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PSEUDO-CATACLASTIC TEXTURE OF REPLACEMENT ORIGIN IN IGNEOUS ROCKS

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Petrographers in recent years have tended to place increasing emphasis upon the importance of replacement processes in igneous rocks. The movement has received impetus from the study of pegmatites, especially by Brögger[1] and Fersman[2] in Europe and by Hess,[3] Landes[4] and Schaller[5] in the United States. These authors have presented convincing evidence for a replacement sequence in the development of these bodies. Other investigators have described instances in which large masses of plutonic rocks appear to have undergone important modifications in chemical and mineralogical composition since their consolidation.

Some authors indicate a belief that large bodies of granite may be wholly or in part of replacement origin. Grout,[6] for example, says:

[1] Brögger, W. C., Die Mineralien d. Syenitpegmatitgänge der Südnorwegischen Augit- und Nephelinsyenite: Allgemeiner Theil, *Zeitschr. Kryst.*, vol. **16**, 1890.

[2] Fersman, A. E., Ueber die Natur der Pegmatitbildungen: *Compt. Rend., Acad. Sci. Russie*, pp. 89–92, 1924.

Fersman, A. E., Ueber die geochemisch-genetisch Klassification der Cranitpegmatite: *Tschermak's Min. Petr. Mitt.*, vol. **41**, pp. 64–83, 1931.

Fersman, A. E., Zur Geochemie der Granitpegmatite: *Tschermak's Min. Petr. Mitt.*, vol. **41**, pp. 200–213, 1931.

[3] Hess, F. L., The Natural History of Pegmatites: *Eng. and Min. Jour.*, vol. **120**, pp. 289–298, 1925.

[4] Landes, K. K., Paragenesis of Granite Pegmatites of Central Maine, *Am. Mineral.*, vol. **10**, pp. 355–411, 1925.

Landes, K. K., Baringer Hill, Texas, Pegmatite: *Am. Mineral.*, vol. **17**, pp. 381–391, 1932.

Landes, K. K., Origin and Classification of Pegmatites: *Am. Mineral.*, vol. **18**, pp. 33–56; 95–104, 1933.

[5] Schaller, W. T., The Genesis of Lithium Pegmatites: *Am. Jour. Sci.* (5), vol. **10**, pp. 269–279, 1925.

Schaller, W. T., Mineral Replacements in Pegmatites: *Am. Mineral.*, vol. **12**, pp. 59–63, 1927.

[6] Grout, Frank. F., *Petrography and Petrology*, New York, **1932**, p. 188.

If a granite magma is intruded into massive quartzites and so disseminated that its channels of access are not visible, it may so largely replace the original as to form a rock indistinguishable from granite. Some intermediate stages in this series of replacement effects suggests that certain large masses of granite may be really results of replacement.[7]

The studies of Sederholm[8] on the pre-Cambrian granites of Finland convinced him that many of these bodies were formed *in situ* by the impregnation of leptites and other rocks of a sedimentary character with fluid emanations from a subjacent magma—a process certainly closely related to that of replacement.

That albitization, a replacement process, may furnish the key to the genesis of the alkaline rocks, is a suggestion advanced by Gillson,[9] a strong advocate of the importance of post-consolidation phenomena in igneous rocks. The suggestion derives support from the investigations of certain British petrographers[10] into the nature and origin of the rocks of the spilitic suite.

Gilluly[11] in a recent paper gives reasons for believing that bodies of albite granite several square miles in area in central Oregon have been formed by hydrothermal alteration of a biotite-quartz-diorite with which they are associated. Gilluly's findings are in accord with the views of Bowen[12] who favors an origin by replacement of all albite-rich rocks.

[7] See also: Quirke and Collins, The Disappearance of the Huronian: *Can. Geol. Surv.*, Mem. **160,** 1930.

[8] Sederholm, J. J., On Migmatites and Associated Pre-Cambrian Rocks of Southwest Finland, Parts I and II: *Bull. Com. Geol. de Finlande,* Nos. **58,** 1923, and **77,** 1929.

Sederholm, J. J., Ueber die Entstehung der migmatischen Gesteine: *Geol. Rundschau*, pp. 174–185, 1913.

Sederholm, J. J., Die regionale Umschmeltzung (Anatexis) erlautert an typischen Beispielen: *Compt. Rend. Congr. geol. internat. Stockholm*, pp. 573–586, 1910.

Sederholm, J. J., On Regional Granitization (or Anatexis): *Compt. Rend., XII, Congr. geol. internat. Canada*, pp. 319–324, **1913.**

[9] Gillson, J. L., Origin of Alkaline Rocks: *Jour. Geol.*, vol. **36,** pp. 471–474, 1928.

[10] Bailey, E. B., and Grabham, G. W., The Albitization of Basic Plagioclase Feldspars: *Geol. Mag.*, pp. 250–256, **1909.**

Dewey, H., and Flett, J. S., On Some British Pillow Lavas and the Rocks Associated with Them: *Geol. Mag.*, p. 209, **1911.**

Wells, A. K., Nomenclature of the Spilitic Suite: *Geol. Mag.*, **1923,** esp. Part II, pp. 62–74.

[11] Gilluly, James, Replacement Origin of the Albite Granite near Sparta, Oregon: *U. S. Geol. Surv., Prof. Paper* **175-C,** 1933.

[12] Bowen, N. L., Diabase and Granophyre of the Gowganda Lake District, Quebec: *Jour. Geol.*, vol. **18,** pp. 658–674, 1910.

Bowen, N. L., *The Evolution of the Igneous Rocks*, Princeton, **1928,** p. 132.

These illustrations could be multiplied many times without exhausting the list.[13] In spite of the generally recognized importance of replacement in petrogenesis, however, little attempt has been made to describe systematically textures which result from, or are characteristically associated with, this process. Textures of replacement origin have been the subject of much study in metalliferous ores, but in rocks they have almost escaped attention, although it is true that certain microstructures such as myrmekites, some types of perthites and occasionally even graphic structure in granites are coming to be regarded as being at least in part the products of metasomatism.

The writer has recently devoted much study to the rocks composing a granite batholith in the northern part of the Inyo-White Mountain range.[14] These rocks give evidence of having been profoundly modified by replacement processes at a time considerably after their consolidation. The changes thus produced include especially the albitization of the potash feldspars, the development of a number of new (post-consolidation) minerals such as sericite, chlorite, epidote and biotite, the introduction of large amounts of silica and the formation of a texture which it is the object of this paper to describe.

It is proposed to designate this texture by the term "pseudo-cataclastic texture" because of its close resemblance to true cataclastic texture. The latter, as is well-known, is a term used by petrographers in the description of rocks which have undergone dynamometamorphism. According to Johannsen[15] it was introduced by Kjerulf in 1855 and applies to a texture "characterized by crushed, fragmentary, deformed, and strained crystals." It is in part synonymous with "mortar-" and "mylonitic texture" but it is a broader term than either of these and includes both of them. In its original usage it does not appear to have extended to chemical changes or to effects produced by circulating solutions in the rock. Later writers have included various mineralogical changes involving recombinations of chemical units among the effects pro-

[13] The idea of granitization by replacement or assimilation (the French word is "digestion") appears to have originated with the French school of petrographers. One of the earliest discussions is contained in the memoir by A. Michel-Levy: Contribution a l'etude du granite de Flamanville et des granites français en general: *Bull. Carte geol. de France*, No. **36**, 1893.

[14] Anderson, G. H., Petrography of the North Half of the White Mountain Quadrangle of California-Nevada. Doctor's Dissertation, California Institute of Technology, **1933**.

[15] Johannsen, A., *A Descriptive Petrography of the Igneous Rocks*, I, **1931**, p. 200.

duced by dynamometamorphism, but, as Sederholm[16] has pointed out, many of these changes can probably take place only in the presence of fluid media. Strictly speaking they are not part of cataclastic texture, although in many cases it is possible that they may be considered to belong to intermediate stages between cataclastic and replacement textures[17] or to the combined effects of pressure and circulating solutions. "Cataclasis," says Sederholm,[18] "is in general a destructive process; it is not creating new minerals or rocks. The use of the term 'dynamometamorphism' for every metamorphic change which cannot otherwise be accounted for should be discontinued as not warranted by facts."

In a rock exhibiting cataclastic texture the primary mineral grains are commonly set in a finer-grained secondary matrix composed of fragments of the adjacent primary grains. The plagioclases will usually have bent or broken twinning lamellae and the quartz will ordinarily show undulatory extinction. The contacts between the older grains and the matrix may be involved but they are not such as would indicate a corrosive attack upon the former. The matrix has been produced principally by mechanical stress—crushing. It may make up a small part or the greater part of the rock, according to the degree of metamorphism.

Although the general picture in pseudo-cataclastic texture may in some cases be remarkably similar to the above, two significant differences are always to be observed. The first of these is in the relation of the matrix to the primary grains. This is invariably strongly suggestive of corrosion of the primary grains by solutions instrumental in depositing the matrix. The contacts are such as cannot conceivably have been formed by pressure alone.

The second important difference is the presence in abundance in rocks exhibiting pseudo-cataclastic texture of new minerals formed at least in part of materials brought in from a source outside the immediate field of observation. The grains of the matrix are not exclusively nor even chiefly mere fragments of the older

[16] Sederholm, J. J., On Migmatites and Associated Pre-Cambrian Rocks of Southwest Finland, Part II: *Bull. Com. Geol. de Finlande,* No. **77**, pp. 29, 128, 1929.

[17] Attention may be called to the views of Barrell, who held that recrystallization in schists and gneisses is largely the result of reaction with the emanations from subjacent batholiths. (Barrell, J., The Relation of Subjacent Igneous Invasion to Regional Metamorphism: *Amer. Jour. Sci.*, (5), vol. **I**, pp. 1–19; pp. 174–186; pp. 255–267. 1925.)

[18] Sederholm, J. J., *Op. cit.*, p. 128.

grains but are of independent, probably hydrothermal, origin. Commonly they include large amounts of quartz, sericite, chlorite, biotite and epidote. If these are also present as primary minerals they usually possess different optical properties in the two modes of occurrence. Myrmekite is nearly always to be observed in or fringing the matrix, especially where the latter borders potash feldspar. The primary grains are commonly much altered—microcline or orthoclase, for example, may be highly albitized and the plagioclase sericitized or saussuritized.

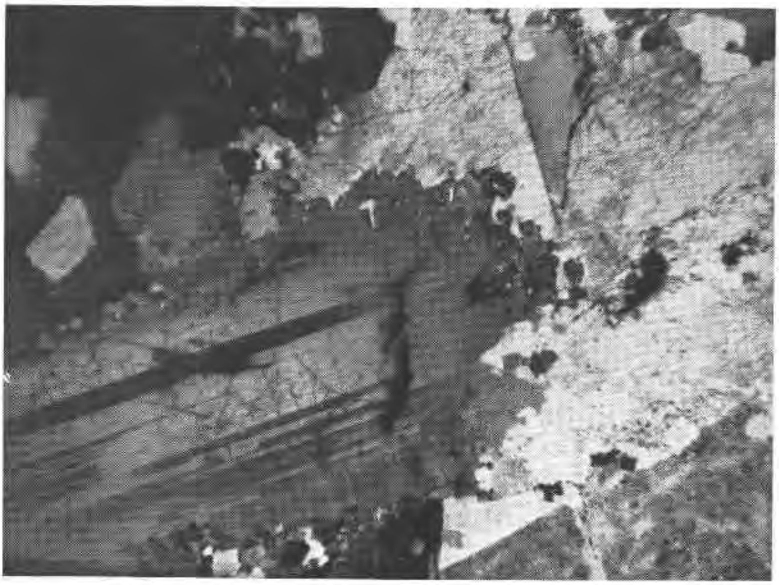

Fig. 1. The large grain of plagioclase extending diagonally downward to the left from the center of the field is readily recognized by its characteristic twinning. The light-colored grain forming most of the right half of the field is potash feldspar, considerably clouded by partial alteration to sodic feldspar. The grain at extinction in the upper left is also potash feldspar. The triangular-shaped grain above and to the right of the center is quartz.

Bordering the plagioclase grain is a fine-grained intergrowth of quartz, feldspar and chlorite closely resembling a trituration zone in a crushed rock. Its true origin by crystallization from replacing solutions is indicated, however, not only by the sinuosity of its contact with the plagioclase, which appears to have been corroded in the process but also by its continuity, more clearly shown upon rotation of the microscope stage, with the lace-like fringe of myrmekite at the end of the plagioclase grain. A similar replacement zone may be seen bordering the triangular-shaped quartz grain above the myrmekite. Crossed nicols, $\times 37$.

In the White Mountains batholith pseudo-cataclastic texture appears to have followed an orderly course of development. In the earliest stage the secondary (matrix) material was confined to narrow, sinuous veins which for the most part followed the contacts between the older minerals. The latter were corroded by the vein-forming solutions. As corrosion proceeded the veins widened and the borders of the older minerals became frayed and ragged. Simultaneously new minerals were precipitated in the veins. The

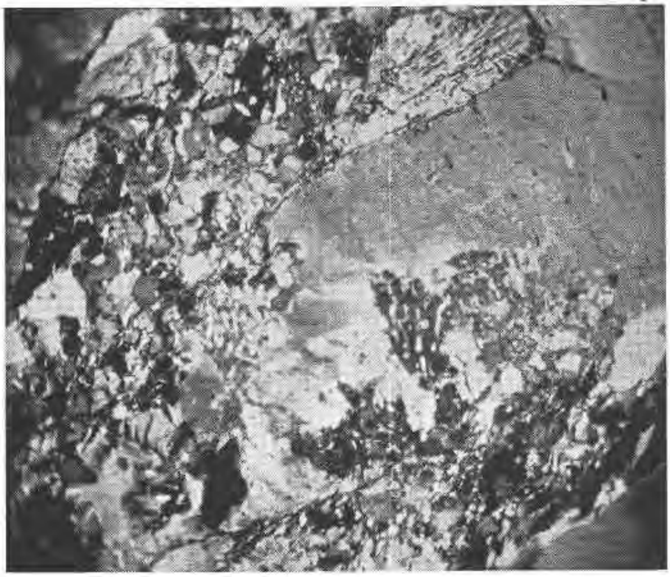

FIG. 2. The large gray grain with the ragged border extending diagonally upward to the right from the center of the view is potash feldspar. It is surrounded by a fine-grained intergrowth of quartz, feldspar, chlorite and epidote, fringed with myrmekite. The appearance of corrosion of the potash feldspar is too obvious to need comment. The light-colored splotchy border of the potash feldspar appears to have been produced by alteration by the corroding solutions. Crossed nicols, ×30.

secondary material formed an ever-increasing proportion of the rock. With continuation of the process the vein-like aspect disappeared. In sections representing advanced stages there are only a few faint relicts[19] of the primary grains scattered through a fine-

[19] "Sick-looking" is a colloquial term which has been used to describe the appearance of these grains. It gives a better picture than any more elegant word that has been suggested.

grained secondary matrix. The entire rock has become to a large extent recrystallized and replaced.

It is a striking fact that the grains of the veins or matrix are seldom of the same minerals as the large (primary) grains in the immediate vicinity. For example, a vein passing between or crossing grains of microcline may contain quartz, albite, epidote and biotite with little or no potash feldspar. Frequently it is fringed with myrmekite. Commonly there is a definite arrangement of minerals in the veins or matrix suggestive of a paragenetic succession which is, however, not constant for the entire rock.

The veins of the earlier stages frequently coalesce to form larger and larger veins so that the pattern may approach arborescent or dendritic forms. This may often be observed within the area represented by a single large section. Conversely, a vein may become narrower and narrower until it finally dwindles to a rather indefinite termination.

Pseudo-cataclastic texture may develop in rocks which have previously been subjected to mechanical deformation. It is reasonable to suppose, indeed, that such rocks would offer an especially favorable opportunity for its development because of the greater ease with which the necessary solutions could gain entrance and circulate. Such instances have actually been observed locally in the White Mountains batholith. In these occurrences the effects of the earlier crushing are plainly evident in the rocks, but the fractures have been healed by minerals deposited from the later solutions.

On the other hand, pseudo-cataclastic texture is often well-developed where evidences of mechanical stress are absent. In such rocks the large primary grains exhibit no fractures, twinning lamellae in plagioclase are not bent or broken and even undulatory extinction in quartz, one of the first evidences of strain, is frequently not to be seen.

In numerous localities on the borders of the White Mountains batholith are bodies of quartz-hornblende diorite. Field evidence clearly indicates that these are early-solidified marginal phases of the main intrusive. Although pseudo-cataclastic texture is everywhere to be observed in some stage of development in the granites of the batholith, it is present only in minor degree in and is frequently completely absent from these early diorites. If the texture were the result simply of mechanical deformation it is reasonable to expect that it would be as clearly exhibited by the diorites as by the granites.

On the other hand, pseudo-cataclastic texture is a conspicuous feature of the aplites and the pegmatites which occur in the intrusive mass itself, and which cannot, therefore, have been formed until after the solidification of the outer parts of the batholith. Pegmatites, moreover, are commonly recognized as being formed of materials which represent the end-stage products of a crystallizing magma. The presence of pseudo-cataclastic texture in these bodies serves to demonstrate that it cannot have been produced by movements within the incompletely solidified mass.

The solutions which produced pseudo-cataclastic texture in the rocks of the White Mountains batholith must have been of very low viscosity. They probably operated under high temperatures and extremely high pressures which enabled them to take advantage of very minute channelways. These they enlarged and extended as they advanced.[20] Quantitative studies undertaken to determine accurately the chemical modifications produced in the rocks by their action are still incomplete, but microscopic observations and calculations clearly indicate that they carried into the rocks large quantities of sodium and silicon and probably also some magnesium and iron. The sodium in part replaced the potassium. in the potash feldspars and in part went to form second-generation albite in the secondary matrix. Contrary to the observations of Bailey and Grabham[21] on the spilites, however, the primary plagioclases are almost free from albitization. The evidence shows that under the conditions prevailing in the rocks at the time these changes occurred, albitization of the plagioclases—even of the more basic interior parts of the zoned crystals—could not take place so long as unaltered potash feldspar remained in the vicinity.

[20] If doubt exists as to the permeability of rocks to solutions of this sort, it should be dismissed. Much evidence has been accumulated by various investigators to show that under such conditions a high degree of permeability does actually exist. "Deuteric minerals," says Gillson (Gillson, J. L., The Granite of Conway N. H., *Am. Mineral.*, vol. **12,** p. 319, 1927) "illustrate, as do the widely disseminated minerals of contact metamorphic zones, the power of these igneous emanations to pervade solid rock without visible channel or fissure, a fact to which Kemp, for example, has already called attention." It should be remembered, moreover, that previously existing channels may have become sealed and rendered indistinguishable by the very solutions which took advantage of them.

[21] Bailey, E. B. and Grabham, G. W., *Op. cit.*

The potassium liberated from the microcline and orthoclase went into the formation of sericite in the secondary matrix or in the primary plagioclases, which are frequently highly sericitized. Some of the potassium in excess may have been lost from the rock. Calcium derived from the primary plagioclases united with iron to form epidote which is commonly present both in the plagioclases and in the secondary matrix. Iron and magnesium, undoubtedly derived in part from the original minerals of the rock but probably increased by additions from some outside source, entered into the formation of the biotite and chlorite commonly present in large quantity in the secondary matrix.

It is apparent, therefore, that conditions favored both the ready interchange of substances within the rock and the introduction of material from an outside source. These conditions were provided by freely-circulating fluid media. That the secondary matrix was formed by precipitation from these solutions is indicated by the presence in it of the same minerals which took part in or were formed as a result of the replacements; namely, albite, sericite, biotite, chlorite and epidote. Mineralogical changes of this type are among the most convincing indications of the true origin of the texture which is here described.

In conclusion, the writer wishes to acknowledge his indebtedness to Dr. Ian Campbell and Dr. Rene Engel of the Division of Geology and Paleontology of the California Institute of Technology for advice and suggestion in making the petrographic studies of which the results are in part presented in this paper, and to these gentlemen and to Professor F. L. Ransome for the critical reading of the manuscript.