AMERICAN JOURNAL OF SCIENCE

JANUARY 1931

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# RETROGRESSIVE METAMORPHISM AND PHYLLONITIZATION.*

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## PART I.

### PURPOSE OF THE PAPER.

During the past thirty years European geologists have made an intensive study of metamorphic rocks with surprisingly interesting results that are so far practically unknown in this country owing to the fact that most of the literature upon the subject is in foreign publications and thus not readily available to English-reading geologists. It is the aim of Part I of this paper to present briefly some ideas about the interpretation of metamorphic rocks that are now current in Europe and of Part II to indicate their bearing upon the study of the crystalline schists of the eastern Appalachians.

### PROGRESSIVE METAMORPHISM.

Instead of being, as in the past, shunned because of their complexity, metamorphic rocks are beginning to come into favor with the petrologist because it is realized that metamorphism actually records in the internal constitution of a rock many of the changes after its consolidation instead of obliterating the evidences of original character. The time has gone when crystalline schists were lumped under such indeterminate phrases as "fundamental or basement complex" and "schists and gneisses of unknown origin." For a good many years, petrologists have studied the basement complexes at close range, have separated and classified the schists and gneisses into lithologic units, and under the guidance of such men as Becke, Grubenmann, Niggli, and Eskola have come to recognize the fact that meta-

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morphism follows a definite and orderly progress by which rocks of given constitution under given conditions of temperature and pressure assume characteristic and recognizable forms. For example, under conditions of increasing temperature and pressure an argillite alters to a slate. A slate in turn is generally conceived of as passing into a fine-grained but perceptibly crystalline phyllite, this in its turn becoming more and more coarsely crystalline until under conditions of moderately high temperature and pressure in the epizone of Grubenmann or upper zone of Becke it becomes either a chlorite-muscovite schist or a chlorite-albite schist according to its original composition. Under higher pressure and temperature conditions in the meso- or katazones of Grubenmann and lower zone of Becke's classification it would become a garnetiferous muscovite-biotite schist or cordierite-sillimanite gneiss. Such is the normal course of progressive metamorphism.

*Equilibrium facies.* According to Becke and Grubenmann, metamorphism meant the adjustment of a rock to changed pressure-temperature conditions that were primarily a matter of depth. As temperature, which is the dominant factor in crystallization of new minerals, is not necessarily dependent upon depth, a somewhat more logical modification of the idea of pressure-temperature influence in metamorphism was introduced by V. M. Goldschmidt and Eskola, who classified metamorphic rocks into mineral facies, or groups of rocks characterized by minerals that were in perfect equilibrium at the time of their formation. This marks the advent of the idea that equilibrium governed by the phase rule plays a large part in the formation of rocks, both igneous and metamorphic. Each equilibrium facies is characterized by a typical mineral assemblage, whose individuals are in equilibrium under the given conditions of pressure, temperature, and concentration. Upon any change in physical conditions a displacement of equilibrium together with a corresponding change in facies should be expected.

Thus *typical minerals* are all those that are in stable equilibrium in a given facies; *critical minerals* are restricted to those that are stable only under the conditions of one given facies and will change upon change of facies. For example, in Eskola's greenschist facies, which corresponds approximately to the epizone class of Grubenmann, *typical minerals* are albite, sericite, chlorite, talc, serpentine, epidote, calcite, and dolomite. All of these minerals are stable under the conditions of the greenschist facies, but some may also occur in other facies. Sericite and chlorite, albite and epidote, however, are critical mineral associations, as these combinations cannot persist out of the field of the greenschist facies, although any one of the individual minerals may be found in more than one facies. Under higher pressure-temperature conditions the constituents rearrange to form muscovite and biotite or hornblende and a plagioclase that is more calcic than albite. Similarly, the only garnet recognized by Grubenmann to occur in the epizone is a manganiferous almandite, while Eskola does not recognize garnet at all as a constituent of his greenschist facies. Almandite, which is cited by Grubenmann as a constituent of the mesozone, is also recognized by Eskola in the amphibolite facies together with grossularite-andradite. The grossularite and almandite molecules persist into the deepest metamorphic zones but are joined there by pyrope; and according to Eskola a garnet that contains more than 30 percent of the pyrope molecule can not exist outside of the eclogite facies. Thus a garnet with a considerable content of MgO is a critical mineral of the deep metamorphic zones of high pressure and temperature, while an almandite molecule may be formed in shallow metamorphic zones under relatively low pressure-temperature conditions and yet may persist under much increased pressure and temperature conditions. The CaO and MgO that enter into carbonate and hydroxyl-bearing silicates near the surface rearrange themselves at greater depths and increased temperature and pressure into the silicates of the grossularite and pyrope molecules.

*Disequilibrium rocks.*—Now in mica schists and phyllites garnet commonly occurs side by side with muscovite and chlorite in apparently stable equilibrium and, moreover, this garnet is often pyropic with a considerable admixture of the grossularite molecule. What has happened here to derange the normal associations of the various members of the garnet series? There are two explanations for such a mineral assemblage. Either it represents a true state of equilibrium, intermediate between the equilibrium of the greenschist and amphibolite facies, in which case the rock deserves a place in a separate mineral facies whose typical minerals are garnet, muscovite, and chlorite, or else it is a *disequilibrium rock*, in which case it finds no place in Eskola's scheme because it merely represents an arrested transition stage from one facies to another, in which the minerals of one facies were in process of adjustment to the conditions of a new facies.

The realization that metamorphic rocks record disequilibrium as well as equilibrium opened up a new vista in petrology, because, as emphasized by Sander,[1] it is the rocks whose mineral assemblages are out of equilibrium that tell the most of the geologic story. The evidences of disequilibrium depend on changes in pressure-temperature conditions and these in turn are caused by geologic changes. Thus although a facies consisting of equilibrium minerals records clearly the geologic conditions under which it was formed, a still more illuminating flood of light is thrown upon the whole tectonic history by the rocks that record the *changes* in geologic environment since their formation.

## RETROGRESSIVE METAMORPHISM.

It is a commonly known fact that a phyllite or chlorite schist of the greenschist facies will change by progressive metamorphism into schist of the floitite and amphibolite facies.[2] Therefore, the alteration of chlorite and sericite to biotite together with the formation of garnet is characteristic of the change from a fine-grained phyllite to a coarser grained biotite schist. But the idea that the reverse process might also be of common occurrence was never emphasized until in 1909, Becke[3] called attention to the existence of some peculiar phyllites and micaceous slates in the High Tauern Alps of the Austrian Tyrol. In general these rocks look exactly like normal phyllites, composed of quartz, albite, chlorite, sericite, and carbonates. But in some places they contain allanite, a mineral characteristic of the old gneisses of the region but absent in the normal phyllites. Moreover he found occasional areas of quartz, feldspar, and muscovite that are coarser grained than would be expected in a normal phyllite. Becke was struck by the fact that the texture of these anomalous areas appears gneissic, and he recognized that such phyllitic rocks are really the result

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[1] Sander, Bruno, Zur Petrographisch-tektonishchen Analyse. Geol. Bundesanstalt (Austria), Jb. **63**, 194, 1923.

[2] Floitite is the name used by Becke (T. M. P. M., **35**, *227*, 1922) for rock that carries biotite together with typical minerals of the greenschist facies. Floitites belong in a facies intermediate between the greenschist and the amphibolite facies.

[3] Uber Diaphthorite, T. M. P. M., **28**, 369-375, 1909.

of a retrogressive instead of a progressive metamorphism, and that the gneissic-looking areas are undestroyed remnants of an original mesogneiss or katagneiss. Such phyllitic rocks owe their appearance to a breaking-down of a coarser-grained gneiss accompanied by the transformation of many of the original constituents into new minerals[4] under conditions of lower metamorphic intensity than those under which the original gneiss was formed. Accordingly, Becke defined those crystalline schists in which the index minerals of an upper zone have been developed at the cost of minerals peculiar to a lower zone as *diaphthorites,* from the Greek root meaning to destroy.

Here opened up new problems for the metamorphic geologist. How many of the phyllites that we meet in the field represent mildly altered argillites on the threshold of their metamorphic career, and how many have as Becke[5] expresses it "seen better days," having been originally schists or gneisses that have later descended the metamorphic ladder?

The far-reaching significance of Becke's idea of retrogression found ready appreciation among European workers in metamorphic rocks and ever since 1909 European literature has been filled with the descriptions of diaphthoritic rocks. Many of these diaphthorites had previously been described as normal quartz phyllites, garnetiferous phyllites, and mica schists without an idea that they record a critical step backward in the metamorphism of the formation from which they were derived. But it has now become a matter of everyday observation that retrogression plays an important part in the history of all highly disturbed metamorphic rocks, such as the crystalline schists of the Alps, the Austrian Waldviertel, the Scandinavian Highland, and the Green Mountain-Blue Ridge Ranges of the Appalachian Mountains together with their eastern foothill belt.

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[4] Such 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, such as the formation of chlorite, albite, hornblende, and epidote in a rock that originally contained pyroxene and a calcic plagioclase. As a matter of fact, 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.

[5] Becke, F., op. cit., p. 375.

As diaphthoresis records changes in geological environment, the geologist to whom the idea is new usually asks at once, why are not all rocks as we now see them diaphthorites? How can rocks of the katazone or eclogite facies arrive at the surface of the Earth without reversal to rocks of the mesozone and epizone on the way up? The answer to this is that although increased temperature promotes the chemical reactions necessary to produce new mineral assemblages, such reactions are slowed down or inhibited by lowering of temperature; thus in passing from higher to lower pressure-temperature conditions there is the same lag in readjustment to the new phase that produces the phenomenon of metastable equilibrium well known to the chemist as undercooling a liquid. By analogy, rocks of the deeper zones that have arrived at the surface by the gradual process of secular denudation may be thought of as undercooled in respect to metamorphism just as the metastable liquid is undercooled in respect to solidification. By the time the rock reaches the surface the undercooling has attained a point where the metamorphism can be considered quenched, much as a glassy lava has become quenched upon its outflow on the Earth's surface. A rock that is at the surface is being weathered and thus more or less rapidly disintegrating, but weathering must be distinguished from diaphthoresis, which is a true metamorphic process and therefore constructive in its net results, although this result is produced by a destruction of the earlier metamorphic constituents. Unless this distinction is borne in mind, confusion may arise from the fact that diaphthoritic rocks show some of the outward characteristics of weathering, such as an abundant development of chlorite and a dull, rather dirty appearance on foliation surfaces—an appearance that has been aptly described as a "diseased" look. In spite of this outward resemblance there is a fundamental difference between diaphthoresis and weathering and under surface conditions metamorphic rocks disintegrate but do not retrogress.

The next question is, Why do diaphthorites ever form? The answer to this is not obvious and is still a subject for investigation. The mere fact that katagneisses do arrive at the surface shows that the rock is able to remain in a condition of apparent (or false) equilibrium even after removal to a new environment to which it is unadjusted. But a katagneiss that has arrived at the Earth's surface as the result of denudation or by any simple upward movement *en bloc* has remained undisturbed by the movement as far as its constituent parts are concerned. All diaphthorites on the other hand are tectonites,[6] and thus affected by the movement down to their ultimate constituents, so that retrogressive crystallization was induced by the differential movements that caused the deformation. Thus, if adjustment to the new pressure-temperature field is to take place, the instigating force or trigger of the reaction must be furnished by a strong differential movement of the constituent parts before or together with the diaphthoresis. Unless these differential movements occur, the rock may move *en bloc* but its metamorphic condition will not retrogress. Even where a rock has undergone strong differential movement, as along either zones of distributive movement or thrust planes, it may not retrogress. Differential movement does not always produce retrogression but it facilitates the process; and the existence of diaphthoresis implies that the rock in question has undergone, since the imprint of the earlier metamorphism, an active deformation of the sort to produce inner differential movements that in some way, whether by increased heat due to friction, or by the facilitated passage of solutions or by both, promote a molecular interchange and rearrangement that results in diaphthoresis. Therein lies the interest of retrogressive metamorphism for the tectonist and therein lies the importance of the proper understanding of rock metamorphism, particularly polymetamorphism, in connection with the tectonic history of a district.

*Evidences of retrogressive metamorphism.*—Therefore in studying tectonics diaphthorites must be distinguished from metamorphic rocks of progressive origin. It is important to realize that a diaphthorite is not in itself a disequilibrium rock, although it can be recognized only by some evidence of disequilibrium in the mineral facies. As a matter of fact the process carried to completion is unrecognizable because the mineral constituents of the resultant rock will be in perfect equilibrium. As Kieslinger[7] remarks, "diaphthoresis is only recognizable where the diaphthoresis is incomplete, and where

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[6] Tectonite is a term used by Sander (K. K. Geol. Reichanst. Verhd. 1912, pp. 249-257) to denote metamorphic rocks deformed by differential movements that integrate into the tectonic movement as a whole. It was erroneously used by Backlund (Geol. Fören. i Stockholm Förhd., **40**, 198, 1912) in a totally different sense to denote a blastomylonite of a crystalline schist.

[7] Kieslinger, Alois, Geologie und Petrographie der Koralpe, I, Wien, Akad. Sitzsber., math. naturw. Kl., **135**, Abt. 1, 8, 1926.

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." Therefore to demonstrate reversal in metamorphism two things are necessary. First the rock must somewhere be caught as it were in the act of changing from one set of characteristic minerals to another; and second, it must be possible to prove that the change is retrogressive, as in the case of garnet or biotite that have altered to chlorite. As in many other geologic processes no one criterion alone is a safe basis for the determination of retrogressive metamorphism, but a combination of several is often a reliable indication of what has taken place.

*Textural criteria.*—Although the mineralogical criteria furnish the only conclusive proof of retrogression, a noticeable change in texture is an inevitable result of the processes that started the change. We have seen that retrogressive metamorphism was originally recognized by Becke in the so-called Kellerjoch gneiss, in reality a rock of phyllitic appearance, that occurs south of the Inn valley, east of Innsbruck. This rock had been considered to be an arkosic feldspathic phyllite. The fact that all the feldspars are Carlsbad twins of microcline made Becke doubtful of the sedimentary nature of the phyllite, and by field study he discovered relics of granite gneiss together with various angular xenoliths and basic schlieren that pointed to an igneous origin, and suggested that the rock was not, as earlier supposed, a normal phyllite. Its phyllitic appearance resulted from the degradation of a rock of originally coarse grain. All such degraded rocks, although not always of diaphthoritic origin, have been called by Sander phyllite-mylonites, or more briefly phyllonites.[8]

Phyllonites have had a very different history from the phyllite that is an argillite just embarking upon its metamorphic career. The phyllonite has been subjected to an intense deformation by which the individual mineral constituents have been finely granulated ("pulverized"), amounting in fact to a mylonitization. Hence the name phyllite-mylonite, which thus means a phyllite produced by mylonitization of an originally coarser-grained rock.

This concept of phyllonitization is as valuable as the recognition of metamorphic retrogression in interpreting the tectonic history of an area. Although many phyllonites are

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[8] Sander, Bruno, loc. cit., p. 301.

diaphthoritic they are not necessarily so, and in order to appreciate clearly the distinction between phyllonitization and diaphthoresis it might be well to consider the precise meaning of mylonitization.

*Mylonitization.*—Mylonitization is not, as implied by many geologic writers, synonymous with fault brecciation or the development of fault gouges. The essential difference is that gouge and breccias are incoherent or recemented particles of variable size while a mylonite is a rock that has been completely crushed under conditions where it can not lose coherence. Mylonite was defined by Lapworth in 1885[9] as a microscopic pressure breccia with fluxion structure in which the interstitial paste is only partly crystalline. The antithesis to this was what Lapworth termed an augen schist, that is a broken and rolled-out rock in which the interstitial paste that cements the lenticular eyes of broken material is completely crystallized into new minerals (neomineralized). All stages between the dominantly cataclastic rocks, mylonites or microbreccias, and crystalloblastic mica-schists were recognized in Lapworth's study of the Eriboll thrust zone of the northwestern Highlands.

Subsequently mylonitization has been variously defined by different geologic writers; some writers, such as Tyrrell, Staub, and Grubenmann-Niggli stressing like Lapworth the fluxion structure (banding) and some, as Quensel and Königsberger, emphasizing the extreme microgranulation of the products of mylonitization regardless of the banded structure. All agree that extreme granulation is a necessary result of mylonitization, and thus it would seem most in keeping with the original definition to restrict the term as its name implies (Greek *μύλγ* = mill) to a process of rolling out or milling by which the rock has been deformed down to its individual mineral grains—in other words, microbrecciated regardless of the banded structure. This microbrecciation or "pulverizing" has taken place under such pressure-temperature conditions that the finely fretted particles are welded together instead of disintegrating into a fault gouge, and the conditions have not been such as to produce neomineralization of all the constituents. Mylonite proper is in fact an ultra-cataclastic rock and its diagnostic feature, in distinction to cataclastic rocks in general, is the microbrecciation produced by the extreme

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[9] Lapworth, Chas., The Highland Controversy in British Geology: Nature, 32, 558-559, 1885.

granulation of the individual mineral grains (Fig. 1). If this distinction is borne in mind, mylonites will not be confused, as often happens, with cataclastic schists and gneisses on one hand, or on the other hand, with those megascopic fault breccias with slight displacement of the fragments that have been called by Quensel[10] kakirites.

Where the neomineralization is at a minimum the rocks are felsitic or cherty in appearance and are known as ultra-mylonites or hartschiefer (Figs. 2 and 3). Such rocks are easily confused with quartzites but may be identified by their weathered rind. Where the compact felsitic rocks that are the result of microbrecciation carry a few recognizable porphyroclasts they were termed by Quensel mylonites, or mylonite schists if they show a parallel lenticular texture.

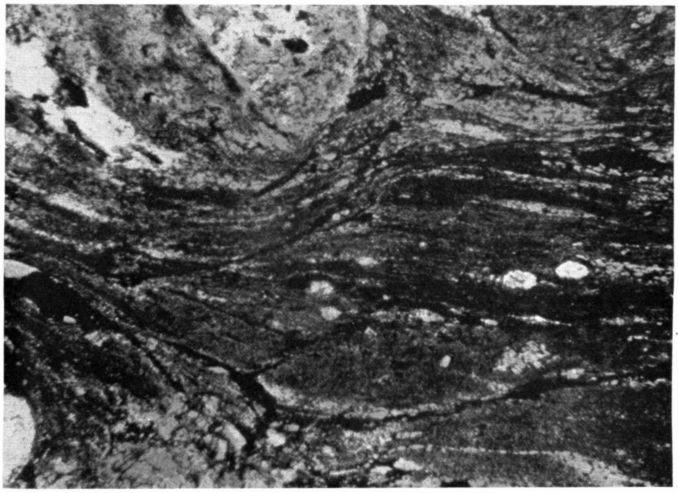

Fig. 1. Mylonite. Tjacktjavagge, Northern Sweden. Shows secondary fluidal structure.

*Neomineralization in mylonites.*—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

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[10] Quensel, Percy, Zur Kenntniss der Mylonitbildung: Bull. Un. Upsala, **15**, 101, 1916. This definition is quite different from that of Holmquist (Geol. Fören. i Stockholm Förhd., **32**, 38, 1910) who calls a kakirite a microbreccia, hence synonymous with mylonite.

deformation has taken place and upon the constitution of the rock that is mylonitized. That is to say, when the deformation takes place under conditions of increased temperature or rapid solution exchange neomineralization among the shattered constituents will be promoted. Also it is a matter of observa-

Fig. 2. Hartschiefer. Ladjovagge, Northern Sweden. From Bull. Univ. Upsala, Vol. 15, 1916.

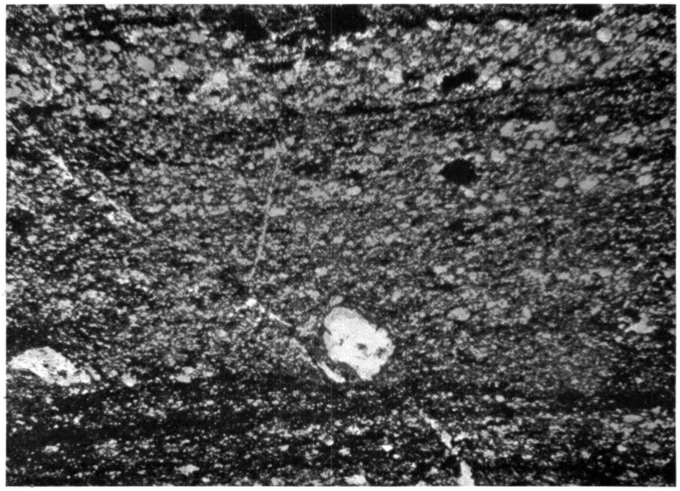

Fig. 3. Photomicrograph of ultramylonite, showing incipient banding. Tjacktjavagge, Northern Sweden.

tion[11] that in partly neomineralized mylonites the parallel structure is caused by the oriented arrangement of the newly crystallized dark mineral while the feldspars remain dominantly cataclastic; therefore, a rock that is rich in dark minerals will show more newly crystallized constituents than a more salic rock.

Rock of this kind has been called augen schist by Lapworth and mylonite gneiss by Quensel. The paste and some of the porphyroclastic "eyes" or lenticles are newly formed but the cataclastic history of the rock can be recognized by the granulation in many of the porphyroclasts (Fig. 4).

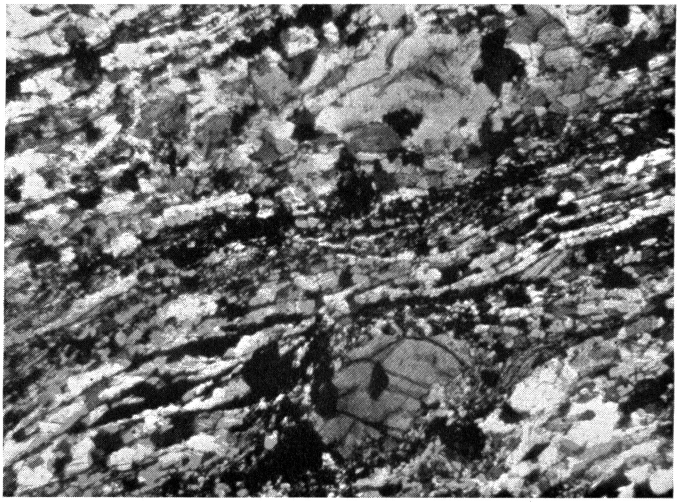

Fig. 4. Mylonite gneiss, Kebnetjåkko, Northern Sweden. Shows combination of cataclastic texture and neomineralization.

Where the neomineralization is so pronounced that the original intense cataclasis of the rock can only be recognized with great difficulty as where the lenticles are made up of completely reorganized material that probably represents comminuted pebbles, Sander[12] has called the rock a blastomylonite, a term that appears to represent the next stage in crystallization to Lapworth's augen schist in which the "eyes" are still

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[11] Quensel, Percy, loc. cit., p. 101.

[12] Sander, Bruno, Uber einige Gesteinsgruppen des Tauernwestendes: Geol. Reichsanst., Jb., **62**, 250, 1912-13.

## ROCKS THAT HAVE UNDERGONE MYLONITIZATION.

(Arranged in order of increasing neomineralization.)

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|---|---|
| 1. Ultramylonite (Quensel) | Cataclasis is predominant. A felsite-like or chert-like rock with no recognizable structure. Aptly called by Termier "purée parfaite." |
| 2. Hartschiefer (Quensel) | Compact felsite-like rocks characterized by a well developed, thinly banded structure. Neomineralization is present to a variable extent but is independent of the banding. |
| 3. Mylonite (Lapworth and Quensel)<br>*Kakirite (Holmquist) | Neomineralization is subordinate. Rock is almost completely microgranulated. A few porphyroclasts remain unreduced. |
| (a) mylonite (Quensel)<br>cataclasite (Grubenmann and Tyrrell) | A microbreccia without parallel texture. |
| (b) mylonite schist (Quensel)<br>mylonite (Grubenmann) | Microbreccia with parallel and lenticular texture. |
| 4. Augen schists (Lapworth)<br>Mylonite gneiss (Quensel)<br>Flaser rocks (Tyrrell) | Neomineralization of the comminuted paste is practically complete. Lenticles are porphyroclastic. |
| 5. Blastomylonite (Sander) | Neomineralization is so far advanced that the mylonitization can only be recognized with difficulty. Lenticles are generally crystalline but probably original porphyroclasts. |
| Appendix. See Fig. 5.<br>Pseudotachylyte (Shand)<br>Trap-shotten gneiss (King and Foote)<br>Flinty crush rock (Clough) | Dike-like occurrences of black aphanitic rocks of the same composition as the including rock. Under the microscope show an indurated black dust or glass. Possibly produced by fritting or by fusion under local development of intense heat. |

* This term is used differently by Quensel to denote a megascopic fault breccia in which the fragments are practically undisplaced and are cemented by partly recrystallized material.

### REFERENCES.

Sander, Bruno, Geol. Reichsanst. (Austria), Jb. **62**, 250, 1912-13.
Lapworth, Charles, Nature, **32**, 559, 1885.
Quensel. Percy, Geol. Inst. Univ. Upsala, Bull. **15**, 99, 100, 1916.
Tyrrell, G. W., The Principles of Petrology, 286, 1927.
Holmquist, Geol. Fören. i Stockholm, Förhd., **32**, 938-939, 1910.
Grubenmann-Niggli, Die Gesteinsmetamorphose, 219, 222, 223, 1924.
Shand, S. J., Quart. Jour. Geol. Soc., **72**, 209, 1917.
Clough, C. T., Geol. Surv. Mem., (Geology of the Cheviot Hills), 22, 1888.
Geol. Surv. Mem. (N. W. Highlands), 124, 221, 250, 1907.
Quart. Jour. Geol. Soc., **65**, 629-631, 1909.
King and Foote (1864), incorrectly considered black streaks in the gneiss of Salem, Madras, to be trap, later identified as indurated black dust formed from pulverization of the gneiss, by Holland, T. H., Geol. Surv. India, Mem. **28**, 198, 248, 1900.

cataclastic although the paste has crystallized. A blastomylonite is produced by a deformation which is partly ruptural and partly crystalloblastic, not by a rehealing crystallization of a previously mylonitized rock. The crystallization in all these partially neomineralized rocks is merely incidental and of variable amount according to the conditions under which the mylonitization took place. The characteristic feature wherein mylonites differ from cataclastic rocks in general is their ultra-cataclasis or intensive rolling out, so that even where much neomineralization accompanies the process as in blastomylonites the texture is still characteristic.

Fig. 5. Pseudotachylyte (pseudoeruptive mylonite), Tyrol. (The dark area crossing the banding of the amphibolite is the pseudotachylyte.) Photograph by Wilhelm Hammer. Jahrbuch der Geol. Reichsanstalt, Vol. 64, 1914.

As shown in the table (page 13) there is much confusion in the nomenclature of mylonites owing to the fact that the same term has been used by various authors in different senses.

### PHYLLONITIZATION.

A phyllonite, or phyllite-mylonite, is 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. This degradation is produced by cataclastic differential movements working along what Sander calls S-planes,[13] that is to say, a plane or a group of parallel planes along which there is the minimum resistance to permanent deformation by compression and tension. Such planes can be produced in various ways. For example, the bedding in sedimentary rocks, igneous flow banding, or fissility in schists all fulfill the definition of S-planes. Sander's concept of phyllite mylonitization supposes that some such previously existing group of parallel planes has been emphasized by a strong differential movement.

The characteristic result of phyllonitization is the production of elongated lenticles or interrupted bands made up of flattened individuals of approximately the same size, and the same optical orientation. Adjacent lenticles differ greatly in size but the individual constituents of each lens are equigranular. The lenticular structure may be megascopic but is frequently only to be recognized under the microscope. These lenticles represent mechanically different material located along the S-planes. Such mechanically different material occurs in conglomerates, graywackes, or porphyritic rocks and reacts to applied force in a different way from the rest of the rock. It does not matter whether the applied force was normal or parallel to the S-plane. If the force is normal, the result will be the spreading apart and thinning of the material until it assumes a lenticular shape. If the force is applied parallel to the S-plane, the deformation will cause a shoving of one layer over another in the S-planes. If the layers between the S-planes are incompetent the result will be a folding of the S-planes. The parallelism of the axial planes of the folds imparts to the rock a parallel structure that crosses the original structure of the S-plane, but this parallel structure is merely the old S-plane transposed to a new position. (See Fig. 6, a and b.) As the folding increases in intensity there is a stretching of material along the flanks of the folds and a thickening at the arches. The arches become sharper as the folds grow closer and eventually the strong differential movement may tear the folds asunder along the stretched limbs and pull apart the arches. Thus the original direction of the S-planes may be completely obliterated but the new S-planes themselves are merely a transposition of the old structure, not a second structure crossing the former. The old structure is in reality

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[13] The term S-planes has a mnemonic significance in allusion to their possible origin as planes of stratification, schistosity, or shear.

present but refolded with a mylonitization along the torn limbs. This process was recognized and followed in all its stages by Heim in his work on the Tessin gneiss in Switzerland.[14] Figures 7 to 10 are reproductions of Heim's photographs of the Tessin gneiss; on the left side of one specimen, Fig. 10, is shown a transition from the folding of the original S-planes to a transposition of the original S on the right side of the specimen that amounts to a practical obliteration of the previous direction of the structure. This phenomenon is of widespread occurrence in certain phyllites and has been variously recognized by American geologists as slip cleavage, strain-slip cleavage, fracture cleavage, etc. It has been described by Heim as Ausweichungsclivage (cleavage that follows the direction of yielding under pressure), and its final stage in which the old S-planes are completely transposed by folding is called Umfaltungsclivage by Sander.

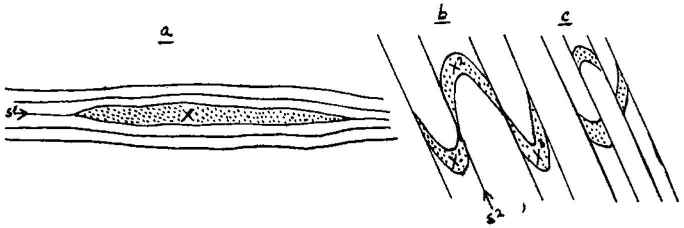

Fig. 6. Diagram showing (*a*) an area x along S-planes that follow a direction, $S_1$. (*b* and *c*) transposition of S-planes from position $S_1$ to $S_2$.

Sander makes a distinction between this Umfaltungs cleavage that follows the plane of a pre-existent S and true cleavage (slaty cleavage) that cuts the old S. The distinction corresponds to the distinction between fracture cleavage and flow cleavage made by Van Hise and Leith.

The emphasis on fracture in distinction to flow is perhaps a little misleading, as Ausweichungs cleavage (the so-called "fracture cleavage") is really a capacity to part or an actual slipping along certain planes that are predetermined by the folding. Along these planes old minerals have been sheared and ruptured or new minerals have been formed. Although the refolding of the S-planes when carried to its extreme results in fracture and slipping, nevertheless the fracture is definitely conditioned by the folding.

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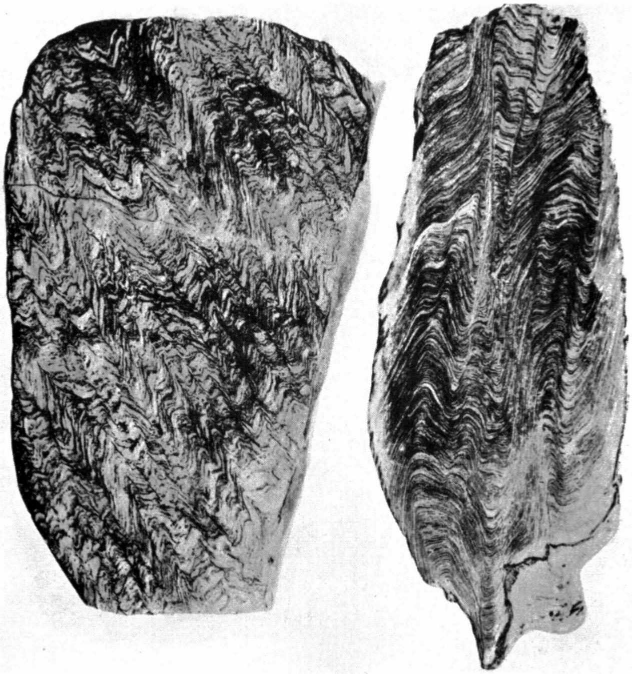
[14] Heim, A., Gneissfältelung in alpinen Centralmassiv: Vierteljahrschrift der Naturf. Gesellsch. in Zurich, Jahrg. 45, 1900.

The name "flow-cleavage" for slaty cleavage is in itself unfortunate, inasmuch as a large part of the mineral parallelism on which slaty cleavage depends is produced not by the flow of pre-existent minerals but by the formation of new minerals. The extent to which slaty cleavage is determined by reorientation of the original minerals is still undetermined.



Figs. 7 and 8. Development of Umfaltungs-cleavage by the transposition of the original S-plane. Tessin gneiss. Switzerland. Photos by Albert Heim.

Born[15] ascribes the chief rôle to the formation of new minerals with parallel orientation and not to rotation of already formed minerals. If this statement should be proved, the terms crystalloblastic cleavage for cleavage produced by the parallel arrangement of new minerals, and cataclastic cleavage for cleavage produced by rupture along stretched folds, might supply precise definitions free from all genetic implications.

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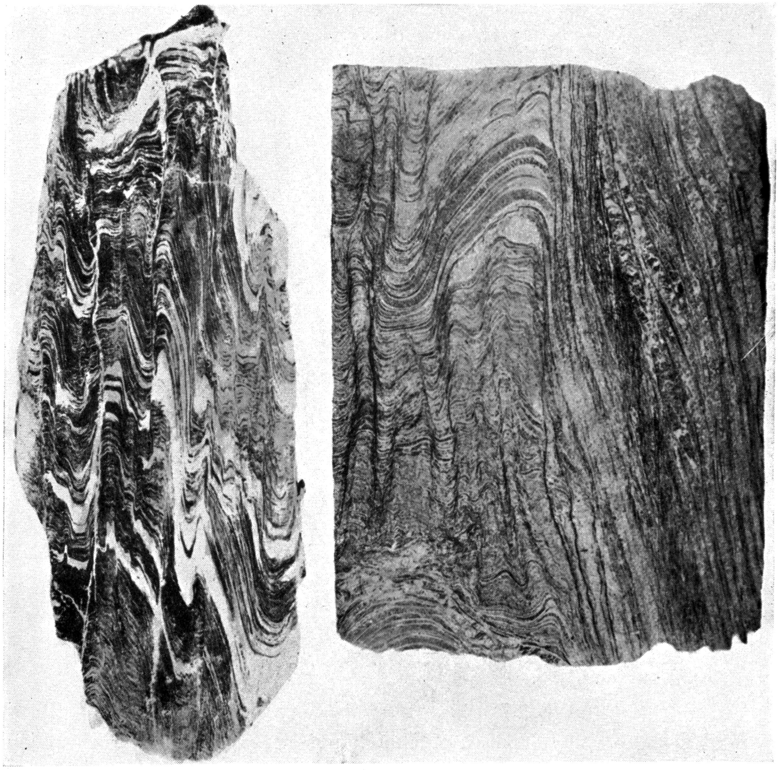
[15] Born, A., Gefügestudien an Gesteinen des varistischen Gebirges—N. Jb. für Min. B. B. 52. B., p. 135, 1925.

The lenticular structure caused by the isoclinal folding and mylonitic shearing out of relatively hard beds is characteristic of phyllites produced by grain-refinement of coarser rocks; and this appearance, which has been called "allure lenticulaire," is one of the most important criteria for the recognition of phyllonites. It is well shown on the right side of the specimen of Tessin gneiss, Fig. 10.



Figs. 9 and 10. Development of Umfaltungs-cleavage by the transposition of the original S-plane. (The right side of Fig. 10 shows typical phyllonitic texture.) Tessin gneiss. Switzerland. Photos by Albert Heim.

Particularly characteristic of phyllonites is the development of quartz lenses or nests of quartz grains that result from the breaking down of larger quartz individuals. The first stage of the quartz deformation is undulatory extinction, which manifests itself very early on account of the high sensibility of quartz to force that will not be sufficient to leave any permanent imprint on other minerals, for example, plagioclase. The undulation banding of quartz is always parallel to the ϵ-direction of the crystal and along this direction there come cracks by which the quartz is eventually broken into nests or aggregates of optically subparallel grains. These nests show all stages of thinning out into lenticles or even disconnected layers of variable size characterized by the subparallel orientation of the grains and by the fact that the grains in each lens or layer are of approximately the same dimensions, owing to the even spacing of the undulation banding in the large individual.

Criteria for the recognition of a phyllonite are therefore:

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-plane because its phyllitic texture is the result of a refolding and transposition 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.

In a regional phyllonitization different specimens will show all transitions from incipient phyllonitization where the transverse character of the relict S-structure can be seen between the folded limbs to a complete new phyllitic texture where the old S is completely sheared out (see Fig. 10).

### RELATION BETWEEN PHYLLONITIZATION AND DIAPHTHORESIS.

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 a 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. For as Sander pointed out in the biotite phyllonite of a Tauern gneiss near Brenner,[16] "there is no reversion of lower zone typomorphic minerals to those of a higher zone." 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 the mineral retrogression, while a phyllonite must be sufficiently cataclastic to reveal its mylonitic origin, but naturally there are all gradations between the strongly cataclastic phyllite-mylonite and the largely crystalloblastic blastomylonite. A phyllonite may be called diaphthoritic only if the original rock can be recognized as a mesogneiss or katagneiss that has been mylonitized under such conditions as to allow partial crystallization of new minerals characteristic of epizone metamorphism.

## MINERALOGICAL CRITERIA OF RETROGRESSIVE METAMORPHISM.

As many phyllonites are diaphthoritic, a phyllonitic texture is suggestive of retrogression in metamorphism, nevertheless for conclusive evidence there must be the characteristic mineral changes. One of the most common is the alteration of biotite to chlorite. But chlorite readily passes into biotite by progressive metamorphism and it is often difficult to tell which way the alteration has gone. Therefore, it is highly probable that retrogressive alteration has escaped recognition in many areas where progressive and retrogressive metamorphism have both taken place, as on the Hardanger Fjord of the Stavanger district in southern Norway.[17] Goldschmidt believes that in the Stavanger district he has both types of metamorphism and he distinguishes between chlorite of progressive and chlorite of retrogressive metamorphism. He considers primary a light-

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[16] Sander, Bruno, Beiträge aus der Zentralalpen zur Deutung der Gesteinsgefüge, Geol. Reichsanst. (Austria), Jb. **64**, p. 584, 1915.

[17] Goldschmidt, V. M., Geol. Pet. Studien im Hochgebirge des südlichens Norwegens. V. Die Injektionsmetamorphose im Stavanger-Gebiete. Vidensk. Skr. I Mat. Nat. Kl., No. **10**, p. 45, 1920.

colored, weakly negative chlorite, in some places altering on the border to biotite, and explains as retrogressive a darker-colored chlorite, either strongly negative or weakly positive, which is replacing biotite and garnet. However, he points out that in some places these criteria do not serve to distinguish between the two kinds.

A common evidence of reversal is the alteration of garnet to chlorite. This produces the anomalous garnet-chlorite schists in which the garnet is disappearing from the rock. The chloritization of garnet is probably easier to recognize than the diaphthoritic chloritization of biotite, because in many places the process brings itself to a premature end by the formation of a shell of chlorite, which surrounds and protects the residual garnet core (Fig. 11). As pointed out by Eskola[18] this chlorite shell acts as an armor against further reaction between the garnet and the surrounding minerals with which the garnet itself was incompatible. Such residual constituents of the original rock he calls "armored relics" or

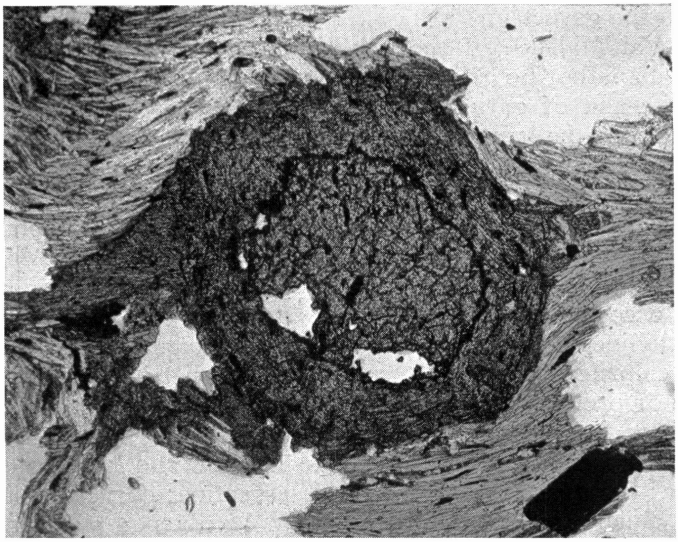

Fig. 11. Diaphthoritic garnetiferous mica schist, near Oxford, Chester Co., Pa. The cracked garnet is the core of the porphyroblast. It is enclosed in a shell of flaky chlorite outlined by a black line of iron oxide.

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[18] Eskola, Pentti, Mineral Facies of Rocks, Norsk Geologisk Tidsk., **6**, p. 150, 1920.

"unstable relics" in contrast to "stable relics" such as quartz that will persist unaltered in various facies. When the original garnet was thoroughly shattered and thus susceptible to complete interaction with the surrounding material, the chloritization may proceed to completion and then the only evidence of the retrogressive character of the chlorite will be its mode of occurrence in knots pseudomorphic after garnet.[19] However, a confirmation of the diaphthoritic alteration from biotite is the presence throughout the chlorite individual of a sagenitic network or of abundant flakes of iron oxide formed by the release of original titanium and iron in the biotite.

In the garnet gneisses of the east side of Monte Braccia in the Val Malenco of the Rhaetic Alps, Cornelius[20] describes the diaphthoritic alteration of a plagioclase to sericite and zoisite and of garnet to both chlorite and ottrelite. At the same time the biotite has completely altered to chlorite except where it was protected by its position within quartz or garnet.

The alteration of staurolite to muscovite (pinite) or to chloritoid[21] and of kyanite to muscovite are other diaphthoritic processes described by Angel from the Stub Alps in Styria.[22] In a recent paper Kieslinger[23] has given an excellent account of the diaphthoritic zone associated with the old crystalline of the Kor Alps. He cites remnants of biotite in the chlorite, also chess-board albite, as relict minerals indicative of previous higher metamorphism. A very complete list of new typomorphic minerals formed at the expense of the old is given: staurolite alters to chlorite and fine scales of mica; hornblende to chlorite and serpentine; garnet to biotite and finally to chlorite; ilmenite to leucoxene; pyroxene to uralite and epidote, biotite to colorless mica and chlorite, and plagioclase of medium composition to albite, sericite, and zoisite, actinolite to clinochlore and antigorite. Rocks of higher metamorphic rank have altered to lower grade facies, as follows: eclogite-amphibolites and amphibolites to uralite schists and green schists, uralite schists to calcite-chlorite

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[19] In the alteration of biotite to chlorite when none of the original mineral remains the mode of occurrence of the chlorite is no clue to its origin because the habit of chlorite and biotite are originally similar.

[20] Cornelius, H. P., Über einige Gesteine der Fedozserie aus dem Disgraziagebiet (Rhätische Alpen), N. Jb. BB. 52 A., p. 6, 1925.

[21] Becke, F., T. M. P. M., **28**, 1909.

[22] Angel, Franz, Mineralmorphologische Bermerkungen zum mittlesteirischen Kristallin, T. M. P. M., **35**, 112, 113, 1922.

[23] Kieslinger, Alois, Geologie und Petrographie der Koralpen I. Wien Akad. Sitzber., math.-naturw. Kl., **135**, Abt. 1, 8-11, 1926.

schist, garnetiferous staurolite-kyanite-mica schists to chloritoid-chlorite-sericite schist, pegmatitic gneisses to crumpled sericite quartzites, and mica schists and gneisses to phyllonites.

Some diaphthorites, particularly the coarser grained varieties, assume the characteristic so-called "diseased" appearance. The color distinctions of the original minerals become dingy owing to the development of new "pathologic" minerals, and the rock has a lustreless appearance that is very similar to the effect produced by weathering.

*Deep-seated diaphthoresis.*—Becke has defined retrogressive metamorphism as the process by which metamorphic minerals of the upper zone are formed by retrogression from minerals characteristic of the lower zone of metamorphism. The resultant rocks were termed diaphthorites, or if the change was merely incipient, diaphthoritic rocks. But in some metamorphic rocks garnet has been found altering to biotite instead of chlorite and a kata-zone pyroxene altering to amphibole. These changes are not exactly diaphthoritic in Becke's sense because neither biotite nor amphibole are typomorphic of upper zone metamorphism. When considered in the light of the threefold Grubenmann classification of depth zones or in the light of Eskola's equilibrium facies it is perfectly evident that these rocks might represent a retrogression of katazone rocks under mesozone conditions, or a change of rocks from the eclogite to the amphibolite facies instead of from amphibolite to green schist.

The occurrence of such a retrogression was first pointed out by Suess in 1913.[24] He recognized a narrow zone of peculiar mica schists in the Lower Austrian Waldviertel and interpreted them as diaphthoritic although they are muscovite-biotite schists quite unlike the diaphthoritic phyllonites of the Tauern Alps.

Suess explains the structure of this area as a block of katagneisses belonging to the Bohemian massif on the west thrust eastward into Moravia over strongly folded phyllites and igneous gneisses. The western block, known as the Moldanubian, is made up of a series of highly crystalloblastic paragneisses of the type termed "Schiefergneiss." These katagneisses contain cordierite, sillimanite, and various other minerals characteristic of intense metamorphism. The

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[24] Suess, F. E., Die Moravischen Fenster und ihre Beziehungen zum Grundgebirge des Hohen Gesenkes, Denkschriften d. K. Akad. d. Wiss. M. N. Kl. Bd. 81, 541-631, 1913.

strongly folded phyllites of the Moravian belt show characteristic epizone metamorphism. Along the surface emergence of the fault at the base of the Moldanubian block there is a belt of rocks that range in appearance from phyllonites in the north to muscovite-biotite schists in the south. These mica schists are typical mesozone rocks. According to Suess the mica schists in the south are the diaphthoritic mesozone equivalents of the Moldanubian schiefer gneisses. Because the reversal in metamorphism took place under mesozone conditions in the southern part of the thrust block, he called the resultant coarse-grained mica schists "Tiefen-diaphthorites," that is deep-seated diaphthorites. Farther north where the thrust block rose higher in the Earth's crust there is a phyllonite at the base of the Moldanubian block that is a diaphthorite in Becke's sense of the word, a rock in which the metamorphic retrogression took place under epizone rather than mesozone conditions.

Thanks to the courtesy of Prof. F. E. Suess the writer has had the opportunity to study representative specimens of the Moravian phyllites, the Moldanubian katagneisses, and the deep-seated diaphthorites derived from these katagneisses. In these specimens the "Schiefergneiss" is a fine-grained aggregate of quartz, plagioclase, hornblende, and abundant biotite. In the hand specimen the rock has the appearance of a pepper-and-salt mixture. Another coarser-grained specimen shows in addition to quartz, feldspar, and abundant biotite a considerable amount of cordierite. The texture is crystalloblastic. In many places the rock carries small garnets; and the accessory minerals are reported to be apatite, zircon, tourmaline, staurolite, and sillimanite or kyanite.

The first stage of alteration of these fine-grained gneisses to mica schist was the development of silvery muscovite flakes on some of the foliation planes. Later the rock shows an increase in the size of the garnets and very abundant development of muscovite, which replaces potassium feldspar and biotite.[25] The muscovite and biotite wrap around the garnet crystals. Kölbl,[26] who has made an exhaustive study of the deep-seated diaphthorites in the mica schist zone, describes how the garnets in the garnetiferous mica schists finally break down under the influence of the intense deformation and alter

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[25] Suess, F. E., loc. cit., p. 584.

[26] Kölbl, Leopold, Zur Deutung der Moldanubian Glimmerschieferzone im niederösterreichischen Waldviertel. Geol. Staatsant (Austria), Jb. 72, 79, 1922.

into eyes of quartz, biotite, feldspar, and iron minerals surrounded by the mica envelope that wrapped around the original garnet. The new biotite formed at the expense of the garnet can be distinguished from the original biotite by its lighter color, irregular boundaries, smaller size, and lack of pleochroic haloes. The mica schist diaphthorites derived from the schiefer gneiss lack the diseased or weathered appearance that is characteristic of the upper zone diaphthorites. Suess[27] has emphasized their complete resemblance to the typical mica schists of mesozone origin. Just as the complete resemblance of some phyllonites to normal phyllites makes their correct interpretation difficult, so the resemblance of mesozone diaphthorites to normal mesozone schists may make the correct interpretation of some apparently normal mica schists a matter for further investigation.

*Objections to the idea.*—The interpretation of the mica schists at the base of the Moldanubian block as diaphthorites has met with several objections. In the first place there is a considerable difference in chemical composition between the Moldanubian schiefer gneisses and the muscovite-biotite schists. The mica schists show a distinct loss of silica, lime, magnesia, and soda, accompanied by a large addition of potash. This difference in composition led Becke to question seriously the diaphthoritic interpretation of these rocks. He called the idea a fascinating one, supported by many good field observations,[28] but he saw chemical-mineralogical objections to explaining the chemical changes on the ground of mechanical disturbance. He preferred to interpret the mica schists and schiefer gneiss as belonging to the same formation but differing in their reaction to the primary metamorphism because they represent layers that were originally of different composition—a view that is supported by the intercalation of schiefer gneiss layers in some parts of the mica schist. On the other hand Suess, who also recognized the difference in composition, emphasized the striking uniformity in composition of the schiefer gneiss together with the uniform change into mica schist near the contact with the Moravian block. He ascribed the formation of the mica schists to the deep-seated diaphthoresis of highly potassic argillaceous layers whose composition was peculiarly susceptible to retrogres-

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[27] Letter to the writer.

[28] Becke, Frederich, Das niederösterreichische Waldviertel, 1. Uebersicht der petrographischen Verhältnisse, T. M. P. M., 32, 198, 1914.

sion.[29] The schiefer gneiss intercalations are regarded as relics of the original katagneiss.

In the latest study of the genesis of these mica schists Preclik[30] supports their retrogressive origin. He considers that certain layers of the schiefer gneiss were peculiarly susceptible to the differential movement that furnishes a path for the indispensable mineralizers and is a necessary preliminary to the diaphthoresis. Aplite intrusions accompanied the deformation and thus the chemical change between the schiefer gneiss and the mica schist was made by injection and mineralization and is not to be regarded as the result of original difference in the composition of the two formations.

Another objection to the idea of deep-seated diaphthoresis was raised by Hinterlechner[31] and later by Limbrock,[32] who claim 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 in that the epizone Moravian phyllites *underlie* the mesozone mica schists.

Sander pointed out long ago[33] that the existence of an abnormal relation of metamorphic facies along the Moldanubian-Moravian contact zone cannot reasonably be cited as an objection to the hypotheses of deep-seated diaphthoresis because the hypothesis, far from ignoring the abnormal relation, was itself advanced in an attempt to explain the abnormalities. It is, however, somewhat puzzling that the underlying block did not advance beyond its original epimetamorphic condition if the overthrust block was retrogressing under mesozone conditions. The explanation may be that the Moravian belt, which had been deformed before the thrust remained inert to internal deformation during the thrust, while the overriding Moldanubian rocks naturally underwent a strong differential movement at the base of the block and therefore were in a condition that favored readjustment to the new conditions, while the underlying block remained passive, in an apparent but false equilibrium.

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[29] Suess, F. E., Bemerkungen zur neueren Literatur über die moravischen Fenster. Mitt. Geol. Ges. Wien., **11**, 103-104, 1918.

[30] Preclik, Karl, Zur Genesis einiger moldanubischer Gesteinstypen I. Centralbl. für Min., Geol., u. Pal., Jahrg. Abt. A, No. 2, 76-77, 1930.

[31] Hinterlechner, Karl, Review of Suess, op. cit., Geol. Reichanst (Austria), Verhd. Jahrg. No. 2, 72-74, 1913.

[32] Limbrock, H., Geologisch-petrographische Beobachtungen im südöstlichen Teil der böhmischen Masse. Geol. Bundesanst. Jb. **75**, 171-172, 1925.

[33] Sander, Bruno, Bemerkungen uber tektonischen Gesteinsfazies und Tektonik des Grundgebirges, Geol. Reichsanst (Austria), Verhd. Jahrg. No. **9**, 240, 1914.

There are manifestly inherent difficulties in proving the existence of deep-seated diaphthoresis, but the idea is a logical outcome of the three-zone concept of metamorphism, and as such as worthy of critical consideration for those schists where such an origin is a possibility. Kieslinger,[34] in an excellent summary of the process of retrogressive metamorphism, has given the following table that shows the behavior of a rock under conditions of deformation in the different depth zones.

Metamorphism of a Crystalline Schist Deformed in Different Depth Zones.

| Deformed in Depth zone | Epischist | Mesochist | Katagneiss |
|---|---|---|---|
| I | Remains same | Progression | Progression |
| II | Retrogression | Remains same | Progression |
| III | Retrogression | Deep-seated retrogression | Remains same |

Retrogressive metamorphism and phyllitic mylonitization are now well established regional phenomena and their recognition in areas of polymetamorphic rocks will often be of invaluable assistance in unravelling problems of inverted stratigraphy. Wherever the existence of diaphthorites can be proved the tectonist must realize that a strong internal differential movement has affected the rocks subsequent to an earlier metamorphism, which was often regional. The recognition of proofs of retrogression may establish or even reveal for the first time a totally unexpected series of events in tectonic history and may help to locate horizons of movement that had never been suspected.

It is perhaps a rather strong temptation to see retrogressive metamorphism where the evidence for it is questionable and a note of warning against this mistake has been sounded by Angel and by Kieslinger. It requires a careful regional study to establish diaphthoritic or phyllonitic zones because the evidence is as a rule not apparent in individual hand specimens. Equally important is it to recognize the evidences where they do exist and to keep in mind the fact that many phyllites and mica schists may have had a more varied career than would be at first suspected.

New Haven, Conn.

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[34] Kieslinger, Alois, Uber Diaphthorese mit Beispielen aus dem ostalpinen Kristallin, T. M. P. M., 39, Mitt. der Wien Min. Gesell., 39, 12-15, 1928.