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MYLONITES FROM THE SAN ANDREAS FAULT ZONE.[1]

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INTRODUCTION.

The San Andreas Fault is one of the most striking structural features in California. The fault zone has been traced more than 500 miles within the confines of the State and extends an unknown distance on the sea floor to the northwest. It is usually described as a roughly vertical shear, although the true dip of the fault, the date at which movements along it began, its relation to other structural features of the State, and many of its other characteristics are as yet imperfectly known. The strike-slip component of the displacement is undoubtedly large and it has been suggested that it may be as much as 25 miles.[2]

Certain parts of the fault zone have been very thoroughly studied. Following the disaster of 1906 the State Earthquake Commission amassed a wealth of detailed information on the nature of the fault[3] and this information has been supplemented in the maps and text of the San Francisco Folio.[4] Noble[5] has made a detailed study of the fault in the Mohave desert region, and discussions of its relations in other areas have been published by many others.[6]

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[1] Presented at the thirty-third meeting of the Cordilleran Section, Geological Society of America, Berkeley, 1934.

[2] Noble, L. F.: The San Andreas Rift and some other Active Faults in the Desert Region of southeastern California. Carnegie Institution Year Book No. 25, p. 420, 1925-26.

Reed, R. D.: Santa Margarita Conglomerate of the Temblor Range. Proc. Geol. Soc. Am. for 1933, p. 310. (June, 1934.)

[3] Lawson, A. C., and others: Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington, Publ. No. 87, 1908.

[4] Lawson, A. C.: The San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

[5] Noble, L. F.: Op. cit., pp. 415-428.

[6] Willis, Robin: Physiography of the California Coast Ranges, Bull. Geol. Soc. Am., Vol. 36, pp. 641-678, 1925.

Reed, R. D.: The Geology of California, Tulsa, 1933.

It is the purpose of this paper to record the presence and significance of unusual cataclastic metamorphic rocks known as mylonites and ultramylonites which are associated with the fault zone.

In the preparation of this paper we have received assistance from a number of sources. Mr. Alexander Tihonrarov, Geological Technician of Stanford University, has aided us greatly by preparing an exceptionally fine series of thin sections from materials that present unusual difficulties to the section maker, and in addition his assistance with the translation of some of the more difficult passages in Russian articles dealing with mylonites has been especially valuable. Professors H. V. Taylor and O. C. Shepard gave their time and equipment to carry out the fusion tests reported in the paper. The loan of specimens or thin sections from Professors Bailey Willis, Adolph Knopf, A. F. Rogers, Howel Williams, and Dr. G. W. Crickmay is gratefully acknowledged. The expenses connected with the preparation of the manuscript and for the chemical analysis were defrayed by a grant from the Research Committee of Stanford University.

DEFINITION OF MYLONITE.

The word mylonite was first used by Lapworth (28)[7] to describe certain laminated or schistose-appearing rocks associated with thrust faults in the Eriboll district of the Northwest Highlands of Scotland. According to Lapworth, "mylonites may be described as microscopic friction breccias with fluxion texture, in which the interstitial dusty, siliceous and kaolinitic paste has only crystallized in part." The word is from the Greek meaning "mill" and Lapworth considered the pulverization of rock material along a great fault to be analogous to the milling of grain. Four conditions are implied in Lapworth's definition and subsequent discussion. First, a mylonite is a microbreccia produced by the milling down of the original rock material into an aphanitic paste which can only be resolved by the microscope; second, the rock must possess a flow structure, or lamination, as a result of the streaking out of the pulverized paste; third, the pulverization must have occurred under such conditions that the rock retains its coherence; and fourth, the rock must be character-

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[7] Numbers in parentheses refer to the bibliography at the end of the paper.

ized by cataclastic rather than crystalloblastic textures. 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. By deforming rocks under strong confining pressure Adams and Bancroft (2, p. 637) have experimentally produced the mylonitic texture in rocks at room temperature without recrystallization.

Since Lapworth's original work on this subject mylonites have been found in many widely separated parts of the world and an extensive literature with representative articles in at least seven different languages has grown up about them (see bibliography at the end of this paper). Many of the later workers have not adhered rigidly to Lapworth's definition and as a result the meaning of the term "mylonite" is at the present time a source of considerable confusion. In general it may be said that the majority of German, Scandinavian, and English writers have followed Lapworth's definition in considering mylonites essentially unrecrystallized, coherent, microbreccias, but some of them have not followed the qualification that the pulverized material must show fluxion structure. Quensel, who has written an excellent and widely quoted article (32) on cataclastic rocks, defines mylonites as microbreccias but recognizes two subvarieties, one of which (*mylonitschiefer*) shows a laminated structure whereas the other (*mylonite im engeren Sinn*) is an essentially directionless microbreccia. On the other hand most French workers, and notably Termier, who has written several important articles on this subject, have departed widely from the original definition. Termier uses the term mylonite in a tectonic rather than a petrographic sense to include all materials formed by crushing no matter what their nature. His point of view is well expressed in a footnote to a paper written in 1928 (38, p. 1247):

> "Comme tous les tectoniciens, nous appelons *mylonite* toute roche écrasée, quelle qu'ait été sa nature originelle et quel que soit le type de son écrasement."

In America the term mylonite has not been widely used, but even in the few articles in which it has been employed the same confusion has arisen.[8] Which of these various meanings will eventually prevail only usage will determine. It has seemed to us that there should be no middle ground and that either the original rigid definition of Lapworth should be adhered to or else the term should be greatly broadened and used in a tectonic sense as Termier has done. The inclusive terms "fault breccia" and "cataclastic rock"[9] are available for tectonic usage, and Grubenmann and Niggli (15, pp. 221-222) have proposed the name "cataclasite" for those microbreccias which do not show fluxion structure. On the other hand no other term adequately fills the place Lapworth assigned to mylonite. To us it seems desirable to retain the original meaning proposed by Lapworth, and this course has been followed throughout this paper.

RELATIONS OF MYLONITES TO OTHER ROCKS.

Mylonites are transitional into a great many different kinds of rocks. By decrease in the degree of coherence they grade into ordinary gouge and finely pulverized fault breccia. By decrease in the degree of crushing they grade into megascopic, coherent breccias to which various names have been applied, and these breccias grade in turn into uncrushed rocks of all kinds. By increase in the degree of recrystallization mylonites grade over into either the progressive or retrogressive (27) varieties of crystalline schists. In some localities (3, 4, 12, 16, 18, 20, 22, 23) it is believed that the temperature generated by friction during fault movements has been sufficient to fuse the mylonite paste to a glass. These fused products have been called "pseudotachylyte" (35) and "flinty crush-rocks," and all transitions are assumed to exist between them and mylonites. More or less elaborate classifications of cataclastic rocks that take into account one or more of these methods of gradation have been proposed by Termier and Boussac (37), Staub (36), Quensel (32), Raguin (33), Shand (35), and others. Most of these classifications do not consider all of the possible gradations because of the fact that each was designed to fit the rocks of a specific area in which not all of the different gradations occur. Many writers, instead of introducing new terms, have preferred to use descriptive phrases such as "fis-

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[8] Cf. the usage of Crickmay (13) with that of C. L. Baker, Jour. Geol., Vol. 40, pp. 577-603, 1932.

[9] Holmquist (21) uses "cataclastic" rock as a synonym for mylonite, but nearly all other authors have used it in a much broader sense.

sured and brecciated granite" (37), "mashed rock" (33), "purée parfaite" = "perfect soup" (37), in describing the various stages in these gradations.

In the glossary below definitions of the more important names in use for cataclastic metamorphic rocks are given. The reader is also referred to the list of definitions given by Quensel (32, pp. 99-100), and by Mrs. E. B. Knopf (27, p. 13). It should be strongly emphasized, as pointed out in the glossary, that there is not universal agreement regarding the meaning of some of these terms. There has also been much duplication in naming. In most cases the relatively few terms listed in the chart in Table I will adequately cover the different varieties of cataclastic rocks that may be encountered.

GLOSSARY.

AUGEN SCHIST.—*Lapworth, 1885.* A rock intermediate between a mylonite and a crystalline schist. The "augen" are porphyroclasts and preserve evidence of cataclastic structure, but the surrounding ground-mass has been recrystallized. Augen schist is the equivalent of mylonite gneiss but is not as thoroughly recrystallized as blastomylonite.

BLASTOMYLONITE.—*Sander, 1912.* A crystalline schist which shows traces of cataclastic structure only very faintly. Augen are common but they have been largely or entirely recrystallized and can only be recognized with great difficulty. The rock represents a more advanced stage of recrystallization than that shown by augen schist or by mylonite gneiss.

CATACLASITE.—*Grubenmann and Niggli.* An aphanitic, structureless cataclastic rock. Differs from mylonite (Lapworth) in the absence of fluxion structure.

FLINTY CRUSH-ROCK.—*Clough.* A dark-colored flinty, or quartzite-like rock found as veins and stringers adjacent to fault zones, and formed by ultracrushing and perhaps partial fusion of the finely comminuted rock powder along the fault. See also ultramylonite, pseudotachylyte, purée parfaite.

GANGMYLONITE (OR DIKE-MYLONITE).—*Hammer, 1914.* An ultramylonite or mylonite which shows intrusive relations to the adjacent rock. Differs from pseudotachylyte in the absence of evidence of fusion, the pseudointrusive habit of the material being due to flowage of the crushed rock powder during cataclasis instead of to the intrusion of a melt.

HARTSCHIEFER.—A name first used by Swedish geologists for strongly banded aphanitic or flint-like rocks of obscure origin associated with mylonites. Under the microscope they show a combination of cataclastic and crystalloblastic textures. There has been much difference of opinion as to their origin, Holmquist (21) even favoring the idea that they are sedimentary rocks. 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.

KAKIRITE.—*Svenonius.* In describing the cataclastic rocks of the Lake Kakir area Svenonius appears to have included under this term rocks that would now be called mylonites as well as more coarsely sheared and brecciated materials, and perhaps some rocks that would be called hartschiefer. Later workers have interpreted the term in different ways. Holmquist (21) regards the term kakirite to be synonymous with mylonite (in Lapworth's sense). Quensel (32), however, considers kakirite to be "a megascopically sheared and brecciated rock in which the fragments of the original material are surrounded by innumerable gliding surfaces in which intense granulation and some recrystallization has taken place." This definition of the term would make it practically synonymous with the very appropriate term "protomylonite" which Backlund (5) has suggested for megascopically brecciated cataclastic rocks.

MYLONITE.—*Lapworth, 1885.* (See that part of this article entitled "Definition of Mylonite.") A coherent, aphanitic, cataclastic metamorphic rock, with fluxion structure, which has been formed by the milling down of rock material to a microscopic breccia as a result of movements along a fault. Cataclastic structure predominates over structures due to recrystallization. Commonly a few porphyroclasts of incompletely crushed material are enclosed in the aphanitic paste. As stated elsewhere in this article the term has been used in widely varying senses by different workers.

MYLONITE GNEISS.—*Quensel, 1916.* A rock intermediate between a mylonite and a crystalline schist, the texture being a combination of cataclastic and crystalloblastic elements. Augen structure is very characteristic, the augen commonly consisting of crushed aggregates of felsic minerals set in a recrystallized matrix containing a greater proportion of ferromagnesian constituents. Equivalent to the "augen schist" of Lapworth.

MYLONITSCHIEFER.—*Quensel, 1916.* This term is synonymous with mylonite (in Lapworth's sense). Quensel used the term to separate laminated mylonites (*mylonitschiefer*) from homogeneous unlaminated cataclastic rocks (*mylonite im engeren Sinn*). The "*mylonite im engeren Sinn*" is the same as the "cataclasite" of Grubenmann and Niggli.

PROTOMYLONITE.—*Backlund, 1918.* A coherent crush breccia made of megascopically visible particles which are commonly lenticular in shape and which preserve faintly the primary structures (stratification, schistosity) of the original rock. Resembles conglomerate or arkose on weathered surfaces. Commonly shows innumerable megascopic gliding surfaces. Equivalent to kakirite (as defined by Quensel), to the "nodular mylonite" of Raguin, and to the "fissured and brecciated granite" of Termier and Boussac.

Unfortunately Holmes (The Nomenclature of Petrology, p. 190) has defined protomylonite as "a mylonitic rock produced from contact metamorphic rocks, granulation and flowage being due to overthrusts following, in the first place, the contact surfaces between the intrusion and the country rock." Although the type protomylonite from Cape Chelyuskin-Sarya on the north tip of Asia has been formed by the brecciation of a banded hornfels it seems evident to the writers from Backlund's description that he intended the term to have wider application than indicated by Holmes. Backlund clearly emphasizes the coarse brecciation, pointing out the resemblance of the rock to conglomerate, and implying in the prefix "proto" that the rock is first in a series of rocks of which mylonite and ultramylonite are representatives.

PSEUDOTACHYLYTE.—*Shand, 1914.* A dark-colored rock of vein-like or pseudo-intrusive habit which bears a strong resemblance to tachylyte, but which has been formed by the local fusion of finely granulated rock powder, and is not attributable to igneous agencies. Differs from most flinty crush-rock in having undergone more thorough fusion, and in being less clearly related to definite fault surfaces. See also ultramylonite, gangmylonite, purée parfaite.

PURÉE PARFAITE.—*Termier and Boussac, 1911.* A microbreccia consisting of particles that have been so finely crushed that the rock resembles chert, or phonolite, or a sort of hard greenish wax. The fracture is scaly, almost homogeneous.

TABLE I.
Cataclastic Rocks and the Processes Concerned in their Origin.

DOMINANT PROCESS			
CRUSHING		RECRYSTALLIZATION	FUSION
Near Surface	*At Depth*		
(Material incoherent or cemented by later secondary processes. Pressure and temperature low.)	(Material remains coherent throughout ruptural deformation. Pressure moderate or strong, temperature low.)	(Ruptural deformation occurs under sufficient pressure and at a high enough temperature to bring about extensive recrystallization.)	(Temperature during deformation high enough to result in partial or complete fusion.)
GOUGE, and finely pulverized fault breccia	ULTRAMYLONITE Some FLINTY CRUSH-ROCK	HARTSCHIEFER	PSEUDOTACHYLYTE Some FLINTY CRUSH-ROCK
	MYLONITE	BLASTOMYLONITE MYLONITE GNEISS	
FAULT BRECCIA	PROTOMYLONITE		

↓ Increase in grain size

Increase in temperature and pressure →

Equivalent to ultramylonite. See also flinty crush-rock, pseudotachylyte.

ULTRAMYLONITE.—*Staub, 1915*; *Quensel, 1916*. An ultra crushed cataclastic rock in which all porphyroclasts have been demolished to breccia streaks and the last relics of the original structure have disappeared, thus producing a homogeneous aphanitic rock of cherty, felsitic, or quartzitic appearance. Equivalent to purée parfaite. Differs from flinty crush-rock and pseudotachylyte in the absence of evidence of fusion.

COMPLEX MYLONITIC ASSEMBLAGES.

At many localities several different varieties of cataclastic rocks occur together forming mapable units which range up to more than 1,000 feet in thickness and which can be traced along the strike for many miles. In Sierra Baias, south of Buenos Aires, a band of quartzitic-appearing mylonite derived from gray granite is reported to be 100 meters thick (6). Demay (14) reports a similar 100 meter band of mylonite derived from gneiss in the Pyrenees. In the Torneträsk region of Swedish Lapland a belt of mylonites and associated hartschiefer reaches a thickness of 300 meters (21). A much more complex unit in which many kinds of cataclastic rocks showing varying degrees of crushing and recrystallization are especially prominent is the "*protogine*" of the Alps (29). In Corsica Termier and Maury (38) report a complex band of crushed rocks reaching the amazing thickness of 24 kilometers, and similar relations are stated by Termier to hold in the Island of Elba, although from a review of the field relations and on the basis of chemical analyses Aloisi (1) has seriously questioned Termier's conclusions regarding Elba. The association of mylonites with zones of "*diaphthorites*," or retrogressive metamorphic rocks, has recently been emphasized by Mrs. E. B. Knopf (27). O. O. Backlund (6) gives an interesting discussion of some of the thicker mylonitic units that have been described and points out the confusion that arose in some regions through mistaking these bands of cataclastic rock for stratigraphic rather than tectonic horizons. This danger is especially great because true mylonites have a very deceptive appearance and it is seldom possible to establish their nature without the aid of the microscope. In hand specimens they may bear a very close resemblance to slate, phyllite, altered banded lava, quartzite, graywacke, chert, and other kinds of rock.

FIELD RELATIONS OF THE SAN ANDREAS MYLONITES.

Detailed mapping in various parts of California has emphasized the fact that the San Andreas should be thought of not as a single fault surface, but as an intricate group of anastomosing fractures occupying a belt that is commonly more than half a mile wide. 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. One mass of breccia of this sort occupies the fault zone in the vicinity of Crystal Springs Lakes and the character of the material is well displayed in a long road-cut on the Skyline Boulevard at a locality about one-half mile (measured along the road) southwest of the point where the boulevard crosses the lake (Locality I, Fig. 1). 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. Many of these rock varieties have clearly been derived from the heterogeneous Franciscan series[10] which crops out extensively in the immediate vicinity, but the parentage of many of the fragments is more obscure. The dark-colored, aphanitic mylonite is the most abundant constituent of the breccia. Megascopically it resembles a slate or phyllite, but the microscope immediately reveals its cataclastic nature. Similar mylonites crop out at another locality (Locality 2, Fig. 1) near the the north end of Crystal Springs Lakes, but the material from this place is not so favorable for microscopic study because hydrothermal action has introduced large amounts of carbonate into the rock subsequent to mylonitization. The exposures between these two localities are very poor, most of the fault zone being occupied by the lake or covered over with a thick mantle of soil. In this soil, however, fragments of mylonitic rock are common.

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[10] Lawson, A. C.: The San Francisco Folio, U. S. Geol. Survey, No. 193, 1914.

Branner, J. C., Newsom, J. F., and Arnold, Ralph: The Santa Cruz Folio, U. S. Geol. Survey, No. 163, 1909.

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

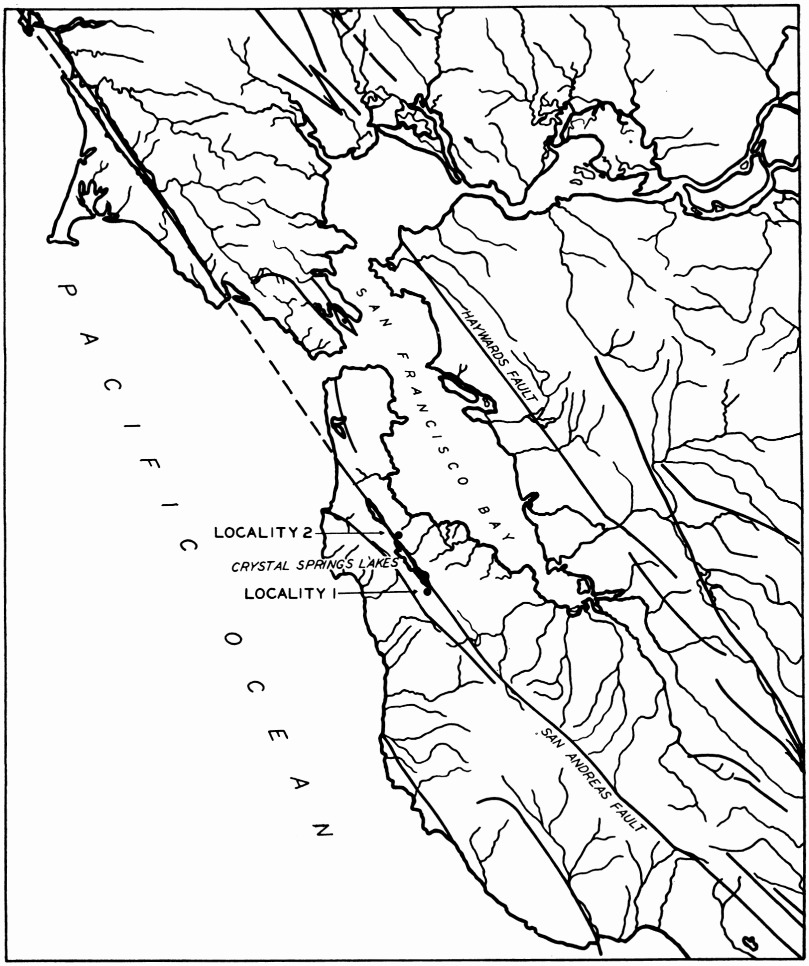

Fig. 1. Map of San Francisco Bay Region Showing Major Faults and the Position of the Two Mylonite Localities.

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 (Fig. 8). 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 miniature 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 dull like slate or may be subvitreous like chert or tachylyte.

MICROSCOPIC CHARACTER.

Under the microscope every stage in the demolishing of original coarse grained rocks to an ultramicroscopic paste can be seen. Various stages in the crushing of the coarse grained Franciscan graywackes and quartzites are shown in Figs. 2 to 7 and a conception of the nature of the process may be more readily won from a study of the photomicrographs than from description. In general, crushing begins by the fracturing of the rock into a coherent breccia or protomylonite whose fragments are megascopically visible. Pronounced

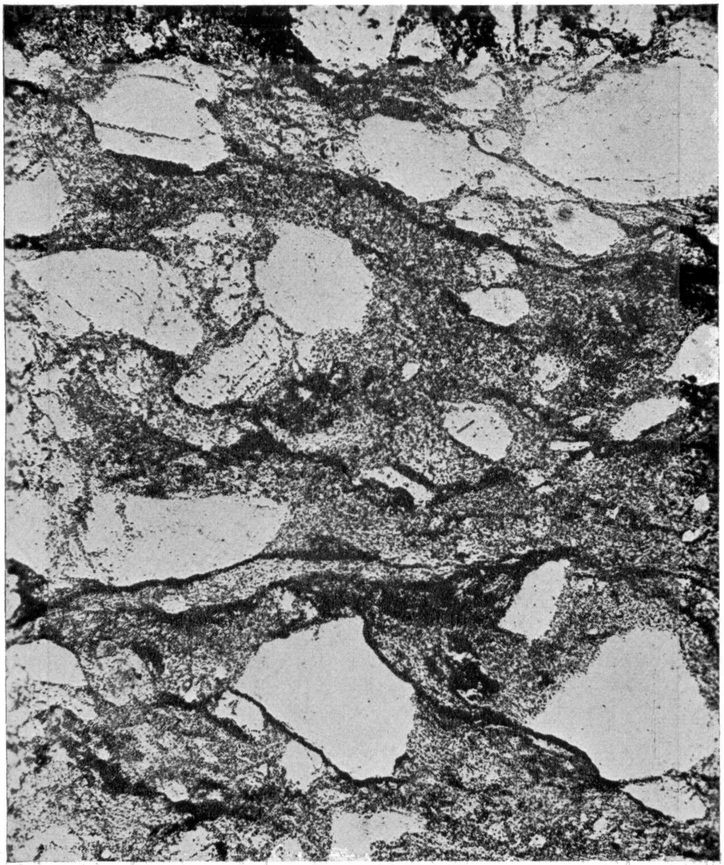

Fig. 2. Photomicrograph of a mylonite with many porphyroclasts. This rock was originally an arkose. About one-third of the original grains survive as porphyroclasts, the rest having been crushed to a microscopic powder. Crystal Springs Lakes, California (Nicols uncrossed, x 25).

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

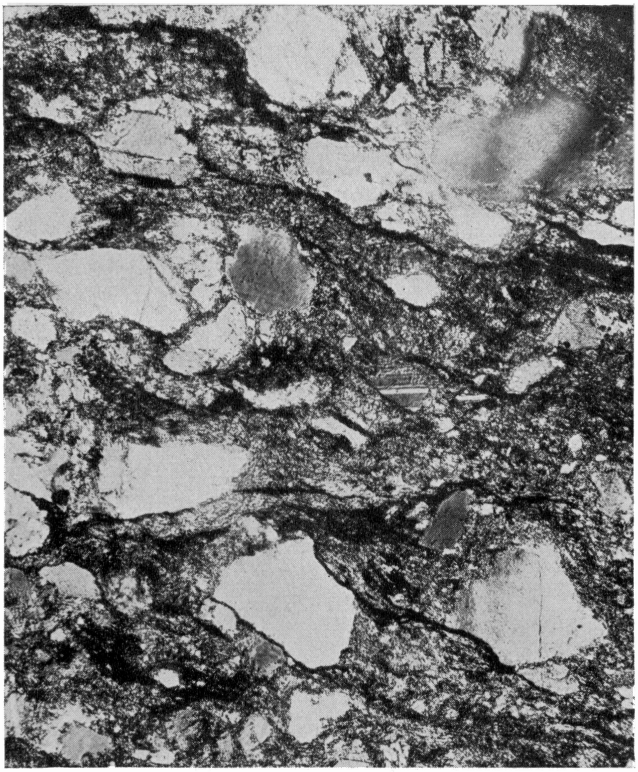

Fig. 3. The same view as Figure 2 under crossed nicols. Note strain shadows in quartz porphyroclasts.

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 (Figs. 2, 4). Complete rolling out of the rock to an ultramicroscopic powder in which none of the eye-shaped

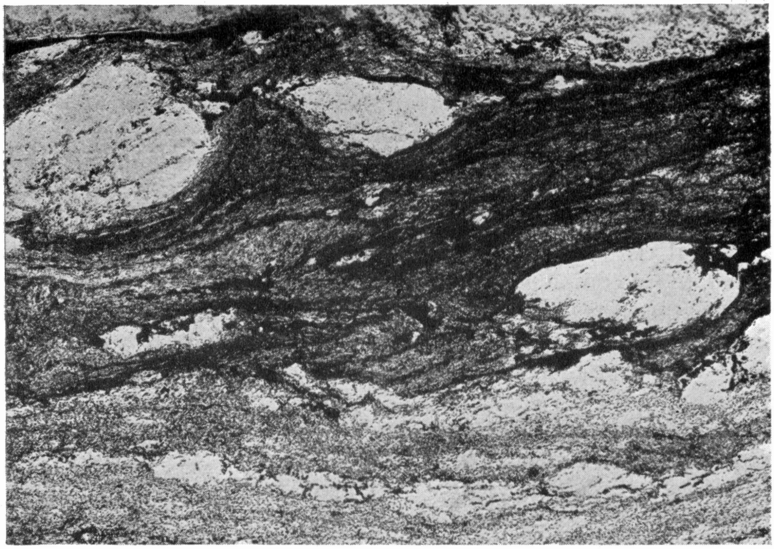

Fig. 4. Photomicrograph of a mylonite with a strongly fluidal groundmass containing a few partially rounded porphyroclasts. Crystal Springs Lakes, California (Nicols uncrossed, x 60).

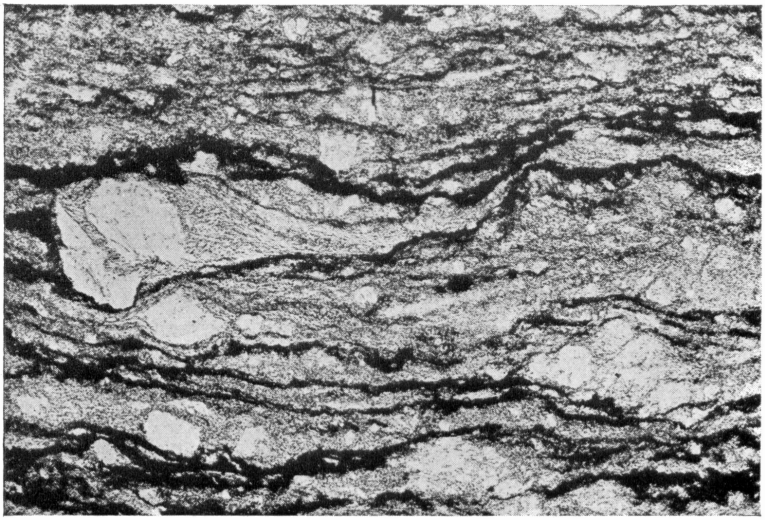

Fig. 5. Photomicrograph of mylonite with well-developed fluxion structure. Note trail of crushed particles to the right of the largest porphyroclast (Nicols uncrossed, x 80).

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 (Fig. 6). 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.

Reduction of the material to an ultramylonitic stage in which the groundmass particles are not definitely resolvable under the microscope is more common in the brittle quartz-rich rocks than in those having an abundance of mafic minerals. The ease with which the ferromagnesian constituents transform by recrystallization results in the development of a chlorite-rich, partially crystalloblastic base before the feldspars are completely reduced to powder.

In all of the mylonites there has been at least some recrystallization of the powdery groundmass, although in the mylonitized quartzites the newly formed minerals make up less than one per cent of the total composition of the rock. The principal new mineral is chlorite, which is practically ubiquitous to all of the mylonites no matter what the nature of the original rock they were derived from. In mylonitized quartzites and graywackes the chlorite is not abundant and is a pale-colored variety with weak pleochroism and very low birefringence. It occurs in little plates that are aligned parallel with the flow structure of the rock so that in thin sections cut at right angles to the flow planes the chlorite appears as tiny rods that bear a strong superficial resemblance to the microlites of a volcanic rock, and this resemblance is especially pronounced in those mylonites having an isotropic groundmass. In a few specimens chlorite forms spherulitic aggregates. In mylonitized diabases and basalts chlorite is very abundant, and in some specimens makes up more than half of the groundmass thus forming a rock which is transitional between a mylonite and a chlorite schist. As in the graywackes the chlorite plates are aligned parallel to the flow structure and they wrap around the feldspar porphyroclasts. In the diabases the chlorite is the normal strongly pleochroic greenish variety with anomalous Berlin blue interference colors.

The marked influence of the original chemical composition and physical properties of the rock in determining the nature of the product that will be developed by deep-seated movement along fault surfaces is well brought out in these rocks from the San Andreas zone. Although serpentine is one of the most abundant rocks in the vicinity, no serpentine mylonites have been found. However, antigorite schists are interwoven in the most intricate manner with almost entirely unrecrystallized mylonites derived from graywackes and quartzite, and with partially recrystallized diabase mylonites. Evidently 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.

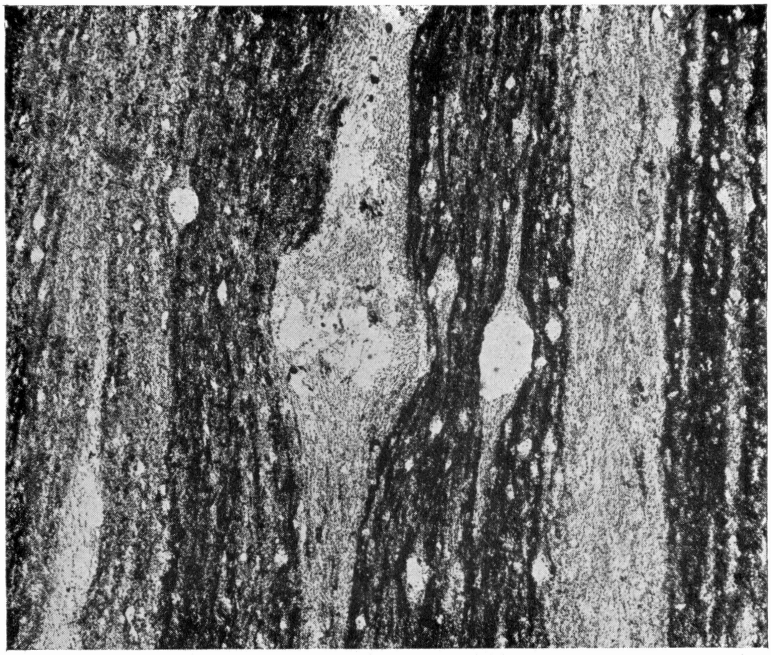

Fig. 6. Photomicrograph of ultramylonite, Crystal Springs Lakes, California. Note well-developed banding and the rounded character of the few surviving porphyroclasts (Nicols uncrossed, x 80).

Minute scales of pale-colored biotite appear in some specimens in place of chlorite. The biotite seems to be very similar to that of the Alsatian mylonites studied by Jung (26) and to that in Argentine mylonites described by O. O. Backlund (6). In a few specimens very minute irregular masses of feldspar have developed. Because of the small size of the crystals the feldspar has not been precisely identified. Although commonly untwinned it locally shows a faint polysynthetic twinning, and because of this feature coupled with its low indices of refraction it is probably albite.

Next to chlorite the most abundant mineral of new formation is quartz. The new quartz appears in two different ways. In some of the mylonites there are thin light-colored bands lying parallel with the foliation and consisting largely of quartz. Unlike the adjacent dark-colored bands these quartzose layers are characterized more by crystalloblastic textures than by cataclastic. The minute quartz grains show sutured boundaries against one another, although the effects of cataclasis can also be seen. In their peculiar combination of cataclastic and crystalloblastic textures these quartz rich bands bear a strong resemblance to the "hartschiefer" of Swedish

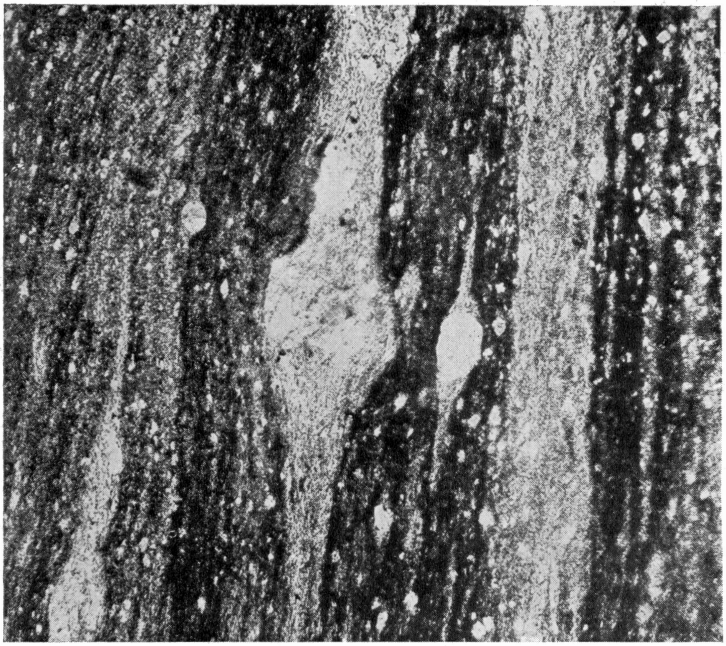

Fig. 7. The same view as Figure 6 under crossed nicols. Note the apparently isotropic character of some of the bands.

Lapland about the origin of which there has been considerable difference of opinion. Quensel (32) regards "hartschiefer" as partially recrystallized ultramylonites which have undergone strong chemical changes during crushing and recrystallization, so as to bring about marked chemical differences between the different bands.[11] On the possibility of such chemical changes during mylonitization very little is definitely known, although the question has received the attention of several writers (8, 10, 31, 32, 36, 39). In the case of a Patagonian quartz porphyry some chemical change during mylonitization is demonstrated by chemical analyses (31), although in the majority of regions the close correspondence in the analyses of the crushed rocks and the parent rocks from which they were derived is noteworthy (16, 18). 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." On the other hand it appears more probable to the writers that they represent small veinlets of quartz introduced into the rock by solutions during an early stage of mylonitization and then partially crushed as mylonitization continued. Still another possibility is that these bands may represent smears from the ultrapulverization and partial recrystallization of large quartz porphyroclasts which were reduced to powder during the last stages of mylonitization, but which were not intimately mixed with the other constituents of the groundmass. This last hypothesis encounters difficulties in explaining the more thorough recrystallization of these streaks than the rest of the rock, however. Mylonitized quartzites in the San Andreas fault zone show less recrystallization than any of the other rocks.

The second way in which new quartz appears is as definite veinlets and irregular masses that fill fractures in the mylonite (Fig. 8). The veinlets follow and also cut across the foliation. The quartz has been obviously introduced by solutions either at a very late stage of mylonitization or entirely subsequent to it. At Locality 2 (Fig. 1) considerable amounts

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[11] On the other hand Holmquist (21) although emphasizing the difficulty of reaching a definite conclusion as to their origin, inclines to the opinion that the hartschiefer of the Torneträsk region are sedimentary, despite the fact that in an earlier paper he had considered them to be cataclastic metamorphic rocks.

of carbonates have been introduced into the rock by solutions subsequent to mylonitization, and now appear both as fracture fillings and as replacements of the groundmass of the rock.

ULTRAMYLONITES WITH AN ISOTROPIC GROUNDMASS.

A few of the specimens of mylonite, and especially some of the specimens of ultramylonite in which granulation has progressed to the stage where all porphyroclasts have disappeared, show a groundmass that is partially isotropic. Commonly the isotropic part occurs in bands or layers which lie parallel with the foliation and fade off gradually into layers with a submicroscopic granular appearance (Fig. 7). The isotropic portion shows good flow structure and in some respects resembles volcanic glass. However, without crossed nicols it can be seen that this isotropic material is so crowded with impurities of various sorts as to render it nearly opaque in thin slivers, and to give it a very cloudy appearance in

Fig. 8. Photomicrograph showing folded flow bands in ultramylonite. Note the secondary quartz veinlets cutting the flow structure. Crystal Springs Lakes, California (Nicols uncrossed, x 60).

thin section. It is also crowded with larger, although still very minute, mineral fragments similar to those in the adjacent crush bands. Probably on account of these numerous inclusions the luster, though subvitreous, is rather dull and the material resembles tachylyte, the variety of basalt glass in which there has been considerable crystallization of the iron ores,[12] more than it does obsidian. Rocks of similar nature are widespread in the Vredefort Mountain Land of South Africa where they occur as dikelike bodies ramifying through nearly all of the formations of the region. The South African geologists believe them to have been molten and apply to them the name "pseudotachylyte" (35) because of their resemblance to basalt glass. They may be of any composition depending upon the nature of the rock they were derived from. In their admirable article on Vredefort Dome, Hall and Molengraaff point out the great mechanical stresses necessary for the uplift of the dome and state (16, p. 97):

"The heating effect of this extraordinary mechanical work has been very great and in places it was great enough to raise the temperature of the triturated rocks above their fusion point. The fused rocks solidified again as pseudo-tachylyte, which thus becomes a true flinty crush-rock." The fact that the pseudotachylyte locally occurs as vein-like injections into rocks that show little evidence of crushing is explained by them as follows (16, p. 111): "in this case the fusion was complete enough to allow the molten rock to flow into cracks and finally to solidify and crystallize at a distance from its place of origin outside the crush-zones, thus forming veins in a country-rock which does not show many signs of crushing, if any . . . the great majority of rocks in the Vredefort area, invaded by pseudo-tachylyte, show more or less marked cataclastic structures, and the cases where the effects of crush are absent near the veins, can be explained by the pseudo-tachylyte having been formed from crushed rocks at some distance, but travelling towards and penetrating fissures and cracks in the non-crushed rocks, in which it is now found solidified." With regard to the solidification of the material they state (p. 98): "In the case of rapid cooling it would

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[12] Peacock, M. A.: The Petrology of Iceland: Part I.—The Basic Tuffs, Trans. Roy. Soc. Edinburgh, Vol. 55, No. 3, 1926.

Peacock, M. A., and Fuller, R. E.: Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, Am. Mineralogist, Vol. 13, 360-384, 1928.

solidify as a vitreous or semi-vitreous rock; cooling somewhat more slowly crystallites or spherulites would develop in the groundmass; cooling still more slowly larger phenocrysts might crystallize in a denser groundmass, and rocks resembling lavas such as e.g. basalts, might be formed."

"Flinty crush-rocks," which are similar in appearance to the pseudotachylyte of South Africa, and to which the same origin has been attributed have long been known in association with the thrust faults in the Northwest Highlands of Scotland (11, 22, 23, 30), and along the ring fault at Glen Coe (12, pp. 629-631). Especially interesting examples have been described by Jehu and Craig from the outer Hebrides (22, 23). The material is stated to be dark-colored and vitreous and it forms a sort of pavement along the thrust plane from which tongues and stringers pass down more or less vertically into the underying rock (p. 432). According to these authors (p. 436), "The association of flinty-crush phenomena with belts of shearing and movement and the independence of the pseudo-tachylytic material of any connection with extrusive rocks in the field, together with its behavior as seen in hand specimens and in microscopic sections, leave no doubt in the mind of the observer that these peculiar rocks are the product of mechanical stresses which at places have raised the temperature to an extent sufficient to bring about partial fusion of the crushed gneisses." Rocks of similar nature have been found in the Eastern Alps (3, 18) and according to Holland (20) the "trap" in the "trap-shotten gneiss" of India is also of this character. Backlund (4) suggests fusion as a possible explanation of black cherty crush rocks derived from the red and gray granites near Buenos Aires. Hall and Molengraaff (16, p. 110) regard the "*purée parfaite*" of Termier and Boussac (37) and the "ultramylonite" of Quensel (32) to be the same as flinty crush-rock although fusion was not admitted by the authors of those terms. They also suggest on the basis of a comparison of photographs that the cataclastic rocks of the Torneträsk region described by Holmquist (21) are of this nature. In a recent paper Crickmay (13) describes vitreous-appearing crush-rocks from Georgia which show marked pseudo-eruptive relations, penetrating the gneisses from which they were derived in simple and branched dike-like forms. Regarding their origin, however, Crickmay states (13, p. 170): "the mylonite is similar to pseudo-tachylyte in being pseudo-eruptive, but there has been no fusion in its development."

Some Scottish geologists have also held the view that flinty crush-rocks are not fused.

After petrographic examination and various laboratory tests of the ultramylonites from the San Andreas fault zone, we have reached the conclusion that the apparently isotropic base of these rocks is certainly not now glass and that there is very little definite evidence favoring the view that they were ever molten. The data upon which this conclusion is based may be summarily listed:

1. *Nature of transition to normally mashed groundmass.*—The bands of isotropic material always grade off very gradually into bands of cataclastic material whose constituent particles can be resolved under the microscope. In thin section it is impossible to tell where one ends and the other begins (Fig. 7). Portions that appear isotropic and homogeneous under a magnification of 250 diameters can be seen to be micro-cataclastic in many cases when the magnification is doubled. In many specimens the homogeneous appearance that is so suggestive of glass completely disappears under the oil immersion lens and the groundmass is seen to be composed largely if not entirely of very minute but yet resolvable particles. No example has been seen of the isotropic material showing sharp contacts with normally crushed material as might be expected to be the case locally if the isotropic material were molten and capable of movement at a different rate than the crushed powder it is associated with.

2. *Index of Refraction Tests.*—The index of refraction of the apparently isotropic material is somewhat variable in different specimens and may even vary slightly in the same thin section. In the specimens tested by the immersion method it is never very far from 1.56 and in all specimens examined in thin section is higher than Canada balsam. A specimen of which a chemical analysis is given in Table II, yielded semi-opaque to turbid apparently isotropic particles whose index determined by the immersion method is 1.562 ± .005. In thin section this specimen shows beautifully developed flow structure. In addition to the isotropic part (which is thickly studded with minute inclusions) there are bands that are ultra-crushed and that show a few minute, very badly pulverized porphyroclasts of quartz. The specimen also shows clear evidence of some recrystallization resulting in the formation

of tiny scales of chlorite. The chemical analysis (Table II) confirms the suggestion won from the field relations that the original rock was a slightly metamorphosed arkose, the analysis disclosing a general similarity to granodioritic rocks, but showing an enrichment of SiO_2 and of Al_2O_3 over that normal to igneous rocks of the same general composition.

TABLE II.

Chemical Analysis and Norm of Ultramylonite from San Andreas Fault Zone.

Analysis		Norm		
SiO_2	66.70%	Quartz	25.38%	
Al_2O_3	15.02	Orthoclase	10.01	
Fe_2O_3	0.83	Albite	35.63	
FeO	4.38	Anorthite	7.51	
MgO	2.64	Corundum	3.47	
CaO	1.50	Hypersthene	14.01	8.71 $FeSiO_3$
Na_2O	4.20			5.30 $MgSiO_3$
K_2O	1.67	Ilmenite	0.46	
TiO_2	0.20	Magnetite	1.16	
H_2O-	0.20			
H_2O+	2.60			

In the Quantitative System the rock would fall into Class II (Dosalane), Order 4 (Austrare), Rang 2 (Dacase), Subrang 4 (Dacose).

Analysis by F. Herdsman, Glasgow, Scotland.

A small portion of this specimen was heated in an oxy-acetylene flame on a carbon block. It fused with evolution of some volatile matter to an extremely viscous liquid which was made into glass by quenching in water. The glass is dark greenish-gray in large pieces, but in thin slivers it is clear and shows a faint apple-green. In appearance it is very different from the unfused product and has a rather striking resemblance to sideromelane, a variety of glass formed when basalt magma is quenched by contact with water or glacial ice.[13] The index of refraction of this material, determined by the immersion method, is 1.530 ± .003, thus appreciably lower than that of the unfused material.

3. *Absence of microlites, trichites, longulites, margarites, etc.*—If the material had ever been melted by movements along the fault it seems improbable that subsequent cooling would have been so rapid that no traces of crystallization ensued. Natural glasses, unless they have been quenched by extrusion

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[13] Peacock, M. A., and Fuller, R. E.: Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau, Am. Mineralogist, Vol. 13, 360-384, 1928.

into water, generally show an abundance of skeletal crystal growths.[14] No crystallites have been observed in the ultramylonites from the San Andreas fault zone. In thin sections cut at right angles to the lamination, however, these rocks do show minute elongated crystals that bear a superficial resemblance to microlites. These crystals are chlorite, however, which could hardly have crystallized as a primary mineral from a melt.

4. *Comparison with fused drill-cores.*—In the process of taking cores in drilling for oil with the rotary drill several cases have been recorded where the rotation of the core barrel has developed enough friction to fuse the rock. A brief description of fused material of this sort has been given by A. F. Rogers,[15] and Bowen and Aurousseau[16] have published a longer paper giving chemical analyses and the results of various laboratory tests. Professor Rogers kindly loaned us samples of his material for examination. It bears very little resemblance to ultramylonite. The glass is clear, and has an index distinctly lower than Canada balsam, though the index is high for a silica-rich glass, perhaps due to contamination with iron from the partial fusion of the bit. In the portions in which fusion is just beginning the groundmass is darker and bears a greater, though by no means a marked resemblance to ultramylonite.

5. *Staining and etching tests.*—An attempt to detect the presence of glass by etching with hydrofluoric acid also failed.

Although these tests indicate that it is improbable that this material was ever fused, the striking similarity of the specimens as observed in thin section to the photomicrographs of pseudotachylyte in the memoir by Hall and Molengraaff (16) is very marked. Fortunately we were able to secure for direct comparison 9 specimens of pseudotachylyte from the Vredefort region. Six of these were collected by Professor Bailey Willis during an excursion of the International Geological Congress in 1928, the remaining three were collected by Professor Chester R. Longwell. These materials in thin section are so strikingly similar to the ultramylonites from the San Andreas fault zone as to leave little doubt but that the

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[14] Harker, A.: Petrology for Students, Cambridge, 150-154, 1923.

[15] Case, J. B.: Notes on the Use of the Core Barrel with Rotary Tools, Calif. Oil Fields, Calif. State Mining Bureau, Vol. 7, No. 9, 6-7, 1922.

[16] Bowen, N. L., and Aurousseau, M.: Fusion of Sedimentary Rocks in Drill Holes, Bull. Geol. Soc. Am., Vol. 34, pp. 431-448, 1923.

two products have had essentially the same origin. Chlorite with the same habit as that in the San Andreas mylonites was noted in some specimens, and the similarity in texture is very marked. Excellent petrographic descriptions of the South African material are given in the memoir by Hall and Molengraaff. Since the index of refraction of the materials was not given by these authors we have attempted to determine it. Many of the specimens are not isotropic, but micro-cataclastic, and much of the isotropic material is so cloudy as to be practically opaque thus rendering precise determination difficult, but in all the specimens examined the refractive index is higher than Canada balsam (1.543). A small piece of pseudotachylyte cutting granite was fused with the oxy-acetylene torch. Before fusion the refractive index, determined by the immersion method, was 1.552 ± .005. The glass formed by quenching is similar to that derived from the San Andreas rock and has a refractive index of 1.520 ± .003.

The abrupt drop in the index of refraction upon fusion and the presence of chlorite, would seem to indicate that glass is not now present in the rock, and that if it ever were present it must have been devitrified or altered. This throws some doubt on the conclusion that fault movements have ever resulted in the fusion of rock. The arguments that have been advanced as indicating that pseudotachylytes and flinty crush-rocks have been fused, or partially fused, are listed below. Following each title is a list of references to the original papers in which details regarding the evidence of fusion are given.

1. *Pseudo-eruptive relations.*—(3; 12, p. 630; 18; 20, pp. 198-202; 16, pp. 93-114 and plates; 22, pp. 430-436; 35). The material occurs in dike-like and vein-like masses that simulate igneous injections. The high mobility of the material is shown by its ability to penetrate minute openings (17, p. 93). This characteristic of pseudotachylyte is the one most frequently cited in support of its origin by fusion.

2. *Selvedges on pseudotachylyte dikes.*—(16, pp. 103-104). Some of the South African veins show borders or selvedges which have been interpreted as being due to changes in the rate of cooling.

3. *Resorption of inclusions.*—(3; 16, pp. 95, 100-101; 20; 22, p. 435; 23, p. 629). Quartz and other minerals are stated to be corroded by the fused groundmass.

4. *Isotropism.*—(3; 16; 18; 22, p. 436; 23, p. 629). In

the majority of cases the authors state that the isotropic material is vitreous.

5. *Presence of spherulites and of incipient crystals in the groundmass.*—(3; 16, pp. 106, 107; 18; 22, pp. 434, 436; 23, p. 629). Plagioclase is reported to occur in spherulites. In another case the spherulites are described as being "of a dark brown color in a light brown base." (22, p. 434.) The small crystals resembling microlites in the groundmass are usually too minute for precise identification but magnetite dust, plagioclase, and amphibole are reported.

6. *Experiments designed to synthesize pseudotachylyte.*—Holland (20) and Angel (3) have sintered, or partially melted, gneiss and state that they have been able to produce material similar to pseudotachylyte.

The features of pseudotachylyte listed above furnish a strong case for its origin by fusion. Nevertheless certain objections can be raised against each of these criteria. Pseudo-eruptive relations are in themselves no proof of fusion. The ability of rock to flow without undergoing either fusion or recrystallization when under strong confining pressure has long been known to field geologists and has been demonstrated experimentally by Adams and Bancroft, who state that rock deformed in this way develops typical mylonitic textures (2, p. 637). Crickmay (13, pp. 166, 170) describes clear cut examples of pseudo-eruptive relations among the mylonites of Georgia, but states specifically that the pseudo-intrusive rocks were not fused, and O. O. Backlund (6) describes very remarkable pseudo-intrusive phenomena shown by granite mylonites in Argentina. Bearth (7) has adopted Hammer's (17) term "gangmylonite" for aphanitic cataclastic rocks that bear pseudo-eruptive relations to the amphibolites and paragneisses that form the base of the Silvretta nappe in the Alps, but does not accept fusion in their production.

The isotropic character of the groundmass material suggests glass. Although several authors have definitely stated that this isotropic material is vitreous (3; 18; 16, p. 98; 22, p. 436) none of them has recorded the index of refraction of the isotropic material, or has made other physical tests useful in comparing it directly with natural and artificial glasses of the same composition. The tests that we have made indicate that the index of refraction is too high for natural glasses of the same composition, and that an abrupt drop in index occurs when the material is fused and converted into glass in the laboratory. There is very little data in the literature regarding the physical properties of the so-called glass. More definite evidence should be presented before we admit its vitreous character. In discussing isotropic crush-rocks from the East Alps Bearth (7, p. 350) says:

> "Wirkliches Glas habe ich nirgends fest-stellen können, vielmehr scheint es, als ob durch die reichliche Ausscheidung von Erz und durch die submikroskopische Dichte des Kornes der isotrope Charakter der Grundmasse nur vorgetäuscht wird."

Spherulites, although common in volcanic glasses, also develop in cherts, muds, and other fine grained materials. Spherulitic aggregates of chlorite are present in some specimens of the San Andreas mylonite and are reported to be present in the Alsatian mylonites (26). Small crystals in the groundmass of the rock that resemble microlites might be developed by metamorphic recrystallization as well as by separation from fusion.

The resorbed character of the inclusions in pseudotachylyte is undoubtedly one of the best evidences of fusion that has been presented, but even this feature is of doubtful importance. In the process of milling down a rock to an ultramicroscopic paste the few porphyroclasts that survive are likely to be well rounded. Selvedges at the borders of pseudotachylyte veins might conceivably develop due to the difference in the rate of flow of crushed material of slightly different granularity.

Although the hypothesis of fusion is attractive as an explanation of these interesting rocks, it does not seem justifiable to take too definite a position on either side of the question until more evidence has been accumulated. Careful tests should be made of the refractive index and other physical properties of the so-called vitreous material so that comparisons may be made with natural and artificial glasses of the same chemical composition. X-ray study of the material might also yield interesting results, although the abundance of minute inclusions of crystalline substances in the supposedly vitreous material would render the analysis of the results difficult. Particular effort should be made to identify correctly the minute mineral particles that have grown in the groundmass in order to ascertain whether they are the kind of minerals that would normally crystallize from a melt or whether they are those characteristically produced by metamorphic processes.

Sir George Beilby[17] proposed the hypothesis that in the polishing of metals a thin film of liquid is developed on the surface of the metal at temperatures well below the fusion point by the friction during polishing. Although this hypothesis was criticized by other chemists it has recently received strong support through experiments conducted in the Imperial College of Science laboratories.[18] R. C. Ray showed that certain changes take place in the physical properties of quartz sand which has been subjected to long continued grinding, and he interpreted these changes as being due to the conversion of some of the material into the vitreous state.[19] The material caught between moving fault surfaces must be subjected to both strong grinding and polishing action. The highly vitreous appearance of slickensides is known to all geologists. Possibly "vitreous" material produced in this way would have different physical properties from glasses of the same composition that have been produced by fusion. Jehu (24) and Hawkes (19) have already proposed the idea that the supposedly vitreous material of pseudotachylyte has been formed in this manner at temperatures well below the fusion point of the parent rock.

The simple pulverization of rock material under great confining pressure to such small size that the constituent particles are too small to be resolved under the microscope would explain the apparent isotropism of the material. This hypothesis would also best explain the refractive index of the material since the values determined are about the mean of the refractive indices of the various minerals presents. Such finely pulverized material might also be expected to have many of the physical properties of glasses, since its state of aggregation would bear many similarities to that of glass, inasmuch as recent work has indicated that the molecules in ordinary glasses are strongly polymerized. In its physical constitution such material may be transitional between the glassy and crystalline states, the individual crystalline particles being reduced to such small size that under the microscope they can no longer exert their own physical characters, the material thus becoming essentially homogeneous.

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[17] Beilby, George: Aggregation and Flow of Solids, 79-121, London, 1921.

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