, chiefly brecciated mylonite, are also present in this segment. In Georgia, the main band of cataclastic rocks is locally more than 2 miles wide, but the zone of shearing and retrogressive metamorphism is generally thinner than in North Carolina. Southwest of Tallapoosa River the Brevard zone and its branches have not yet been studied in detail, but it appears that the rocks there are similar to those of the Flowery Branch to Tallapoosa River segment.

The character and origin of the Brevard zone is currently in dispute. Some geologists have presented evidence that it is a great strike-slip fault with some vertical displacement (Reed and others, 1961; King, 1964; Reed and Bryant, 1964; Higgins, 1966); others believe it is an "alpine type root zone" or zone of "Verschluckung" (Burchfiel and Livingston, 1967, 1968; Livingston and Burchfiel, 1968); still others recognize sedimentary characteristics in the zone (Hurst and Crawford, 1964; Dunn, Butler, and Justus, 1968; Dunn, Butler, and Weigand, 1968). Nevertheless, the presence of cataclastic rocks in the zone is indisputable.

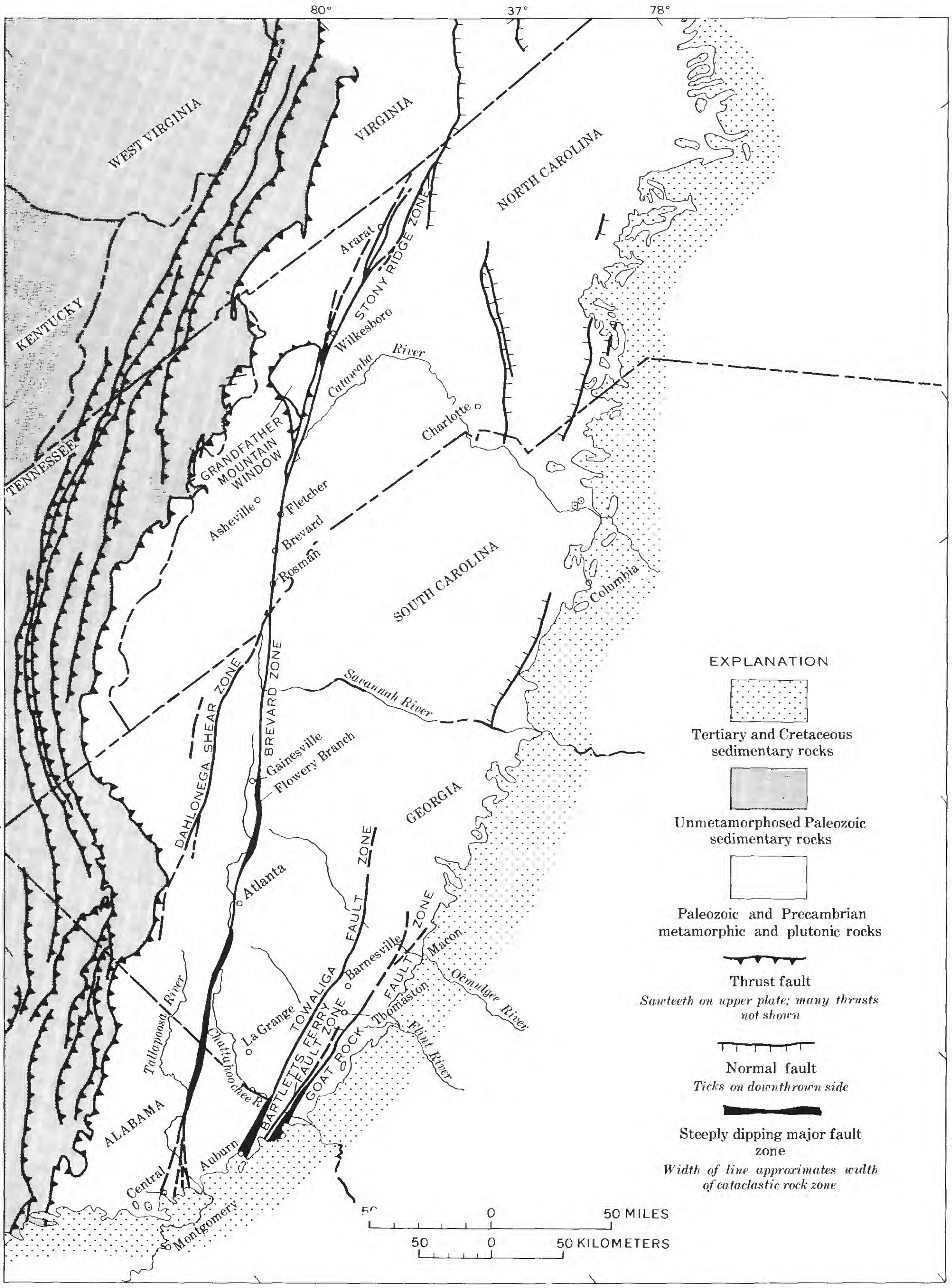


FIGURE 27.—Generalized geologic map of the Brevard zone, southeastern United States (modified from Fisher and others, 1970).

Reed and Bryant (1964, p. 1182–1183) gave a vivid "verbal cross section" of the southeast border of the Brevard zone in North Carolina:

The rocks of the Inner Piedmont more than 5 miles southeast of the Brevard zone are all of high metamorphic grade and display no conspicuous cataclastic features. The plagioclase is generally andesine; aluminous rocks contain sillimanite, and calcareous rocks contain diopside. Foliation has diverse strikes and low to moderate dips, generally to the south or southeast. Lineation is marked by alignment of fibrous sillimanite and prismatic hornblende, by elongate clots of biotite, and by crenulations in foliation planes and generally plunges gently or moderately eastward. The mineral alignment is apparently due to growth parallel to crenulation axes.

About 4 miles from the Brevard zone the metamorphic grade is lower. Sillimanite disappears, although staurolite and kyanite are found locally; polymetamorphic textures become increasingly apparent. Foliation assumes a consistently northeast strike, parallel to the Brevard zone, and subhorizontal cataclastic lineation parallel to the strike becomes prominent. This lineation is marked by streaks of fine recrystallized mica on foliation planes, crushed and drawn out feldspar porphyroclasts, and aligned aggregates of recrystallized quartz. Long axes of boudins of amphibolite and of competent lime-silicate rocks in the gneisses are generally parallel to it. Axes of isoclinal folds also generally trend northeast, but many display steeper and more erratic plunges. Within 2–3 miles of the Brevard rocks of the Inner Piedmont belt are conspicuously cataclastic and polymetamorphic. The schists contain porphyroclasts of muscovite, plagioclase, and locally of staurolite and kyanite set in a matrix of fine-grained, recrystallized quartz, biotite, muscovite, epidote, and plagioclase. Both the plagioclase porphyroclasts and the fine-grained recrystallized plagioclase are either oligoclase or sodic andesine, indicating recrystallization under medium-grade conditions.

Adjacent to the Brevard zone the medium-grade polymetamorphic rocks are retrogressively metamorphosed to low grade: plagioclase is partly or completely altered to albite, and biotite is replaced by chlorite. The textural contrasts, as the Brevard zone is approached, are particularly conspicuous in the Henderson Gneiss. Fine-grained biotite-quartz monzonite gneiss containing large augen of microcline is reduced to blastomylonitic gneiss [mylonite gneiss of my classification; table 1] and finally to blastomylonite in and near the Brevard zone.

For the most part, the rocks in the Brevard zone are typical cataclastic rocks like those defined, described, and illustrated elsewhere in this paper. However, two types of rock in and near the zone are particularly interesting, chiefly because identical rocks occur in association with the Brevard throughout its extent: (1) Porphyroclastic phyllonites, called "phyllonitic schists" by Reed and Bryant (1964, p. 1181), and "muscovite-eyed phyllonites" by Higgins (1966, p. 27–28), occur intermittently in the Brevard zone from Alabama to northern North Carolina. These rocks typically have a lustrous gray, silvery-gray, gray-green, or blue-green phyllitic groundmass and contain bent porphyroclasts of muscovite or sericite, which have a "fish-scale" appearance on foliation planes and a ragged, "flagellate" appearance in cross section. These bent porphyroclasts of mica give the foliation planes a "curly" or "wavy" appearance. Reed and Bryant (1964, p. 1189) cited evidence that some of these rocks are diaphthoritic in the Grandfather Mountain Window area, but near Atlanta, Ga., they may be simply phyllonitic (Higgins, 1956, p. 27); (2) Rocks called "button schists" by Higgins (1966, p. 27), and simply "polymetamorphic schists" by Reed and Bryant (1964) are intimately associated with the Brevard zone throughout its extent and have a remarkably identical appearance all along the zone. These rocks are not strictly cataclastic, because they have crystalloblastic textures, but it is obvious that they have been much sheared and recrystallized, and, in fact, they may be blastomylonites in which the crystalloblastic process has completely dominated cataclasis. They are characterized by two subparallel cleavages that cause distinctive buttons upon weathering (Crickmay, 1952, p. 26).

THE MOINE THRUST ZONE, NORTHWEST HIGHLANDS, SCOTLAND

The Moine thrust zone angles across northwest Scotland in a sinuous course from Whiten Head to Point of Sleat, Isle of Skye (fig. 28). This thrust zone is probably the best known and most closely studied fault zone in the world, and it was here that much of the geology of the Northwest Highlands was first unraveled (Peach and others, 1907). It was also along the Moine thrust zone that mylinites were first recognized, described, and defined (Lapworth, 1885; Peach and others, 1907). In fact, this zone and the adjacent areas have probably had more influence on geology, particularly structural geology, than any other area of comparable size on earth.

The Moine thrust zone is a belt of two to four major overlapping thrust faults (fig. 28; Peach and others, 1907; Bailey, 1935; Wilkinson, 1955; Johnson, 1957; Christie, 1963; Barber, 1965) and numerous minor faults. The basic geology of the zone has been known for more than 60 years (Peach and others, 1907); recent work has chiefly added details and refined interpretation. Although Christie's (1963) proposal of 6 miles of strike-slip movement was strongly opposed by Johnson (1965) and by Barber (1965), all who have studied the zone agree that the major component is thrust. Each of the thrusts in the zone appears to be overlapped in turn by the overlying one (Peach and others, 1907; Christie, 1963; Barber, 1965), and the Moine thrust, generally regarded as the most important, locally overlaps them all and carries crystalline schists of the Moine series over Lewisian, Torridonian, and Cambrian rocks to the west (fig. 28). Both imbricate structure, or

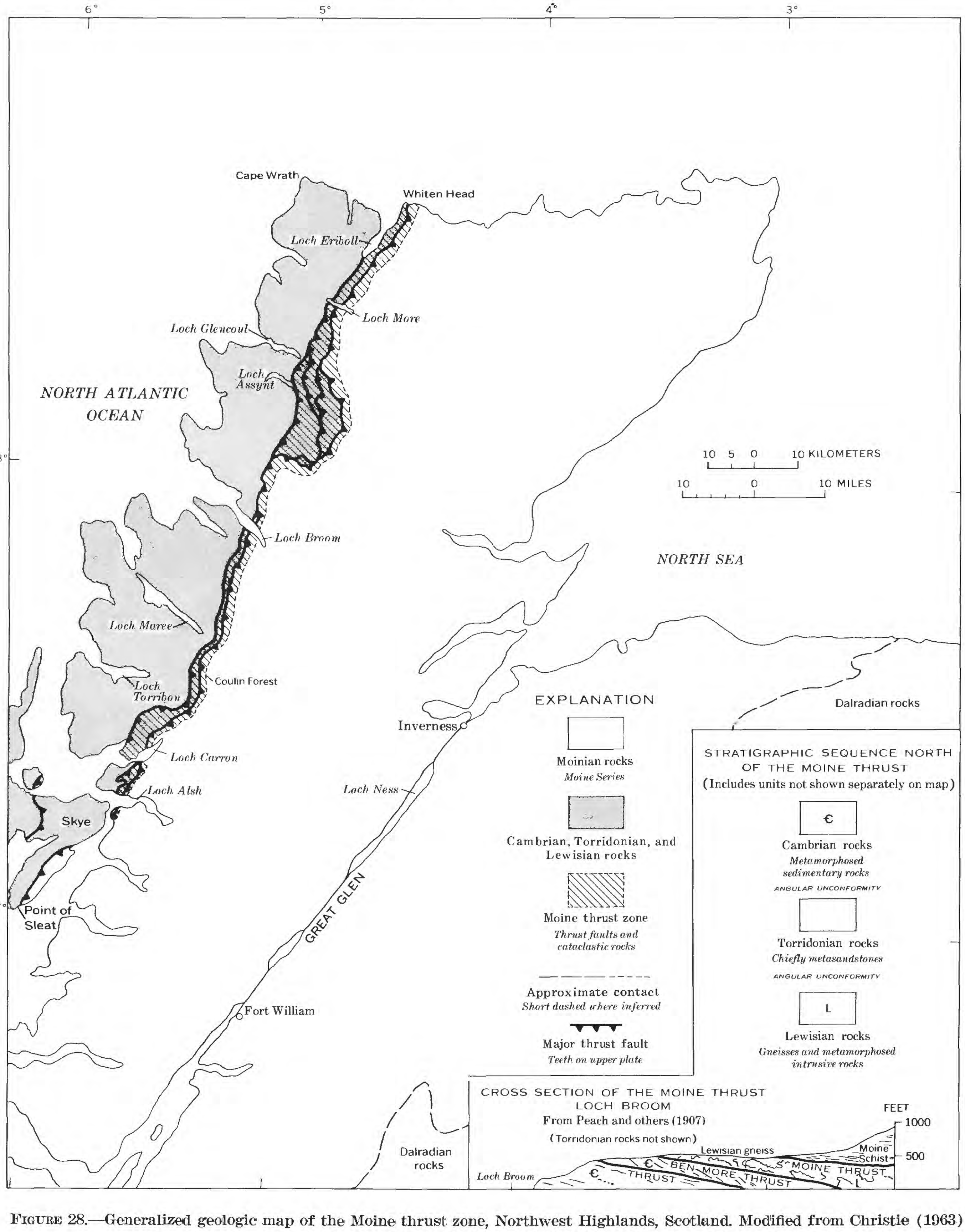


FIGURE 28.—Generalized geologic map of the Moine thrust zone, Northwest Highlands, Scotland. Modified from Christie (1963) and Peach and others (1907).

Schuppen Struktur, and nappe structure are locally developed along the zone.

Excellent reviews of the history of interpretation and research on the Moine thrust zone have been published by McIntyre (1954) and Christie (1963).

Cataclastic rocks are found all along the Moine thrust zone, and all of the major rock groups in the thrust zone, Lewisian, Moinian, Torridonian, and Cambrian have locally been cataclastically deformed. Generally, the most intensively deformed rocks occur in narrow bands immediately adjacent to the thrust planes, whereas less intensively deformed, more recrystallized and neomineralized rocks occur in broad zones between and structurally above the faults. Near the Moine thrust, the Moine schists are retrogressively metamorphosed.

Barber has described the gradational cataclasis in the Kishorn nappe of Lochalsh and Lochcarron (1965, p. 217–219):

> Specimens of Torridonian Sandstones, collected across the outcrop in Lochalsh, show increasing signs of cataclasis from west to east. In the west, sandstones of the Applecross Group have a typical sedimentary texture, with only occasional fractured felspar grains. Further east the sandstones develop a 'mortar' texture with large fragmented felspar grains embedded in a fine-grained groundmass. Towards the contact with the overlying Lewisian the texture in the Torridonian becomes lenticular, with shear surfaces developed around the original grains, which are now lozenge-shaped and enclosed by groundmass minerals to form augen structures. At the contact with the Lewisian, the Torridonian Sandstones have been completely converted to mylonite.
>
> Throughout the Torridonian the minerals in the groundmass are quartz, white mica and chlorite. The major differences in the groundmass, seen in thin sections taken across the area from west to east are; that the groundmass makes up an increasing portion of the whole rock; and that the flaky constituents have an increasingly parallel orientation. The end products of these trends are most fully developed in the mylonites, where relict felspar grains are scattered through a fine-grained groundmass. The minerals of the groundmass have a strong preferred orientation, giving the rock a pronounced fissility.
>
> *　　*　　*　　*　　*
>
> Every stage of deformation from unaltered Lewisian rocks to their mylonitic derivatives occurs in the Kishorn Nappe. The most highly deformed rocks occur at the contact with the Torridonian, but the amount of deformation decreases rapidly eastwards through the Lewisian.

Christie (1963) has given detailed descriptions of the cataclastic rocks of the Moine thrust in the Assynt region (fig. 28). The following generalized description, using my terminology,[5] is paraphrased from his numerous local descriptions (1963, p. 357, 362, 364, 369, 375, 378, 410):

[5] Christie (1960, 1963) devised a system of terminology in which "mylonitic rock" is used as a general term for all cataclastic rocks, monocataclastic rocks are called "primary mylonitic rocks," and polycataclastic rocks are called "secondary mylonitic rocks."

The horizon or "surface" mapped as the Moine thrust is commonly not a fault surface, but a boundry between rocks of different composition and original age, with similar fabric and texture, in a zone of extensive penetrative movement; only locally is it a sharply defined "surface." Cataclastic rocks of various types are commonly developed both above and below the "surface" mapped as the Moine thrust. Generally, the most intensively mylonitized rocks, including protomylonites, mylonites and phyllonites, ultramylonites, blastomylonites, and mylonite gneisses, occur in a zone 100–250 feet thick above the thrust "surface," and for a few feet below it.

Within the upper zone there is a gradation; the most intensively mylonitized rocks occur in the lower part and grade upward by increase in grain size, decrease in degree of lamination, and increase in degree of neomineralization and recrystallization, across an arbitrary contact, into phyllonitic and diaphthoritic schists of the Moine series. These schists, called "crumpled schists," "frilled schists," "puckered schists," and "oyster-shell rock" by Peach and others (1907, p. 481, 502, 505, 598), are remarkably similar to the "button schists," "phyllonitic schists," "curly schists," and "wavy schists" bordering fault zones in other parts of the world (Crickmay, 1933, 1952; Reed and Bryant, 1965; Reed, 1964; Higgins, 1966). The foliation of the cataclastic rocks and of the Moine schists is parallel to the Moine thrust. The thinner zone of cataclastic rocks beneath the thrust "surface" shows a gradation similar to that of the upper zone, except that the gradation is ultimately into normal gneisses and quartzites.

Polycataclastic rocks are also present along the Moine thrust. According to Christie (1963, p. 369) "The effects of secondary deformation increase toward the Moine thrust." Brecciated mylonites, brecciated blastomylonites, and even mylonitized mylonites occur locally within the zones of monocataclastic rocks. There are also separate zones east of the Moine thrust composed almost entirely of polycataclastic rocks—chiefly phyllonitized mylonites. Some of these are locally more than half a mile wide.

The effects of cataclasis generally decrease gradually in the Moine schists east of the Moine thrust, and in most areas the schists a mile or so away from the thrust show little evidence of abnormal penetrative movement.

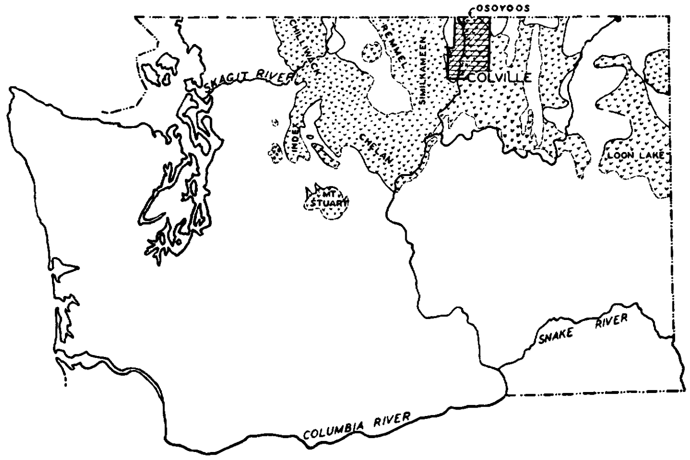
PROTOCLASTIC BORDER, COLVILLE BATHOLITH, WASHINGTON

The Mesozoic Colville batholith (Waters and Krauskopf, 1941) is a complex plutonic mass that occupies the region between the Okanogan and Columbia Rivers in northern Washington (fig. 29). The batholith intrudes folded late Paleozoic and Triassic metasedimentary and metavolcanic rocks, but although the contact is markedly discordant, contact metamorphic effects are slight or absent. The central parts of the batholith are not unusual, being chiefly structureless granodiorite similar to numerous other batholiths and plutons of this general region. However, this central mass grades outward into a belt of complexly foliated and swirled gneiss, which in turn grades outward into a remarkable border phase that resembles a fault zone more than part of an igneous intrusion. This is the classic *protoclastic border* of the Colville batholith (Waters and Krauskopf, 1941), probably the largest, best exposed, and best known occurrence of protoclastic rocks in the world. The rocks of this border are cataclastic rocks, but rather than being formed in a fault zone, propelled by tectonic forces during metamorphism, they were produced when the almost solid intrusive body rose and pulverized its own nearly crystallized border.

Waters and Krauskopf (1941) divided the eastern part of the batholith into three facies (fig. 29): (1) the "gneissic and protomylonitic facies," consisting chiefly of markedly foliated gneisses and rocks with cataclastic textures, in a peripheral zone from a few yards to about 4 miles wide; (2) the "swirled and porphyritic gneiss facies," consisting chiefly of protoclastic gneisses, augen gneisses, and migmatitelike "swirled" gneisses, in a zone about 1 to 5 miles wide; and (3) the "homophanous granodiorite facies," consisting of structureless, or nearly structureless, granodiorites, in the central parts of the batholith. They emphasized (p. 1379) that all of the contacts are arbitrary and gradational, and that each of the facies contains some rocks characteristic of the others.

Waters and Krauskopf (1941) presented good evidence that the batholith deformed its own nearly solid periphery as it rose, and that the deformation was not a later metamorphic or tectonic event. Of the protoclastic rocks in the gneissic and mylonitic facies they stated (1941, p. 1406):

> During the rise several definite autometamorphic rock types were produced. Local areas of protomylonite and some rare thin bands of lustrous material approaching pseudotachylite, are present. . . . The mylonites usually show effects due to recrystallization in greater or less degree, and commonly grade into rocks best described as blastomylonites. These in turn grade into coarser-grained rocks with granoblastic texture which may or may not show a gneissic banding. . . . All of the various metamorphic rock varieties mentioned, and particularly the more siliceous granoblastic types, show every transition into definite igneous rocks, and indeed are in many cases so permeated with magmatic material as to make their classification as igneous or metamorphic a purely arbitrary matter.



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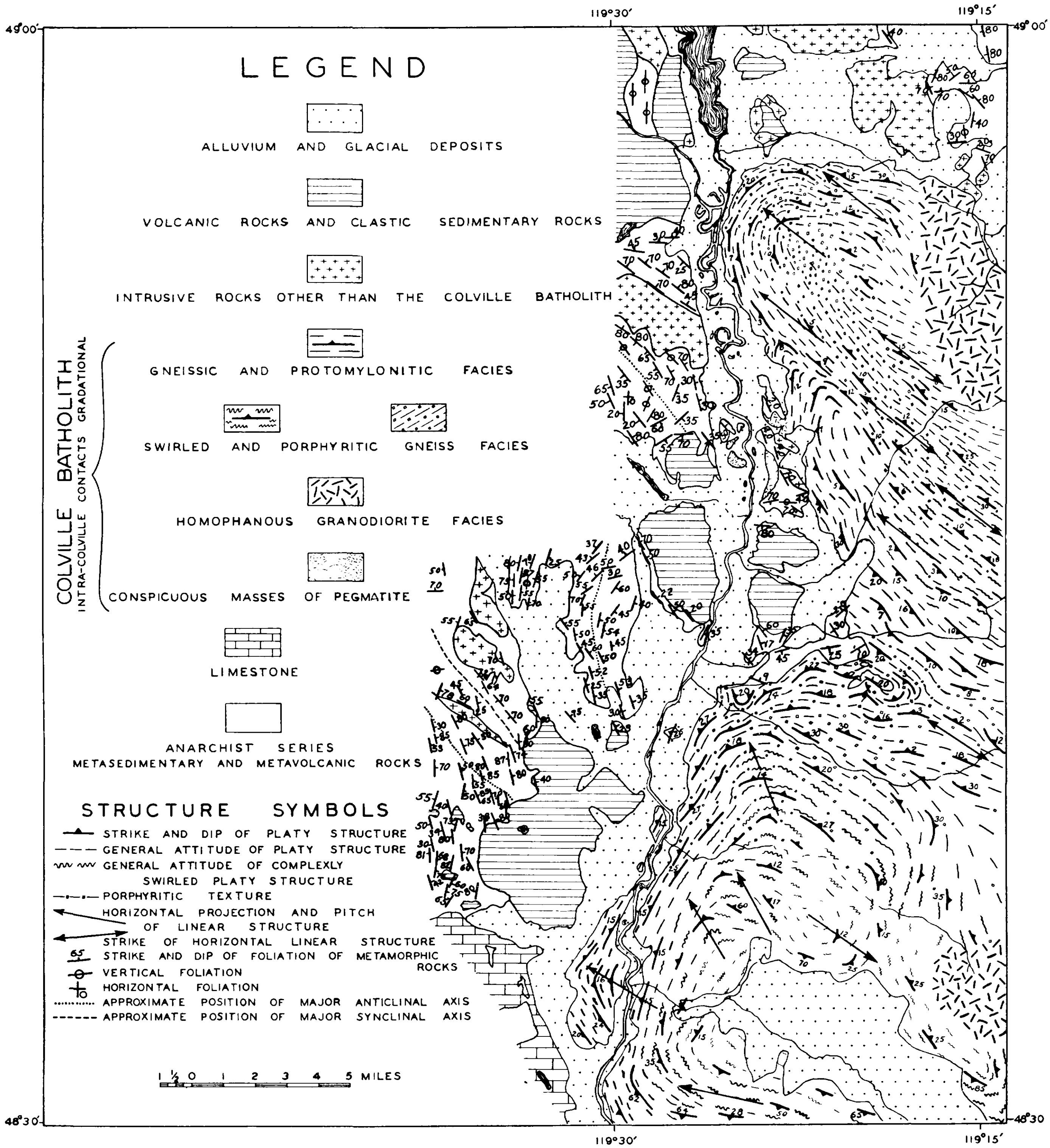
They (Waters and Krauskopf, 1941) described rocks resembling ordinary cataclastic rocks in the field, except for the gradation into plutonic rocks, and the confinement to and conformity with the batholith's border (fig. 29). Many of these rocks have porphyroclasts of feldspar with crush trails, megascopic fluxion structure, and a fine-grained groundmass. However, the microscopic textures of these rocks are unusual. According to Waters and Krauskopf (1941, p. 1407–1408):

> Microscopic study reveals a quartz-orthoclase mesostasis permeating the rock, filling cracks and openings in broken porphyroclasts, and wandering along the crush bands. Locally this mesostasis collects in pools from which irregular ramifications go forth into the pulverized rock. The quartz-orthoclase liquid seems to have been active chemically and apparently has greatly aided recrystallization of the adjacent mylonitic paste * * *
>
> *   *   *   *   *
>
> * * * evidence clearly shows that at the time of their development magmatic juices and fluids still formed at least a part of the rock that was being deformed; rock flowage was accomplished in a crystal mesh which still contained a small proportion of interstitial liquids * * *
>
> *   *   *   *   *
>
> Only rarely are mylonitic rocks found completely free of new minerals developed by recrystallization of the cataclastic paste.

In summary they say (p. 1392) of some of the more recrystallized protoclastic rocks:

> At all events, the rock described seems best classified as an igneous rock. Most of it has been formed by direct precipitation from a magmatic solution, but the course of the solidification was interrupted by a period of mechanical movement which deformed and partially granulated the early solidified components. These strained components were then partially recrystal-



B

FIGURE 29.—Index map showing location of Colville batholith and other Mesozoic intrusive rocks in Washington (*A*); geologic map of the border of the Colville batholith (*B*). From Waters and Krauskopf (1941).

lized and were also cemented by final crystallization of the still liquid residuum.

The crucial point is that these granulated rocks have been cemented and made coherent by crystallization from magmatic solutions.

A HYPOTHETICAL FAULT ZONE

Figure 30 shows the relations of different kinds of cataclastic rocks in a hypothetical fault zone, based on zones described in the literature and on my own observations.

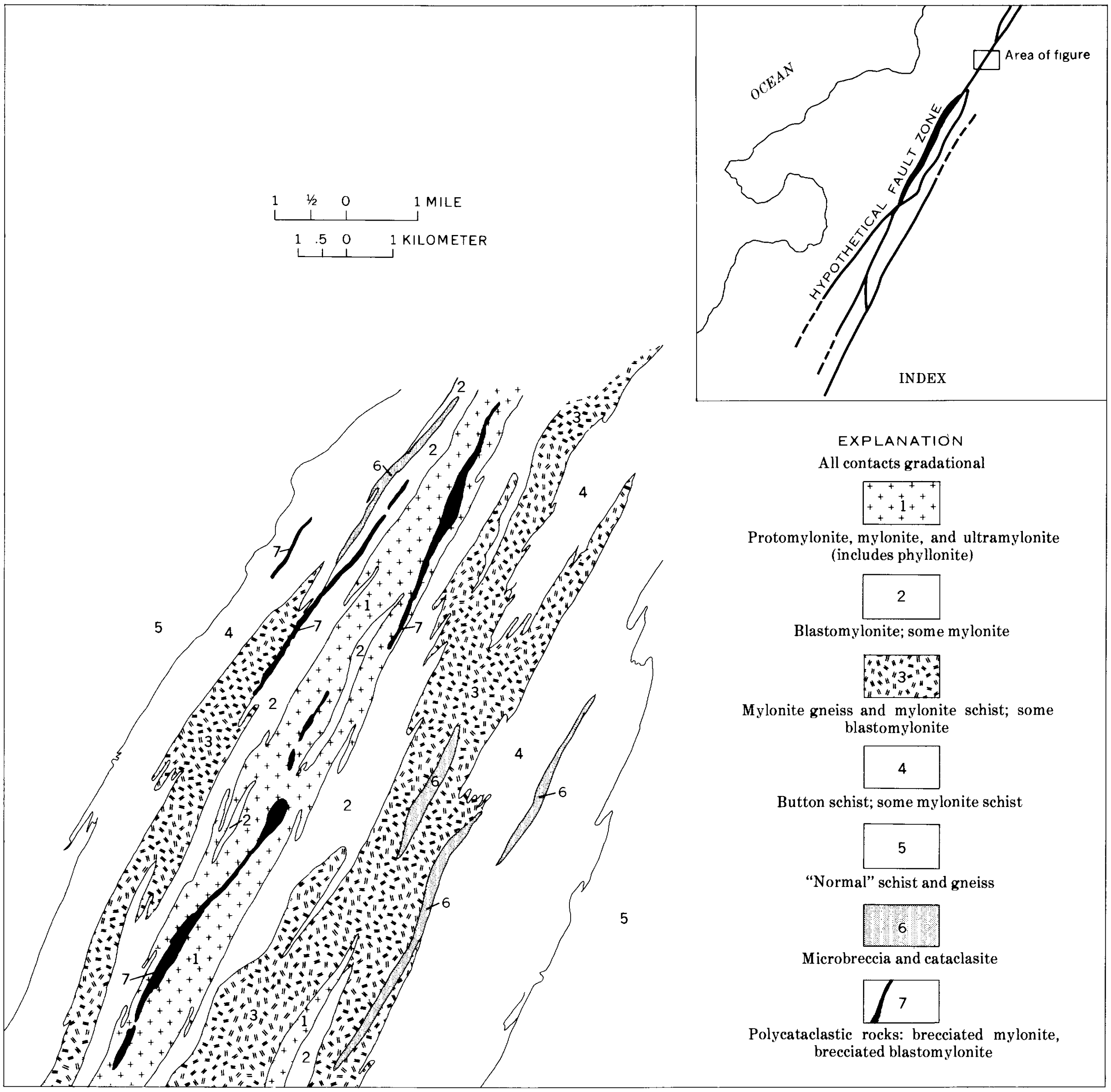


FIGURE 30.—Geologic map of a hypothetical fault zone showing typical relations of various types of cataclastic rock.

THEORETICAL ASPECTS OF CATACLASTIC ROCKS AND PROCESSES INVOLVED IN FORMATION

Theories of cataclasis and related metamorphic processes are as yet incompletely formulated, and experimental study in this area has lagged far behind studies of other rock-forming processes. Therefore, the statements and conclusions presented here are largely qualitative, tentative, and somewhat speculative.

RECRYSTALLIZATION-NEOMINERALIZATION

In his definition of *mylonite*, Lapworth (1885, p. 559—*see* p. 7 this paper), referred to secondary crystals of quartz and mica in mylonites, and noted that the "interstitial paste" had "only crystallised in part."

Knopf (1931, p. 10–11) followed Lapworth, stating:

> Although a true mylonite is dominantly cataclastic, even ultra-cataclastic, nevertheless there is a variable amount of newly formed minerals in mylonitic rocks dependent upon the conditions under which the deformation has taken place and upon the constitution of the rock that is mylonitized.

Knopf (1931, p. 5) also distinguished between recrystallization and neomineralization:

> * * * a combination of the old constituents into new minerals is usually called recrystallization by English-speaking writers on metamorphic geology. However, the so-called recrystallization is generally a development of new minerals from the original constituents * * * the term recrystallization is only justified where certain constituents such as calcite and quartz have newly crystallized without change of chemical constitution. It has been suggested by A. Knopf that neomineralization be used to denote the transformation of the old mineral constituents into minerals of new and different composition.

Waters and Campbell (1935) made it clear that there was some recrystallization-neomineralization in mylonite, as they used the term, but in their discussion of coherence they made the following statement (1935, p. 475):

> The retention of coherence in the rock during crushing may be due not so much to the welding together of the broken particles by newly formed minerals as Lapworth emphasized, as it is to the fact that the rock was fractured under such great confining pressure that the surfaces of movement never opened widely enough to break the molecular bonds between them.

Some later workers have overlooked all but the first part of this statement, and have given *mylonite* the connotation of completely lacking recrystallization.

All the cataclastic rocks (excepting gouge and fault breccia) that I have seen, and all those shown in photomicrographs in the literature, show some degree of recrystallization-neomineralization. Certainly there is less recrystallization-neomineralization in rocks of the sequence *protomylonite-mylonite-ultramylonite* than in the sequence *mylonite gneiss* (*mylonite schist*)*-blastomylonite*, and, in fact, this difference in degree of recrystallization-neomineralization is used to distinguish between them, but all are to some degree recrystallized and (or) neomineralized. The molecular bonds in mylonites have been broken, and the particles have been disjoined and partially rehealed by concurrent recrystallization-neomineralization. This has in effect overprinted but not destroyed the cataclastic texture.

I disagree with Waters and Campbell (1935, p. 475) regarding the coherence of cataclastic rocks. I believe the retention of coherence *is* due primarily to the metamorphic "welding" effect of recrystallized and newly formed minerals. This growth takes place concurrently, and probably repeatedly, with the granulation. Of course the coherence does result from high confining pressures, but not simply or directly from this alone. Rather, the confining pressure, along with the effects of high temperature, fluid content, and shearing, causes the new mineral growth and recrystallization of old minerals. Thus, coherent cataclastic rocks are basically metamorphic rocks and are limited to metamorphic and plutonic terranes.

RELATIONS BETWEEN DIFFERENT KINDS OF CATACLASTIC ROCKS

Major fault zones generally contain more than one kind of cataclastic rock. Most zones contain rocks of the series *protomylonite-mylonite-ultramylonite*, the series *mylonite gneiss-blastomylonite*, and the series *microbreccia-cataclasite*, and many contain, in addition, retrograde cataclastic rocks and polycataclastic rocks (*see* section on *examples of cataclastic rock zones*, p. 39). Commonly, these different kinds of rock are intimately associated in the zone; contacts are gradational and mappable units are intricately intercalated (fig. 30). The relationships and characteristics of these different kinds of rock are important in interpreting the conditions and time of their formation and in interpreting fault zones.

ASSOCIATION OF BLASTOMYLONITES AND MYLONITE GNEISSES WITH PROTOMYLONITES, MYLONITES, AND ULTRAMYLONITES

When blastomylonites and mylonite gneisses are present in the same zone with protomylonites, mylonites, and ultramylonites, both groups of rocks tend to occur in parallel or subparallel outcrop bands whose borders are gradational and ill defined (fig. 30). Fluxion structure in both groups commonly has the same trend and dip (Clarke, 1952; Hsu, 1955b; Sutton and Watson, 1959; Christie, 1960, 1963; Reed, 1964; Barber, 1965;

Bentley, 1969), and the same minor structures (folds and kinks, etc.) are generally common to both (Hsu, 1955b; Christie, 1963; Barber, 1965). Both groups may have mineral assemblages of the same metamorphic facies, or even the same mineral assemblages (Clarke, 1952; Hsu, 1955b; Sutton and Watson, 1959; Christie, 1960, 1963; Reed, 1964). What factors, then, account for the different manner in which the rocks of the two groups have reacted to cataclastic metmorphism in the same zone? Do the blastomylonites and mylonite gneisses represent an earlier period, episode, or phase of metamorphism, as some have suggested? Or do they represent a later period, episode, or phase, as suggested by Johnson (1961), Sutton and Watson (1959), and Barber (1965)?

Evidence from many fault zones favors the idea that the blastomylonites and mylonite gneisses formed at essentially the same time as the protomylonites, mylonites, and ultramylonites (Sander, 1912; Knopf, 1931; Crickmay, 1933; Waters and Campbell, 1935; Clarke, 1952; Hsu, 1955b; Christie, 1960, 1963; Reed and Bryant, 1964; Reed, 1964; and others). Blastomylonites are not mylonites which have been later recrystallized. This is demonstrated by the fact that blastomylonites and mylonites are commonly found adjacent to each other in a single fault zone; contacts are gradational and even intercalated; and the rocks are in the same metamorphic facies. Moreover, the mylonites have the same recrystallized and neomineralized texture as the blastomylonites, only to a lesser degree. If a later period, episode, or phase of metamorphism caused the recrystallization-neomineralization of the blastomylonites, then it should have affected the mylonites to the same degree. The blastomylonites commonly pass by gradation into mylonite gneisses. If one assumed that a later metamorphism formed the blastomylonites, then one could also assume that the mylonite gneisses represent still a third episode, period, or phase of metamorphism.

Probably the most feasible explanation for the essentially simultaneous formation of the two different groups of rocks in a single zone is that the rate or intensity of cataclasis (or both of these) was different. Thus, although both groups of rocks were being metamorphosed under the same conditions of temperature, confining pressure, and fluid pressures, and under the same chemical conditions, the protomylonites, mylonites, and ultramylonites were formed in sub-zones of more intense cataclasis, or in subzones where the rate of cataclasis was greater, or both.

Alternatively, perhaps the blastomylonites and mylonite gneisses did form slightly earlier than the protomylonites, mylonites, and ultramylonites, but within the same phase, period, and episode of metamorphism. Perhaps the subzones of most intense, or higher rate, cataclasis shifted from time to time (figs. 31, 32), the least recrystallized-neomineralized rocks representing the last location of the subzones.

RELATION OF MICROBRECCIAS AND CATACLASITES TO ROCKS WITH FLUXION STRUCTURE

In contrast to the relationship between different kinds of rocks with fluxion structure, the relationship between rocks with fluxion structure and rocks of the series *microbreccia-cataclasite* is commonly clear; the

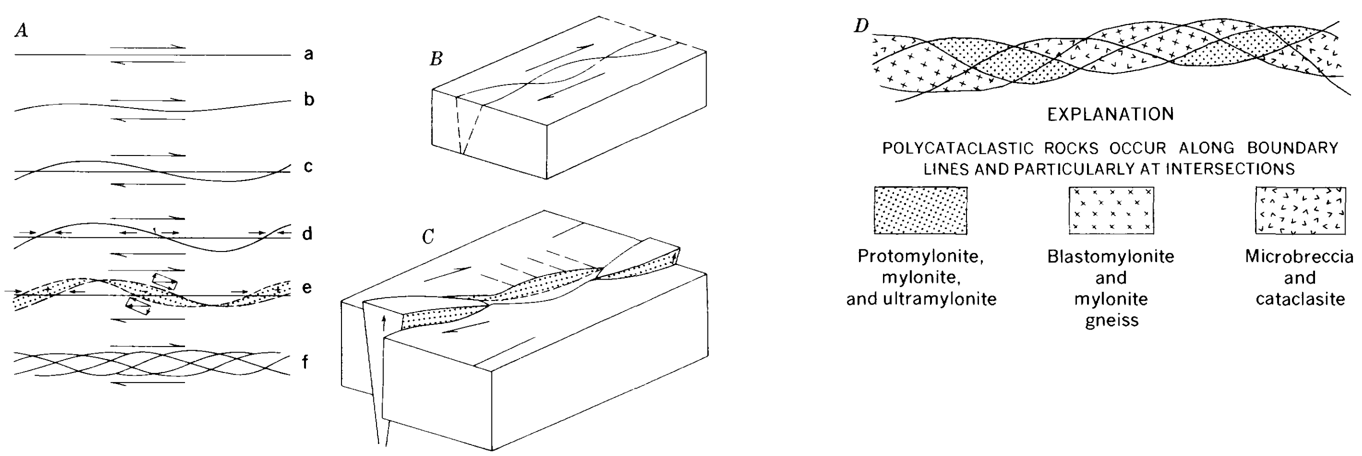


FIGURE 31.—Development of a braided fault zone. Differences in lithology produce frictional differences and uneven movements, thus creating undulations. Continued movements give rise to alternating areas of relative tension and compression (*A–C*, from Kingma, 1958). *D*, shows the theoretical distribution of types of cataclastic rock in a system like that hypothesized by Kingma (1958). The various types would be formed at about the same time, and the difference in effects of cataclasis would be the result of differences in relative tension and compression.

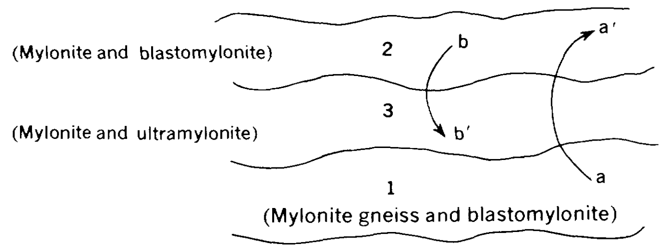


FIGURE 32.—Schematic diagram of one possible mechanism for producing different types of cataclastic rock in a single fault zone during a single period of movement. The zone of most intense cataclasis shifts or jumps, and movement *a–a'* (which does not necessarily involve 3) is earlier than movement *b–b'*, but with within the same period. Further shifts would produce polycataclastic rocks, as would overlaps of zones of most intense cataclasis.

latter are generally younger (Peach and others, 1907, called them "crush breccias" and "crush conglomerates"; Grubenmann and Niggli, 1924; Hsu, 1955b; Johnson, 1957, 1961; Christie, 1960, 1963; Schoch, 1962; Reed, 1964; Higgins, 1966, 1968; Grant, 1967, 1968; Dalziel and Bailey, 1968). The contacts of microbreccias and (or) cataclasites with the fluxion-structured rocks in a fault zone, and with crystalloblastic rocks outside the fault zone, are generally discordant, and the trend of bands of these "structureless" cataclastic rocks may be at high angles to the zone, to the fluxion structure or lamination of the other rocks in the zone, and to the foliation of rocks outside the zone. Quite commonly, it can be shown that microbreccias and cataclasites are polycataclastic, proving that they are younger because they formed by brecciation of the other rocks. Moreover, there is general agreement that the microbreccias and cataclasites formed under less intense conditions of cataclasis than the rocks with fluxion structure, and also under less intense metamorphic conditions (see Christie, 1960, p. 90–91, and Reed, 1964, p. 675–676). The manner of deformation is different. For example, as Christie (1960, p. 90) noted, quartz and feldspar alike are deformed by cataclastic breakdown to the same degree. Reed (1964, p. 676) stated:

> . . . the mylonites are characterised by fluxion banding presumably produced by long-continued movement in one direction, whereas the structureless cataclasites were probably produced by repeated movements in different directions.

Also, there are obvious fabric differences between the two groups of rocks; rocks with fluxion structure have directed fabrics (anisotropic), whereas microbreccias and cataclasites tend to have isotropic fabrics.

DEVELOPMENT OF CATACLASTIC TEXTURES

Waters and Campbell (1935, p. 484–488) gave a detailed description of the development of cataclastic textures in San Andreas fault zone rocks near Crystal Springs Lakes, Calif.:

> Under the microscope every stage in the demolishing of original coarse grained rocks to an ultramicroscopic paste can be seen. . . . In general, crushing begins by the fracturing of the rock into a coherent breccia or protomylonite whose fragments are megascopically visible. Pronounced strain shadows appear in the quartz even though little shearing is visible in thin section. Further movement results in the formation of a thin film of crush powder between the mineral grains forming typical "mortar structure." The next stage is the development of a closely spaced series of microscopic shears in the individual mineral grains. With further crushing, films of pulverized material form along the microscopic shears and grow at the expense of the mineral grains until finally the uncrushed material between adjacent shears is isolated as streaks, lenticles, and irregular masses in the powdery groundmass. Complete rolling out of the rock to an ultramicroscopic powder in which none of the eye-shaped porphyroclasts are left is rare. The small round particles resist further milling to an unusual degree and even in those cases where the groundmass has been reduced to such small fragments that it becomes practically isotropic some of the porphyroclasts commonly survive. Feldspar seems to be more resistant to crushing than quartz, as shown by the fact that feldspar porphyroclasts are relatively more abundant in the more completely pulverized mylonites.

Similar descriptions have been written by nearly all who have seriously considered cataclastic rocks (for example, see Quensel, 1916; Crickmay, 1933; Clarke, 1952).

Different minerals react differently to cataclasis. Some minerals are apparently easily granulated or sheared, whereas others resist comminution and form porphyroclasts; some recrystallize, whereas others preserve their cataclastic shapes. It is possible to construct a generalized "cataclastic reaction series" based on empirical observations (table 2).

MICAS

Micas are apparently easily deformed and are commonly the first minerals affected by cataclasis. Generally, the micas recrystallize as the cataclasis proceeds, but their new "aberrant" shapes record the deformation. Large micas are first deformed into lens- or spindle-shaped masses. As cataclasis proceeds, these are ground down, and fine recrystallized micas are streaked out along the fluxion planes and around porphyroclasts of

TABLE 2.—*Generalized reaction of various minerals to cataclasis*

1. Easily deformed minerals which generally deform by recrystallization and preserve little or no evidence of cataclasis:
   - Carbonate minerals
   - Epidote minerals
   - Some amphiboles
2. Minerals which generally deform by comminution and recrystallization, but which preserve evidence of cataclasis:
   - Micas
   - Many amphiboles
   - Some quartz
3. Minerals which deform chiefly by comminution with good preservation of cataclastic textures:
   - Most quartz
   - Plagioclase
   - Garnet

One can construct a generalized "cataclastic reaction series" based on empirical observations:

Most easily comminuted	Increase→	Micas Quartz Feldspar Garnet	Decrease→	Tendency to form porphyroclasts

other minerals. These fine micas may be further comminuted, or may be kinked or bent. Some large micas may remain as recrystallized porphyroclasts.

Biotite seldom undergoes cataclasis without chemical change. Iron is commonly expelled from biotite to form magnetite, which occurs in thin streaks along fluxion planes and helps define them. The optical characteristics of the biotite in cataclastic rocks commonly indicate that it is poorer in iron than that of the undeformed parent rock. Titanium may also be expelled from biotite during cataclasis to enter sphene (see Hsu, 1955b, p. 253).

QUARTZ

Quartz, like the micas, is one of the first minerals affected by cataclasis. It first becomes elongated and strained; undulatory extinction and fine deformation lamellae appear. After this initial stage, which appears to be common to all kinds of quartz-bearing rocks, the behavior of quartz seems to follow two different patterns in different kinds of rock. In very quartz rich rocks, such as orthoquartzites and protoquartzites, the quartz further elongates, becomes lens-shaped, and granulates at the edges so that a fine quartz mortar fills the sheared interstices between the fractured and deformed grains. The mortar is generally slightly recrystallized. In less quartz rich rocks, such as metagraywacke or granite, the quartz grains become increasingly shattered throughout, but comminution of the grains is not so much a gradual process from the outside inward. Perhaps this difference is due to the presence of feldspars in the less quartz rich rocks, which act as resistant masses and prevent the quartz from deforming in a partially plastic manner. After this "second stage" the behavior of quartz again is similar in all kinds of rock. With increasing cataclasis, the quartz fragments disintegrate by fracturing, seemingly "all at once," into a fine granular mass which forms much of the matrix and is arranged in fluxion bands or stringers around porphyroclasts of other minerals. Only rarely are porphyroclasts of quartz larger than the general matrix size observed. Commonly, some of the quartz is recrystallized into thin "flamboyant" stringers which undulate with, and help to define, the fluxion structure. Generally, the recrystallized quartz of these stringers is itself severely strained.

FELDSPARS

In marked contrast to quartz, feldspars are notably resistant to crushing during cataclasis, and as a result comprise the most common porphyroclasts in cataclastic rocks. Comminution of feldspar grains is from the outside inward and generally starts in most grains only after comminution of quartz is well advanced. First, the corners of a crystal, or any projections from an irregularly shaped grain are broken or ground off. These small feldspar fragments join the quartz in the fine matrix, and become rounded by granulation. Further comminution of the main feldspar grain is by attrition, as it rolls between differentially moving fluxion planes or bands, until the porphyroclast is round or oval. Some large porphyroclasts may separate along flaws or along well developed cleavage planes, to begin the rounding process all over again. As cataclasis proceeds still further, the feldspar porphyroclasts continue to comminute by rounding until there is complete reduction. Round, as opposed to irregularly shaped or oval, porphyroclasts are most common in ultramylonites.

GARNET

Garnet generally appears to be quite resistant to cataclasis. In some cataclastic rocks where the matrix is extremely fine grained and even the feldspar porphyroclasts are few and small, large garnet porphyroclasts survive. Comparison with cataclastically undeformed garnets in the parent rocks shows that the garnets in the cataclastic rocks have merely had their corners rounded off and have been little reduced in size. Garnets apparently react to cataclasis by rolling between differentially moving fluxion planes or layers. Under conditions in which quartz and some feldspar recrystallize and deform in a partially plastic manner by elongation, as in many blastomylonites and mylonite gneisses, garnets may also be elongated or even smeared. In the most intensively mylonitized rocks, garnets may be cracked and separated, the cracks commonly being filled by a "mortar" of quartz and feldspar, but seldom are they completely ground down and the pieces streaked out along fluxion planes. Are garnets so resistant to cataclasis because, being initially nearly round, they can easily roll and thus escape much further comminution; or, is there simply a relative difference in relation to quartz and to a lesser extent feldspar?; or, do the garnets continually recrystallize as the comminution takes place?

Probably each factor is the most important in certain rocks, and in some rocks all three may be important. That garnets have commonly been rotated and rolled during deformation is well documented for noncataclastic rocks (Peach and others, 1912; Schmidt, 1918; Becke, 1924; Mügee, 1930; Guilluly, 1938; Knopf and Ingerson, 1938; Fairbairn, 1949; McLachlan, 1953; Spry, 1957, 1963; Rosenfeld, 1960, 1968; Peacey, 1961; Hopson, 1964; and others) and for cataclastic rocks (Crickmay, 1933; Clarke, 1952; Sclar, 1958; Sutton and Watson, 1959; Johnson, 1961; and others). Many garnets in cataclastic rocks (particularly in mylonites and ultramylonites) have a rounded cataclastic shape (for example, see: Crickmay, 1933, p. 168; Sutton and Watson, 1959, pl. 1; Sclar, 1958, p. 78, 79), but nearly euhedral garnets are seen in some cataclastic rocks (chiefly in blastomylonites, but in some mylonites also), and Sutton and Watson (1959) have described and illustrated garnets in recrystallized cataclastic rocks (chiefly blastomylonites) that have a round porphyroclastic core surrounded by a euhedral shell riddled with tiny inclusions from the cataclastic matrix.

DEVELOPMENT OF FLUXION STRUCTURE

There are several hypotheses and much confusion regarding the origin of what has been called "fluxion structure." Most of the confusion has stemmed from lack of proper definition of the terms *fluxion structure*, *compositional layering*, and *color lamination*. As a result, some geologists have considered the origin of color lamination or compositional layering, calling them fluxion structure, whereas others considered the origin of cataclastic foliation, with or without color lamination or compositional layering. *Fluxion structure*, as used in this paper, is defined on page 3, and refers only to cataclastic foliation. *Compositional layering*, defined in the glossary (p. 72), refers only to layering in which adjacent layers differ in mineral and chemical composition. *Color lamination*, also defined in the glossary, generally includes compositional layering, but refers only to color differences in adjacent layers, which in some cases may be due simply to grain size.

The generally accepted hypothesis of the origin of fluxion structure is essentially that envisioned by Lapworth (1885) and expounded by Waters and Campbell (1935, p. 482–484); see quote p. 59 of this paper). According to this hypothesis, fluxion structure is really flow structure. It is the textural expression left by differentially moving fine planar masses of comminuted material developed and propelled by shearing. These masses or layers flowed around obstructions or porphyroclasts in a manner similar to highly viscous siliceous lavas flowing around phenocrysts and inclusions. Just as microlites and crystallites in the lava tend to concentrate between laminar flow layers or within certain thin layers, the finer mineral fragments (particularly of metallic and micaceous minerals) in the cataclastic rocks tend to concentrate between the laminar flow layers of the cataclastic matrix, thus defining these layers. The process starts with lenselike and wavy shear planes, grades with further cataclasis into subparall shear planes, and finally into laminar flow layers. As large porphyroclasts are ground down between the moving layers, the ground-off material is streaked out between the layers, further defining the fluxion structure by streaky compositional differences. The process in this stage is essentially one of milling.

DEVELOPMENT OF COMPOSITIONAL LAYERING AND COLOR LAMINATION

Compositional layering and color lamination are common to many mylonites, ultramylonites, and blastomylonites and have been confused with fluxion structure. There are several hypotheses regarding the origins of these features.

ORIGINAL GRAIN SIZE DIFFERENCES

Crickmay (1933, p. 170) proposed that the color lamination in some mylonites and ultramylonites originated because of grain size differences in the parent gneiss. He thought that cataclasis started at first in the finer grained layers of the gneiss, providing these layers with a "head start," so to speak, which was maintained as cataclasis proceeded through the mylonite and into the ultramylonite stage. This produced mylonites and ultramylonites in which some layers are more finely comminuted than others and hence of different color.

VARIABLE DEGREES OF COMMINUTION

Waters and Krauskopf (1941, p. 1407), in discussing some of the protoclastic rocks in the border zone of the Colville batholith, stated:

> The banding so conspicuous in hand specimen is due to variable degrees of crushing in different layers.

Crickmay (1933, p. 176) also noted that the layering in some mylonites and ultramylonites is due to: "the interlayering of completely and incompletely crushed material."

Variable degrees of comminution in different "layers" accounts for the color lamination of some mylonites, ultramylonites, and blastomylonites in the Brevard zone, in the Towaliga fault zone, and in the Cucamonga Canyon zones (also see Hsu, 1955b). This is illustrated in figure 10.

ORIGINAL COMPOSITIONAL LAYERING

Original compositional layering in the parent rocks may account for the color lamination and cataclastic compositional layering of some cataclastic rocks. Sclar (1958, p. 66) stated this possibility for some mylonites and ultramylonites near Preston City, Conn.

GLIDE-FOLD SCHISTOSITY

Christie (1963, p. 383–384) suggested that "glide-fold schistosity" or "*Gleitfaltschieferung*" (Kienow, 1953) was probably important in producing the color lamination of some mylonites, ultramylonites, and blastomylonites. Under this mechanism, to paraphrase Christie, slip surfaces become unstable during movement and bend into intrafolial flexural slip folds, which become overturned in a direction related to the sense of shear. A new schistosity develops by shearing of the limbs of the smallest scale folds. This schistosity is more stable than the original, but it is rapidly rotated toward the plane of the latter (fig. 33).

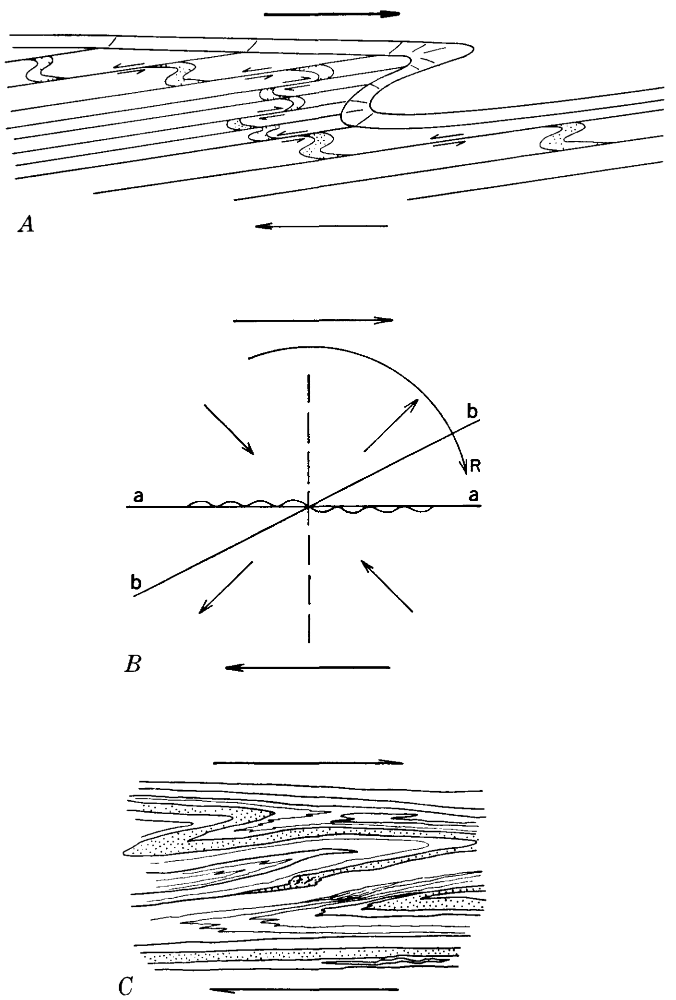


FIGURE 33.—Development of "glide-fold schistosity." *A*, Diagram showing development of "glide-fold schistosity." *B*, Analysis of movement in "glide folding." Long arrows indicate the sense of shear; short arrows denote axes of "compression" and "tension." The stable glide-fold schistosity (b–b) is rotated in the direction shown by the arrow (R) to the unstable orientation (a–a). *C*, The sense of slip indicated by intrafolial folds. From Christie, 1963, figure 19.

CATACLASTIC METAMORPHIC DIFFERENTIATION

The term *metamorphic differentiation* was introduced by Stillwell (1918) for processes by which contrasting mineral assemblages develop from an initially uniform rock during metamorphism. Stillwell and many later workers (Eskola, 1932; Read, 1933) considered metamorphic differentiation as almost purely a chemical process. Others (Harker, 1932) discounted its importance entirely. Sander (1930, p. 269–275) believed that there is an interplay of mechanical and chemical activity in the process of metamorphic differentiation, but he assigned an auxiliary role to the mechanical factor.

In 1932, Schmidt (p. 183–187) proposed a hypothesis of purely mechanical metamorphic differentiation. He showed that rolled wrought iron consists of alternating layers of perlite and ferrite produced mechanically by the rolling process and suggested that slip surfaces formed in the early stages of deformation of a heterogeneous rock are irregular, discontinuous, and commonly located within crystals or crystal aggregates of those minerals that can readily adjust their lattices to the imposed stresses by translation gliding, twin gliding, or recrystallization. Minerals less susceptible to such deformation may at first form "projections" interrupting the early formed slip surfaces, but as deformation proceeds, the obstructions are mechanically eliminated and segregated. Penetrative movement in major slip surfaces rolls out the easily deformable minerals (quartz, calcite, plagioclase) into continuous bands. The platy or prismatic minerals are drawn into subparallel position (crystal form orientation) by flow movement involved in the deformation.

Turner and Verhoogen (1960, p. 586) stated:

Schmidt's hypothesis explains how two physically dissimilar sets of minerals could be separated from one another; but to what extent this mechanism actually operates in metamorphism remains dubious in view of the undoubted fact that solution and crystallization usually play an important role in shaping the fabric of deformed rocks, and in the absence of experimental proof that under metamorphic conditions quartz and albite are more ductile than mica, chlorite, and epidote. . . . It would seem, then, that development of laminated structure in regionally metamorphosed rocks is a complex process involving solution, crystallization, and mechanical deformation, acting together or in alternating combinations as the selective agents of metamorphic differentiation.

In 1916 (before Stillwell named the process of metamorphic differentiation), Quensel (1916, p. 95–97, 103–105, 107–116) had considered *hartschiefer* (in my classification a variety of *blastomylonite*) as partially recrystallized ultramylonite that had undergone strong chemical changes during crushing and recrystallization to bring about marked chemical differences between the different bands. He described bands of felsic minerals alternating with bands rich in chlorite and micas, and suggested that the differences were brought about during crushing and recrystallization (neomineralization).

Wenk (1934, p. 221–226) described layered mylonite associated with its nonlayered parent in the Silvretta gneiss of Switzerland. The compositionally layered cataclastic rocks (mylonite and ultramylonite) occur as relatively thin zones at or near the contacts of the allochthonous gneiss block. Wenk concluded that mechanical processes had transformed the augen gneiss into layered cataclastic rocks.

In 1935, Waters and Campbell (p. 478), referring to hartschiefer, stated:

In the opinion of most Swedish geologists they differ from ultramylonite, which they resemble rather closely, in the remarkable banding, a feature that is regarded to be the result of metamorphic differentiation.

In their discussion of the San Andreas cataclastic rocks, they (1935, p. 482–494) noted:

* * * at one place there is an even alteration of black mylonite with layers of antigorite schist, the individual layers locally averaging less than an inch in thickness.

They also described (1935, p. 482, 488–494) rocks that were originally "altered basalts or diabases" but are now laminated mylonites and ultramylonites. After describing (p. 490) mylonites with alternating "dark-colored bands" and "quartzose layers," they stated (p. 491):

If chemical differentiation of material during mylonitization does take place, it may well be that the rocks from the San Andreas fault zone showing these peculiar layers of quartz rich material represent an early stage in the transformation of a crushed rock to a chemically differentiated "hartschiefer."

Turner (1941), in his often cited paper describing metamorphic differentiation in the Otago schists, emphasized the great amount of shearing involved in their formation and, in fact, called them "blastophyllonites." Although he dwelt upon the chemical factors of the differentiation, the great amount of shearing and mechanical deformation involved in the production of the banded rocks from massive parent rocks is quite clear from his descriptions.

Sclar (1950, 1958, p. 64–66, 70–75) described layered cataclastic rocks derived from nonlayered parent rocks. Regarding the origin of a layered ultramylonite developed from nonlayered biotite-cummingtonite-hornblende gneiss he stated (1958, p. 74–75):

Metamorphic differentiation resulting from the solubility factor alone is ruled out in this case by the fact that shearing stress was the 'triggering' mechanism for metamorphic differentiation of the gneiss, and the observation that metamorphic differentiation increases with increasing cataclasis. Therefore, in the light of present knowledge the question of the mechanism(s) by which metamorphic differentiation of the gneiss was accomplished may be resolved into a discussion of the relative importance of the mechanical factor as opposed to the chemical factor. In other words, was the layering produced because of the difference in mechanical behavior of light and dark minerals under shearing stress (Schmidt-Wenk hypothesis) or was the layering produced by the interplay of cataclasis and chemical activity in which a critical grain size is reached through granulation, resulting in increased chemical activity that promotes segregation of light and dark minerals by means of the solubility principle (Sander-Turner hypothesis)? The writer believes that the weight of evidence supports the Schmidt-Wenk hypothesis. The critical evidence is as follows: 1) the exceedingly fine-grained apparently cataclastic fabric of the light-colored laminae, and 2) the increase in metamorphic differentiation toward the bottom of the gneiss block.

With respect to the first point, if sufficient aqueous pore solutions were available to promote solution of the quartz and plagioclase, and redeposition in layers parallel to the active s-planes after the rock was reduced to a critical grain size, then it is difficult to understand why the ultramylonite did not become a coarse-grained laminated blastophyllonite similar to those described by Turner (1941). It cannot be claimed that temperatures were too low to allow the comminuted paste to attain a moderate grain size. Temperatures during mylonitization were high enough to prevent diaphthoresis, and the deformation therefore took place under at least low-rank mesozonal conditions. Thus it appears more probable that lack of pore solutions rather than lack of heat to promote chemical activity was responsible for failure of the rock to become a coarse-grained laminated blastophyllonite. If this is correct, then Schmidt's mechanical process of metamorphic differentiation is favored.

The mylonite layers in the gneiss, the mylonite that grades into the ultramylonite, and the ultramylonite itself are all almost submicroscopic in grain size. Nevertheless, neither the mylonite nor the mylonite layers in the gneiss are laminated. As increasing movement from top to bottom of the block parallel to the foliation of the gneiss is indicated by increasing pulverization of the gneiss in the same direction, a second approximation may be made by correlating metamorphic differentiation with the distance traveled by different parts of the block. This satisfies the observation that metamorphic differentiation increases from top to bottom of the block, and suggests that metamorphic differentiation can be correlated with granulation only because increasing transport of minerals under shearing stress has resulted in increasing cataclastic reduction. The writer therefore concludes that the degree of perfection of the lamination is probably a function of the kinematics of the gneiss during mylonitization.

In a later paper Sclar (1965, p. 612) stated:

Mechanical metamorphic differentiation is likely to be restricted to narrow fault zones of intense penetrative movement of limited thickness, whereas chemical or chemical-mechanical metamorphic differentiation is more likely to be widespread and even regional in extent.

* * * pre-existing mixtures of rock-forming phyllosilicates and/or inosilicates with tectosilicates that are involved in deep-seated zones of penetrative movement may be segregated into phyllosilicate and/or inosilicate layers and tectosilicate layers as a result of differences in mechanical behavior between contrasting crystal structures under high confining pressure and intense shearing stress.

Figure 10*B* is a photomicrograph of one of the rocks described by Sclar.

Prinz and Poldervaart (1964) described a 15-foot-thick zone of compositionally layered mylonite in a 150-foot-thick metadolerite dike. They described how the metadolerite grades into partly mylonitized rocks and finally into layered mylonite, and gave (p. 743) chemical analyses of the original unsheared rock and the light and dark layers of the mylonite. By comparing the sum of empirically observed percentages of light layer and dark layer analyses with the chemical composition of the unsheared metadolerite, they showed that the layered mylonite was produced from the unlayered metadolerite. Their evidence for metamorphic differentiation due to mechanical factors is quite strong. Regarding minerals they stated (p. 743): "Petrographic observations indicate that in the mylonitization of metadolerite, pyroxenes were more ductile than plagioclase, which was brittle."

In surveying the literature, one becomes aware that where the case for metamorphic differentiation is strong, evidence for shearing deformation and great penetrative movement is also strong; conversely, where the case for metamorphic differentiation is weak, the lack or weakness of deformation or shearing is apparent. Therefore, it appears that mechanical factors are much more important in metamorphic differentiation than has previously been acknowledged by most geologists.

Examination of cataclastic rock suites from the San Andreas fault zone, the Törnetrask region, the Brevard fault zone, and other areas shows that as granulation increases, lamination or banding due to compositional differences also becomes more pronounced. Ultramylonites show more precise compositional banding than mylonites. The nature of this banding, where determinable, involves segregation of framework silicate minerals from layer and (or) chain silicates, although it generally involves partial rather than complete segregation.

In summary, the banding common to many cataclastic rocks probably results from cataclastic metamorphic differentiation progressing with the granulation.

FOLDS IN CATACLASTIC ROCKS

Small-scale folds, with amplitudes generally less than 2 feet (61 cm), are relatively common in some fluxion-structured cataclastic rocks (Peach and others, 1907, p. 506–507; Read, 1931, p. 10; Wilson, 1953; McIntyre, 1954; Hsu, 1955b, p. 281, 287–288, 342, 346–347; Wilkinson, 1955; Johnson, 1957, 1961; Christie, 1963; Barber, 1965; Dalziel and Bailey, 1968; Bentley, 1969). Although various names have been applied to the cataclastic rocks in which the folds occur, almost all are recognizable, either through microscopic study or through descriptions and (or) illustrations in the literature, as blastomylonites with varying degrees of recrystallization and neomineralization. In fact, some authors have commented on the large degree of recrystallization and neomineralization in these rocks (Hsu, 1955b, p. 281; Johnson, 1957, p. 263, 1961, p. 419, 422–423; Christie, 1960, p. 87, 1963, p. 358; Barber, 1965, p. 224–225; Dalziel and Bailey, 1968, p. 543). As far as I can determine, very few (if any?) folds have been observed in rocks, which should be called protomylonite, mylonite, or ultramylonite.

Most of the folds in cataclastic rocks are similar slip folds (Ramsay, 1967; Whitten, 1966), and many are intrafolial (*see* Christie, 1963, p. 363, 367, 371, 377, 383–84, 423, 425; Hsu, 1955b, p. 281, 347; see also fig. 34). In some folds, particularly from the Moine thrust zone (*see* Christie, 1963), fluxion structure is axial-planar to the compositional layering that defines the folds. Johnson (1957, 1961, 1965) interprets this as resulting from more than one phase or episode of deformation; Christie (1963) interprets it as resulting from glide folding. Wilson (1953), McIntyre (1954), and Christie (1963) have noted the contrast between the "brittle" style of deformation in cataclastic rocks and the "plastic" style of folding in crystalloblastic rocks away from fault zones.

Perhaps the fact that cataclastic rocks with folds are nearly always blastomylonites (includes rocks that some workers have termed *phyllonites*), is significant with regard to the style of folding. Blastomylonites with their concomitant cataclasis and recrystallization-neomineralization would be expected to submit to shearing by transposition of earlier formed planar features. Thus, "drag" between differentially moving fluxion planes or fluxion layers might fold the material between the planes to produce small folds with the fluxion structure axial-planar. This could occur during a single phase of deformation.

The style of most folds in cataclastic rocks is remarkably similar to that of folds in obsidian flows (fig. 35*A*), and in some cataclastic rocks (fig. 35*B*, *C*) it can be shown that the folds developed because of the "drag" of differentially moving fluxion planes. This is accentuated where less mobile parts of the rock (porphyroclasts, phenocrysts, etc.) have added to the drag. Some folds in obsidian flows even have axial-plane "foliation" (fig. 35*D*), similar to that of some folded cataclastic rocks. Perhaps then, the folds, the axial-plane foliation, and the orthorhombic fabric of some cataclastic rocks (see Johnson, 1967) are caused by differential movement in more than one direction, just as it is in large obsidian flows. The internal movements in cataclastic rocks with fluxion structure may be remarkably similar to the internal movements in obsidian flows.

Another important point regarding folds in cataclastic rocks is their orientation with respect to the fault zone and the direction of tectonic transport. In the cataclastic rocks of the Moine thrust zone (chiefly blastomylonites), the axes of small folds commonly trend approximately normal to the trend of the fault zone and plunge down the dip of the overriding block (Johnson, 1957; Christie, 1963, p. 359, 360–361, 370–371, 374, 376). Christie (1963) interprets this as evidence of some strike-slip displacement along the zone to provide some tectonic transport approximately normal to the fold axes. Johnson (1957, 1961, 1965) and Barber (1965) interpret these folds as secondary features imposed on features of the main, earlier thrust deformation and find no evidence of strike-slip displacement.

Few other fault zones have been studied in as much detail, throughout so much of their extent, or by as many different workers, as the Moine thrust zone. However, Bentley (1969) reports early "drag" folds with steeply plunging axes in blastomylonites along the Goat Rock, Towaliga, and Bartletts Ferry fault zones in Alabama (fig. 26), and interprets them as resulting from strike-slip displacements, and Grant (1968) reports bending of early fold axes by strike-slip displacements along the Towaliga fault zone in Georgia. Folds in blastomylonites are also found in the Brevard zone near Atlanta, Ga. There, most of the folds have axial planes striking roughly parallel to the trend of the zone and dipping steeply to the southeast.

RELATION OF MINOR TO MAJOR STRUCTURE

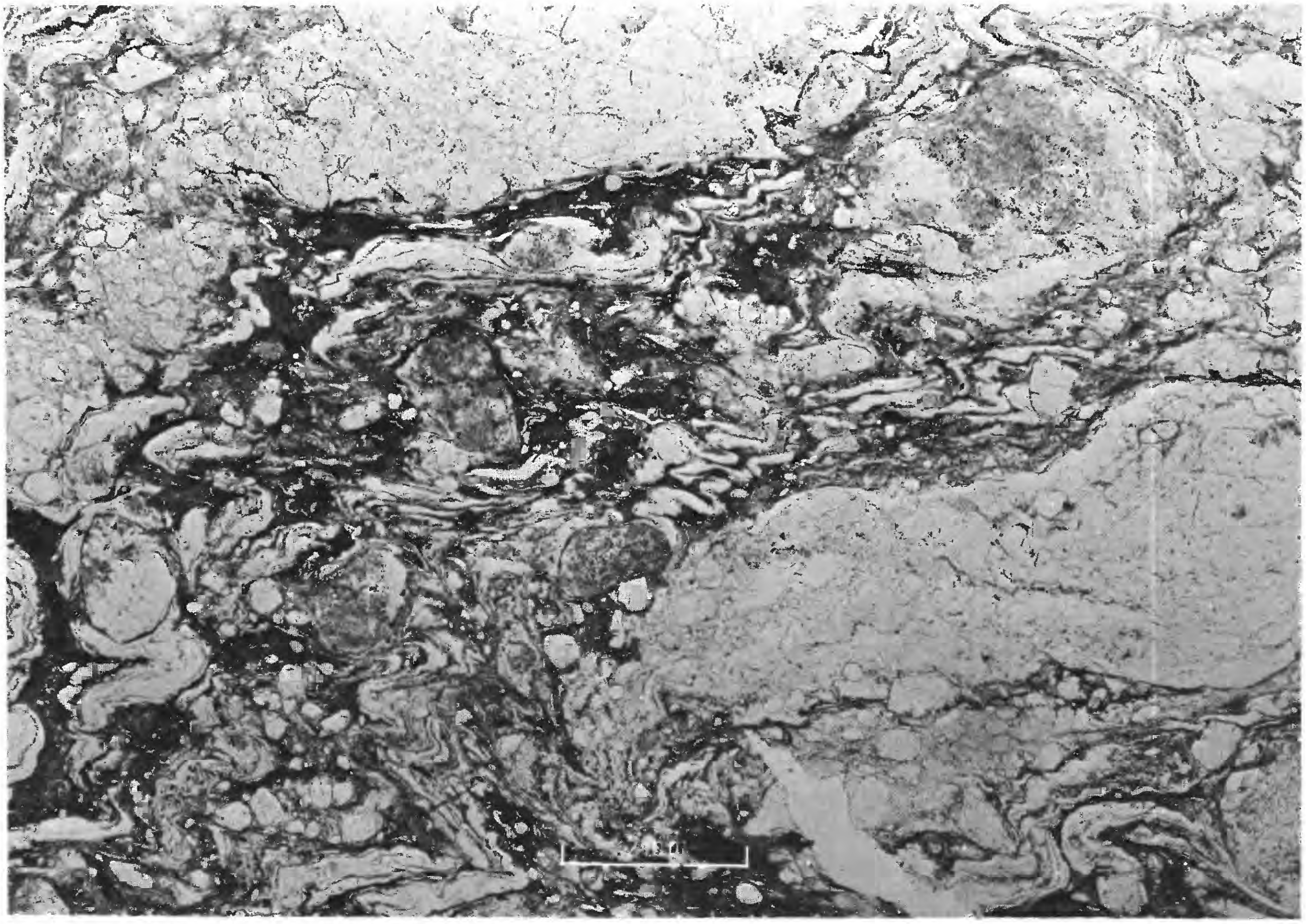
Pumpelly, Wolff, and Dale (1894, p. 158) long ago recognized that minor structure commonly reflects major structure. This may also be true with regard to cataclastic structures and textures. Relations and features seen in thin sections of cataclastic rocks commonly reflect in a general way those seen in hand sample, outcrop, and at map scale (fig. 36). In some thin sections and hand samples, the intercalation of finely comminuted cataclastic rocks with coarser varieties and of less recrystallized types with recrystallized and even totally crystalloblastic rocks is commonly matched by the map patterns of major cataclastic zones. Minor structures in cataclastic rocks of a zone may be matched by major features of a larger area containing the zone.

CONDITIONS OF CATACLASTIC ROCK FORMATION

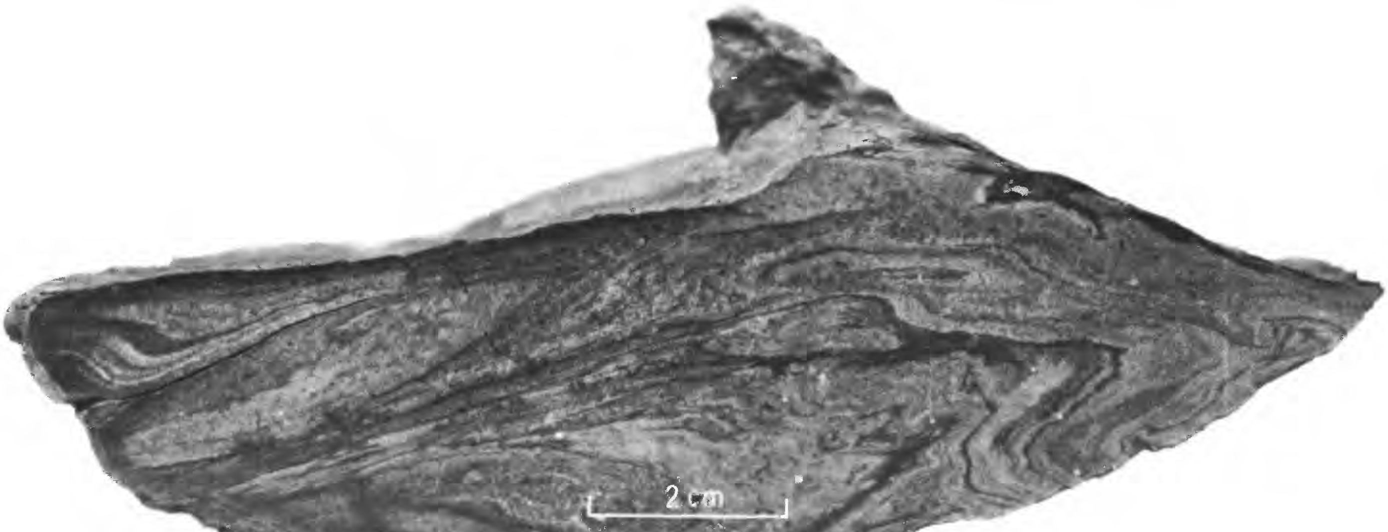
The variables generally considered to control metamorphism are: temperature, lithostatic pressure, fluid pressure, shearing stress, rock composition, reaction rates, and fugacities of oxygen and carbon dioxide (Yoder, 1955; Hsu, 1955b; Turner and Verhoogen, 1960; Turner, 1968). Cataclastic rocks are primarily metamorphic rocks, and all these variables must influence their genesis. In cataclastic rocks, however, we must add the factors of differences in amount of deformation and differences in the reaction of different minerals to stress.

In 1932, Harker (1950) was one of the first to consider some of the variables controlling cataclastic rocks. He thought that cataclasis could be classed separately from other types of metamorphism, as is evident from the following statement (1950, p. 169):

> Mylonitization, as contrasted with brecciation of a less drastic kind, requires a notable pressure, implying a considerable depth of cover. At such a depth the temperature too must doubtless be above the ordinary, but it does not appear that the elevation of temperature is such as to remove the process from the category of purely dynamic metamorphism as here understood.



A



B

Harker was puzzled because the cataclastic rocks obviously formed at relatively high temperatures, yet were not recrystallized or neomineralized to the degree common to normal crystalloblastic rocks formed under similar temperatures. Hsu (1955b) faced similar problems in his study of the Cucamonga Canyon area in California. There, cataclastic quartz-feldspar rocks and crystalloblastic amphibolites are intimately interlayered and show evidence of being syngenetic. Hsu (1955b, p. 272) stated:

Apparently, the Cucamonga Canyon mylonites and amphibolites are syngenetic; while the quartz-feldspar granulites were being deformed cataclastically to form mylonites the pyroxene-rich granulites were deformed through neomineralization and recrystallization to form amphibolites; both processes took place under the P–T–X conditions represented by the amphibolite facies and under intense shearing stress.

Hsu (1955b, p. 272) explained the occurrence as follows:

The fact that the amphibolites are predominantly granoblastic, whereas the interlayered and quartz-feldspar rocks are predominantly mylonitic, may not be coincidental. The H_2O component in a metamorphic system takes part in mineral reactions: it could promote the formation of biotite through reactions with hypersthene and/or garnet; it could promote the uralitization of pyroxenes; it could promote the epidotization of plagioclase; and it could promote the chloritization of various ferromagnesian minerals. The P–T–X conditions determine in which mineral reaction the H_2O component should participate. Under the conditions represented by the amphibolite facies, the uralitization of pyroxenes in rocks of gabbroic bulk composition is the most favorable reaction; the felsic rocks of the granulite facies contain mineral assemblages that are stable also in the amphibolite facies. Thus a thermodynamic potentiai was set up so that the H_2O component migrated into the mafic rocks to promote the amphibolitization of pyroxenes, whereas the felsic parts of the Cucamonga Canyon system became, or remained, poor or deficient in H_2O. Consequently, active synkinematic neomineralization was possible in mafic rocks, forming granoblastic amphibolites; at the same time, the felsic rocks underwent cataclastic deformation under a dispsenic [sic—should read dipsetic] condition, the little H_2O that was present promoting the incipient neomineralization.

Hsu (1955b, p. 312) also proposed that:

* * * the partial pressure of the hydrous phase, rather than the amount of water present, plays a vital role in determining the nature of the equilibrium assemblage for a rock of a given bulk composition.

Hsu's (1955b, p. 312) variables would therefore be: temperature, hydrostatic pressure, partial pressure of the hydrous phase, and "other factors (X)."

Hsu's work emphasized the importance of water content and P_{H_2O} in determining the formation and mineralogy of cataclastic rocks. More recent work has shown that the chemical activities of various elements and compounds are also important in metamorphism, and therefore in cataclastic rock formation as well (see Turner, 1968).

Experimental studies of rock deformation are not yet sufficiently far advanced to warrant quantitative statements regarding the physical and chemical conditions of cataclasis. We do know that: (1) increase in confining pressure without temperature change causes increase in ultimate strength, strain, and commonly in conjugate shear angle; (2) increase in temperature without change in confining pressure causes decrease in ultimate strength, but not necessarily increase in strain. We know that the main effect of increasing confining pressure in triaxial-test experiments is to cause a significant increase in amount of flow before rupture and a significant increase in the rupture strength of the material.

Experimental data suggest that cataclasis operates by uniform flow (Badgley, 1965, p. 25), at least in the finer-granulated rocks. Therefore it may be classed as plastic deformation and considered graphically. If we use this approach, published curves can give us a general idea of the conditions of cataclasis (see Griggs and others, 1960). It must be emphasized, however: (1) that these curves do not depict all the conditions of natural cataclasis, but only give a general idea of these conditions; and (2) that most of the experiments have been conducted using marbles, limestones, shales, and other easily deformed rocks, whereas most cohesive cataclastic rocks were formed from felsic or siliceous rocks.

FIGURE 34.—Intrafolial folding in blastomylonites. *A*, Photomicrograph showing intricate "plastic style" intrafolial folding in a polycataclastic blastomylonite from a fault zone near the northwestern edge of Straight Fork window, eastern Great Smoky Mountains, North Carolina (furnished by J. B. Hadley, U.S. Geological Survey); plane-polarized light. Most of the porphyroclasts are feldspar. The large light areas are cataclasite; they are virtually "megaporphyroclasts" in the polycataclastic, blastomylonitic matrix. The rock is fairly well recrystallized. Parent rock was a biotite-plagioclase-potassium feldspar gneiss (*see* Ravensford body, Hadley and Goldsmith, 1963, p. 816). *B*, Overturned, isoclinal, intrafolial folds in blastomylonite from the Goat Rock fault zone, near Goat Rock Dam, Alabama. Note style of folding, and compare with Plate 1b, Christie (1963, p. 423).


1 cm
A


B
2 cm

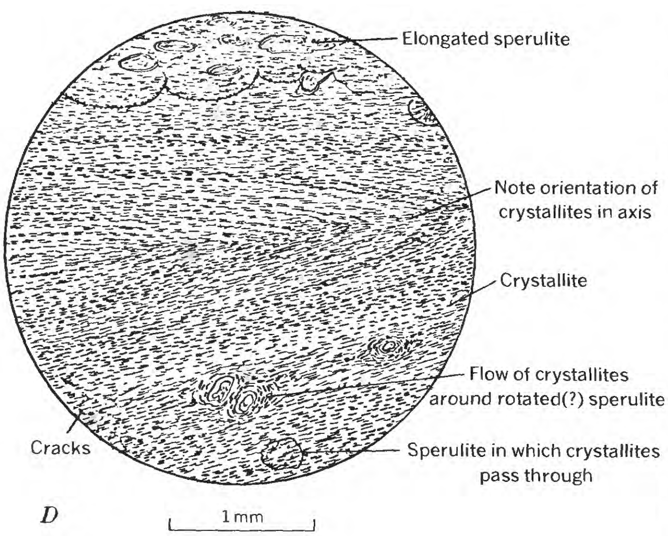


FIGURE 35.—Intrafolial folds in obsidian and blastomylonite. *A*, Overturned, isoclinal fold in flow banded obsidian from Big Obsidian Flow, Newberry Caldera, central Oregon. The light layers are pumiceous obsidian; the dark layers are glassy obsidian. Movement direction is to the left in this photograph, but a prominent lineation on flow band surfaces, caused by elongated vesicles (the black holes visible in cross section here), indicate that movement also occurred normal to the main movement or flow direction (that is, movement in *B*). The round shape of many of the vesicles in cross section shows that the movement was not chiefly a flattening component, but more like a spreading. There is also a grooving lineation parallel to the main movement direction (*A*). The fold is of the "intrafolial" type, similar to folds common in cataclastic rocks. *B*, *C*, Blastomylonite from the Towaliga fault zone in Alabama. *B* shows hand sample with straight fluxion structure overall and parallel color and compositional layering. *C* is an enlargement of part of *B*, showing intrafolial folds (f), and disruption of fluxion structure and layering around porphyroclasts. The swirled area(s) is a fold formed by differentially moving planes and then further rotated and "rolled up." *D*, Microdrawing of obsidian from Obsidian Canyon, Yellowstone National Park, showing an intrafolial style fold with crystallites oriented parallel to the axial plane. Elongated spherulites suggest late movement when the obsidian was in a semicrystalline state.

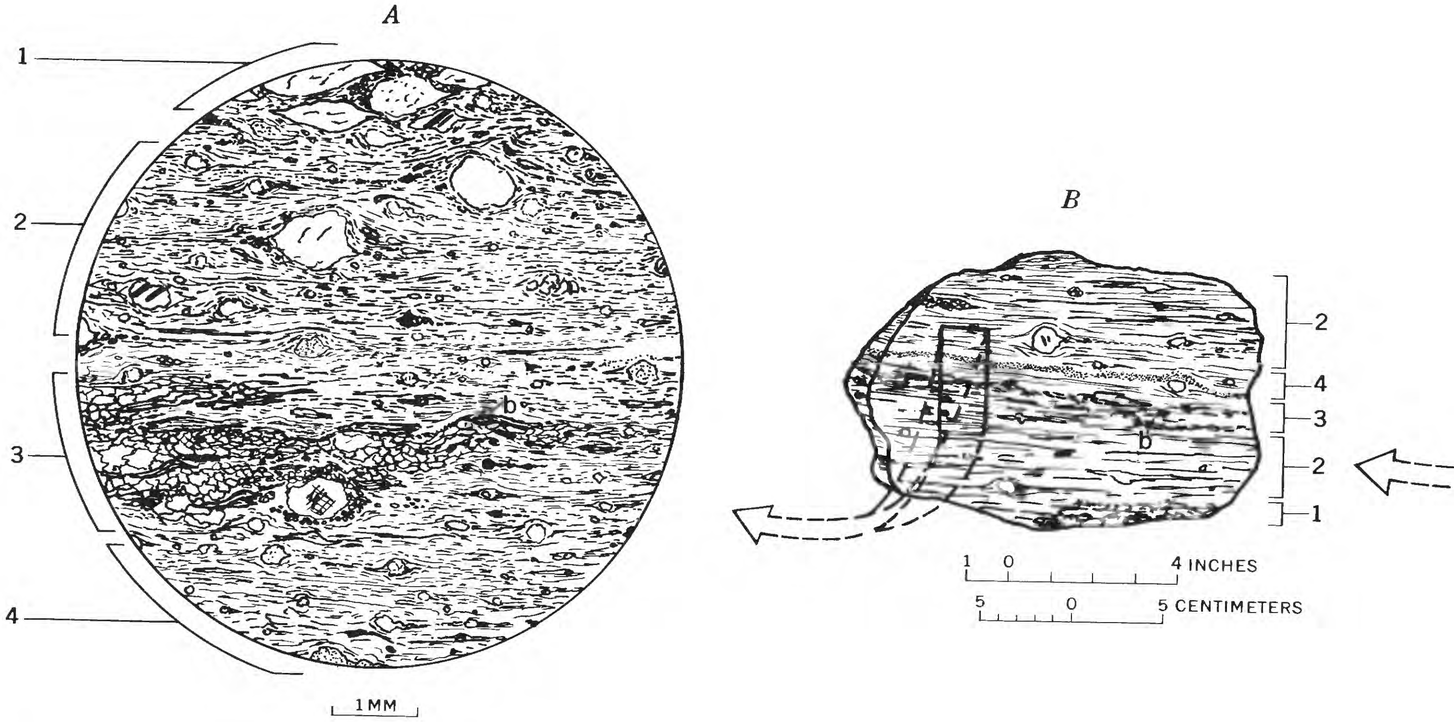
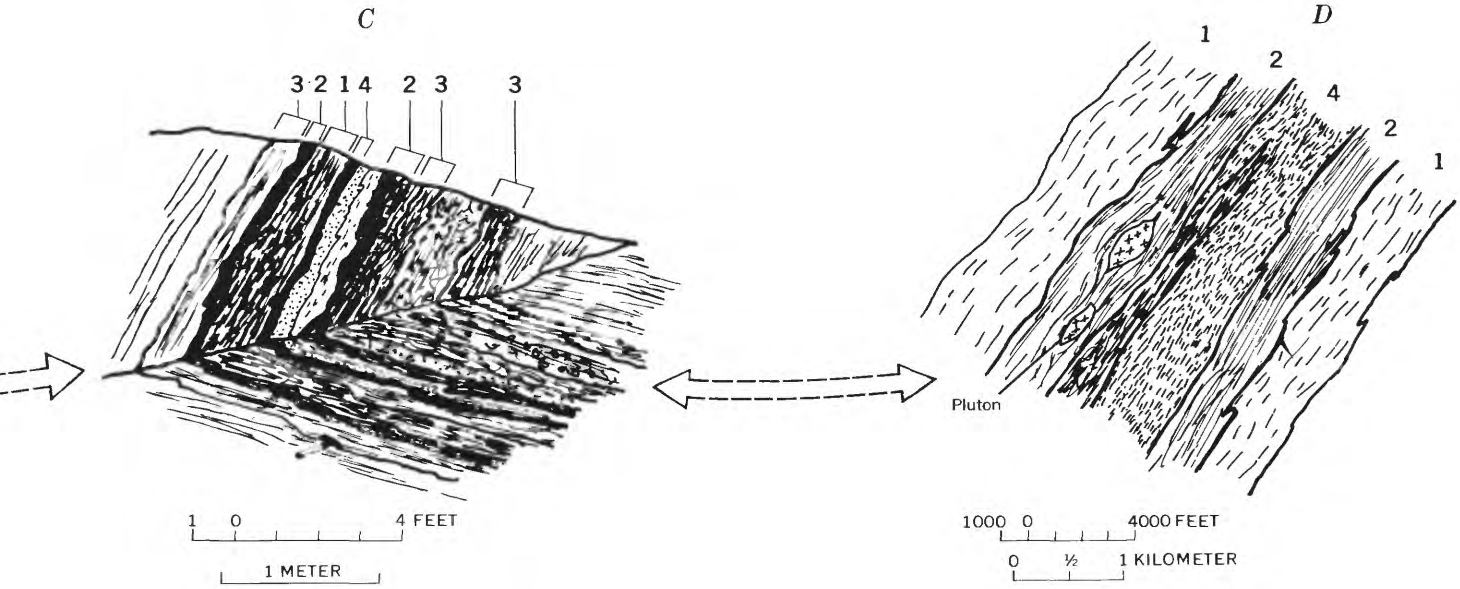


Figure 36.—Relations of various cataclastic textures in thin section (*A*), hand sample (*B*), outcrop (*C*), and on map (*D*). 1, Coarser graine
catclastic rock—chiefly blastomylonite (note biotite (b) in *A* and *B*) ; 4, fine- to very fine graine



cataclastic rock—chiefly protomylonite; 2, medium- to fine-grained cataclastic rock—chiefly mylonite; 3, recrystallized-neomineralized cataclastic rock—chiefly ultramylonite. Rock in all cases was originally a coarse-grained gneiss.

GLOSSARY

(Lower case boldface type is used for the cataclastic rock terms of table 1, Classification of Cataclastic Rocks, when they are defined in the glossary. Rock terms not used in the classification are in italics. Other terms are not in bold type or italics.)

"allure lenticulaire" (Knopf, 1931): The lenticular structure caused by isoclinal folding and cataclastic shearing-out (both generally and on a microscopic scale) of relatively resistant beds or layers of a rock during phyllonitization.

augen: A lenticular or rounded mineral or aggregate of minerals larger than the general groundmass grain size of a rock. Auge is German for eye, and augen in rocks are commonly eye-shaped, the spindle-shaped ends extending parallel to the foliation. Augen are most commonly of feldspar (particularly K-feldspar), and are most commonly present in gneisses. They may be porphyroblastic or porphyrociastic.

augen gneiss: A gneiss characterised by augen. Most augen gneisses are crystalloblastic and essentially noncataclastic; some are actually mylonite gneisses.

augen schist (Lapworth, 1885): Equivalent to mylonite gneiss. See **mylonite gneiss.**

compositional banding: See color lamination and layering.

Bewegungsbild (Sander, 1930): "Movement-picture". See movement picture.

blastomylonite: A coherent rock intermediate between medium- to fine-grained mylonite or ultramylonite and a crystalline schist or gneiss because its texture is the result of combined cataclastic and crystalloblastic processes. It is *not* produced by later recrystallization or neomineralization of a previously mylonitized rock; cataclasis and neomineralization-recrystallization are concurrent, producing a rock in which crystalloblastic texture appears to have overprinted the basic mylonite texture. Porphyroclasts in blastomylonite are generally smaller than about 0.5 mm and may show recrystallization. They make up less than about 30 percent of the rock. Discussion p. 13.

blastomylonitic gneiss (Reed and Bryant, 1964, p. 1181): ". . a gneissic rock consisting of 10–90 per cent porphyroclasts set in a matrix of blastomylonite."

blastophyllonite (Turner, 1941): Turner used this term for phyllonites with a high degree of neomineralization and recrystallization. The rocks are covered by the term blastomylonite as defined in this paper.

brecciated mylonite: A fault breccia composed of fragments of mylonite—a polycataclastic rock formed by the action of a second phase, episode, or period of cataclasis on a mylonite. Brecciated ultramylonite is similarly defined.

"button schist": A common field term for rocks in which micaceous porphyroclasts or porphyroblasts form button-like structures upon weathering. It is also used for rocks in which two cleavages intersect at an angle to produce button shaped or lens-shaped fragments (See Crickmay, 1952; Reed and Bryant, 1964; Higgins, 1966). Similar rocks have been called "wavy schist," 'frilled schist," "curly schist," "phyllonitic schist," "crumpled schist," "puckered schist," "eyed schist," "eyed phyllonite," "fish-scale schist," and "oyster-shell rock."

cataclasis: The process by which rocks are broken and granulated due to stress and movement during faulting; granulation or comminution. See p. 2.

cataclasite: An aphanitic, structureless cohesive cataclastic rock in which most of the fragments are less than about 0.5 mm, and make up less than about 30 percent of the rock. Essentially like a mylonite but lacking fluxion structure. Discussion p. 6.

cataclastic: Pertaining to rocks affected by cataclasis.

cataclastic foliation: Fluxion structure. See **fluxion structure.**

cataclastic metamorphic differentiation: metamorphic differentiation produced by cataclasis. See metamorphic differentiation.

cataclastic rock: A general term for any rock produced by cataclasis, regardless of whether or not the rock is coherent.

cohesion (coherent, cohesive): In this paper cohesion pertains to primary cohesion. See primary cohesion.

color lamination: Layering due to color differences, regardless of origin, in adjacent layers of rock whether on a megascopic or microscopic scale.

comminution: Reduction in size of the constituents of a rock due to cataclasis.

compositional layering: Layering due to chemical and mineralogical differences in the adjacent layers, regardless of origin. May include color lamination.

confining pressure: An equal, all-sided pressure. In the crust of the earth it is lithostatic pressure resulting chiefly from the load of overlying rocks. In experimental work it is a hydrostatic pressure, commonly produced by liquids.

"crumpled schist": A fairly common field name for phyllonitic rocks in which the lenticular structures may give rise to an uneven wavy surface. See "button schist."

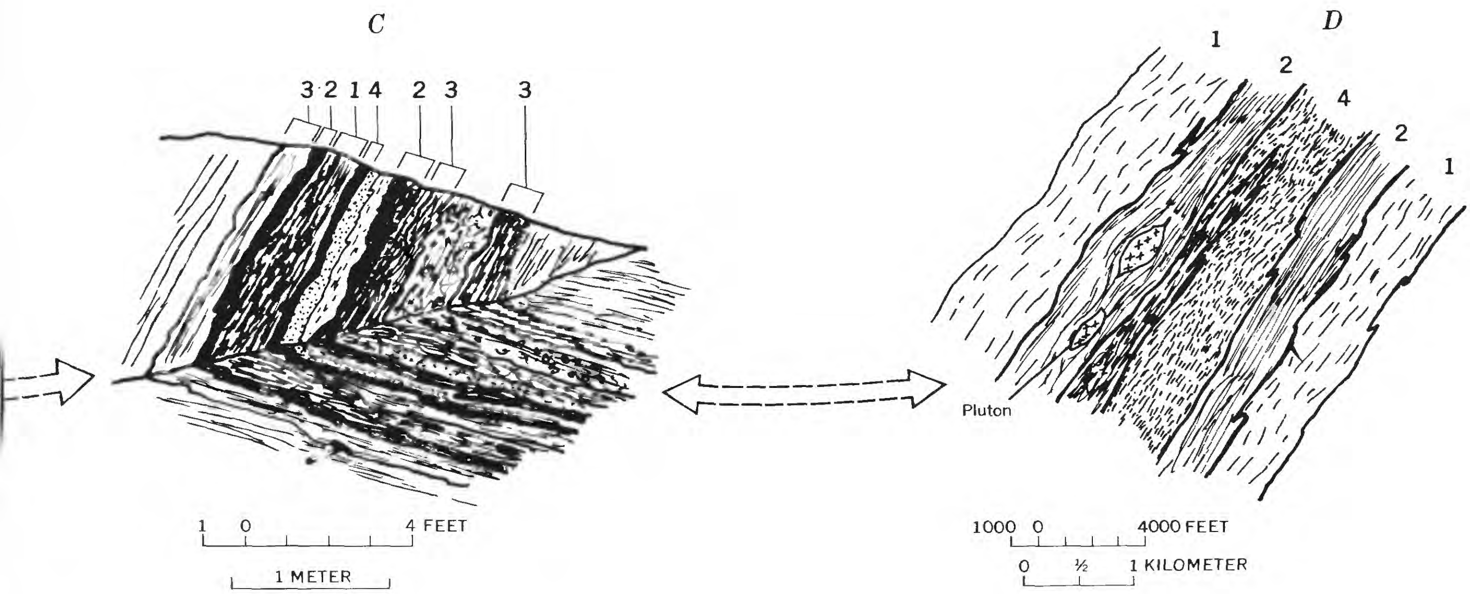
crush-breccia (Tyrrell, 1926): Equivalent to microbreccia. See **microbreccia.**

crush-rock: A field term used by early workers for many different kinds of cataclastic rock, but particularly for those without fluxion structure.

cryptomylonite (Scott and Drever, 1953): Essentially equivalent to flinty crush rock. See flinty crush-rock. Also see hyalomylonite.

crystalloblastic (Becke, 1904): A crystalline texture due to metamorphic growth of minerals in solid rocks by recrystallization and/or neomineralization. In this texture the essential constituents have crystallized simultaneously and not in sequence. A constructive texture as opposed to cataclastic texture which is chiefly destructive.

"curly schist": A fairly common field term for phyllonitic rocks in which lenticular structures may give the rock an uneven wavy surface upon weathering (see Reed, 1964). See "button schist."



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compositional layering: Layering due to chemical and mineralogical differences in the adjacent layers, regardless of origin. May include color lamination.

confining pressure: An equal, all-sided pressure. In the crust of the earth it is lithostatic pressure resulting chiefly from the load of overlying rocks. In experimental work it is a hydrostatic pressure, commonly produced by liquids.

"crumpled schist": A fairly common field name for phyllonitic rocks in which the lenticular structures may give rise to an uneven wavy surface. See "button schist."

crush-breccia (Tyrrell, 1926): Equivalent to microbreccia. See **microbreccia.**

crush-rock: A field term used by early workers for many different kinds of cataclastic rock, but particularly for those without fluxion structure.

cryptomylonite (Scott and Drever, 1953): Essentially equivalent to flinty crush rock. See flinty crush-rock. Also see hyalomylonite.

crystalloblastic (Becke, 1904): A crystalline texture due to metamorphic growth of minerals in solid rocks by recrystallization and/or neomineralization. In this texture the essential constituents have crystallized simultaneously and not in sequence. A constructive texture as opposed to cataclastic texture which is chiefly destructive.

"curly schist": A fairly common field term for phyllonitic rocks in which lenticular structures may give the rock an uneven wavy surface upon weathering (see Reed, 1964). See "button schist."

diaphthoresis (Becke, 1909): Retrogressive metamorphism. See p. 40–44.

diaphthorite: A rock with relict minerals of a higher grade or facies of metamorphism which have been changed or partly changed elsewhere in the rock by retrogressive metamorphism (diaphthoresis) to minerals of a lower grade or facies of metamorphism. Diaphthorites are not necessarily cataclastic. See p. 16–21.

diaphthoritic: Pertaining to rocks affected by diaphthoresis. See diaphthoresis.

diaphthoritic phyllonite: A phyllonite that shows evidence of diaphthoresis. See 16–21.

dike-mylonite (Hammer, 1914): An ultramylonite or mylonite that shows intrusive relations to the adjacent rock. The intrusive habit is due to flowage of crushed rock powder during cataclasis (see Crickmay, 1933; Knopf, 1931; Higgins, 1966) or to selective cataclasis of igneous dikes (see Peach and others, 1907). This term should not be used as a rock name because it merely denotes mode of occurrence.

dipsetic: dry; a condition of thirst; producing thirst. See Hsu (1955b, p. 272).

en echelon: Parallel but offset structural features; parallel features not in the same line.

episode: One of two or more divisible time or feature-producing units of a period of metamorphism or a period of deformation.

"eyed phyllonite": See "eyed schist."

"eyed schist" (Knopf, 1931): A cataclastic schistose or phyllonitic rock in which porphyroclasts or porphyroblasts, generally of mica, appear as "eyes" in the finer grained matrix. This is a fairly common field term, equivalent to "fish-scale phyllonite," to some "button schists," "curly schists," "wavy schists," and "oyster-shell rocks," and to the "phyllonitic schist" of Reed and Bryant (1964). See "button schist."

fabric: (Paterson and Weiss, 1961; Turner and Weiss, 1963) The fabric of a body is ". . . the internal geometric configuration of its elementary parts and of any characteristic features to which the arrangement of these parts gives rise." (Turner and Weiss, 1963, p. 19).

fault breccia: A rock composed of angular to rounded fragments, formed by crushing or grinding along a fault. Most fragments are large enough to be visible to the naked eye, and they make up more than 30 percent of the rock. Coherence, if present, is due to secondary processes.

fault gouge: Pastelike rock material formed by crushing and grinding along a fault. Most individual fragments are too small to be visible to the naked eye, and fragments larger than the average groundmass grains make up less than 30 percent of the rock. Coherence, if present, is due to secondary processes.

fault pug: Reed (1964, p. 652–654) used this term for shattered, altered, structureless rocks similar to fault gouge, but formed from schistose rocks. According to Reed, the rocks are incoherent, and are in the same category as fault breccias and fault gouge with regard to conditions of formation.

fault zone: As opposed to a fault which is by definition a plane of movement, a fault zone is a zone of faulting. A fault zone may consist of many separate fault planes concentrated in a relatively narrow zone or may be a zone of distributed movements with few or no distinct fault planes.

felsic: Refers to quartz, feldspars, and feldspathoids. The U.S. Geological Survey recommends the terms felsic and (or) silicic in place of "acid," because the former are more precise. For example, quartzites are silicic; rhyolites and granites are felsic.

"fish-scale phyllonite": See "eyed schist."

fissility (fissile): A property of splitting easily along closely spaced planes which may be parallel or may lie at low angles to one another. A rock with fissility is described as fissile.

"fissured and brecciated granite" (Termier and Boussac, 1911): Descriptive phrase used by some early workers for cataclastic rocks.

"flamboyant quartz": A descriptive term for the wavy stringers of strained or granulated quartz common to many blastomylonites and mylonite gneisses, and present in some mylonites.

flaser gneiss (Tyrrell, 1926): As Tyrrell used this term it is equivalent to mylonite gneiss and to some protomylonite. Tyrrell (1926, p. 286) defined flaser rocks as ". . . rocks in which lenticles of relatively-unaltered material are preserved in a finely crushed and partially-recrystallized matrix." Flaser is German for streaks or lenticles, and many geologists have used flaser gneiss, flaser rock, flaser gabbro, etc., for any streaked rock, regardless of the origin of the streaky, lenticular structure. (See Heinrich, 1956.)

flaser structure: See flaser gneiss.

flinty crush-rock (Clough, 1888, p. 22): Used by most early workers (see Clough, 1888; Peach and others, 1907, p. 124, 141, 151–153, 190, 196, 214–216, 244–250; Clough and others, 1909, p. 629–631; Jehu and Craig, 1923, p. 430–436, 1925, p. 629–630; Dougal, 1928) as a field term for many varieties of fine-grained, aphanitic, flinty-appearing cataclastic rock. Generally defined as a dark-colored, flinty or glassy rock found as veins and stringers associated with fault zones and formed by ultracrushing and partial fusion of finely comminuted rock powder along the fault zone. Some of the rocks called flinty crush-rock are intrusive (and even nonintrusive) finely comminuted mylonites and ultramylonites; others are pseudotachylite. Where melting or fusion can be proved, the term pseudotachylite should be used; where melting or fusion are absent, an applicable name from the classification (table 1) should be used, regardless of intrusive relationships. See discussion p. 21–30.

flow structure (flow-structure): See fluxion structure.

fluidization (Reynolds, 1954): An industrial process whereby gas is passed through fine-grained particles to facilitate movement or chemical reaction. Reynolds (1954) and Christie (1960) considered pseudotachylite a result of fluidization. See p. 30.

fluxion banding: See fluxion structure.

fluxion lines: Lines of minerals, grains, etc. defining fluxion structure. See fluxion structure.

fluxion structure (fluxion texture): Cataclastically produced directed penetrative texture or structure commonly involving a family or set of *s*-surfaces; cataclastic foliation. May be visible megascopically or only microscopically. Does not necessarily involve compositional layering or lamination, although many examples do show such layering. Discussion p. 3, 61. See color lamination and compositional layering.

foliation: Any type of recognizable *s*-surfaces of metamorphic (includes coherent cataclasis) origin.

form orientation: (after Sander, 1930) Directed penetrative texture; the fabric of a tectonite.

"frilled schist": See "button schist."

gangmylonite (Hammer, 1914): Equivalent to dike-mylonite. See dike-mylonite.

glide-fold schistosity (Gleitfaltschieferung): (Kienow, 1953; Christie, 1963) A schistosity developed by shearing of the limbs of small-scale folds. This schistosity is rapidly rotated toward the plane of the original schistosity. See p. 62 and figure 33.

gouge: See **fault gouge.**

gneiss: Relatively coarse grained metamorphic rock in which the schistosity and foliation are less well defined than in schist because of the preponderance of felsic minerals over micaceous minerals. Most gneisses are granitic in composition. Irregular to regular banding is common, but not requisite for use of the term "gneiss." Some gneisses are plutonic and should be so designated. Distinction from schist on one hand, and from granite on the other is arbitrary and gradational.

"granite": A general term referring to any medium- to coarse-grained, quartz- and feldspar-bearing, hypabyssal or plutonic-appearing rock.

granite: Specific name for a medium- to coarse-grained rock consisting of potassium feldspar and quartz with sodic plagioclase, typically oligoclase, present in distinctively lesser amounts than the potassium feldspar (according to Williams and others (1954), alkali feldspar constitutes more than two-thirds of the total feldspar); biotite, and (or) hornblende, and (or) muscovite are commonly present in accessory amounts. (See Dietrich and Mehnert, 1961).

granitic rock ("granitic rock"): General term for "granites." See "granite."

hartschiefer (Holmquist, 1910): Originally used for blastomylonites with well-developed parallel compositional layering or color lamination. Hartschiefer has also been used for rocks that are probably metamorphosed sediments, and for layered mylonites and ultramylonites. Discussion p. 30.

hyalomylonite (Scott and Drever, 1953): Essentially equivalent to pseudotachylite. Scott and Drever (1953, p. 123) stated: "The terms 'cryptomylonite' and 'hyalomylonite' will be used, respectively, for material the determination of which is hampered by its relative opacity, and to material characterised by an abundance of easily determinable glass." See pseudotachylite and discussion p. 21–30.

intrusive: Applies to a rock body that has moved from its place of origin into another rock.

kakirite (Svenonius, 1892): Svenonius used this term for many different kinds of cataclastic rock. Holmquist (1910) used it for cataclastic rocks without "parallel structure," and stated that kakirite has the structure of a "microbreccia." Holmquist's photomicrographs of "kakirite" (1910, p. 939) appear to be cataclasite. Quensel (1916, p. 100) stated that he agreed with Svenonius and Holmquist on the definition of kakirite, but defined it (1916, p. 99) as: "In einem in makroskopischen Dimensionen brecciierten Gestein sind die relativ weniger zertrümmerten Bruchstücke des Ausgangsmateriales auf allen Seiten von Rutsch- oder Kluftflächen umgeben, in denen eine intensive Zermahlung neben Mineralneubildung sich geltend macht." Translated into English this would imply that there are shear planes or gliding surfaces in the rock (see Waters and Campbell, 1935, p. 478; Christie, 1960, p. 83), thus making it more like protomylonite than like cataclasite.

lamination: See color lamination.

layering: See compositional layering.

lenticular structure (lenticular texture): Structure or texture characterized by lenses or lentils of rock material separated and defined by *s*-surfaces having doubly-convex relationships.

mafic: Refers to the dark minerals of a rock; minerals rich in iron and magnesium. The U.S. Geological Survey recommends the term mafic in place of basic, because it is more precise. For example, gabbros and basalts are mafic rocks.

"mashed gneiss": Field term used by early workers for various kinds of cataclastic rocks.

metamorphic differentiation (Stillwell, 1918): Refers to various processes by which contrasting mineral assemblages develop from an initially uniform rock during metamorphism. Discussion p. 62–64.

microbreccia: An intensively fractured but unground (fragments have not rolled) cohesive breccia in which the grains and fragments are without form orientation. Fragments may range from megascopic to about 0.2 mm and are separated by finer grained material. Fragments larger than 0.2 mm make up more than about 30 percent of the rock. Discussion p. 6.

micro-breccia (Tyrrell, 1926): Equivalent to microbreccia. See **microbreccia.**

monocataclastic: Applies to rocks that have been affected by only one episode, phase, or period of cataclasis.

monometamorphic: Applies to rocks that have been affected by only one episode, phase, or period of metamorphism.

mortar (Törnebohm, 1880): From Swedish *Murbruk* (mortar). Refers to fine-grained rock powder between porphyroclasts or within shears in a rock; like mortar between stones or bricks.

mortar structure (mortar texture) (Törnebohm, 1881): Refers to a structure or texture in rocks characterized by mortar between and around porphyroclasts, or filling shears between unground fragments of the rock. See mortar.

movement picture (Sander, 1930): The kinematic concept that the nature of the geometric order of a body reflects the geometric order of the differential displacements, rotations, and strains that must be present during deformation of a real polycrystalline body. See Turner and Weiss (1963, p. 9, 367–378).

mylonite: A coherent microscopic pressure-breccia with fluxion structure which may be megascopic or visible only in thin section and with porphyroclasts generally larger than 0.2 mm. These porphyroclasts make up about 10 to 50 percent of the rock. Mylonites generally show recrystallization and even new mineral formation (neomineralization) to a limited degree, but the dominant texture is cataclastic. Discussion p. 7.

mylonite gneiss (mylonite schist): A coherent rock intermediate between a protomylonite or coarse mylonite and a crystalline gneiss or schist because its texture is the result of combined cataclastic and crystalloblastic processes. Augen structure is characteristic, the augen generally being porphyroclasts or crushed aggregates of felsic minerals. The augen, although commonly recrystallized, preserve evidence of cataclastic texture by their shapes and by the crush trails commonly associated with them; the surrounding groundmass has been recrystallized and or neomineralized, although it too may show palimpsest cataclastic texture. Most of the porphyroclasts are larger than about 0.5 mm and they make up more than about 30 percent of the rock. Discussion p. 11–13.

mylonitschiefer (Quensel, 1916): Essentially equivalent to mylonite schist. See **mylonite gneiss (mylonite schist).** Also see discussion p. 11–13.

mylonitic: Meaning mylonitelike. Pertains only to protomylonites, mylonites, and ultramylonites.

mylonitization: The process by which mylonites are formed; a subdivision of the process of cataclasis which pertains only to the production of protomylonites, mylonites, and ultramylonites.

neomineralization: The process of metamorphic transformation of the old mineral constituents of a rock into new minerals of different composition; new mineral growth. Discussion p. 57.

neomineralization-recrystallization: Used in this paper for neomineralization and (or) recrystallation.

"*nodular mylonite*" (Raguin, 1926): Raguin used this term for course megascopic breccias. It is essentially equivalent to protomylonite. See **protomylonite.**

"*oyster-shell rock*" (Peach and others, 1907, p. 598): Essentially equivalent to "eyed schist." See "eyed schist" and "button schist."

period: Time or event of metamorphism or of deformation; separated from other periods by times of distinct nondeformation or nonmetamorphism; generally represents a long time and may be divisible into episodes, which may in turn be divisible into phases. See episode and phase.

phacoidal structure (Peach and others, 1907): Lenticular structure at outcrop scale, in which large lenticular (doubly convex) masses of unfoliated to poorly foliated rock are enclosed in sheared well-foliated rock. A sort of "mega-flaser structure." Well described (1907, p. 149, 169, 263, 504) and well illustrated (1907, p. 29) by Peach and others. Heinrich (1956) has used phacoidal in a microscopic sense for the textures of mylonite gneisses and related rocks. However, Peach and others (1907) apparently limited the term to outcrop-scale features, which seems desirable as there are other terms for the miscroscopic textures.

phase: Theoretically, the smallest divisible time or feature-producing unit of metamorphism or deformation; two or more phases form an episode. Something like a "pulse" of activity within the larger, longer event. See episode and period.

phyllitic: Phyllite-like; having the appearance of a phyllite.

phyllitic diaphthorite: A retrogressive metamorphic rock with the appearance of a phyllite. Not necessarily a cataclastic rock. See p. 16–21.

phyllonite: Phyllite-mylonite; A rock of phyllitic appearance formed by mylonitization of an originally coarser grained rock. See p. 16–21.

phyllonitic schist (Reed and Bryant, 1964): Reed and Bryant (1964, p. 1181) define phyllonitic schist as: ". . . a schist partly retrogressively metamorphosed to phyllonite and containing 10–90 percent porphyroclasts (chiefly of mica) in a matrix of phyllonite." They probably coined this term to avoid using such names as "eyed schist," "eyed phyllonite," and "button schist," previously used for rocks along the Brevard zone (see p. 49–51, this paper), and to express the retrogressive nature of the rocks. However, their definition carries the unfortunate connotation that phyllonites are produced by retrogressive metamorphism (see p. 11, 16–21, this paper). Phyllonitic schist is essentially equivalent to diaphthoritic phyllonite. See diaphthoritic phyllonite, and **phyllonite.**

phyllonitization: The cataclastic process by which phyllonite is produced. Essentially, mylonitization of a schistose or micaceous rock. Does not necessarily involve diaphthoresis. See mylonitization.

phyllonitized: Applies to a rock that has undergone phyllonitization. See phyllonitization.

plastic deformation: A permanent, nonelastic, change in shape of a solid that does not involve failure by rupture. It may involve recrystallization, gliding within individual crystals or grains, and rotation of grains. Diagrammatically, it is nonelastic deformation past the yield point.

"*plicated schist*": See "button schist."

polycataclastic: Applies to rocks that have been affected by more than one period or episode of cataclasis (as opposed to monocataclastic). See p. 30–31.

polyepisodic: Applies to rocks remetamorphosed during two or more episodes of metamorphism (polyepisodic metamorphic rocks), or to rocks affected by two or more episodes of cataclasis (polyepisodic cataclastic rocks).

polymetamorphic: Applies to rocks that have been affected by more than one period of metamorphism (as opposed to monometamorphic). See p. 30–31.

porphyroblast: A relatively large crystal or mineral grain developed during metamorphism by neomineralization and (or) recrystallization. Porphyroblasts are larger than the matrix which encloses them.

porphyroclast: A relatively large fragment of a crystal, mineral grain, or aggregate of crystals or grains, in a cataclastic rock. Porphyroclasts are not produced by neomineralization or recrystallization (as opposed to porphyroblasts), but may be recrystallized in blastomylonites and mylonite gneisses.

primary cohesion: Refers to congenital coherence of a rock, as opposed to that produced by secondary cementation. Essentially metamorphic cohesion.

protoclasis: Cataclasis of an igneous body, or parts of an igneous body, due to late intrusive movements of, or within, that body, generally before it has completely crystallized. See p. 13.

protoclastic rocks: The products of protoclasis are called protoclastic rocks. They may be indistinguishable from other cataclastic rocks, except for their intimate association with, or localization within, the parent igneous body. See p. 13.

protomylonite: A coherent crush-breccia composed of megascopically visible fragments which are generally lenticular and are separated by megascopic gliding surfaces filled with finely ground material. The fragments, or "megaporphyroclasts," make up more than about 50 percent of the rock. Protomylonite commonly resembles conglomerate or arkose on weathered surfaces. Features of the original rock, such as stratification and schistosity, may be preserved in the larger fragments. Discussion p. 7.

pseudoeruptive: Early workers used this term for cataclastic rocks showing intrusive relationships. Same as intrusive. See intrusive.

pseudointrusive: Early workers used this term for cataclastic rocks showing intrusive relationships. Same as intrusive. See intrusive.

pseudotachylite: A glassy rock generally resembling tachylite, commonly of intrusive habit and closely associated with faults or fault zones. The groundmass of the rock is composed mainly of glass which in some cases contains microlites of feldspar, vesicles, spherulites, amygdules, or partially melted rock and mineral fragments. The rock fragments may be cataclastic or undeformed. Pseudotachylite probably forms by melting due to frictional fusion during faulting of already-hot rocks; generally rocks heated by igneous intrusions. Discussion, p. 21–30.

"puckered schist": See "button schist."

purée parfaite (Termier and Boussac, 1911): Termier and Boussac used this term, which means "perfect soup," for rocks that are compact, finely-ground "microbreccias" in which the particles are so fine grained that the rocks resemble chert or hard wax. Essentially equivalent to cataclasite. See **cataclasite.**

recrystallization: Metamorphic crystallization of new mineral grains from old minerals of the same chemical constitution (for example, quartz from quartz); as opposed to neomineralization. See neomineralization.

retrograde: Applies to the products of retrograde metamorphism. See retrograde metamorphism.

retrograde metamorphism: The process by which rocks of a higher grade or facies of metamorphism are changed or partially changed to rocks of a lower grade or facies of metamorphism; diaphthoresis. The process is not necessarily related to or associated with cataclasis. See diaphthoresis and discussion p. 16–21.

retrograde rocks: See diaphthorite.

retrogressive: Retrograde.

s-surface (Sander, 1911): Any kind of penetrative planar structure in rocks.

schist: A schistose metamorphic rock whose main constituent minerals are visible in hand sample with the naked eye; platy and (or) micaceous minerals are generally the most important and abundant constituents. See gneiss.

schistosity: Foliation defined by platy and (or) micaceous minerals. See foliation.

"shatter granite": Field term used by early workers for various kinds of cataclastic rocks.

shear: The effect produced by action of a shearing stress. Verb: to subject a body to shear.

shearing stress: A stress causing or tending to cause two adjacent parts of a solid to slide past one another parallel to the plane of contact.

shear zone: A zone of shearing in rocks; essentially like a fault zone. but more specific because it excludes zones of faulting not associated with shear. See Sutton and Watson (1959, p. 4–5). See fault zone.

silicic: Refers to silica minerals, chiefly quartz; rocks are silicic if characterized by quartz. The U.S. Geological Survey recommends the term silicic in place of acid, because it is more precise. See felsic and mafic.

strain: Deformation resulting from applied force; the changes in geometric properties induced in a body in response to stress.

stress: Force per unit area of the surface to which it is applied; a body in equilibrium under the action of a system of forces is said to be in a state of stress (Turner and Weiss, 1963, p. 259).

structure: The mutual relationships in space (geometric configuration) of various components of a rock (crystals, parts of crystals, multigranular aggregates, or microscopically irresolvable groundmass materials), and any characteristic features to which the arrangement of these parts gives rise. Europeans have traditionally used *texture* for what Americans call *structure*, and vice versa. Here, following Turner and Verhoogen (1960), the two terms are considered interchangeable when applied to metamorphic rocks.

tachylite (tachylyte): Dark basaltic glass.

tectonic breccia: Same as fault breccia. See **fault breccia.**

texture: Interchangeable with structure with regard to metamorphic rocks. See structure.

tectonite (Sander, 1912, 1930): A rock whose "fabric clearly displays coordinated geometric features related to continuous flow during its formation." (Turner and Weiss, 1963, p. 39).

transposition foliation: See Umfaltungs-cleavage.

trap-shotten gneiss (King and Foote, 1864): A term used by early workers for dark-colored cataclastic rocks that show intrusive habit. See flinty crush-rock and discussion of pseudetachylite p. 21–30.

ultimate strength: The greatest stress that a substance can stand under normal short-time experiments. The highest point on a stress-strain curve.

ultramylonite: A coherent, aphanitic, ultracrushed pressure breccia with fluxion structure, in which most of the porphyroclasts have been reduced to breccia streaks and the few remaining porphyroclasts are smaller than 0.2 mm. These porphyroclasts make up less than about 10 percent of the rock. As in protomylonite and mylonite, recrystallization-neomineralization is present but is subordinate to cataclastic texture. In hand specimen and outcrop, ultramylonites are commonly homogeneous-appearing rocks (although many have compositional layering), easily confused with chert, quartzite, or felsic volcanic rock. Ultramylonite represents the highest stage in intensity of mylonitization in the series *protomylonite-mylonite-ultramylonite*. Discussion p. 9–11.

Unfaltungs-cleavage (Umfaltungsclivage—Sander, 1911, 1923): (Knopf, 1931) The final stage of strain-slip cleavage in which the old *s*-planes are completely transposed by folding and shearing. (Turner and Weiss, 1963, p. 92) ". . . *transposition* of an initial layering or foliation from one dominant orientation to another, with the appearance of what is effectively a new foliation discordant to the rotated gross orientation of the initial layering." See glide-fold schistosity.

uniform flow: Macroscopically homogeneous plastic deformation. The part of the stress-strain curve past the yield point.

"*wavy schist*": See "button schist."

ANNOTATED BIBLIOGRAPHY

Like most bibliographies this one is incomplete. I have made no attempt to include every publication in which cataclastic rocks are mentioned but not described. In addition, I have undoubtedly missed many publications in which cataclastic rocks are described as part of a general study of an area or problem. Many Russian and Italian contributions have probably also been overlooked.

No attempt is made to completely abstract the articles in this bibliography. The annotations are, in most cases, intended only to give the user an idea of what the article is about and to cite, where possible, some of its chief contributions.

It is not the purpose of this bibliography to cover all the experimental work that might be related to cataclastic rocks. Generally, studies of specific minerals have been excluded; most of the references included pertain to rock deformation. Many of the experimental references are not annotated, either because the title is sufficient, or because the data are so voluminous as to make annotation impractical.

Adams, F. D., 1896, Geology of a portion of the Laurentian area lying to the north of the island of Montreal: Canada Geol. Survey Ann. Rept., v. 8, pt. J, 184 p.

Granulated anorthosites are attributed to protoclasis. Of historical interest as the first description of cataclastic rocks in Canada. See especially p. 106–115.

——— 1910, An experimental investigation into the action of differential pressure on certain minerals and rocks, employing the process suggested by Professor Kick: Jour. Geology, v. 18, p. 489–525.

One of the earliest experimental studies; chiefly of historical interest.

Adams, F. D., and Bancroft, J. A., 1917, On the amount of internal friction developed in rocks during deformation and on relative plasticity of different types of rocks: Jour. Geology, v. 25, p. 597–637.

Chiefly of historical interest. One of the first references to experimentally produced mylonitic texture. Deformed rocks at room temperature under confining pressure.

Alf, R. M., 1943, Mylonites in the eastern San Gabriel Mountains: California Jour. Mines and Geology, v. 39, no. 2, p. 144–151.

Brief field and petrographic description of protomylonites, mylonites, and ultramylonites in Evey Canyon, San Gabriel Mountains, Calif.

——— 1948, A mylonite belt in the southeastern San Gabriel Mountains, California: Geol. Soc. America Bull., v. 59, no. 11, p. 1101–1120.

Describes protomylonites, mylonites, and ultramylonites in several cataclastic rock zones in a 50-square-mile area of the southeastern San Gabriel Mountains, including Cucamonga and San Antonio Canyons. *Mylonite* is used as a general term. "Chemical analyses and other data indicate that the mylonites were derived chiefly from a dark quartz diorite, and to a lesser extent from a paler quartz monzonite, without much mixing of the two source materials. The mylonite zones were intruded by the quartz monzonite and probably by the quartz diorite. Possibly the main mass of mylonite was formed by the crushing of a barely consolidated upper portion of a quartz diorite pluton, as one or more tectonic episodes during the general period of plutonic intrusion" (part of author's abstract). Good photomicrographs. See also Hsu, 1955b.

Aloisi, Piero, 1910. Le cosi-dette Miloniti dell' Isola d'Elba: Soc. toscana di. Sci. Nat., Atti, Mem. 27, p. 3–16.

Description of cataclastic rocks in a zone on the island of Elba. Disagrees with Termier (1909a, b, c) with regard to the thickness of the zone and the conditions of cataclasis.

Ambrose, J. W., 1936, Progressive kinetic metamorphism in the Missi Series, near Flinflon, Manitoba: Am. Jour. Sci., 5th ser., v. 32, no. 190, p. 257–286.

Attributes progressive metamorphism (garnet grade) to heat developed by shearing.

Anderson, G. H., 1934, Pseudo-cataclastic texture of replacement origin in igneous rocks: Am., Mineralogist, v. 19, no. 5, p. 185–193.

Good discussion of cataclastic textures. Describes pseudocataclastic textures in which there is commonly corrosion of primary grains by solutions instrumental in depositing the matrix. Grain boundaries and contacts are not formed by pressure alone. New minerals are abundant. Plagioclase twin lamellae and quartz grains show little or no evidence of strain. "* * * pseudocataclastic texture is often well-developed where evidences of mechanical stress are absent" (p. 191).

Andreatta, Ciro, 1952, Polymetamorphose und Tektonik in der Ortlergruppe (Vortragsinholt, Bonner Kolloquim 1951): Neues Jahrb. Mineralogie, Monatsh., no. 1, p. 13–28.

——— 1954a, Stoffmobilisterungen und Stoffbewegungen bei der tektonischen Metamorphose: Neues Jahrb. Mineralogie, Monatsh., no. 1–2, p. 2–17.

Deals with chemical changes during metamorphism due to tectonic movements ("tectonic metamorphism").

——— 1954b, Appunti sul metamorfismo; I, Mobilizzazione e movimenti di materia nel metamorfismo tettonico: Soc. Miner. Italiana, Rend. an. 10, p. 45–61.

Concludes that during tectonic metamorphism ions and groups of ions move in aqueous solutions from one place in a rock mass to another and form crystal structures oriented by pressure.

——— 1954c. Bemerkungen über die Metamorphose; 1, Stoffmobilisierung und Stoffbewegungen bei der tektonischen Metamorphose: Fortschr. Mineralogie, v. 32, p. 56–57.

Attempts to define the conditions under which changes of structure and composition of rocks can take place during metamorphism caused by tectonic activity.

Andreatta, Ciro, 1962. Id polymetamorfismo nel quadro dei problemi concernenti la poligenesi della rocce. Der Polymetamorphismus im Rahmen der Probleme, welche die Polygenesis der Gesteine betreffen: Acta. Geol. Alpina, no. 8, p. 81–92.

Good discussion of polymetamorphism.

Angel, Franz, 1931, Einige neuerliche Pseudotachylytefunde in den östereichischen Zentralalpen; Geol. Bundensanst. Wien Verh., p. 143–153.

Describes partially fused cataclastic rocks in the Alps.

——— 1965, Retrograde Metamorphose und Diaphthorese: Neues Jahrb. Mineralogie Abh., v. 102, p. 123–176.

Mineralogical and chemical discussion of retrogressive metamorphism. "There exist several kinds of retrograde metamorphism, of which diaphthoresis is but a special case, and progressive-final-retrograde metamorphism another" (part of author's abstract). He questions the classical "depth-zone" concepts.

Armstrong, Elizabeth, 1941, Mylonization of hybrid rocks near Philadelphia, Pennsylvania: Geol. Soc. America Bull., v. 52, no. 5, p. 667–694.

Describes "vertical, winding myonite zones" which "outline lenticular masses of less sheared rocks and in some places attain a thickness of a quarter of a mile" (part of author's abstract). Notes presence of some porphyroblasts in the cataclastic rocks (p. 679). Describes folds in the mylonites (p. 680). Uses *mylonite* as a general term for various cataclastic rocks, most of which appear to be blastomylonites. Photomicrographs and outcrop photographs.

Backlund, H. (Helge) G., 1913, Algunas observaciones sobre rocas notables, provenientes de Olavarria (Buenos Aires): Argentine Republic Dirección General de Minas, Geologia e Hidrología, Bol. no. 2, ser. B, 37 p.

Describes intrusive phenomena shown by a thick band of mylonites and ultramylonites south of Buenos Aires, Argentina. Suggests fusion as an explanation for the black, cherty crush rocks produced from red and gray granites. Good review of other cataclastic rock zones known at that time, and good discussion of various cataclastic rocks and their nomenclature. Hand-sample photographs. It should be noted that Waters and Campbell (1935, p. 481) confuse this reference with Baklund (1924).

Backlund, H. (Helge) G., 1918, Petrogenetische Studien an Taimyrgesteinen: Geol. Fören. Stockholm Förh., v. 40, p. 101–203.

Discusses some of the thicker mylonite units described at that time and the confusion resulting from mistaking these bands of cataclastic rock for stratigraphic horizons.

Backlund, H. G., 1924; *see* Baklund, O. O., 1924.

Bailey, S. W., Bell, R. A., and Peng, C. J., 1958, Plastic deformation of quartz in nature: Geol. Soc. America Bull., v. 69, no. 11, p. 1443–1466.

Baklund, O. O. [Backlund, H. (Helge) G.], 1924, O milonitakh i tektonitakh [On mylonites and tectonites]: Mineralogicheskoe Obshchestvo, Leningrad, Zapiski, ser. 2, v. 52, p. 145–168.

Original definition of *protomylonite*. Describes protomylonites on Cape Chelyuskin-Sarya, U.S.S.R., on the northern tip of Asia. Emphasizes the coarse brecciation and the resemblance to conglomerate. Implies in the prefix *proto* that the rock is first in a series (protomylonite-mylonite-ultramylonite). Helge G. Backlund was called O. O. Baklund by the Russians; see note under Backlund (1913) regarding confusion of references.

Barber, A. J., 1965, The history of the Moine thrust zone, Lochcarron and Lochalash, Scotland: Geologists' Assoc. Proc., v. 76, pt. 3, p. 215–242.

Describes mylonites, phyllonites, and brecciated mylonites. Notes that most of the cataclastic rocks are recrystallized. Good description of the gradation between unmylonitized metamorphosed sandstone and the same sandstone after mylonitization. Folded cataclastic rocks are also described.

Bateman, J. D., 1940, An Archean mylonite from northwestern Ontario: Am. Jour. Sci., v. 238, no. 10, p. 742–750.

Describes a 1,500-foot-wide zone of cataclastic rock. Chemical analyses of parent rock and cataclastic rocks indicate that loss of silica was the only bulk chemical change during cataclasis.

Bearth, Peter, 1933, Über Gangmylonite der Silvretta : Schweizer. Mineralog. Petrog. Mitt., v. 13, p. 347–355.

Describes pseudotachylite veins ("gangmylonite") in amphibolites and paragneisses at the base of the Silvretta nappe. Does not accept the idea of fusion in their genesis.

Becke, Frederich, 1909, Über Diaphthorite: Tschermaks mineralog. Petrog. Mitt., v. 27, p. 369–377.

First recognition of retrograde metamorphism. Describes diaphthoritic phyllonites produced from high-grade gneisses. First definition of *diaphthorite* from the Greek root, meaning "to destroy." Defines as diaphthorites those crystalline schists in which the index minerals of a lower grade (zone) have been developed at the cost of minerals peculiar to an upper zone.

——— 1913, Übersicht der petrographischen Verhältnisse, *in* Becke, Frederich, Himmelbauer, A., Reinhold, C., and Görgey, R., Das niederösterreiche Waldviertel: Tschermaks mineralog. Petrog. Mitt., v. 32, p. 185–217.

Discusses the chemical-mineralogical objections to explaining the chemical changes in the Moldanubian block described and discussed by Suess (1913) and Kölbl (1922) as due to mechanical disturbance. Interprets the mica schists and gneiss as belonging to the same formation, but differing in reaction to the primary metamorphism because they represent layers originally of different composition. Good discussion of chemical changes during dynamic metamorphism.

Becke, Frederich, 1916, Fortschritte auf dem Gebiete Metamorphose: Fortschr. Mineralogie, Kristallographie, Petrographie, v. 5, p. 210–264.

Discusses possible chemical changes due to mylonitization. See particularly p. 234–238.

Bennington, K. O., 1956, Role of shearing stress and pressure in differentiation as illustrated by some mineral reactions in the system BgO-Sio_2-H_2O: Jour. Geology, v. 64, no. 6, p. 558–577.

Proposes a mechanism for differentiation due to shearing. The development of layering and more massive lenticular differentiation under prolonged shearing stress and high pressure is considered. Suggests that shear-differentiation accounts for the areal distribution of many serpentinites and dunites.

Bentley, R. D., 1969, Strike slip faults in Lee County, Alabama [abs.]: Geol. Soc. America, Abstracts with Programs for 1969, pt. 4, p. 5.

Describes three major fault zones, Towaliga, Goat Rock, and Bartletts Ferry fault zones, in the Alabama Piedmont, and the cataclastic rocks found in these zones (see Examples section of text).

Berg, George, 1912, Die krystallinen Schiefer des östlichen Riesengebirges: Preussische geol. Landesanst. Abh., new ser., v. 68, p. 1–188.

See comment after entry of Berg, 1923.

——— 1923, Der Granit des Riesengebirges und seine Ganggesteine: Preussische geol. Landesanst. Abh., new ser., v. 94, p. 1–90.

This paper and Berg (1912) give results of a study of the Riesen area, Germany. Description of epizonal diaphthoresis of the metamorphosed margin of a granite pluton.

Beringer, C. C., 1943, Geologisches Wörterbuch: Stuttgart, Ferdinand Enke Verlag, 154 p.

Defines *diaphthorite* on p. 28.

Bisschoff, A. A., 1963, The pseudotachylite of the Vredefort dome: Geol. Soc. South Africa Trans., v. 65, p. 207–230.

Suggests gas-fluxing as origin of pseudotachylite.

Bonney, T. G., 1886, The anniversary address of the president, Prof. T. G. Bonney: Geol. Soc. London Quart. Jour., v. 42, Proc., p. 38–115.

"Pressure Metamorphism" p. 94–101; excellent descriptions and discussions of cataclastic rocks, in England and continental Europe. Describes phyllites (phyllonites) produced by comminution of granitic gneisses.

———1902, On the relation of certain breccias to the physical geography of their age: Geol. Soc. London Quart. Jour., v. 58, p. 185–203.

Borg, I. Y., and Handin, John, 1966, Experimental deformation of crystalline rocks: Tectonophysics, v. 3, no. 4 (spec. issue), p. 249–368.

Describes deformation under "shallow" conditions (1kb, 150°C) of 18 igneous and metamorphic rocks, and under "deep" conditions (5kb, 500°C) of the minerals biotite and plagioclase.

Borg, I. Y., and Turner, F. J., 1953, Deformation of Yule Marble, Part VI, Identity and significance of deformation lamellae and partings in calcite grains: Geol. Soc. America Bull., v. 64, no. 12, pt. 1, p. 1343–1352.

Born, Axel, 1925. Gefügesftudien an Gesteinen des Varistischen Gebirges: Neues Jahrb. Mineralogie, Beilage-Bd., v. 52, Abt. B, p. 123–161.

Describes slaty cleavage and its development. Good discussion of neomineralization.

Bowden, F. P., Stone, M. A., and Tudor, G. K., 1947, Hot spots on rubbing surfaces and the detonation of explosives by friction: Royal Soc. (London) Proc., v. 188, p. 329–349.

Frictional production of hot spots on moving surfaces.

Bowden, F. P., and Tabor, D., 1950, The friction and lubrication of solids: Oxford, Oxford Univ. Press, 372 p.

Detailed consideration of friction.

Bowden, F. P., and Thomas, P. H., 1954, The surface temperature of sliding solids: Royal Soc. (London) Proc., v. 223, p. 29–40.

If two polished surfaces are rubbed together at speeds as low as 1 or 2 feet per second, and under a load of 1,000 grams, visible hot spots will appear.

Bowen, N. L., and Aurousseau, M., 1923, Fusion of sedimentary rocks in drill holes; Geol. Soc. America Bull., v. 34, no. 3, p. 431–448.

Describes rocks fused by rotation of the core barrel of a rotary oil drill, giving chemical analyses and results of various laboratory tests.

Bridgman, P. W., 1935, Effects of high shearing stress combined with high hydrostatic pressure: Phys. Rev., v. 48, p. 825–847.

——— 1936, Shearing phenomena at high pressure of possible importance to geology: Jour. Geology, v. 44, no. 6, p. 653–669.

Brögger, W. C., 1890, Die Mineralien der Syenitpegmatitgänge de Südnorwegischen Augit- und Nephelinsyenite; allgemeiner Teil: Zeit. Krystallographie u. Mineralogie, v. 16, p. 104–120.

First used the word *protoclastic*, p. 105.

Bryant, Bruce, 1966, Formation of phyllonites in the Grandfather Mountain area, northwestern North Carolina: U.S. Geol. Survey Prof. Paper 550–D, p. D144–D150.

Detailed discussion of chemical conditions and changes during phyllonitization. Also describes physical aspects of phyllonitization.

Bryn, K. O., 1959, Et funn av pseudotachylitt i S. Trøndelag, og en teori for dannelson: Norges Geol. Undersøkelse, no. 211 (Årbok 1959), p. 8–17.

Describes and gives analyses of pseudotachylites from localities in Norway and concludes that they formed by fusion of the rocks at local "hot spots" in a fault zone. Gives no proof of fusion.

Buddington, A. F., 1939, Adirondack igneous rocks and their metamorphism: Geol. Soc. America Mem. 7, 354 p.

Detailed descriptions of cataclastic and protoclastic rocks. Definitions (in the sense he uses them, p. 252–253): *mortar gneiss, augen gneiss, mylonite, ultramylonite, ultracataclastic mylonite, flaser gneiss, granoblastic gneiss*. Uses *ultramylonite* for rocks without fluxion structure, and *ultracataclastic mylonite* for finely comminuted rocks with fluxion structure. Good discussions of recrystallization and crystalloblastic growth. Notes a concentration of magnetite in many of the cataclastic rocks (p. 317).

Burton, C. K., 1965, Wrench faulting in Malaya: Jour. Geology, v. 73, no. 5, 781–798.

Describes major wrench-faults with shearing and chloritization of the rocks along them.

Butler, J. R., and Dunn, D. E., 1968, Geology of the Sauratown Mountains anticlinorium and vicinity, North Carolina: Southeastern Geology, Spec. Pub. 1, p. 19–47.

Describes the Stony Ridge fault zone in North Carolina. Microbreccias and cataclasites, which are referred to as mylonites, are described and illustrated in drawings (p. 33). Some of the rocks appear to be polycataclastic.

Carstens, C. W., 1925, Zur Frage der Genesis der Eisenerzvorkommen von Fosen, Norwegen: Zeit. Praktisch Geologie, v. 33, p. 94–102.

Discusses the possibility of chemical changes during mylonitization. Concludes that some changes can generally be noted between cataclastic rocks and their parent rocks but gives no satisfactory explanation for the changes.

Carter, N. L., Christie, J. M., and Griggs, D. T., 1964, Experimental deformation and recrystallization of quartz: Jour. Geology, v. 72, no. 6, p. 687–733.

Carter, N. L., and Friedman, Melvin, 1965, Dynamic analysis of deformed quartz and calcite from the Dry Creek Ridge anticline, Montana: Am. Jour. Sci., v. 263, no. 9, p. 747–785.

Case, J. B., 1922, Notes on the use of core barrel with rotary tools: California State Mining Bur. Summary of Operations California Oil Fields, v. 7, no. 9, p. 6–7.

Brief description of fused rocks produced by friction from rotation of the core barrel of a rotary drill.

Christie, J. M., 1958, Dynamic interpretation of the fabric of dolomite from the Moine thrust-zone in north-west Scotland: Am. Jour. Sci., v. 256, no. 3, p. 159–170.

——— 1960, Mylonitic rocks of the Moine thrust-zone in the Assynt region, north-west Scotland: Edinburgh Geol. Soc. Trans., v. 18, pt. 1, p. 79–93.

Considers the terminology, classification, and characteristics of cataclastic rocks. Uses *mylonitic rocks* as a general term for all cataclastic rocks. Descriptions, illustrations, and theories of the origin of cataclastic rocks in the Moine thrust area. Quoted and cited widely in this text.

——— 1963, The Moine thrust zone in the Assynt region, northwest Scotland: California Univ. Pubs. Geol. Sci., v. 40, no. 6, p. 345–419.

Detailed description, petrofabric study, and petrogenetic consideration of cataclastic rocks in the Moine thrust zone. Uses nomenclature of Christie, 1960. Quoted and cited widely in this text.

——— 1967, The structure of mylonite zones and their tectonic implication [abs.]: Am. Geophys. Union Trans., v. 48, p. 214.

In many fault zones, high-grade mineral assemblages crystallized *during* deformation. The mylonite zones formed contemporaneously with regional metamorphism of the rocks on one or both sides of the zone. Interprets the structure of "mylonite zones" in terms of a model in which subcrustal convection is the cause of orogeny.

Clarke, J. W., 1952, Geology and mineral resources of the Thomaston quadrangle, Georgia: Georgia Geol. Survey Bull. 59, 99 p.

Describes and illustrates cataclastic rocks along the Towaliga and Goat Rock fault zones in the Georgia Piedmont. Good descriptions of progressive cataclasis of several types of rock, and the reactions of various minerals to this comminution. Describes and illustrates "button schists." Quoted and cited in this text.

Clough, C. T., 1888, The geology of the Cheviot Hills: England and Wales Geol. Survey Mem., 60 p.

(especially p. 22–24). First definition of *flinty crush-rock* as "A dark-colored flinty, or quartzite-like rock found as veins and stringers adjacent to fault zones, and formed by ultra-crushing and perhaps partial fusion of the finely comminuted rock powder along the fault" (p. 22). Also uses *flinty crush-rock* as a general term for many types of cataclastic rock.

Clough, C. T., Maufe, H. B., and Bailey, E. B., 1909, The cauldron subsidence of Glen Coe, and the associated igneous phenomena: Geol. Soc. London Quart. Jour., v. 65, p. 611–676.

Describes cataclastic rocks in conjunction with study of the caldera in the Northwest Highlands of Scotland. In the Glen Coe "flinty crush-rocks," fragments of quartz embedded in a fine-grained groundmass showing perfect flow structure are commonly free from any strain shadows. Concludes that the rock has been partially fused, and suggests that small microlites in the groundmass developed by contact metamorphism due to later intrusions.

Conley, J. F., and Drummond, K. M., 1963, Brecciated dikes in the southern Piedmont and mountain regions of North Carolina [abs.]: Geol. Soc. America, Spec. Paper 76, p. 241.

See Conley and Drummond, 1965.

——— 1965, Ultramylonite zones in the western Carolinas: Southeastern Geology, v. 6, no. 4, p. 201–211.

Describes and illustrates cataclastic rocks occurring as dikelike bodies as much as 27 miles long. The terms *mylonite* and *ultramylonite* are incorrectly used for microbreccias and cataclasites. Except for this inaccuracy, the descriptions are good.

Conybeare, C. E. B., and Campbell, C. D., 1951, Petrology of the red radioactive zones north of Goldfields, Saskatchewan: Am. Mineralogist, v. 36, nos. 1–2, p. 70–79.

Good descriptions of cataclastic rocks.

Cornelius, H. P., 1925, Über einige Gesteine der 'Fedozserie' aus dem Disgraziagebiet (Rhätische Alpen): Neues Jahrb. Mineralogie Beilage Bd., v. 52, Abt. A, p. 1–50.

Describes pseudotachylite.

Corstorphine, G. S., 1897, Report of the Geologist to the Commission: Cape of Good Hope Geol. Comm. Ann. Rept., p. 3–43.

Summary of geologic knowledge of southwestern Cape of Good Hope area, South Africa, to 1897. Mentions sheared granites and states that the shearing is " * * * due most probably to movement while consolidation was going on * * *."

Crickmay, G W., 1933, The occurrence of mylonites in the crystalline rocks of Georgia: Am. Jour. Sci., 5th ser., v. 26, no. 152, p. 161–177.

Describes cataclastic rocks from several Georgia fault zones. Well illustrated. Describes intrusive, branching, dikelike, unfused "mylonites." Notes resistance of feldspar to comminution as opposed to quartz and attributes the difference to original larger grain size of the feldspar, so that ". . . preferential cataclasis proceeds to reduce the smaller grains first to the state of a mylonite" (p. 177). Good discussions of cataclasis. Gives some criteria for distinguishing cataclastic rocks from volcanic rocks. Quoted and cited widely in this text.

——— 1952, Geology of the crystalline rocks of Georgia: Georgia Geol. Survey Bull. 58, 54 p.

Describes several cataclastic rock zones in Georgia. Good description of "button schists."

Dalziel, I. W. D., and Bailey, S. W., 1968, Deformed garnets in a mylonitic rock from the Grenville Front and their tectonic significance: Am. Jour. Sci., v. 266, no. 7, p. 542–562.

Terminology of Christie (1960) for cataclastic rocks is used. Brief description of blastomylonites along the Grenville Front in Canada. X-ray study of garnets in blastomylonites along with detailed structural information. ". . . the deformation of garnet in the mylonitic rocks near Coniston must have taken place under relatively high temperature/low strain rate conditions" (p. 560). Conclude that garnets may be of use as deformation ellipsoids: "The crystals have no crystallographic preferred orientation, but where bend axes in the structure can be detected on Laue photographs, they consistently lie in the mylonitic foliation nearly normal to a prominent regional lineation (elongation of quartz and porphyroclastic feldspar grains)" (authors' abstract). It should be noted that the "porphyroclastic feldspar grains" appear recrystallized in their photomicrographs; in fact, the rocks appear to be blastomylonites.

Demay, A., 1927, La zone mylonitique de Grimaud, et la tectonique du massif des Maures: Geol. Soc. France Bull., ser. 4, v. 27, p. 279–336.

Describes a 100-meter-thick band of "mylonite" derived from gneiss in the Pyrenees. Good petrographic descriptions.

de Sitter, L. U., 1964, Structural geology (2d ed.): New York, McGraw-Hill Book Co., 530 p.

Describes and defines some cataclastic rocks (p. 77–78): *tectonic breccia, mylonite, ultramylonite, pseudotachylite.* The definitions are very general. Gives examples of some cataclastic ("mylonite") zones (p. 78–79, 164, 414–418).

Dibblee, T. W., Jr., 1967, Areal geology of the western Mojave Desert, California: U.S. Geol. Survey Prof. Paper 522, 153 p.

Several zones of "mylonitic rocks" are described (p. 9).

Dietrichson, Brynjulf, 1953, Pseudotachylit fra de kaledonske skyvesoner i Jotunheimens forgårder, Gudbrandsdalen, og deres dannelsesbetingelser: Norges Geol. Undersøkelse, no. 184, p. 23–70.

Describes pseudotachylites from localities in Norway.

Dougal, J. W., 1928. Observations on the geology of Lewis (Outer Hebrides): Edinburgh Geol. Soc. Trans., v. 12, p. 12–18.

Describes a thick zone of "flinty crush-rock." Concludes that the rock formed by fusion during Caledonian thrusting. Good photomicrographs of stellate groupings of hornblende crystals in some of the "flinty crush-rocks."

Eskola, Pentti, 1920, Mineral facies of rocks: Norsk Geol. Tidsskr., v. 6, p. 143–194.

Describes "armored relics" of garnet enveloped in chlorite and explains how the retrogression at first tends to destroy the garnet, but the product of the retrogression (chlorite) protects the garnets from further destruction and preserves them as evidence of a higher grade. This enables recognition of the diaphthoresis.

——— 1932, On the principles of metamorphic differentiation: Finland Comm. Géol. Bull. 97, p. 68–77.

A classic discussion of metamorphic differentiation. Particularly good for chemical considerations.

——— 1939, *in* Barth, T. F. W., Correns, C. W., and Eskola, Pentti, Die Entstehung der Gesteine: Berlin, Springer, p. 263–407.

Classic discussion of metamorphic principles, including retrogressive metamorphism.

Eyles, V. A., and MacGregor, A. G., 1952, The Great Glen crush-belt: Geol. Mag., v. 89, no. 6, p. 426–436.

Essentially a reply to Shand (1951), this paper describes the cataclastic zones and rocks in the Great Glen fault zone, Scotland.

Fairbairn, H. W., 1939, Hypothesis of quartz orientation in tectonites: Geol. Soc. America Bull., v. 50, no. 10, p. 1475–1491.

——— 1949, Structural petrology of deformed rocks [2d ed.]: Cambridge, Mass., Addison-Wesley Press, 344 p.

——— 1950, Pressure shadows and relative movement in a shear zone: Am. Geophys. Union Trans., v. 31, no. 6, p. 914–916.

Fairbairn, H. W., and Hawkes, H. E., Jr., 1941, Dolomite orientation in deformed rocks: Am. Jour. Sci., v. 239, no. 9, p. 617–632.

Flett, J. S., 1912, Geology of the Lizard and Meneage: England and Wales Geol. Survey Mem., Explanation Sheet 359, 280 p.

Describes protoclastic gabbro, p. 88–90.

Flinn, Derek, 1961, On deformation at thrust planes in Shetland and the Jotunheim area of Norway: Geol. Mag., v. 98, no. 3, p. 245–256.

Brief description of cataclastic rocks associated with thrust faults in the Shetland Islands of Scotland and with the Jotun thrust in Norway.

Friedman, Melvin, 1963, Petrofabric analysis of experimentally deformed calcite-cemented sandstones: Jour. Geology, v. 71, no. 1, p. 12–37.

——— 1964, Petrofabric techniques for the determination of principal stress directions in rocks, *in* Judd, W. R., ed., State of stress in the earth's crust: New York. Ab. Elsevier Pub. Co., p. 450–552.

Gangopadhyay, P. K., and Johnson, M. R. W., 1962. A study of quartz orientation and its relation to movement in shear folds: Geol. Mag., v. 99, no. 1, p. 69–84.

Gives petrofabric data and interpretation on a folded mylonite and cataclastic quartzites from the Moine area, Scotland.

Gavelin, A. O., 1910. Om relationera mellan graniterna, grönsternarna och kvartsit-leptit-serien inom Loftahammarområdet: Sveriges geol. Undersøkning, Ser. C., Afhandlingar och Uppsatser, no. 224, 116 p.

Describes cataclastic rocks in the Rapatales region of Sweden. See Hamberg, 1910.

Goldschmidt, V. M., 1921, Geologische-petrographische Studien im Hochgebirge des südlichens Norwegens; V. Die Injektionsmetamorphose im Stavanger-Gebiete: Vidensk.-selsk. Skr., Kristiania, I, 1920, no. 10, 142 p.

Both retrogressive and progressive metamorphism have affected the Stavanger district, Norway. Goldschmidt distinguishes between chlorite of progressive metamorphism and chlorite of retrogressive metamorphism and gives criteria for the recognition of each type.

Goldschmidt, V. M., 1943, Om friksjonsglass (pseudo-tachylitt) i fjelkjeden: Geol. Fören. Stockholm Förh., v. 65, no. 1, p. 83–84.

A field and petrographic study of pseudotachylite.

Grant, W. H., 1967, Geology of the Barnesville area and Towaliga fault, Lamar County, Georgia: Atlanta, Georgia Geol. Soc., Guidebook 2nd ann. field trip, 16 p.

Descriptions, field relations, petrofabrics, and interpretations of various cataclastic rocks in the Towaliga fault zone of Georgia. See Examples section of this paper.

——— 1968, Movements in the Towaliga fault zone, Pike and Lamar Counties, Georgia [abs.]: Geol. Soc. America, Southeastern Sect. 17th Ann. Mtg. Program, p. 40–41.

Interprets cataclastic rocks and their petrofabrics along the Towaliga fault zone of Georgia. Concludes there has been a complex sequence of movement. See Examples section of this paper.

Griggs, D. T., 1936, Deformation of rocks under high confining pressure: Jour. Geology, v. 44, no. 5, p. 541–577.

Rocks under high confining pressure are capable of sustaining shearing stress many times greater than those under atmospheric pressure.

——— 1940a, Experimental flow of rocks under conditions favoring recrystallization: Geol. Soc. America Bull., v. 51, no. 7, p. 1001–1022.

——— 1940b, Experiments in dynamic metamorphism [abs.]: Geol. Soc. America Bull., v. 51, p. 1928.

Griggs, D. T., and Blacic, J. D., 1964, The strength of quartz in the ductile regime [abs.]: Am. Geophys. Union Trans., v. 45, no. 1, 102–103.

Griggs, D. T., and Miller, W. B., 1951, Deformation of Yule Marble, Part I, Compression and extension experiments on dry Yule Marble at 10,000 atmospheres confining pressure, room temperature: Geol. Soc. America Bull., v. 62, no. 8, p. 853–862.

Griggs, D. T., Turner, F. J., Borg, Iris, and Sosoka, John, 1951, Deformation of Yule Marble, Part IV, Effects at 150° C: Geol. Soc. America Bull., v. 62, no. 12, pt. 1, p. 1385–1406.

——— 1953, Deformation of Yule Marble, Part V, Effects at 300° C: Geol. Soc. America Bull., v. 64, no. 12, pt. 1, p. 1327–1342.

Griggs, D. T., Turner, F. J., and Heard, H. C., 1960, Deformation of rocks at 500° to 800° C, *in* Griggs, D. T., and Handin, J. W., eds., Rock deformation, a symposium: Geol. Soc. America Mem. 79, p. 39–104.

The most complete published experimental study to date pertaining to the conditions of mylonitization.

Grubenmann, U., and Niggli, Paul, 1924, Die Gesteinsmetamorphose: Berlin, Bornträger, 539 p.

Especially p. 219–223. Original definition of *cataclasite*. Discussion of *mylonite* with emphasis on fluxion structure. Other aspects of metamorphism, cataclasis, and diaphthoresis are also discussed in this classic work.

Hadley, J. B., and Goldsmith, Richard, 1963, Geology of the eastern Great Smoky Mountains, North Carolina and Tennessee: U.S. Geol. Survey Prof. Paper 349–B, 118 p.

Describes augen gneisses, "zones of shearing," and "mylonites" (especially p. 87–88). Good outcrop photographs. "The fact that the mylonite cuts across older structural features and is not greatly recrystallized indicates that it formed relatively late in the deformation of the region." (p. 88).

Hall, A. L., and Molengraaff, G. A. F., 1925, The Vredefort mountain land in the southern Transvaal and the northern Orange Free State: Koninkl. Akad. Wetensch. Amsterdam Verh., (sec. 2), v. 24, no. 3, 183 p.

Includes a detailed study of the pseudotachylites described by Shand (1917). Textural, field, and analytical data support Shand's contention that the pseudotachylite is similar in composition to the rock in which it occurs. Chilled borders on some pseudotachylite dikes are described.

Hamberg, Axel, 1910, Gesteine und Tekonik des Sarekgebirges: Geol. Fören. Stockholm Förh., v. 32, p. 725–749.

Describes cataclasis in the Rapatales region, Sweden. "The least metamorphism is seen in numerous rocks where narrow oblique cracks can be perceived along the borders of the mineral grains. * * * By more through-going cataclasis the cracks become covered with muscovite, biotite, amphibole, chlorite, etc. * * * The greatest transformation is shown in the completely laminated rocks in which orthoclase, microcline, soda-potash feldspar and augite are missing, but in which muscovite, albite, zoisite, and hornblende appear. * * * Such beds show such a complete plane-parallel structure that one may confuse them with sediments if one has not perceived their genetic association and the fact that they are composed of the same materials as the associated igneous rocks." (literal translation, p. 733).

Hammer, Wilhelm von, 1915, Das Gebiet der Bündnerschiefer im Tirolischen Oberinntal: Geol. Reichsanstalt, Wien, Jahrb., v. 64, p. 443–567.

First use of the term *gangmylonite* (or dike-mylonite) for cataclastic rocks showing intrusive relations to their country rocks. According to Hammer, there is no evidence of fusion, the intrusive habit being due to flowage of crushed rock powder during cataclasis. Photomicrographs are presented which were later used by Knopf (1931, p. 14) to illustrate pseudotachylite.

——— 1930, Über Pseudotachylyt in den Ostalpen: Geol. Bundesanst., Wien, Jahrb., v. 80, 571–585.

Field and petrographic description of pseudotachylite.

Handin, J. W., 1957, Experimental deformation of rocks and minerals: Colorado Sch. Mines Quart., v. 52, no. 3, p. 75–98.

Handin, J. W., and Fairbairn, H. W., 1955, Experimental deformation of Hasmark dolomite: Geol. Soc. America Bull., v. 66, no. 10, p. 1257–1273.

Handin, J. W., and Griggs, D. T., 1951, Deformation of Yule Marble, Part II, Predicted fabric changes: Geol. Soc. America Bull., v. 62, no. 8, p. 863–886.

Handin, J. W., and Hager, R. V., 1957, Experimental deformation of rocks under confining pressure; tests at room temperature on dry samples: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 1, p. 1–50.

——— 1957, Experimental deformation of rocks at high temperature; tests at high temperature: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 12, p. 2892–2934.

Handin, J. W., Higgs, D. V., and O'Brien, J. K., 1960, Torsion of Yule Marble under confining pressure, *in* Griggs, D. T., and Handin, J. W., eds., Rock deformation, a symposium: Geol. Soc. America Mem. 79, p. 245–274.

Harker, Alfred, 1950, Metamorphism: London, Methuen, 362 p.

First edition published in 1932. Good discussion of cataclasis. Definitions of some cataclastic rocks: *crush breccia, crush conglomerate, mylonite.* Excellent drawings, including some of Lapworth's (1885) original mylonite and of various stages of cataclasis of the Lewisian gneiss. See particularly p. 165–169. Discusses retrograde metamorphism (p. 344–358). Regarding flow structure in mylonite (p. 168–169): "A laminated structure results, closely resembling the flow-structure in a rhyolitic lava, emphasized by trains of magnetite-dust or thin streaks of colour representing the breaking down of some particular mineral of the original rock."

——— 1964, Petrology for students [8th ed.]: Cambridge, Cambridge Univ. Press, 283 p.

Discusses various occurrences of cataclastic rocks, and gives descriptions of many British occurrences. Dynamic metamorphism is discussed on p. 268–277.

Hatheway, R. B., 1969, Cataclastic rocks in southwestern Maine [abs.]: Geol. Soc. America, Abstracts with Programs 1969, [v. 1], pt. 1, p. 26–27.

Good brief description of cataclasites, mylonites, and ultramylonites that occur in a fault zone 15 miles long and up to 4 miles wide.

Hawkes, Leonard, 1929, Pseudotachylyte: Geol. Mag., v. 66, p. 143–144.

Considers pseudotachylite to result from the grinding and polishing of material caught between moving fault surfaces.

Heard, H. C., 1963, Effect of large changes in strain rate in the experimental deformation of Yule Marble: Jour. Geology, v. 71, no. 2, p. 162–195.

Heard, H. C., and Carter, N. L., 1968, Experimentally induced "natural" intragranular flow in quartz and quartzite: Am. Jour. Sci., v. 266, no. 1, p. 1–42.

Heim, Albert, 1900, Gneissfältelung in alpinem Centralmassiv, ein Beitrag zur Kenntnis der Stauungsmetamorphose: Naturf. Gesell. Zürich, Vierteljahrsschr., v. 45, p. 205–226.

Describes various stages in development of *Umfaltungsclivage*, so common in phyllites and particularly in phyllonites. Calls the first stage *Ausweichungsclivage* (cleavage that follows the direction of yielding under pressure). Detailed, well-illustrated study of this phenomenon in the Tessin gneiss of Switzerland.

Heinrich, E. W., 1956, Microscopic petrography: New York, McGraw-Hill Book Co., 296 p.

Describes, defines, and illustrates several types of cataclastic rocks (p. 184–187). Divides cataclastic rocks into four categories: *brecciated rocks, phacoidal rocks, mylonitic rocks, vitrified rocks.* Discusses cataclastic textures (p. 176), and crystalloblastic textures (p. 176–178). Uses the term "*phacoidal rocks*" (p. 185): "In phacoidal rocks the characteristic textural feature consists of ellipsoidal or lensoid units in a finer-grained matrix that is brecciated and sheared." Also uses the term "*blastocataclasites*": "Cataclasites that show some recrystallization effects have been termed blastocataclasites."

Higgins, M. W., 1966, The geology of the Brevard lineament near Atlanta, Georgia: Georgia Geol. Survey Bull. 77, 49 p.

Describes and illustrates various rocks in the Brevard zone (p. 27–42). Photomicrograph of a polycataclastic rock (p. 34). Some of the rocks are incorrectly named. See Examples section of this paper.

Hinterlechner, Karl, 1913. Review of Suess: Geol. Reichanst., Wien, Verh., Jahrg. 1913, p. 72–74.

Objects to Suess' idea of "deep-seated' diaphthoresis.

Holland, T. H., 1900, The charnockite series, a group of Archean hypersthenic rocks in peninsular India: India Geol. Survey Mem. 28, pt. 2, 249 p.

Especially p. 198–202. Describes "trap-shotten" charnokite gneisses. Holland crushed a sample of the host rock, and heated it until "* * * a very imperfect fusion * * *" occurred. "The result [p. 200] was a fritted black cake having the lustre of a tachylite and showing in thin section a black structureless matrix including angular fragments of quartz: in fact, the fritted charnokite powder very closely resembled the so-called strings of trap in these breccia bands."

Holmes, Arthur, 1928, The nomenclature of petrology [2d ed.]: London, Thomas Murby & Co., 284 p.

Defines many cataclastic rocks. Does not consider lamination or flow structure necessary to use the term *mylonite.*

Holmquist, P. J., 1903, En geologisk profil öfver den skandinaviska fjällkedjan vid Torneträsk: Geol. Fören. Stockholm Förh., v. 25, p. 27–78.

One of the earliest published references to *hartschiefer* which Holmquist considers cataclastic rocks. "The laminated Hartschiefers are opaque granulitic rocks that show a remarkable similarity to certain schistose-quartzites. * * * Under the microscope they appear as quartz and feldspar rich rocks with a variable content of mica * * *

* * * * *

From these circumstances I reach the conclusion that the schistose Hartschiefer are (granitic) mylonites" (literal translation, p. 27, 73). He goes on to give textural, chemical, and field evidence to support his conclusion.

——— 1910, Die Hochgebirgsbildungen am Torneträsk in Lappland: Geol. Fören. Stockholm Förh., v. 32, p. 913–983.

A detailed study of the Torneträsk rocks. Uses *cataclastic rock* and *mylonite* as synonyms. The more or less clearly schistose and laminated rocks are grouped as *hartschiefer.* Holmquist questions his earlier interpretation (1903) and considers that the hartschiefer may be metamorphosed sedimentary rocks. He ascribes the fabric and neomineralization of the hartschiefer and amphibolites to "Differential Gleitungen" (p. 954). See discussion of hartschiefer in text.

Hsu, K. J., 1955a, Monometamorphism, polymetamorphism, and retrograde metamorphism: Am. Jour. Sci., v. 253, no. 4, p. 237–239.

Comprehensive discussion of the terms in the title and their meanings. "Only rocks which record a history of two or more periods of metamorphism that present no obvious genetic connection are polymetamorphic. * * * Rocks that have been reconstituted repeatedly during different stages of one single period of metamorphism should be known as monometamorphic. * * * For diaphthoretic changes in response to falling temperatures during monometamorphism we might use the term *monometamorphic diaphthoresis.* * * * For diaphthoretic changes in response to rising or falling temperatures during a later period of metamorphism we might use the term *polymetamorphic diaphthoresis* * * *" (p. 238–239). See discussion of polycataclastic and polymetamorphic rocks in this text (p. 30).

——— 1955b, Granulites and mylonites of the region about Cucamonga and San Antonio Canyons, San Gabriel Mountains, California: Calif. Univ. Pubs. Geol. Sci., v. 30, no. 4, p. 223–352.

Very comprehensive study with definitions, discussions, illustrations, classification, and some analyses. States that the term *mylonite* should not specify that the rock must retain its coherence at the time of cataclasis, but that it might be later recrystallized enough to make it coherent and still be a mylonite. Uses *coarse-, medium-,* and *fine-grained mylonite,* based on matrix grain sizes, and also, *protocataclasite,* and *ultracataclasite.* (See especially p. 251–252). Quoted and cited widely in this text; see Examples section.

Humphrey, F. L., and Allard, G. O., 1968, The Propria geosyncline, a newly recognized Precambrian tectonic province in the Brazilian shield: Internat. Geol. Cong., 23d, Prague, 1968, Rept., Proc. of Sec. 4, p. 123–139.

Especially p. 130–132. Describes "shear zones" and "mylonitized zones" as much as 20 km long and as much as 60 m wide.

Jeffreys, Harold, 1942, On the mechanics of faulting: Geol. Mag., v. 79, no. 5, p. 291–295.

"Along a belt of overthrusting fused and partly fused rocks may have a wide distribution and such pseudotachylytes are held to have been made amorphous by heat generated by friction. * * * Consideration of the temperature attainable should therefore give a maximum time of formation for any dislocation containing pseudotachylyte" (p. 291). Attempts to quantify rate of faulting based on pseudotachylite, but notes that faults containing pseudotachylite are comparatively rare, meaning "* * * that this is a special faster than average type of faulting" (p. 291). See discussion of pseudotachylite in this text.

Jehu, T. J., 1925, Observations on flinty crush-rocks: Geol. Soc. Edinburgh Trans., v. 11, p. 405–406.

Considers flinty crush-rock and pseudotachylite to originate when rock material is caught between moving fault surfaces and "vitrified."

Jehu, T. J., and Craig, R. M., 1923, Geology of the Outer Hebrides. Part 1, The Barra Isles: Royal Soc. Edinburgh Trans., v. 53, p. 419–441.

Describes extensive occurrences of flinty crush-rocks which are directly associated with faulting. Attributes origin of flinty crush-rocks to fusion during thrusting. Cites spherulites and corroded quartz grains in the rocks as evidence of fusion. See especially p. 430–436.

——— 1925, Geology of the Outer Hebrides. Part 2, South Uist and Eriskay: Royal Soc. Edinburgh Trans., v. 53, p. 615–641.

Describes flinty crush-rocks and gives evidence of fusion for their origin. Evidence includes; (1) an isotropic groundmass which the authors contend is vitreous; (2) corroded quartz grains; (3) spherulites and incipient crystals in the "glassy" groundmass.

——— 1933, Geology of the Outer Hebrides. Part 5, North Harris and Lewis: Royal Soc. Edinburgh Trans., v. 57, p. 839–875.

Good descriptions of flinty crush-rocks.

Johannsen, Albert, 1931, A descriptive petrography of the igneous rocks; Volume I, Introduction, textures, classifications, and glossary: Chicago, Univ. of Chicago Press, 267 p.

Definitions (p. 163–237): autoclastic (p. 168), dynamometamorphism (p. 174), groundmass (p. 179), metamorphism (p. 185), porphyroblast (p. 193), aphanitic (p. 201), augen (p. 202), autoclastic (p. 203), cataclastic (p. 204), crystalloblastic (p. 207), flasrig (p. 211), fluxion (p. 212), granoblastic (p. 213), mortar (p. 224), mylonitic (p. 224), palimpsest (p. 226), protoclastic (p. 230).

Johnson, M. R. W., 1957, The tectonic phenomena associated with the post-Cambrian thrust movements at Coulin, Wester Ross; Pt. 2. The structural geology of the Moine thrust zone in Coulin Forest, Wester Ross; Geol. Soc. London Quart. Jour., v. 113, pt. 2, no. 450, p. 241–270

Chiefly a structural study, but descriptions of cataclastic rocks near thrust planes are included. Folds in cataclastic rocks are described.

——— 1961, Polymetamorphism in movement zones in the Caledonian thrust belt of northwest Scotland: Jour. Geology, v. 69, no. 4, p. 417–432.

Detailed descriptions and illustrations of a variety of cataclastic rocks. Cataclastic events are integrated by petrographic and petrofabric analysis into the interpretation of the geologic history. Evidence is given for four phases in the structural-metamorphic history, with cataclastic rocks of different types produced by at least three of these phases. Notes selective cataclasis of pegmatites. Good descriptions of cataclastic differences being dependent on original rock type. Most rocks described are recrystallized and neomineralized.

——— 1962, Relations of movement and metamorphism in the Dalradians of Banffshire: Edinburgh Geol. Soc. Trans., v. 19, pt. 1, p. 29–64.

Gives textural evidence for polymetamorphism.

——— 1963, Some time relations of movement and metamorphism in the Scottish Highlands: Geol. en Mijnbouw, v. 42, no. 5, p. 121–142.

Gives evidence that deformation is "* * * a promoter of metamorphic reactions * * *" (p. 127) and that strong tectonism aids attainment of chemical equilibrium. Discusses retrogressive metamorphism. Attempts to place mylonitization in a time-sequence of events.

——— 1967, Mylonite zones and mylonite banding: Nature, v. 213, no. 5073, p. 246–247.

Interprets mylonite zones and mylonite banding as surfaces of flattening strain and relates the banding to slaty cleavage in origin.

Johnson, R. J., and McConnell, R. B., 1951, Notes on the geology of the northern part of the Ruwenzori Mountains: Geol. Mag., v. 88, no. 4, p. 249–256.

Description of mylonites and other cataclastic rocks in a thick zone in Africa.

Jonas, A. I., 1932, Structure of the metamorphic belt of the southern Appalachians: Am. Jour. Sci., ser. 5, v. 24, p. 228–243.

Brief description of retrogressive cataclastic rocks and polymetamorphic rocks along the Brevard zone. See examples section of this text.

Jung, Jean, 1925, Sur quelques types de roches écrasèes des Vosges: Acad. Sci., Paris, Comptes Rendus, v. 180, p. 839–840.

Field and petrographic description of cataclastic rocks from the Vosges, France.

——— 1928, Contribution á la géologie des Vosges Hercyniennes d'Alsace: Service Carte Géol. Alsace et Lorraine Mem. 2, p. 1–481

Description of some Alsatian cataclastic rocks, chiefly mylonites and "flinty crush-rocks." Notes spherulitelike aggregates of chlorite in the "flinty crush-rocks," and formation of new minerals (quartz and feldspar) in some of the mylonites.

Kalkowsky, E., 1886, Review of Kjerulf (1885): Neues Jahrb., ser. II, ref. 244.

Uses the term *Kataklas-Structure.*

Kennedy, W. Q., 1946, The Great Glen fault: Geol. Soc. London Quart. Jour., v. 102, pt. 1, no. 405, p. 41–72.

Study of a major fault zone with emphasis on determination of offset. Field description of cataclastic rocks, chiefly mylonite.

Kienow, Sigismund, 1953, Über Gleitfaltung und Gleitfaltschieferung: Geol. Rundschau, v. 41, p. 110–128.

Detailed discussion, explanation, and illustrations of glide-fold schistosity and its development. See also Christie (1963, p. 382–384) and section on glide-fold schistosity in this text.

Kieslinger, Alois, 1926, Geologie und Petrographie der Koralpe, I: Akad. Wiss., Wien, Sitzsungsber., Math. Naturwiss. Kl., v. 135, p. 1–42.

"* * * diaphthoresis is only recognizable where it is incomplete, and where a metamorphic facies of the lower zone is completely transformed into an upper zone facies the new rock can no longer be distinguished from a primary phyllite." (literal translation, p. 8) The zones refer to depth zones.

——— 1928, Über Diaphthorese mit Beispielen aus dem Ostalpinen Kristallin: Tschermaks mineralog. petrog. Mitt., v. 39, p. 12–15.

Good description of the diaphthoritic zone associated with the "old crystalline" of the Kor Alps. Cites remnants of biotite in chlorite, and chess-board albite as relicts of higher metamorphism. Gives a valuable list of new "typomorphic minerals" and the old minerals from which they formed.

King, P. B., and Ferguson, H. W., 1960, Geology of northeasternmost Tennessee: U.S. Geol. Survey Prof. Paper 311, 136 p.

Describes "mylonites," "phyllonites," "flaser gneisses," and "mortar gneisses" in fault zones in northeast Tennessee. Good outcrop photographs. Defines terms (above) as used (p. 17).

King, W., Jr., and Foote, R. B., 1864, On the geological structure of the districts of Trichinopoly, Salem, etc., Madras: India Geol. Survey Mem. 4, p. 223–379.

Especially p. 271. Describes "trap-shotten gneiss." See discussion of pseudotachylite in this text.

Kjerulf, Th., 1885, Grundfjeldprofilet red Mjosens sydende: Nyt Mag. Naturvidenskaberne, v. 29, p. 215–294.

First use of the word *cataclastic*. "* * * applies to a texture characterized by crushed, fragmentary, deformed, and strained crystals." (Literal translation from p. 288.) It is in part synonymous with "mortar-structure," but is a broader term.

Knopf, E. B., 1931, Retrogressive metamorphism and phyllonitization: Am. Jour. Sci., ser. 5, v. 21, p. 1–27.

Review, discussion, definition, and classification of the processes in the title, of cataclastic rocks, and of polymetamorphic and polycataclastic rocks. A classic paper on cataclastic and polymetamorphic rocks. Quoted and cited widely in this text. See especially the section of this paper on phyllonites and diaphthorites (retrograde rocks).

Knopf, E. B., and Ingerson, Earl, 1938, Structural petrology: Geol. Soc. America Mem. 6, 270 p.

A comprehensive work on structural petrology, with a large amount of petrofabric data on cataclastic rocks. Good discussions of cataclastic textures and processes. Especially valuable because it presents many of Sander's ideas and techniques in English.

Königsberger, J. G., 1912, Die kristallinen schiefer der Zentralschweizerischen Massive und Versuch einer Einteilung der kristallinen Schiefer: Internat. Geol. Cong., 11th, Stockholm, 1910, Comptes rendus, v. 1, p. 639–671.

Proposes a classification of crystalline schists, with a group called *dynamo-metamorphic schists* which "includes mylonites."

Kölbl, Leopold, 1922, Zur Deutung der moldanubischen Glimmerschieferzone im niederösterreichischen Waldviertel: Geol. Bundesanst., Wien, Jahrb, v. 72, p. 81–104.

A study of "deep-seated diaphthorites" in the mica schist zone described by Suess (1913). The mica schist diaphthorites lack the diseased or weathered appearance characteristic of the "upper-zone" diaphthorites.

Lambert, I. B., and White, A. J. R., 1965, The Berridale wrench fault; a major structure in the Snowy Mountains of New South Wales: Geol. Soc. Australia Jour., v. 12, pt. 1, p. 25–34.

Brief field description of cataclastic rocks incidental to description of a major fault zone.

Lamplugh, G. W., 1903, The geology of the Isle of Man: Great Britain Geol. Survey Mem., 620 p.

Describes "crush-conglomerates" developed in a banded series of alternating grits and shales (p. 55–58).

Lapworth, Charles, 1885, The Highland controversy in British geology; its causes, course, and consequences: Nature, v. 32, p. 558–559.

Original use and definition of the term *mylonite*. Mylonites and related rocks, such as *augen schists*, are described. See discussion of *mylonite*.

Imbrock, H., 1925, Geologisch-Letrographische Beobachtungen im südöstlichen Teil der Böhmischen Masse zwischen Marbach und Sarmingstein a.d. Donau: Geol. Bundesanst., Wien, Jahrb. 75, p. 129–180.

Objects to the idea of "deep-seated diaphthoresis" (see Kölbl, 1922; Suess, 1913, 1918), and claims that the conditions along the eastern edge of the Moldanubian block are abnormal from the point of view of the depth-zone concept of metamorphism, because the epizone Moravian phyllites underlie the mesozone mica schists.

Lundgren, Lawrence, Jr., 1969, Cataclastic deformation of the Hebron Formation, southeastern Connecticut [abs.]: Geol. Soc. America, Abstracts with Programs 1969, [v. 1] pt. 1, p. 38.

Describes "blastomylonitic quartz-biotite schists" with "ultramylonite sheets." Describes kink folds in blastomylonite, and folds "* * * formed during ductile faulting when horizontal movement was accommodated by pervasive granulation of quartz and biotite (but not plagioclase) * * *. Notes that * * * "the last formed (ultramylonite) behaved much like intrusive basaltic magma."

MacGregor, A. G., 1952, Metamorphism in the Moine nappe of northern Scotland: Edinburgh Geol. Soc. Trans., v. 15, p. 241–257.

Brief descriptions of cataclastic rocks, chiefly blastomylonites. Description of folds in these cataclastic rocks.

Magnusson, N. H., 1937, Den centralvärmländska mylonitzonen och dess Fortsättning i Norge: Geol. Fören. Stockholm Förh., no. 409, v. 59, no. 2, 205–228.

Describes mylonite and other cataclastic rocks in a thick Norwegian fault zone (p. 205).

Malaroda, Roberto, 1946, Revisione e aggiornamento della sistematica delle tettoniti a deformazione post-cristallina: Soc. Mineralog. Italiana Rend., v. 3, no. 3, p. 150–171.

Describes and discusses a large "mylonite" zone in northern Italy. Theoretical aspects and definitions are discussed. Malaroda devises a workable classification of cataclastic rocks. Well illustrated. Very good bibliography.

Marshall, P., 1904, Magnesian rocks at Milford Sound: New Zealand Inst. Trans., v. 37, p. 481–484.

Describes mylonitized peridotites and discusses the cataclastic textures.

Martin, Henno, 1935, Bruchtektonik und Mylonite in Südschwedan [abs.]: Geol. Rundschau, v. 26, no. 1–2, p. 144–145.

Maske, S., 1957, The diorites of Yzerfontein, Darling, Cape Province: Stellenbosch Univ. Ann., v. 33, Sec. A, nos. 1–11 (1957), p. 23–69.

Describes "crush breccias" intimately associated with "fine black mylonites."

McCallien, W. J., 1934, Metamorphic diffusion: Finland Comm. géol. Bull. 104, p. 11–27.

McIntyre, D. B., 1954, The Moine thrust—its discovery, age, and tectonic significance: Geologists Assoc. (London) Proc., v. 65, pt. 3, p. 203–219.

Brief description of cataclastic rocks along the Moine thrust in Scotland, chiefly blastomylonites. Description of folds in blastomylonites.

Michel-Levy, A., 1928, Sericitoschistes des chaines du Mont-Blanc et des Aiguilles Rouges qui sont des Mylonites recristallisées postérieures au granite: Géol. Soc. France Bull., ser. 4, v. 28, p. 255–260.

Description of a complex "unit" in the Alps called the "protogene," with many kinds of cataclastic rocks showing varying degrees of crushing, neomineralization, and recrystallization.

Nel, L. T., 1927, Geology of the country around Vredefort; An explanation of the geological map: South Africa Geol. Survey, 130 p.

Includes a comprehensive chapter on pseudotachylite occurrences in the classic Vredefort area, South Africa. Good descriptions of pseudotachylite. Concludes that the mylonites, flinty crush-rocks, and pseudotachylites are the products of mechanical stresses, culminating in fusion. Considers the enstatite granophyre to be a recrystallized pseudotachylite.

Noble, L. F., 1926, Report of the California Earthquake Commission: Carnegie Inst. Washington Year Book 25, p. 415.

Brief description of crushed and shattered rocks in the San Andreas fault zone.

Nockolds, S. R., 1940, Petrology of rocks from Queen Mary Land: Australasian Antarctic Exped., 1911–1914, Sci. Repts., ser. A, v. 4, pt. 2, p. 15–86.

Describes a granitic boulder from a moraine on Cape Charcot, Queen Mary Land, Antarctica, cut by a vein of pseudotachylite that resembles very closely the pseudotachylite of Parys (Parijs), Orange Free State, South Africa (see Shand, 1917), but which contains elliptical vesicles that indicate the igneous nature of the rock. This is the first report of such vesicles in pseudotachylite. See discussion of pseudotachylite in this text. There is no field evidence that the rock described by Nockolds actually is pseudotachylite and not an igneous rock.

Norton, W. H., 1917, A classification of breccias: Jour. Geology, v. 25, p. 160–194.

Oulianoff, Nicolas, 1942, Effet de l'écrasement natural et experimental: Lausanne Univ. Lab. Géologie, Geographie Physique, Minéralogie, et Paleontologie Bull. 76, 7 p.

Discusses some of the crushed rocks produced experimentally and attempts to relate them to naturally produced cataclastic rocks.

——— 1955, Écrasement sans trituration et mylonitisation des roches: Eclogae Geol. Helvetiae, v. 47, p. 377–381.

Discussion of cataclastic rocks, cataclasis, and faulting.

Park, R. G., 1961, The pseudotachylite of the Gairloch district, Ross-Shire, Scotland: Am. Jour. Sci., v. 259, no. 7, p. 542–550.

Describes pseudotachylites and shows that they contain spherulites and relict glass, the presence of which proves that some Scottish flinty crush-rocks were once molten. Photomicrographs.

Peach, B. N., Horne, John, Gunn, W., Clough, C. T., and Hinxman, L. W., 1907, The geological structure of the Northwest Highlands of Scotland: Great Britain Geol. Survey Mem., 668 p.

Many types of cataclastic rocks are described and discussed in this thorough and classic account of Highland geology. The authors conclude that "flinty crush-rocks" (a term used both for rocks showing evidence of fusion and as a general field term for dense, flinty cataclastic rocks of various types) and mylonites were "* * * formed simultaneously in different parts of the same line of movement" (p. 153). There is a detailed description of Lapworth's (1885) Eireboll district and its rocks. Conditions of cataclasis are discussed (p. 598). The intimate relationship between various types of dikes and faulting with cataclasis is repeatedly mentioned. The ideas and nomenclature of this 1907 paper have greatly influenced later thought regarding cataclastic rocks and many other aspects of geology. Quoted and cited widely in this text.

——— 1913, The geology of central Ross-shire: Scotland Geol. Survey Mem., 114 p.

Occurrences of cataclastic rocks are described and discussed, but most of the ideas are the same as those expressed in Peach and others (1907).

Peach, B. N., and Horne, John, 1930, Chapters on the geology of Scotland: London, Oxford Univ. Press, 232 p.

Brief accounts of the more important fault zones, including summarized descriptions of cataclastic rocks.

Phillips, F. C., 1937, A fabric study of some Moine schists and associated rocks: Geol. Soc. London Quart. Jour., v. 93, pt. 4, no. 372, p. 581–616.

See Phillips, 1945.

——— 1945, The micro-fabric of the Moine schists: Geol. Mag., v. 82, no. 5, p. 205–220.

Good petrofabric data on cataclastic rocks. "In a crushed quartzose rock * * * lenticular grains of highly strained quartz lie in a fine-grained mylonitic matrix. These lenticular grains show a concentration of optic axes nearly normal to the schistosity. If it can be reasonably supposed that the original rock showed the normal type of girdle, this mylonite presents an interesting example of the differential yield of quartz grains to the shearing according to the attitude of their internal structure in relation to the impressed shear planes" (p. 213–214). "I would draw a careful comparison between the readiness with which quartz suffers recrystallization and the reluctance which it shows to undergo reorientation" (p. 219). Notes faulted pegmatites and veins (p. 214–215) in noncataclastic rocks.

Philpotts, A. R., 1964, Origin of pseudotachylites: Am. Jour. Sci., v. 262, no. 8, p. 1008–1035.

Comprehensive field, petrographic, petrologic, mineralogic, and chemical study of pseudotachylite.

Offers abundant evidence that pseudotachylite forms by complete melting of already-hot rocks during faulting. Gives criteria for distinguishing pseudotachylite from other similar cataclastic rocks. See discussion of pseudotachylite in this text.

Philpotts, A. R., and Miller, J. A., 1963, A Pre-Cambrian glass from St. Alexis-des-Monts, Quebec: Geol. Mag., v. 100, no. 4, p. 337–344.

Good description of pseudotachylite.

Pitcher, W. S., Elwell, R. W. D., Tozer, C. F., and Cambray, F. W., 1964, The Leannan fault: Geol. Soc. London Quart. Jour., v. 120, pt. 2, no. 478, p. 241–273.

Brief description of "mylonites" and "tectonic breccias" incidental to the discussion of a large wrench-fault in Ireland.

Pochin Mould, D. D. C., 1946, Geology of the Foyers granite: Geol. Mag., v. 72, p. 249–265.

Brief description of "crush zones and movement lines" in Foyers granite, near the Great Glen of Scotland.

Preclik, Karl, 1930, Zur Genesis einiger Moldanubischer Gesteins typen I: Centralblatt Mineralogie, Geologie, Paläontologie, Jahrg. 1930–A, p. 61–78.

Restudy of the area in Austria studied by Suess (1913). Gives evidence to support retrogressive origin of the rocks.

Prinz, Martin, and Poldervaart, Arie, 1964, Layered mylonite from Beartooth Mountains, Montana: Geol. Soc. America Bull., v. 75, no. 8, p. 741–744.

Describes a metadolerite dike traversed by a fault zone. Gives conclusive petrographic, petrologic, and chemical evidence of cataclastic metamorphic differentiation producing compositional layering from the nonlayered parent rock. See section on cataclastic metamorphic differentiation in this text.

Quensel, Percy, 1913, Die Quartzporphyr- und Porphyroid-Formation in Südpatagonien und Feuerland: Upsala Univ, Geol. Inst. Bull., v. 12, no. 2, p. 9–40.

Describes mylonitization of a "quartz porphyry" and discusses the chemical changes occurring during mylonitization, as shown by chemical analyses.

——— 1916, Zur Kenntnis der Mylonitbildung, erläutert an Material aus dem Kebnekaisegebiet: Upsala Univ., Geol. Inst. Bull., v. 15, p. 91–116.

Comprehensive discussion and classification of cataclastic rocks, with many definitions. Original definition of *kakirite* (see glossary of this paper). Detailed discussion of *ultramylonite* (see discussion of *ultramylonite* in this text). Original use of the term *mylonite gneiss* (see discussion of *mylonite* in this text). Quensel used the term *mylonite schist* for laminated cataclastic rocks; unlaminated cataclastic rocks were considered *mylonite* (also see Knopf, 1931). Considered *hartschiefer* to be chemically differentiated, recrystallized mylonitic rocks. His definitions and photomicrographs have been widely used by several later workers (for example, see Knopf, 1931).

Raguin, E., 1926, Au sujet de divers genres de "mylonites granitiques" le long des lignes de dislocation de l'Quest du Plateau Central: France Serv. Carte Géol. Bull., v. 29, no. 261, p. 213–230.

One of the early attempts at a classification of cataclastic rocks. Good field descriptions of cataclastic rocks along a fault zone in France.

Ramberg, Hans, 1952. The origin of metamorphic and metasomatic rocks: Chicago, Univ. Chicago Press, 317 p.

Discusses chemical principles of metamorphic differentiation (p. 212–228). Mechanical differentiation is discussed on p. 226, "* * * it is empirically found that although there are variations in details as to the minerals which tend to cosegregate, it appears to be generally true that minerals which go together in concretionary growth also go together in secretionary growth or in banded growth under shearing."

Ramsay, J. G., 1958, Moine-Lewisian relations at Glenelg, Inverness-shire: Geol. Soc. London Quart. Jour., v. 113, pt. 4, p. 487–523.

Especially p. 494–495. Describes cataclastic rocks (chiefly blastomylonites) in the Moine thrust zone, Scotland. Also describes minor folds in these cataclastic rocks.

Read, H. H., 1931, The geology of central Sutherland: Scotland Geol. Survey Mem., 238 p.

Brief description of cataclastic rocks associated with thrust faults.

——— 1933, On quartz-kyanite rocks in Unst, Shetland Islands, and their bearing on metamorphic differentiation: Mineralog. Mag., v. 23, p. 317–328.

Detailed discussion of the origin of kyanite-quartz bands and veins in pelitic schists on Unst. Suggests that the bands are the result of metamorphic differentiation.

——— 1934, Age problems of the Moine Series of Scotland: Geol. Mag., v. 71, no. 841, p. 302–317.

Uses the term "dislocation metamorphism" to denote the cataclastic action in the vicinity of thrust faults.

——— 1937, Metamorphic correlation in the polymetamorphic rocks of the Valla Field block, Unst, Shetland Islands: Royal Soc. Edinburgh Trans. v. 59, pt. 1, p. 195–221.

In the Valla Field block, a first metamorphic episode resulted in the production of garnet-staurolite-kyanite-biotite gneiss. It was followed by a second episode during which this assemblage was not stable, and a chloritoid-chlorite-muscovite schist was formed from the gneiss. In the Saxa Vord structural unit, a first metamorphism produced staurolite, andalusite, and garnet. On this a second metamorphism was superposed, characterized by the formation of chloritoid and kyanite. Along the mechanical junction of the two structural units, all pelitic rocks adjacent to the belt of special movement were converted into chlorite-sericite phyllites—a type example of *metamorphic convergence.*

——— 1951, Mylonitisation and cataclasis in acidic dikes in the Insch (Aberdeenshire) gabbro and its aureole: Geologists' Assoc. (London) Proc., v. 62, pt. 4, p. 237–247.

Describes cataclastic rocks localized in dikes.

——— 1957, The granite controversy: London, Murby, 430 p.

Good discussion of diaphthoresis (p. 296–300), and of polymetamorphism versus monometamorphism (p. 305–308). Numerous scattered descriptions of cataclastic rocks, processes, and zones, many of which are associated with intrusive phenomena. (See *mylonites* in Read's index).

Reed, J. C., Jr., and Bryant, Bruce, 1964, Evidence for strike-slip faulting along the Brevard zone in North Carolina: Geol. Soc. America Bull., v. 75, no. 12, p. 1177–1196.

Good descriptions of cataclastic and polymetamorphic rocks along the Brevard zone (see Examples section of this text). "The nomenclature of polymetamorphic cataclastic rocks is complex and confusing, so we therefore define the following terms in the sense used in this paper:" (p. 1180). Definitions of *porphyroclast, blastomylonite, blastomylonitic gneiss, phyllonite,* and *phyllonitic schist* are given (see Glossary of this paper). They use *phyllonite* for rocks that should be called *diaphthoritic phyllonite* (see discussion of retrograde cataclastic rocks in this paper). Excellent photomicrographs. Good descriptions of relations between various kinds of rocks in the zone and on either side. See Examples section of this text.

Reed, J. J., 1957, Fault zones in part of the Rimutaka Range: New Zealand Jour. Sci. and Technology, ser. B, v. 38, no. 7, p. 686–687.

Describes a 5,000-foot-thick zone of "autoclastic breccia," which he states is a possible example of protomylonite.

——— 1964, Mylonites, cataclasites, and associated rocks along the Alpine fault, South Island, New Zealand: New Zealand Jour. Geology and Geophysics, v. 7, no. 4, p. 645–684.

Good detailed descriptions, illustrations, and discussions of all types of cataclastic rocks. Classification is particularly good. Describes retrogressive metamorphism of cataclastic rocks. Suggests that the silicification common to many cataclastic rocks may be a retrograde feature. Divides rocks along Alpine fault zone into "augen mylonite and mylonite," blastomylonite, and "schist-derived mylonite." The three groups are interpreted as having formed at three distinct levels within the earth's crust, so that their juxtaposition along the Alpine fault is evidence of three distinct periods of movement (p. 675). States that mylonites pass into Haast Schist, and concludes that the type of metamorphism changed, so that mylonite-blastomylonite-schist are gradational. Good definitions. See Examples section of this text.

Reinhard, Martin, and Preiswerk, H., 1927, Über Granitmylonite im Aiguilles-Rouges-Massiv (Westliches Wallis): Naturf. Gesell. Basel Verh., v. 38, p. 188–200.

Describes mylonite and several other types of cataclastic rock.

Reynolds, D. L., 1954, Fluidization as a geological process, and its bearing on the problem of intrusive granites: Am. Jour. Sci., v. 252, no. 10, p. 577–614.

Describes and explains the process of fluidization. Concludes, from recent work on "fluidized" solid-gas systems, that the South African pseudotachylites were originally composed of finely ground particles transported to their present location as a suspension in rapidly moving gas. This process was thought to explain the extreme mobility commonly demonstrated by the intricate narrow networks of veins of pseudotachylite, and the nondilational form of some of the dikes. (See McBirney, 1963; Philpotts, 1964.) See discussion of pseudotachylite in this text.

Rogers, A. W., 1897, report on the survey of the Stellenbosch district: Cape of Good Hope Geol. Comm. Ann. Rept., 1897, p. 45–49.

Regarding a granite mass in the Stellenbosch area of South Africa "along a few planes parallel with the general foliation, the rock resembles a very fine-grained slate. This fine-grained rock may be the result of crushing. The foliated granite passes into normal rock by insensible gradations * * *" (p. 48).

——— 1905, An introduction to the geology of Cape Colony: London, Longmans, Green and Co., 463 p.

Especially p. 32–53. Describes a protoclastic border of a gneissic granite and states that some of the rocks are mylonite.

——— 1911, Geological Survey of parts of Van Rhyns Dorp and Namaqualand divisions: Cape of Good Hope Geol. Comm. 16th Ann. Rept., 1911, p. 9–84.

Especially p. 29. Describes thin pseudotachylite veins in a gneiss.

Rüger, L., 1928, Über Blastomylonite in Grundgebirge des Odenwaldes: Verein Erdkunde Darmstadt Notizblatt, 1927, ser. 5, p. 219–231.

Salop, L. I., 1949, Psevdotakhitity iz Pribaikalya i zapadnogo Zabaikalya i problema ikh genezisa: [Pseudotachylites from the cis-Baikal and western trans-Baikal regions and the problems of their genesis]: Akad. Nauk SSSR, Izv., Ser. Geol., no. 5, p. 40–56.

Describes pseudotachylites in amphibolites. The pseudotachylites contain microlites of feldspar and extremely embayed fragments of quartz, both well illustrated in the paper. Chemical analyses show the similarity in composition between the pseudotachylites and the rocks in which they occur. Concludes that the pseudotachylites were formed by melting of the host rocks along a thrust fault.

Sander, Bruno, 1911, Über Zusammenhänge zwischen Teilbewegung und Gefüge in Gesteinen: Tschermaks mineralog. petrog. Mitt., v. 30, p. 281–314.

Discusses some of the fundamental principles involved in the origin of fabric. First use of the term *phyllonite* for phyllite-mylonite. See discussion of phyllonite in this text.

Sander, Bruno, 1912, Über einige Gesteinsgruppen des Tauernwestendes: Geol. Reichsanst., Wien, Jahrb., v. 62, p. 219–228.

Original use and definition of the term *blastomylonite* (see discussion of blastomylonite in this text). First use and definition of *tectonite,* as a metamorphic rock deformed by differential movements that integrate into the tectonic movement as a whole.

——— 1914, Bemerkungen über tektonischen Gesteinsfazies und Tektonik des Grundgebirges: Geol. Reichsanst., Wien, Verh., Jahrg. 1914, no. 9, p. 220–240.

Points out that the existence of an abnormal metamorphic facies relation along the Moldanubian-Moravian contact zone cannot be cited as a reasonable objection to the hypothesis of deep-seated diaphthoresis because the hypothesis was itself advanced in an attempt to explain the abnormalities (see Suess, 1913, 1918; Limbrock, 1925).

——— 1914, Beiträge aus den Zentralalpen zur Deutung der Gesteinsgefüge: Geol. Reichsanst., Wien, Jahrb., v. 64, p. 567–634.

In the biotite phyllonite of a Tauern gneiss near Brenner, "* * * there is no reversion of lower zone typomorphic minerals to those of a higher zone . . ." (meaning depth zones not grades)—so a phyllonite may be formed by the degradation of a highly crystalloblastic schist, and yet not be diaphthoritic." (p. 584).

——— 1930, Gefügekunde der Gesteine: Vienna, Springer, 352 p.

A classic study of petrofabric theory and techniques. Contains fabric analyses of cataclastic rocks and discussion of their origins.

——— 1950, Einführung in die Gefügekunde der geologischen Körper; II, Die Korngefüge: Vienna, Springer-Verlag, 409 p.

Scheumann, K. H., 1961, Mineralfazies und Kinematik: Neues Jahrb. Mineralogie, Mh. 6, p. 121–123.

Schmidt, Walter, 1932, Tektonik und Verformungslehre: Berlin, Borntraeger, 208 p.

Proposes and explains a purely mechanical hypothesis of metamorphic differentiation. Uses data from experimental work with metals as examples. See discussion of cataclastic metamorphic differentiation in this text.

Schoch, A. E., 1962, The cataclasites of Northwest Bay: Stellenbosch Univ. Annals, v. 37, ser. A, no. 10, p. 659–808.

Detailed descriptions and statistical structural analysis of various types of cataclastic rocks in South Africa. "The cataclastic deformation features, which were mapped in detail, are of three types, namely a coarse bodily shattering of the granite, numerous vertical black streaks of mylonitisation, and broad zones of comminution up to six hundred feet in width" (part of author's abstract). Proposes a complex partially quantitative classification with numerous terms. Uses *cataclasite* both as a specific term and as a general term for all cataclastic rocks.

Scholtz, D. L., 1946, On the younger pre-Cambrian granite plutons of the Cape Province [presidential address]: Geol. Soc. South Africa Trans. and Proc., v. 49, p. 35–82.

Describes crush zones in some plutons and mylonite zones crossing others. States (p. 65) that stress was responsible for the development of local gneissic granite with mortar structures and anastomosing veins of mylonite, "* * * while zones of black cataclasite up to five hundred feet in width occur in the older granite at Northwest Bay." See Schoch, A. E. (1962).

Schwartz, G. M., and Todd, J. H., 1941, Comments on retrograde metamorphism: Jour. Geology, v. 49, no. 2, p. 177–189.

(p. 178) "In many instances the terms 'retrograde metamorphism,' 'regressive metamorphism,' and 'diaphthoresis' are not being used in precise accordance with their original connotations." Gives a very complete list of mineral changes attributed to retrograde metamorphism (p. 179). Notes that hydrothermal changes are often retrogressive, and many retrogressive changes involve a hydration. "It seems permissible to question the validity of the general statement that temperatures (usually) drop so rapidly as to greatly inhibit retrograde reactions. It seems more likely that the failure to react is due to the absence of some essential component rather than merely to temperature conditions." (p. 185). Also see Knopf (1931) and Hsu (1955a).

Sclar, C. B., 1950, Origin of a layered ultramylonite from southeastern Connecticut [abs.]: Geol. Soc. America Bull., v. 61, p. 1501.

Ascribes origin of the layered rock to cataclastic metamorphic differentiation.

——— 1958, The Preston gabbro and the associated metamorphic gneisses, New London County, Connecticut: Connecticut Geol. Nat. History Survey Bull. 88, 136 p.

Good descriptions and discussions of cataclastic rocks. Well illustrated. Excellent discussion of and evidence for cataclastic metamorphic differentiation. Quoted and cited extensively in this text; see section on cataclastic metamorphic differentiation.

——— 1965, Layered mylonites and the processes of metamorphic differentiation: Geol. Soc. America Bull., v. 76, no. 5, p. 611–612.

Gives good evidence supporting cataclastic metamorphic differentiation, with discussion of the theory. Quoted extensively in this text; see section on cataclastic metamorphic differentiation.

Scott, J. S., and Drever, H. I., 1953, Frictional fusion along a Himalayan thrust: Royal Soc. Edinburgh Proc., sec. B, v. 65, pt, 2, p. 121–140.

Describes a glassy rock formed by frictional fusion. The glass is vesicular, has a refractive index of 1.5. and occurs in the plane of a thrust fault. A gradation can be traced from undeformed rock through mylonite to the fused rock. This is the first conclusive proof of sufficient frictional heat produced in a fault zone to produce melting of the rock. Well-illustrated. The terms *cryptomylonite* and *hyalomylonite* are used (see Glossary of this text). See discussion of pseudotachylite in this text.

Sederholm, J. J., 1913, On regional granitization (or anatexis): Internat. Geol. Cong., 12th, Toronto, 1913, Comptes rendus, p. 319–324.

"Cataclasis is in general a destructive process; it is not creating new minerals or rocks. The use of the term 'dynamometamorphism' for every metamorphic change which cannot otherwise be accounted for should be discontinued as not warranted by facts," (p. 323).

Seidlitz, W. von 1910, Ueber Granit-mylonit und ihre tektonische Bedeutung: Geol. Rundschau, v. 1, p. 188–197.

Discusses chemical changes during mylonitization.

Semenenko, N. P., 1960, Theory of metamorphism of mobile zones: Internat. Geol. Cong., 21st Copenhagen, 1960, Rept. pt. 14, p. 62–71.

Shand, S. J., 1917, The pseudotachylyte of Parijs (Orange Free State), and its relation to "trap-shotten-gneiss" and "flinty-crush-rock": Geol. Soc. London Quart. Jour., v. 72, pt. 3, p. 198–221

Introduction of the term *pseudotachylyte,* for dark, aphanitic rocks found as veins and networks in the granite near Parijs (Parys) Orange Free State, Africa. Shand thought that the rupturing of the rock was due to shock rather than shearing and that incandescent gases had produced the pseudotachylite. Good descriptions and illustrations of the rocks. Discussion at the end of article contains comments and alternate hypotheses by several geologists. See discussion of pseudotachylite in this text.

——— 1951, Mylonite, slickensides, and the Great Glen fault: Geol. Mag., v. 88, no. 6, p. 423–428.

Cursory discussion of some of the aspects of mylonite formation. Concludes that the general absence of mylonite along the fault zone invalidates Kennedy's (1946) strike-slip hypothesis. Clearly, Shand expected to find veinlike cataclastic rocks resembling pseudotachylite. See Eyles and MacGregor's (1952) reply to Shand.

Smyth, C. H., Jr., 1896, Metamorphism of a gabbro occurring in St. Lawrence County, New York: Am. Jour. Sci., 4th ser., v. 1, p. 273–281.

Describes cataclasis in the gabbro: "In the first type, the rock as a whole retains its original structure, the outlines of the different minerals being slightly changed; but all of the constituents are, at the same time, reduced to fine grains, giving a cataclastic structure (except for residual cores of the feldspars). As the crushing becomes more intense, the mineral outlines change, and a more or less pronounced parallel structure results. In this stage the rock is made up of very fine grains of pyroxene, hornblende, feldspar and scapolite * * * In the other type of secondary structure the rock is a well defined gneiss. It is apparently much finer grained than the previous variety, but in reality is coarser, the individual grains being many times larger than in the cataclastic rock. * * * This rock is composed of feldspar, with pyroxene or hornblende, or more generally, both. Between this phase of the rock and that with cataclastic structure intermediate phases occur, showing that the development of cataclastic structure is the first step in the process of converting gabbro into gneiss" (p. 277).

Snook, J. R., 1965, Metamorphic and structural history of "Colville batholith" gneisses, north-central Washington: Geol. Soc. America Bull., v. 76, no. 7, p. 759–776.

Describes and illustrates mylonites, mylonite gneisses, and microbreccias in the border area of the Colville batholith. Disagrees with Waters and Krauskopf (1941), and proposes that rather than being protoclastic, the rocks are cataclastic and produced by a later deformation. See Examples section of this text.

Staub, Rudolf, 1915, Petrographische Untersuchungen im Westlichen Berninagebirge: Naturf. Gesell. Zurich Vierteljahrsschrift, v. 60, p. 55–336.

Especially p. 71–91. Extensive consideration of cataclastic rocks, with a proposed classification. "The formation of mylonites is not considered as an act of metamorphism due to recrystallization and remineralization, but as a purely mechanical rock forming process in which crushing and especially rolling, play a significant role. Where the rolling process has failed, the rocks can just as well be considered as merely cataclastic. Mylonites are always laminated rocks. (literal translation.) Divides mylonites into six types on the basis of grain size.

——— 1928, Der Bewegungsmechanismus der Erde dargelegt am bau der irdischen gebirgssyteme: Berlin, Gebrüder Borntraeger, 270 p.

Describes cataclastic rocks. According to Staub, the extreme form of ultramylonitization has been reached when the matrix appears as a glasslike substance and the porphyroclasts have diminished to a diameter less than 0.02 mm. See discussion of ultramylonite in this text.

Stillwell, F. L., 1918, The metamorphic rocks of Adelie Land: Australasian Antarctic Exped., 1911–1914; Sci. Repts., ser. A, v. 3, pt. 1, p. 1–230.

First use of the term *metamorphic differentiation,* for various processes by which contrasted mineral assemblages develop during metamorphism from an initially uniform rock. See discussion of cataclastic metamorphic differentiation in this text.

Suess, F. E., 1913, Die moravischen Fenster und ihre Beziehungen zum Grundgebirge des Hohen Gesenkes: Akad. Wiss., Wien, Math.-Naturwiss. Klasse, Denkschr., v. 88, p. 541–631.

First noted that retrogression need not go "all the way," that Kata-zone rocks might go to "Meso-zone rocks" under "Meso-zone conditions" and never reach the "Epizone" stage. Good description and interpretive discussion of a diaphthoritic zone in the Austrian Waldviertel. See Becke (1913), Suess (1918), Kölbl (1922), Limbrock (1925), and Preclik (1930) for discussions of this controversial zone.

——— 1918, Bemerkungen zur neueren Literatur über die moravischen Fenster; Geol. Gesell Wien, Mitt., v. 11, p. 103–104.

Reply to Becke (1913) (see Suess, 1913). Ascribes the formation of mica schists in the Moldanubian block to deep-seated diaphthoresis of highly potassic argillaceous layers whose composition was peculiarly susceptible to retrogression. The "schiefer gneiss" intercalations are regarded as relics of the original "Katagneiss."

Suggate, R. P., 1963, The Alpine fault: Royal Soc. New Zealand Trans. Geology, v. 2, no. 7, p. 105–129.

Cataclasis and mylonitization (p. 115–116) are described along with detailed description and discussion of the Alpine fault zone of New Zealand. Good brief description of the field relations of some of the rocks and their relation to the fault movements (see also Reed, 1964). See Examples section of this text.

Sutton, John, and Watson, Janet, 1951, The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the north-west Highlands, and its bearing on the chronological classification of the Lewisian: Geol. Soc. London Quart. Jour., v. 104, p. 241–307.

Describes "shear belts" with various cataclastic rocks. Also describes "mylonite belts."

——— 1959, Metamorphism in deep-seated zones of transcurrent movement at Kungwe Bay, Tanganyika Territory: Jour. Geology, v. 67, p. 1–13.

One of the most detailed descriptions of blastomylonites. Other cataclastic rocks are also described. Wide "shear belts" and thin "mylonite belts" are distinguished and mapped. Good descriptions of the mineralogical changes in some of the shear belts. "The mylonite gneisses can be arranged in a series showing increasingly complete mechanical breakdown, while the noncataclastic types form a second series which appears to show increasing degrees of crystallization. * * * The end point of the first series is a minutely granular rock which does not differ greatly from the starting point of the second series." (p. 6). Describes blastomylonite in which recrystallization-neomineralization has allowed growth of subhedral mineral rims crowded with inclusions of the cataclastic matrix material of the rock. The rims of the minerals are of the same material as the relict rounded cores. There was no retrogression. Very well illustrated.

Svenonius, F., 1892, Om berggrunden i Norrbottens län och untsigterna till brytvärda Apatitförekomster derstädes: Sveriges Geol. Unders., ser. C, Afhandlingar och Uppsatser, no. 126, 43 p.

Describes cataclastic rocks in a thick zone.

——— 1900, Översikt af Stora Sjöfallets och angränsande Fjälltrakters geologi: Geol. Fören. Stockholm Förh., v. 22, p. 273–322.

First use of the term *kakirite* for the strongly brecciated rocks that lie above the Silurian crystalline rocks in the region of Storce, Sweden. Good descriptions.

Taubeneck, W. H., 1967, Notes on the Glen Coe caldron subsidence, Argyllshire, Scotland: Geol. Soc. America Bull., v. 78, no. 11, p. 1295–1316.

Describes and discusses the flinty crush-rocks at Glen Coe (p. 1307–1308). Attributes origin of the rocks to fluidization and denies cataclasis.

Teall, J. H. H., 1918, Dynamic metamorphism; a review, mainly personal: Geologists Assoc. (London) Proc., v. 29, p. 1–15.

Descriptions and photomicrographs of Lapworth's (1885) original mylonites. Quoted in this text. See discussion of mylonite in this text.

Termier, Pierre, 1909a, Sur les nappes de l'île d'Elbe: Acad. Sci., Paris, Comptes rendus, v. 148, p. 1648–1651.

Brief description of a thick band of cataclastic rocks on the island of Elba.

——— 1909b, Sur les relations tectoniques de l'île d'Elbe avec la Corse et sur la situation de celle-ci dans la chaine alpine: Acad. Sci., Paris, Comptes rendus, v. 149, p. 11–14.

Describes a band of cataclastic rocks on Elba, and a similar band on Corsica. Relates the cataclastic zones to the tectonics of the islands and to the Alps.

——— 1909c, Sur les granites, les gneiss et les porphyres écrasés de l'île d'Elbe: Acad. Sci., Paris, Comptes rendus, v. 148, p. 1441–1445.

A more detailed description of the cataclastic rocks of Elba described in two previous papers (1909a, b).

Termier, Pierre, and Boussac, J., 1911, Sur les mylonites de la région de Savone: Acad. Sci., Paris, Comptes rendus, v. 152, p. 1550–1556.

Describes a complete transition between undeformed granite and mylonite. According to the degree of mylonitization, they differentiate: (1) fissured and brecciated granite; (2) granite incompletely crushed, but laminated; (3) granite with lamination more intense; (4) crushing incomplete, without lamination; (5) crushing more complete—no mineral discernible to naked eye; (6) *Puree Parfaite*—"perfect soup"; (7) lamination of the preceding soup. (literal translation).

Termier, Pierre, and Maury, E., 1928, Nouvelles observations géologiques dans la Corse Oriental; Phenoménes d'écrasement et de laminage; mylonites et bréches tectoniques: Acad. Sci., Paris, Comptes rendus, v. 186, p. 1247–1251.

Field and petrographic description of a complex 24-km-wide band of cataclastic rocks on Corsica. They use the term *mylonite* in a general rather than specific way, to include all materials formed by crushing, regardless of their nature.

Theodore, T. G., 1966, The fabric of a high-grade mylonite zone in southern California [abs.]: Am. Geophys. Union Trans., v. 47, no. 3, p. 491–492.

"Phase petrology of the nonmylonitic rocks indicates almandine-amphibolite facies metamorphism. Subsequent granitic intrusives caused a breakdown of biotite and muscovite to give sillimanite, K feldspar, and iron ores. The mylonitic rocks contain the same mineral assemblages as the others, with no evidence of retrogressive metamorphism. The nature of the folds suggests that pervasive lateral shear movements, normal to the lineation but without constant sense, have affected the mylonite zone. The predominant type of quartz fabric has orthorhombic symmetry and consists of crossed girdles of *c* axes, intersecting in the plane of the foliation, normal to the lineation; a single or divided maximum occurs at the girdle intersection. The orthorhombic quartz fabrics suggest flattening normal to the foliation planes and elongation parallel to the lineation. Analysis of preferred orientation of quartz in a fold suggests: (1) that the shear folding continued while the orthorhombic quartz fabrics were developing, or (2) intermittent shear displacements, perhaps along zones at high angles to the maximum compressive stress, have occurred after initiation of the flattening. It appears that the complexly deformed mylonite zone formed at depth in a mobile region of the Earth's crust undergoing high-temperature metamorphism * * *" (part of author's abstract).

Thoreau, J., 1935, Contribution à l'étude des roches du substratum cristallin des bassins Lulua Bushimail au sud du 7e paralléle: Louvain Univ., Inst. geol. Mém., v. 8, p. 293–326.

Describes thick zones of blastomylonites in the Belgian Congo.

Tilley, C. E., 1947, The dunite-mylonites of St. Paul's Rocks (Atlantic): Am. Jour. Sci., v. 245, no. 8, p. 483–491.

Describes dunite and peridotite cataclastic rocks, chiefly mylonites. Well illustrated. The textures in these rocks were formerly thought to be volcanic flow features. Notes regeneration of fosterite veins after mylonitization.

——— 1966, A note on the dunite (peridotite) mylonites of St. Paul's Rocks (Atlantic): Geol. Mag., v. 103, no. 2, p. 120–123.

Brief description of the cataclastic rocks. See Tilley, 1947.

Törnebohm, A. E., 1880, Några ord om granit och gneis: Geol. Fören. Stockholm Förh., v. 5, p. 233–248.

First use (p. 244) of the term *mortar structure* (Murbruk—Swedish for mortar).

Tullis, Jan, 1968, Preferred orientation in experimental quartz mylonites [abs.]: Am. Geophys. Union Trans., v. 49, no. 4, p. 755.

Turner, F. J., 1941, The development of pseudo-stratification by metamorphic differentiation in the schists of Otago, New Zealand: Am. Jour. Sci., v. 239, no. 1, p. 1–16.

A classic paper on metamorphic differentiation. Deals mainly with the chemical factors of differentiation, but also describes the great amount of shearing and mechanical deformation involved, and calls the rocks "blastophyllonites." See section on cataclastic metamorphic differentiation in this text.

——— 1942, Preferred orientation of olivine crystals in peridotites, with special reference to New Zealand examples: Royal Soc. New Zealand Proc. and Trans., v. 72, pt. 3, p. 280–300.

Describes and discusses the fabric of a cataclastic dunite. "Complete lack of orientation of the space-lattice is attributed to the destructive process of cataclasis as opposed to plastic deformation of other rocks." (p. 292).

——— 1948, Mineralogical and structural evolution of the metamorphic rocks: Geol. Soc. America Mem. 30, 342 p.

Defines *diaphthoresis* (p. 6): "A metamorphic assemblage of minerals formed at high temperature is converted to an assemblage stable at lower temperatures." Also good petrofabric data.

——— 1968, Metamorphic petrology; mineralogical and field aspects: New York, McGraw-Hill Book Co., 403 p.

Good discussion of metamorphic conditions which can be used to imply, very generally, conditions of formation of some cataclastic rocks. Good discussion of retrograde metamorphism.

Turner, F. J., and Chih, C. S., 1951, Deformation of Yule Marble, Part III, Observed fabric changes dues to deformation at 10,000 atmospheres confining pressure, room temperature, dry: Geol. Soc. America Bull., v. 62, no. 8, p. 887–906.

Turner, F. J., Griggs, D. T., Clark, R. H., and Dixon, R. H., 1956, Deformation of Yule Marble, Part VII, Development of oriented fabrics at 300° C–500° C: Geol. Soc. America Bull., v. 67, no. 9, p. 1259–1294.

Turner, F. J., Griggs, D. T., Heard, H. C., and Weiss, L. E., 1954, Plastic deformation of dolomite rock at 380° C.: Am. Jour. Sci., v. 252, no. 8, p. 477–488.

Turner, F. J., and Verhoogen, John, 1960, Igneous and metamorphic petrology [2d ed.]: New York, McGraw-Hill Book Co., 694 p.

This classic book has excellent discussions of the conditions of metamorphism. Some cataclastic rocks are defined in a general way (p. 452–454). There are good discussions of petrofabrics, origin of structural features (foliation, cleavage, etc.), metamorphic differentiation, and retrogressive metamorphism.

Turner, F. J., and Weiss, L. E., 1963, Structural analysis of metamorphic tectonites: New York, McGraw-Hill Book Co., 545 p.

A comprehensive textbook on petrofabrics and the geometry of rock deformation. Contains many references to and discussions of cataclastic rocks and their fabrics, as well as good discussions of the origin and development of structural features. The chapter (8) on experimental deformation of minerals and rocks is particularly valuable.

Tweto, Ogden, and Sims, P. K., 1963, Precambrian ancestry of the Colorado mineral belt: Geol. Soc. America Bull., v. 74, no. 8, p. 991–1014.

Describes various cataclastic rocks along shear zones in the Rocky Mountains. Describes a "new" biotite gneiss formed from mylonitic rock. The gneiss contains relict fragments of mylonite as inclusions. Describes late breccias and gouge formed from older cataclastic rocks. Especially good for descriptions of polycataclastic rocks.

Tyrrell, G. W., 1924, the geology of Prince Charles Foreland, Spitzbergen: Royal Soc. Edinburgh Trans., v. 53, p. 443–478.

Describes and illustrates "hartschiefer" formed from banded siltstones, quartzites, and "crush breccias." Other cataclastic rocks are briefly described.

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——— 1926, The principles of petrology: London, Methuen, 349 p.

Definitions, descriptions, drawings, and discussions of many types of cataclastic rocks. Defines (p. 271–272): *cataclastic structure, porphyroclastic structure;* (p. 281–288) *crush-breccia, micro-breccia, flaser-rocks, mylonite, kakirite, crush-conglomerate, cataclasite, mylonite-schist, ultramylonite, flinty crush rock,* and *hartschiefer.* See Glossary this text.

Van Bemmelen, R. W., 1936, Over de zoogenaamde "Smelt-mylonieten" (=pseudotachylieten): Geol. Mijnbouw, v. 15, no. 9, p. 74–79.

Good discussion of pseudotachylite.

Van Diver, B. B., 1967, Contemporaneous faulting-metamorphism in Wenatchee Ridge area, northern Cascades, Washington: Am. Jour. Sci., v. 265, no. 2, p. 132–150.

Describes and illustrates various cataclastic rocks. "It should be noted that schistosity, on the whole, is largely a phenomenon of fine compositional layering produced by direct shearing, rather than strong form or situation of crystals" (p. 140). Describes and discusses compositional adjustment accompanying cataclasis; "* * * ferromagnesian content is directly proportional to the degree of cataclasis" (p. 143). Gives two "tenable" explanations: "(1) Selective shearing of more mafic original rock types; and (2) basification of original quartz diorite or leuco-dioritic material, principally by hydrothermal leaching of silica and alkalies during syn-metamorphic faulting." (p. 143).

Vogel, D. E., 1967, Petrology of an eclogite- and pyrigarnet-bearing polymetamorphic rock complex at Cabo Ortegal, N.W. Spain: Leidse geol. Mededel., v. 40, p. 121–213.

Von Seidlitz, W., 1910, Ueber Granit-mylonit und ihre tektonische Bedeutung: Geol. Rundschau, v. 1, p. 188–197.

Discusses chemical changes during mylonitization.

Waters, A. C., 1932, A petrologic and structural study of the Swakane gneiss, Entiat Mountains, Washington: Jour. Geology, v. 40, no. 6, p. 604–633.

Petrographic and field descriptions of cataclastic rocks, and of their gradational characters into noncataclastic rocks. Notes preferential cataclasis of pegmatites. Notes preferential demolition of quartz relative to feldspar.

——— 1938, Petrology of the contact breccias of the Chelan batholith: Geol. Soc. America Bull., v. 49, no. 5, p. 763–794.

Waters, A. C., and Campbell, C. D., 1935, Mylonites from the San Andreas fault zone: Am. Jour. Sci., 5th ser., v. 29, no. 174, p. 473–503.

Probably the most comprehensive review of cataclastic rock nomenclature in the literature. Cataclastic rocks are described, illustrated, discussed, analyzed, and classified. Extensively and widely quoted and cited in this text. See particularly the Examples section (San Andreas fault zone) of this text.

Waters, A. C., and Krauskopf, K. B., 1941, Protoclastic border of the Colville batholith: Geol. Soc. America Bull., v. 52, no. 9, p. 1355–1418.

Classic account of protoclasis. Describes, illustrates, and interprets the protoclastic rocks of the batholith. Conceptual discussions are particularly valuable. See Examples section of this text.

Wegmann, C. E., 1935, Preliminary report on the Caledonian orogeny in Christian X's Land (north-east Greenland): Medd. om Grønland, v. 103, no. 3, 59 p.

Good descriptions of mylonites. Considers mylonitization along thrusts later than the crystallization of the rocks that are thrust.

——— 1938, Geological investigations in southern Greenland; Part I. On the structural divisions of southern Greenland: Medd. om Grønland, v. 113, no. 2, 148 p.

Devises a schematic correlation chart (fig. 15) for temperature and movement phases during metamorphism in southern Greenland. Considers mylonitic activity as the last phase.

Wegmann, Eugéne, 1963, Note sur les mylonites du type de Sidi Ferruch (Algérie): Geol. Rundschau, v. 53, p. 314–324.

Description and interpretation of cataclastic rocks along a major north African fault zone. Uses the term *mylonite* for several different types of cataclastic rock.

Wenk, Edward, 1934, Beiträge zur Petrographie und Geologie des Silvretta Kristallins: Schweizer. Mineralog. Petrog. Mitt., v. 14, no. 1, p. 196–278.

Describes layered mylonite associated with its nonlayered parent rock in the Silvretta gneiss and concludes that mechanical processes have transformed the unlayered augen gneiss into layered cataclastic rocks. Good description of cataclastic rocks. See section on cataclastic metamorphic differentiation in this text.

——— 1937, Zur Genese der Bändergneise von Ornö Huvud: Upsala Univ. Geol. Inst. Bull., v. 26, p. 53–89.

Gives evidence that a banded gneiss (mylonitic) developed from unlayered parent rock through mechanical metamorphic differentiation. See section on cataclastic metamorphic differentiation in this text.

Wilkinson, P., 1955, The structural history of the region east of Loch Eriboll, Sutherland, *in* Phillips, F. C., Structural petrology and problems of the Caledonides: Advancement Sci., London, v. 12, no. 49, p. 573–574.

Good, brief description of folds in cataclastic rocks (blastomylonites?).

Willemse, J., 1936, On the old granite of the Vredefort region: Univ. of Zurich, Inaugural Dissert.

See Willemse, 1938.

——— 1938, On the old granite of the Vredefort region and some of its associated rocks: Geol. Soc. South Africa Trans., v. 40, p. 43–119.

Restudy of the Parijs (Parys) rocks (see Shand, 1917; Hall and Molengraaff, 1925). Concludes that there is evidence for nothing more than extreme crushing of the rocks, with a small amount of recrystallization to produce the spherulites and microlites.

Williams, Howel, Turner, F. J., and Gilbert, C. M., 1954, Petrography—An introduction to the study of rocks in thin sections: San Francisco, W. H. Freeman and Co., 406 p.

Definitions, discussions, and drawings of many types of cataclastic rocks. Good general discussion of cataclastic and crystalloblastic deformation (p. 199–200). Divides cataclastic rocks into three categories (p. 199–208): cataclasites, mylonites, phyllonites. Defines: *mylonite* (p. 200–201), *pseudotachylite* (p. 201), *augen gneiss* (p. 203), *cataclasite* (p. 204–205), *phyllonites* (p. 206–208). Discusses *flaser granite* and *flaser gabbro* (p. 204). All definitions relatively general.

Wilson, Gilbert, 1953, Mullion and rodding structures in the Moine series of Scotland: Geologists' Assoc. London Proc., v. 64, pt. 2, p. 118–151.

Describes minor folds in cataclastic rocks (chiefly blastomylonites). Contrasts the "plastic" style of folding in the Moine schists with the "brittle" style of folding in the blastomylonites of the Moine thrust zone.

Wiseman, J. D. H., 1932, A contribution to the petrology of the metamorphic rocks of East Greenland: Geol. Soc. London Quart. Jour., v. 88, pt. 3, p. 312–349.

Suggests (p. 335) that the metamorphism of the sedimentary rocks resulted from heat generated by thrust movements.

Wurm, A., 1935, Über tektonische Ausschmelzungsgesteine und ihre Bedeutung: Zeitchr. Vulkanologie, v. 16, no. 2, p. 98–119.

Good descriptions and discussions of pseudotachylites.

Zawadynski, L., 1952, Geologisch-petrographische Untersuchungen in der Valle Onsernone (Tessin); zur Petrographie der Kataklasite: Schweizer. Mineralog. Petrog. Mitt., v. 32, no. 1, p. 1–110.

Describes brecciated cataclastic rocks recemented by secondary mineralization (p. 19). Terms them "secondary kakirites."

Zwart, H. J., 1963, On the determination of polymetamorphic mineral associations: Geol. Rundschau, v. 52, p. 38–65.

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