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METAMORPHISM AND ITS PHASES [1]

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INTRODUCTION

Science is the coordination of fact with fact, fact with principle, and principle with principle. It depends on the rigorous use of words. Neither fact nor principle nor coordination can rise into full consciousness until phrased in unimpeachable terms. Unceasing attention to the

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use of words therefore represents a principal duty of every scientific investigator. Experience shows how hard it is, in a fluid science like geology, to hold technical words to constant, universally accepted definitions. The causes of this unrest are many: progress in the discovery of facts, progress in coordination, progress in interpretation or theory, and, one must add, the varying subjectivity, if not carelessness, of writers.

Few geological topics are as far-reaching and profoundly important as rock metamorphism. Few have had, and are having, such increase of content, both empirical and theoretical. Invented eighty years ago, the words "metamorphic" and "metamorphism" are almost as old as scientific geology. Unnumbered facts and theoretical ideas have been clustered under these captions. How far have their original definitions borne the strain of new discoveries? What changes in their definition have been proposed since the issuing of the first edition of Lyell's "Principles of Geology"? Is any definition of metamorphism acceptable to the geological profession as a whole? To what extent should theoretical explanation enter into its definition and into that of each of its phases? Is a systematic classification of metamorphic processes possible? In view of much uncertainty as to conditions affecting the development of crystalline schists, is an attempt to form such a classification at the present time advisable?

These are the questions to be discussed in the following pages. The writer's form of statement has been made clearer as the result of debates with his colleagues, Professors Graton, Palache, and Warren, and especially because of analysis of the original manuscript by Mr. A. S. R. Wilson, candidate for the doctor's degree at Harvard University.

Definition of Metamorphism

FORMER USE OF THE TERM

Early in its history, though not at the beginning, "metamorphism" was used in two different senses, and corresponding definitions are still recognized by some authors. "Metamorphism in the broader meaning" approximates more nearly to the literal etymology, denoting simply rock alteration. "Metamorphism in the narrower meaning" has led to several definitions, all of which, however, disregard literal etymology and exclude rock weathering, or rock cementation, or concretionary action, or all of these examples of alteration, from the field of metamorphism.

The range of the definitions is illustrated in the ensuing historical sketch, which, brief as it is, suffices to show the need of a universal language in dealing with multitudes of facts and principles vital to geology.

HISTORY OF THE WORD "METAMORPHISM"

In the first edition of his "Principles of Geology" (1833, volume 3, page 374) Lyell introduced "metamorphic" to geology. Neither there nor in later editions does he appear to have used the noun "metamorphism," but he wrote of "metamorphic rocks" and the "metamorphic theory." The very invention of the Greek compound, identical in literal meaning with the familiar "transformed" or "transforming," shows from the start that Lyell did not intend his word to cover all rock alterations.

He later elaborated the theory of metamorphism, in his "Elements of Geology" (1838), stating (page 219): "Metamorphic . . . expresses a theoretical opinion that . . . strata, after having been deposited from water, acquired by the influence of heat and other causes a highly crystalline texture." On page 23 one reads: "It is true that all metamorphic strata must have been deposited originally at the surface, or on that part of the exterior of the globe which is covered by water; but, according to the views above set forth, they could never have acquired their crystalline texture unless they had been modified by plutonic agency under pressure in the depths of the earth." He continued (page 379): "The metamorphic rocks must be the oldest—that is to say, they must lie at the bottom of each series of superimposed strata—because the influence of the volcanic heat proceeds from below upwards."

From the sixth to the last edition, Lyell's "Principles" contained the following passage, giving a virtual definition of metamorphism: "The transmutation [of fossiliferous strata into such rocks as gneiss, mica schist, or marble] has been effected by the influence of subterranean heat acting under great pressure, and aided by thermal water or steam and other gases permeating the porous rocks, and giving rise to various chemical decompositions and new combinations" (sixth edition, 1840, London, volume 1, page 320).

Lyell early adopted the view that magmatic and connate gases and vapors, as well as mere heat, are important agencies in metamorphism ("Elements of Geology," 1838, page 246).

Durocher (1846, page 546) defined metamorphism as (translated) "the sum of the effects of transformation, of change of nature or texture, which the rocks composing the earth's crust have undergone." He pointed out that metamorphic rocks are most developed in regions affected by crustal deformation, though also habitually along igneous contacts. He laid great stress on the influence of heat in metamorphism, yet classified as metamorphic several types of change at ordinary temperatures, including oxidation and hydration of rocks by weathering, as well as concretionary action.

Virlet (d'Aoust)—1847, page 502—used the expression "métamorphisme normal" to signify the alteration of rocks by interior heat acting at a time when the earth's crust was comparatively thin; he assumed the alteration to have been aided by pressure, and especially by the presence of water, both magmatic and connate. Virlet described "normal metamorphism" as also "general." He held that primitive rocks as such can no longer be found at the surface of the globe, because they have all been metamorphosed since their original "refroidissement." As indicating his grasp of the importance of solvents in metamorphism, he wrote that, if original crust rocks were ever discovered, they must prove to be free from water. Three years before (1844, page 846) Virlet had emphasized the injection theory of gneiss, using the expression "roches d'imbibition," a formula for an essential idea in French thought on the problem of metamorphism, since the days of Boué and de Beaumont.

A formal definition by Studer (1847, page 116) shows how early the conflict began between the Lyellian conception of metamorphism and the formally logical use of the word in its literal meaning of "transformation." Translated, Studer's statement runs as follows: "Metamorphism in the broader sense [includes] all effects exercised on rocks through forces other than gravity and cohesion. Metamorphism in the narrower sense is confined to rock transformations which are produced, not through the influence of the atmosphere or of the water on the earth's surface, but, directly or indirectly, through activities which originate in the interior of the earth."

In his Lehrbuch der Geognosie, C. F. Naumann (1850, page 751) distinguished "normal or general metamorphism" from "abnormal or local metamorphism." Translated, his words are: "Normal metamorphism is the transformation of a rock through a quite general cause, which has affected the rock in its entire extension and represents a regular (gesetzmässigen) and necessary phase in the gradual development of the rock. Abnormal metamorphism is the transformation of a rock through extraordinary causes, a transformation which has affected the rock only in certain parts of its extent, without marking a necessary stage in the development of the rock."

Among the phases of normal metamorphism Naumann included the consolidation (cementation) of sand, pebbles, and mud—to form, respectively, sandstone, conglomerate, and argillite. He recognizes, however, that many of the transformations necessary in the development of a rock, such as cementation, and also the changes in rocks produced by volcanic exhalations, are not covered by "metamorphism in the narrower sense." Naumann stated that the use of the word in the narrower sense was customary in 1850. He specially emphasized the rise of the isogeotherms in geosynclinals as one important condition for normal metamorphism, but makes no mention of mountain-building in this connection.

According to Naumann, abnormal or local metamorphism is characterized by "evident" causes, in contrast to the more hidden or "latent" (von Morlot) causes of normal metamorphism. The chief "evident" causes he lists: (1) combustion, as in the case of changes in clays through the burning of a coal bed; (2) volcanic gases and vapors, as in the conversion of limestone into gypsum by exhaled hydrogen sulphide; (3) magmatic heat at igneous contacts, and (4) impregnation with water and hydrous solutions, as in the case of local dolomitization or silicification.

Delesse (1857, page 90) held that "metamorphism in its most general meaning" includes all alterations undergone by rocks. He made the distinction between normal or general metamorphism and abnormal or special metamorphism, the former being due to invisible causes, the latter being due to "accidental but visible" causes operating over small, separated areas. This dichotomous division carries the implication that, for practical purposes, Delesse really excluded weathering from the list of metamorphic processes.

Daubrée (1860, page 59) introduced the expression "métamorphisme régional" as an improvement on ("plus juste que") "métamorphisme normal" and as less vague than "métamorphisme général." He gave no formal definition of regional metamorphism. Though dwelling on the rôle of crustal deformation in the evolution of the Precambrian gneisses and schists, Daubrée argued energetically against strict uniformitarianism as applied to the genetic problem of the crystalline schists. He wrote (page 123): "The old gneisses testify to the high temperature of the earth's surface in ancient times."

In the present connection Lossen's writings are noteworthy for two reasons. He included lithifaction or consolidation (Festwerdung) of sediments among the metamorphic processes. He introduced (1875, page 970, or at an earlier date) the first technical name, "Dislocationsmetamorphismus," for the concept already described by Baur, Sharpe, Sorby, and others, and now generally called dynamo-metamorphism or dynamic metamorphism.

Von Hauer (1878, page 109) defined "metamorphism in the widest sense" as including "the sum of the changes which rocks undergo after their formation (Bildung), through the influence of heat, or chemical agents, or of both together, . . . the changes not going so far that the masses are completely destroyed (zerstört) and therewith cease to be rocks (Gebirgsarten)." In this sense he held that all rocks are metamorphic;

for example, the cementation of loose sand by the infiltration of calcium carbonate furnishes a metamorphic rock, and a somewhat hydrated lava is metamorphic. However, according to general usage, only those rocks are called metamorphic in which alteration has reached a higher degree and has taken the form of new crystallizations. He gave pseudomorphism as a type of metamorphism with this narrower definition. He treated diagenesis as a "Mittelweg" between metamorphism and original "Bildung." Weathering was excluded from the phases of metamorphism.

Phillips (1885, page 356 ff) described as metamorphic "all those parts of aqueous strata which have been transformed in structure or appearance by subterranean heat, or heat developed by pressure applied since their deposition." He recognized two kinds of metamorphism: *structural*, due to burial (pressure and heat) or to orogenic movement (as in the origination of cleavage), and *molecular*, not expressly defined, but illustrated by the conversion of "earthy" carbonate of lime into marble.

According to Prestwich (1886, page 397), "metamorphism is that molecular and structural change in the strata of the sedimentary series, or in the rocks of igneous origin, whereby they have undergone a transformation in the chemical combination of their elements, in mineral constituents, and in structure, so that their original condition has been more or less modified and altered and their characters disguised." He points out that this is in a sense true of all stratified rocks, since nearly all have been changed by cementation, segregation, infiltration, or pressure. He concluded that the term "metamorphism" should be restricted to "those greater chemical and mineral changes, caused by heat combined with pressure and moisture." Prestwich distinguished contact, regional, and normal metamorphism.

Regional metamorphism includes (1885, page 425, and 1886, page 408) "changes effected by the agency of the physical causes to which Mr. Mallet referred the fusion of the volcanic rocks, namely, *the heat produced locally within the crust of the earth by transformation into heat of the mechanical work of compression, or of crushing of portions of that crust.*" In the 1885 paper, page 425, he wrote: "Normal metamorphism I would confine to signify, as hitherto, the changes caused by the heat due to depth, on the supposition of the existence of a heated central nucleus of the earth." However (page 430), "normal metamorphism depends not so much on high temperature as on pressure and the presence of water." To its operation he attributed (1886, page 413) the larger and more common class of metamorphosed strata, the alteration of which has been due to a cause more general than igneous-rock heat (contact metamorphism) or orogenic-crush heat (regional metamorphism). This general cause is the internal heat of the earth, which becomes efficient only after burial.

Teall (1888, page 438) wrote of "metamorphism": "This word is usually restricted in geological literature to changes which a rock undergoes in mineralogical or chemical composition and internal structure through the operation of heat, heated water, or vapor, and mechanical agencies. It is either local or regional." He excludes (page 410) weathering and also the effects of "thermal waters, fumarole and solfataric action." He recognizes only contact and dynamic (called "regional" in the earlier part of his book) metamorphism.

Reyer (1888, page 554) made metamorphism include the disintegration of rocks through weathering; the mere cementation of loose material into coherent rocks; and the recrystallization of rock material in depth, giving pseudomorphism as an example.

Harker (1889) published a brief general discussion of the nature of metamorphism. Under that name he groups (page 15) "all processes which result in a partial or complete crystallization or recrystallization of solid masses of rocks." His "hydro-metamorphism" implies low pressure and low temperature and is illustrated in the deposition of interstitial quartz during the conversion of sandstone into quartzite—a common kind of cementation. Harker prefers "thermo-metamorphism" to "contact metamorphism," defining the former as alteration under conditions of low pressure and high temperature. Conditions of high pressure and high temperature lead to "dynamo-metamorphism," while those of high pressure and high temperature lead to "plutono-metamorphism." He states that dynamo-metamorphism implies "a *direct* correlation between mechanical and chemical energy." His classification is avowedly made "for rough purposes."

In his Traité de Géologie, de Lapparent (1893, page 584) defined metamorphism as including all changes "affecting rocks after their deposition"; and again (page 711) as "the sum of the chemical changes made after the deposition of sediments." In another passage (page 612) he expressly states that the alteration of rocks by the weather and by the penetration of surface waters is to be regarded as a metamorphic process. Yet throughout the long sections of his book that deal with weathering and the effects of percolating water the words "metamorphism" and "metamorphic" never appear. Instead, he uses "alteration" and "transformation." In practice, therefore, he found it unnecessary to use "metamorphism" according to either of his broad definitions.

Zirkel (1893, I, page 572) designated metamorphism as the phenomenon "that a given rock has, through a geological cause which is independent of the original formation (Bildung) of that rock, undergone such a change that a well characterized *new* rock *type* is developed." He excludes weathering from its list of phases.

Turning to J. D. Dana's Manual of Geology, one reads (1895, page 310): "Under metamorphism might be included the chemical changes in rocks and minerals that take place at ordinary temperature. But these run down into the common results of decay and are more conveniently kept separate." While thus excluding weathering, Dana thought that the cementation of sediments should be regarded as a phase of metamorphism. He distinguished local and regional metamorphism, the latter being (1) incipient, (2) crystallinic, (3) paramorphic, (4) metachemic, or (5) endo-crystallic. According to the source of the heat involved, he further distinguished "statical" and "dynamical" metamorphism. Statical metamorphism is (page 440) "that dependent on heat of a statical source—the earth's mass and the vapors about it." This kind characterized the "Lithic Era" in the globe's history, the long period before the ocean condensed on the original crust. In this matter Dana was evidently not a uniformitarian.

His Archeozoic æon was (page 441) characterized by dynamical metamorphism, which is "dependent on heat from a dynamical source—that is, heat generated by movements in the thickening crust." On the other hand, he notes (page 322) that "the earth's internal heat has always been a contributor to the heat of the earth's crust, and much more so formerly than now, and would, therefore, have supplemented largely the heat generated by friction." From a passage on the same page of the Manual one must infer that Dana regarded "dynamical metamorphism" and "regional metamorphism" as rigorous synonyms.

In the last edition of his Textbook of Geology, A. Geikie (1903, page 424) defines metamorphism of rocks as "rearrangement of their constituent minerals, and most frequently the production of a new crystalline structure." A fuller statement is given on page 764: "Mere alteration by decay is not what geologists denote by metamorphism. The term has been, indeed, much too loosely employed; but it is now generally used to express a change in the mineralogical and chemical composition and in the internal structure of rocks, either locally, by intruded masses of highly heated material, or regionally, through the operation of mechanical movements, combined with the influence of heat and heated water or vapor." However, Geikie does regard mere "induration" of discrete materials as a metamorphic process.

Geikie adopted the dichotomous division into contact metamorphism and regional metamorphism. He recognizes deep burial as one of the causes of metamorphism, but decides (page 805) that the "statical phase" of regional metamorphism is "not so striking in results as dynamical metamorphism."

According to Van Hise (1904, page 32), metamorphism "means any change in the constitution of any rock." He therefore includes all weathering processes; all other changes produced by vadose waters; the cementation of sediments or pyroclastic rocks; as well as rock changes due to heightened pressure or temperature, or both. Basing his work on the theses that (page 40) "the only workable classification of metamorphism is geological," and that (page 43) depth is "the most important of the influences which determine the character of the alterations of rocks," Van Hise considers these in terms of his zones of katamorphism and anamorphism.[2]

Chamberlin and Salisbury (1906, volume 1, pages 426 and 432) apply the term "metamorphism" to the "more profound changes" in rocks, the "more profound changes of induration and composition . . . essentially reconstruction." They exclude both weathering and mere cementation from the list of metamorphic processes, though pointing out that metamorphism is often "but an extension and intensification" of the change called induration or cementation. As usual in modern textbooks, dynamic action is emphasized; Chamberlin and Salisbury do not mention static or load metamorphism.

Haug (1907, pages 176-177, 185) does not give a formal definition, but states that high temperature, high pressure, and the presence of water are essential to true metamorphism. He apparently excludes from it hydration, oxidation, cementation, and decalcification. He divides metamorphic processes into two classes—"contact" and "general." Like Termier, he denies the power of dynamic metamorphism to do more than *mechanically* change a rock or to affect its mineralogical composition. Haug adopts Michel Lévy's view that contact metamorphism becomes confluent with "general" metamorphism as the depth increases.

In the last edition of his "Elemente der Gesteinslehre," Rosenbusch (1910, page 72) excluded weathering and decomposition in general from the list of metamorphic processes, though stating (page 578) that diagenesis is transitional into metamorphism. He defined diagenesis as comprising all changes in a sediment during and after its deposition until the stage of consolidation (Verfestigung) is reached; diagenesis may even

[2] When used geologically—that is, in reference to depth below the earth's surface—the "katamorphic" and "anamorphic" of Van Hise have respective meanings nearly opposite to the "katogen" and "anogen" of Becke (1892, page 297), or Kalkowsky (1886, page 29), or Haidinger (1850, page 301). See also B. Cotta's "Geologische Fragen," Freiberg, 1858, page 94, where the author formally adopts the latter pair of words, coined by Haidinger, to express a dichotomous division of all rock alterations. Leith and Mead (1915, page xix) have so redefined "katamorphism" and "anamorphism" that these processes are thereby to be considered as having no necessary relation to depth at all. Once again it is clear how the student of the future will be troubled by the flux of definition and usage.

include (page 485) certain changes induced by moderate deformation. Besides contact metamorphism, Rosenbusch admitted only dynamic metamorphism, which he named in 1886. For the latter Rosenbusch gave regional metamorphism, mechanical metamorphism, and dislocation metamorphism as synonyms. On page 73 is the following definition (in translation): "As dynamo-metamorphism we designate the sum of the changes in the mineralogical constitution and structure of a rock, due to the effect of orogenic processes. . . . We regard pressure as the operating factor in dynamo-metamorphism, without specifying whether pressure acts directly, as such, or indirectly, as, for example, through a rise of temperature." A further indication as to what he thought concerning the real nature of metamorphism as a whole, a passage on page 575 may be quoted, in translation: "The crystalline schists are eruptive or sedimentary rocks which have undergone geological transformation under the essential control of the geo-dynamic phenomenon ['Gebirgsdruck,' orogenic pressure]." Throughout his writings there appears to be no hint that load metamorphism need be considered.

Apparently Grubenmann excludes weathering and ordinary cementation from the field of metamorphism. However, he adds to the complexity of the problem by dividing (1910, page 45) rock transformations into three classes: *a,* metamorphism in the narrower sense; *b,* contact metamorphism; and *c,* metamorphism by magmatic injection and assimilation. Though he explains the crystalline schists as chiefly the product of mountain-building, he recommends (page 126) that the term "dynamo-metamorphism" be wholly given up, since it easily leads to the wrong notion that purely mechanical or pressure phenomena are implied. He actually suggests that the simple word "metamorphism" should be used in its place!

Scott (1911, pages 406 and 409) defines metamorphism as the "profound transformation of a rock from its original condition by means other than those of disintegration." He believes that the consolidation of sediments should be regarded as a phase of metamorphism, yet groups its processes in two classes only, under the captions contact metamorphism and regional *or* dynamic metamorphism.

Lindgren (1913, page 66 to 69) writes that metamorphism "has lately been employed in a wide sense, so as to cover any change in the composition and structure of a rock, through whatever agency and with or without gain or loss of substance. In this wide sense the term would include weathering and ordinary alteration of rocks at no great depth. This usage was adopted by Van Hise, but is not generally accepted, and the tendency seems to be to reserve the term for cases where the transformation of one rock to another is strongly marked, as in gneiss from granite or mica schist from clay shale. Though the mechanical effects of pressure may be conspicuous, metamorphism is always characterized by chemical changes in the component minerals; the composition of the rock itself may remain constant." He gives a definition of *weathering* as including "the changes of rocks near the surface due to the decomposing and oxidizing action of percolating waters above the permanent water level." The *zone of weathering* has a depth "determined by the level of the ground water or by the depth to which free oxygen can penetrate in large quantities."

Tornquist, in a recent textbook (1913, page 18), distinguishes as (*a*) "regionalmetamorph" those metamorphic rocks which have originated in their present form under a heavy rock cover; as (*b*) "kontaktmetamorph" those which owe their present character to the influence of igneous magma; and as (*c*) "dynamometamorph" those developed under orogenic pressure. The separation of (*a*) and (*c*) is worthy of note. Tornquist makes two astonishing suggestions. He proposes to call the change from clay to shale "Fossilisierung"; the change from shale to clay slate "Veränderung," and the change from clay slate to phyllite or mica schist "Metamorphose."

According to Boeke (1915, page 384), metamorphism represents the sum of the effects of high temperature, or high pressure, or both, so acting on a solid ("fertig gebildete") rock that its constituents are no longer in physico-chemical equilibrium. He admits three kinds: (*a*) dynamic metamorphism, with pressure playing the principal rôle; (*b*) thermometamorphism, with temperature in the principal rôle; and (*c*) contact metamorphism, which in his view implies the entrance of foreign substances, derived from invading magma, and further implies metasomatic interchange. Boeke makes no explicit statement as to the relative significance of either load or static metamorphism. He seems to exclude weathering and ordinary cementation from the domain of metamorphism.

Pirsson (1915, page 315) defines metamorphism as "a general term for all those changes by which the original characters of rocks are more or less completely altered, in that their component kinds of minerals and textures are transformed into other minerals or textures, or both." He considers weathering effects as, "strictly speaking," metamorphic; but, like de Lapparent, he felt no need of using "metamorphic" in systematic chapters dealing with the work of the atmosphere and the production of soils. Like Schuchert, his collaborator, and like nearly all other writers, Pirsson excludes the regolith, as well as gravels, sands, shales, etcetera, from the class of metamorphic rocks, thus implying a failure of the broader definition of metamorphism to match the needs of general geology. Pirsson recognizes two kinds of metamorphism, contact and regional, the latter covering (page 319) dynamic metamorphism "as a pronounced phase of it in one direction." He uses the expression "constructive metamorphism" for Van Hise's "anamorphism"—that is, recrystallization in the "zone of rock-flowage"—but adds (page 316) that simple downward pressure, "static pressure . . . appears to have little altering effect on rocks."

Ries and Watson (1915, pages 200-204) follow Van Hise in defining metamorphism "as any change in any rock, regardless of origin," thus including weathering changes in "alteration or metamorphism proper." They hold that static metamorphism and pressure metamorphism both "refer to quiescent conditions."

In their new book, Leith and Mead write (1915, page xvii): "Rock metamorphism is here defined to cover all mineralogic, chemical, and physical changes in rocks subsequent to their primary crystallization from magma. . . . We shall follow Van Hise by including under metamorphism not only development of schistose and crystalline rocks, but also all changes involved in rock weathering and cementation."

F. W. Clarke (1916, page 583) introduces his chemical discussion of the subject thus: "In its widest sense the adjective metamorphic may be applied to any rock that has undergone any sort of change. Practically, however, it is used to describe a well defined class of rocks in which the transformation from an original form has been nearly complete. A slightly altered igneous or sedimentary rock is not commonly called metamorphic; neither is a mass of decomposition products so designated. . . . Some varieties of metamorphism are entirely physical or structural, and therefore will not be considered in this memoir. Metamorphoses which represent only a development of slaty or schistose structure are of this kind. In most cases, however, metamorphism is accompanied by chemical changes, which are indicated by the production of new minerals, and this sort of metamorphism concerns us now. It may be regional, when large areas are affected, or a phenomenon limited to a contact between two reacting rocks; but these distinctions are of little significance chemically."

Dictionaries and encyclopedias reflect a diversity of usage similar to that illustrated in the foregoing extracts from standard works on geology.

The 1895 edition of the Century Dictionary (New York) gives this definition of metamorphism: "The process of metamorphosing or changing the form or structure; specifically, chemical change and rearrangement of the constituents of a rock by which they are made to assume new forms and made to enter into new combinations, the most important result of these changes being that the rock becomes harder and more crystalline in structure."

According to the Standard Dictionary (New York, 1895), metamorphism comprises "the changes that go on in rocks, due to recrystallization of their constituents, either with or without alteration in the chemical composition of the mass. The most important agents of metamorphism are *heat*, *moisture*, or other mineralizing factor, and *pressure*." These are made active either by intrusion of igneous masses or by dislocations or movements of the earth's crust. Cementation by the enlargement of mineral grains is regarded as a metamorphic process. Static metamorphism is described as including "changes produced largely by pressure without great shearing or dislocation of the rock-masses."

The New International Dictionary (New York, 1904) regards metamorphism as covering only the "profound changes" in rocks and excludes weathering and decomposition. It recognizes only two kinds—contact and regional.

The New English Dictionary (Oxford, 1908) defines metamorphism as "the process of change of form or structure produced in a rock by various natural agencies" and adds: "*Metamorphic.* Of a rock or rock formation; that has undergone transformation by means of heat, pressure, or natural agencies"—an extraordinary solecism!

Flett, in the 1911 edition of the Encyclopædia Britannica, defines metamorphism as "the alteration of rocks in their structural or mineral characters by which they are transformed into new types." He excludes weathering, decomposition, and cementation. He admits two kinds: (1) "contact or thermal," and (2) "folding or regional," making no mention of load or static metamorphism.

DISCUSSION OF THE OLDER DEFINITIONS OF METAMORPHISM

A review of the literature thus shows that "metamorphism" has been used in at least five different senses.

1. Authors defining it as including "all changes" in rocks, after the original embodiment of those rocks as distinct masses of material, are: Durocher (1846), Kalkowsky (1886), Reyer (1888), Van Hise (1904), De Launay (1905), Kemp (1908), and Leith and Mead (1916).

2. Authors excluding weathering processes, but including cementation, are: Virlet (1847), Lossen (1872), von Hauer (1878), Green (1882), Phillips (1885), Teall (1888), Lawson (1888), Harker (1889), Roth (1890), the writers in the Century Dictionary (1895) and Standard Dictionary (1895), Dana (1895), A. Geikie (1903), the writer in the New

International Dictionary (1904), Hatch (1909), Rosenbusch (1910), Scott (1911), Becke (1911), Lindgren (1913), and probably Zirkel (1893).

3. Authors formally defining metamorphism in the broader sense, but in actual practice excluding weathering processes, are: de Lapparent (1893), Merrill (1897), Pirsson and Schuchert (1915), F. W. Clarke (1916), and Lahee (1916).

4. Authors excluding from the definition both cementation and weathering are: Lyell (1838), Chamberlin and Salisbury (1906), Haug (1907), Flett (1911), Tornquist (1913), Boeke (1915), and Cleland (1916).

5. Authors defining metamorphism in a broad sense and also in a narrower sense (excluding at least weathering processes) are: Studer (1847), Naumann (1850), Delesse (1857), Prestwich (1886), Grubenmann (1910), and Ries and Watson (1915).

None of the long list of writers has been guided by the strict logic of the literal etymology. In no case has rock folding been included among the metamorphic processes, though the mere folding of beds is a manifest transformation in a most literal sense. Thus, without exception, geologists have appreciated the uselessness of "metamorphism," if that word be given its broadest possible meaning.

Their right to restrict its meaning, in the interests of clear thinking and writing, is abundantly illustrated in the history of words. For the navigator, "chronometer" has not its literal meaning, but applies only to a very small class of time-keepers. Astronomers arbitrarily exclude comets and stars from the class of planets, the "wanderers." The architect's "dome," a synonym of "cupola," has only an indirect relation to the original Greek word, for the Greek house or temple was not in cupola form. The crystallographic "dome" is no more thoroughly entrenched in the English language because it recalls the actual form of the Greek *domos*. In zoology the meaning of "mollusk" is universally restricted far within the limits set by its etymology, and "metamorphosis" itself is as narrowed for technical biology as "metamorphism" has been narrowed by Lyell and many of his successors.

The degree to which strict etymology should be disregarded is, then, clearly a question of expediency. That it is difficult to answer in a way to win general consent is obvious to the student of definitions in the latest textbooks, dictionaries, and Government reports. The history of opinion during earlier decades is also somewhat discouraging; yet a critical comparison of the older and newer writings seems to suggest a way out of the present confusion.

In the first place, the great majority of geologists have, with Lyell himself, favored the exclusion of weathering from the group of metamorphic processes. Among the few who do not follow tradition is Van Hise, who, however (1904, page 163), emphasizes "the fact that the alterations in the belt of weathering are very different from [those in] the belts below." He continues: "In many places the change in the character of the alterations in passing from the belt of weathering to the belt of cementation is very sudden." Leith and Mead likewise distinguish a "belt of weathering" (perhaps better called a *shell* of weathering) wherein rock alterations are more or less sharply distinct from those induced at greater depths in the earth. The suggestion of Lindgren and others that the alterations properly referable to weathering are confined to the earth shell above the water table is a more precise expression of the same general idea and is worthy of special consideration as a possible criterion for distinguishing metamorphic changes from weather changes. That there are transitions between the sets of conditions leading respectively to ordinary rock-weathering and to the development of certain crystalline schists is not a compelling consideration. The existence of transitions in most natural phenomena ought not to, and does not, discourage the effort to classify. In their fundamental division of rock changes into katamorphic and anamorphic, Van Hise and his followers have not been deterred by the fact that both of these classes of alterations are displayed within the limits of a single rock body or even within the limits of an original rock-forming mineral. The lower boundary of the shell of weathering is certainly at least as definite as the boundary between the katamorphic and anamorphic shells.

The chief reason for the exclusion of weathering processes is, of course, to save the word "metamorphism," to prevent its overburdening. As used by the Van Hise school, it is equivalent to "alteration," and the more recondite word becomes practically useless. If these authorities were followed in this matter, two most useful words would become as unnecessary as they are, respectively, in Van Hise's "Treatise on Metamorphism" and Leith and Mead's "Metamorphic Geology." On the other hand, there is the utmost need for "metamorphism" as a designation for rock changes in depth, having nothing directly to do with weather alteration.

Weathering processes already demand whole volumes for their summarizing. The geological profession is not likely to agree with the proposal to consolidate that immense subject with the yet vaster one relating to rock changes under conditions of high pressure, high temperature, or both; nor are most geologists to be attracted by a definition of "metamorphic rocks," which are thereby made to include residual clays and soils, glacial deposits, shale, limestones, etcetera. Leith and Mead (1915, page 215), like Kemp (1908, page 144), are logically compelled to do this, but the result only goes to show the difficulties raised by their definition, for all geologists are vitally interested in the classification of rocks as well as in that of metamorphic processes.

Before attempting a definition that may meet the approval of the majority, a list of the alterations affecting rocks below the shell of weathering should be scrutinized. It covers:

1. Simple crushing.
2. Consolidation by pure cohesion.
3. Consolidation by cements, amorphous and crystalline.
4. Consolidation by both cementation and recrystallization.
5. Concretionary action.
6. Pseudomorphic changes in constituent minerals.
7. Polymorphic changes in constituent minerals.
8. Devitrification.
9. Recrystallization in general.
10. Volatilization; for example, dehydration, carbonization of organic matter.
11. Complete fusion or simultaneous solution of most of the rock constituents.

The simple crushing of a rock or its consolidation by pure cohesion, in neither case accompanied by new crystallizations, is not usually regarded as an independent metamorphic process. Both are very rare phenomena. Some mylonites and other breccias may represent the one, as a few stratified rocks may represent the other.

The problem of rock cementation is much more difficult. Most writers have, apparently, voted to regard it as a phase of metamorphism. Since cementation merges into load metamorphism with utter gradualness, and since the conditions of cementation are largely of the same quality with those controlling both load and dynamic metamorphism, this view of the majority seems well taken. For practical reasons, however, the writer believes it best to admit in true metamorphism only those kinds of cementation that are accompanied by new crystallizations in the rock body concerned.

By common agreement concretionary action, pseudomorphism, polymorphism, and devitrification are regarded as phases of metamorphism as well as of rock weathering.

Nearly or quite complete melting or solution of a rock, even though followed by crystallization, is usually treated as a magmatic, rather than a metamorphic, phenomenon. With that understanding the following definitions have been framed.

Opinion is divided concerning the place of mere volatilization without the formation of new crystalline matter. The change from lignite, through bituminous coal, to anthracite has been sometimes described as "metamorphic." Yet geological manuals and special works on coal, in describing this change, very seldom use the word. "Transformation" is there commonly preferred to "metamorphism," which is thus unnecessary in dealing with the coals. A mud is altered in composition by the expulsion of some of its water, and a bituminous sediment is altered by the expulsion of natural gas or oil; but few geologists are impelled to call either an instance of metamorphism. For reasons to be stated in a following section, it seems better to exclude all such cases of pure volatilization from the domain of metamorphism.

PROPOSED DEFINITION OF METAMORPHISM

If pure volatilization were included, metamorphism might be defined as the sum of the processes which, working below the shell of weathering, lead to the alteration of rocks through the activity of solutions—gaseous, liquid, or solid—the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents.

If volatilization be excluded (as here advocated), metamorphism may be defined as the sum of the processes which, working below the shell of weathering, lead to the alteration of rocks through the *constructive* activity of *solutions*—gaseous, liquid, or solid—the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents. More concretely, the definition may be phrased thus: *Metamorphism is the sum of the processes which, working below the shell of weathering, cause the recrystallization of the original crystalline materials in rocks (with or without chemical reactions) or the crystallization of original amorphous materials in rocks, the change in each case not being accompanied by general melting of the rock or by general simultaneous solution of its constituents.*

New crystallization in non-magmatic rock substance is the one basic principle that seems best to express the essential idea shared by Lyell and most other geologists since 1833. That petrographical criterion has its counterpart in the physico-chemical criterion of the alternative definition, namely, the proof of the constructive activity of solutions. The definition covers the unequivocal changes, such as those from granite to gneiss, from argillite or volcanic ash to schist, from limestone to marble, from argillite to hornfels. It covers also the change from coal to graphite, the change from anhydrite to gypsum, the change from calcareous mud to partly crystalline limestone, devitrification, and the consolidation of sediments when accompanied by the formation of crystalline cement. So defined, in terms of the *end result* of various processes, "metamorphism" has still an enormous extension in geology. The classification of those processes, founded on their fundamental causes, is the next step in a scientific description of metamorphism itself. Especially after one has tried to form a rigorous, yet practical classification, he realizes the value of restricting "metamorphism" in the measure just suggested. Only with completed analysis of this kind can the full meaning and validity of the necessarily abstract definition be appreciated.

Definition of "metamorphic Rock"

Perhaps a word as to its relation to the expression "metamorphic rock" may not be out of place. Every modern writer holds that not all rocks in which metamorphic processes have operated are to be technically called "metamorphic." Irrespectively of the definition of the key word, the class of metamorphic rocks groups only those that result from essential change in the *body* of each original rock. According to the proposed definition of metamorphism itself, this change must involve new crystallizations which are distributed through the rock body as a whole, affecting most or all of it. The criterion for a metamorphic rock is therefore double. When applied to the classification of rocks, there appears to be conflict with common usage in only one respect. A volcanic glass, completely devitrified in depth because of influences other than those connected with its original magmatic state, is logically to be assigned to the metamorphic rocks. This departure from tradition is intrinsically not a very serious matter, on account of the small volume of glass in the earth's crust. The assignment may be defended on the ground that a bed of graphite, derived from another kind of amorphous material, is regularly put in the class of metamorphic rocks.

Classification of metamorphic Processes

Requirements of a working classification

An ultimate systematization of metamorphic phases would be based strictly on the origin of these alterations. Since the conditions of change are not fully known, the ideal is yet to be reached. The best classification now possible could represent no more than a summary report of progress in interpretation. Nevertheless, it should embody the minimum number of terms and definitions which can not apply after an indefinite expansion of knowledge on the subject. Every student of metamorphism knows the difficulty of framing definitions which are at once stable in the face of new discoveries and yet are of meaning intensive enough to match contemporary knowledge. Subdivisions should, moreover, be elastic enough to take in metamorphic phenomena whose causes are not now fully understood.

The problem of fruitful subdivision is specially insistent for field geologists. Hence the classification to be proposed is primarily geological. The dichotomous division into katamorphism and anamorphism may prove to have very great value in the description of rock or ledge. But, especially in field geology, an indication as to the controlling cause of a solutional change generally means much more than does a mere indication as to how the reactions ran in the solution. If increase of pressure is required to shift equilibrium in a given direction, the origin of the pressure increase may be immaterial to the student of the reaction as a purely physico-chemical change. On his part the geologist is deeply concerned with the cause of the pressure increase. Is it due to orogenic compression or to burial under a thickening cover of sediments or volcanic rocks? The professional injunction to answer such a fundamental question should be reflected in the main classification. If heightened temperature is the chief cause of new crystallizations in a rock, the geologist must go further than the physical chemist and ask whether the heating has resulted from the proximity of igneous masses or from orogenic crushing. In general, the physical chemist may be content with the laboratory report that a certain rock has been developed by anamorphic processes; the geologist is much more interested in the condition of the earth's crust which has led to that anamorphic assemblage of minerals.

The prevailing classifications do, in fact, aim to meet this chief requirement on the part of the geologists. The deeper meaning of metamorphism as one aspect of the development of the globe as a whole has given life to such widely used terms as "dynamic metamorphism," "static metamorphism," "load metamorphism," and "contact metamorphism." So firmly fixed are these, no acceptable classification is henceforth likely to dispense with most of them, if indeed with any of them.

Unfortunately, each of the names already given to different phases of metamorphism has, like the key word itself, had varying definitions. It becomes necessary in each case to decide what is the most advisable definition before incorporating that term in the system.

As a general rule, the phases of metamorphism have been given names that must be arbitrarily defined, else they would have been nearly or quite useless. Objection has been made to "dynamic metamorphism" on the ground that all metamorphism means movement—of mass or molecule. The same principle would destroy "pressure metamorphism," for all metamorphism takes place under some pressure, and "load metamorphism," for all metamorphism takes place under some load. In a literal sense nearly all metamorphism is "hydro-metamorphism," since water is a participant in most recrystallizations in rocks. Similarly, all metamorphism is "thermal metamorphism," for some heat is indispensable throughout. Happily, the inventors of the names here considered have not been bound by verbal form. They have treated words as tools and not as masters; as representative and not as directly connoting all the ideas symbolized by the individual words.

A brief survey of the varieties of usage will aid in choosing, for some of the terms employed in the proposed classification, those definitions that seem best to meet the present and future needs of geological science. After that review, a few other expressions appearing in the scheme will be introduced and discussed.

DEFINITION OF REGIONAL METAMORPHISM AND LOCAL METAMORPHISM

Three different meanings have been assigned to "regional metamorphism." Its originator, Daubrée (1860, page 59), did not define it formally. As already noted, he saw in it an improvement, as a synonym, on the "normal metamorphism" of de Beaumont, Virlet, Naumann, and others. Daubrée thus seems to have intended the expression to cover only those changes in rocks which are due to simple burial and the emanation of heat or hot gases from the earth's interior. In this sense Brauns (1896, page 278), Termier (1903, page 581), Doelter (1906, page 175), Coleman (1910, page 615), and Tornquist (1913, page 18) use the term.

Prestwich (1886, page 408), Teall (1888, page 418), de Lapparent (1893, page 1574), Rosenbusch (1910, page 72), Scott (1911, page 409), Flett (1911), page 219), and Holmquist (1916, page 145) define or use it as equivalent to "dynamic metamorphism."

A. Geikie (1903, page 766), Kemp (1908, page 113), Pirsson (1915, page 319), Ries and Watson (1915, page 208), and F. W. Clarke (1916, page 583) describe regional metamorphism as that kind which, by its nature, is likely to affect *extensive areas,* and do not inject into its definition any reference to the cause of the alteration beyond the statement that the rock alteration is *not genetically connected with the eruption of magma.*

The third definition has many adherents other than those just named. They have felt the necessity of a term with just this limited connotation, simple and somewhat negative as it is. Abundant experience has set up special claims for their definition—claims so strong that its retention in a working classification seems highly expedient.

The correlative term *"local metamorphism"* is preferable to "contact metamorphism," for a reason to be more fully seen in a following section on "load-contact metamorphism." Many Precambrian terranes have been metamorphosed by a combination of causes involving both igneous intrusion and widely spread, truly regional conditions of recrystallization, namely, those of load metamorphism. One can not say whether the necessarily local, igneous-rock influence or that of load cooperating with general earth heat is the more important. It seems best, therefore, to group both load metamorphism and load-contact metamorphism under the one head of local metamorphism, which is thus defined as *metamorphism genetically connected with the eruption of magma.*

Like "regional metamorphism," the term "local metamorphism" may yield its place when origins have become sufficiently ascertained. Until that distant day each will continue to serve a most useful purpose as one member in the grand, dichotomous division of all metamorphic processes.

DEFINITION OF DYNAMIC METAMORPHISM

Rosenbusch's definition of dynamo-metamorphism has been given above. He added (1910, page 73) the following statements: "That it effects immediate changes in the structure of the rock concerned—through stress, crushing, displacement, stretching, cleaving—can not be doubted; whether it directly causes chemical alteration is not fully proved, but probable. In any case it facilitates the access of transforming agents and extraordinarily increases the amount of surface on which those agents may act. Thus in dynamo-metamorphism we have displacement in the rock and the development of a new structure" (translated).

Harker (1889, page 16) supplements Rosenbusch's definition with the theoretical view that the term should imply conditions of low temperature and high pressure.

De Lapparent (1893, page 1406) understood dynamic metamorphism as resulting "from the mechanical actions (French, 'actions') to which the solid rocks are subjected during the building of mountains." On page 1573 he remarked: "The orogenic action does not seem to be limited to the production of mechanical effects. It appears to have been also a potent cause of metamorphism." On page 612 a formal definition is given as follows: Dynamic metamorphism is "the sum of the changes which orogenic movements have occasioned, either in compressing and dislocating the minerals or in facilitating the circulation of hot waters, capable of reacting on the mineral species existing in the rock." De

Lapparent evidently thought that the term should mean much more than pure crushing.

Zirkel (1893, I, page 604) was of opinion that "dynamo-metamorphism," as denoting merely the participation of a force, is a too general name.

Termier (1903, page 580, and 1910, page 588) considers that dynamic metamorphism "deforms but does not transform," and has strenuously advocated its disuse in scientific writing. Grubenmann (1910, page 125) also recommends its abolition, since, in his opinion, the name leads to the wrong notion, that mere pressure suffices for the rock alterations observed in mountain-built areas. Van Hise (1904, page 763) holds that the term is "objectionable for many reasons"; that "fracturing in the belt of cementation is equally dynamic metamorphism," and that (page 39) "in an exact sense all metamorphism is dynamic . . . dynamo-metamorphism refers to conditions of motion." Leith and Mead (1915, page 207) make "dynamic metamorphism" a rigorous synonym of "rock flowage." Similarly, Lahee (1916, page 231) regards the development of schistosity at right angles to the vertical stress of mere load as one type of dynamic metamorphism.

Without further extracts from the recent literature, a serious divergence of view is obvious. Termier's position can be understood only on the supposition that he defined "metamorphism" in a manner unacceptable to most geologists. More specifically, he does not regard new crystallizations as implied in the use of this key word; neither does he follow the definition of dynamic metamorphism given by Rosenbusch and practically adopted since 1889 by the majority. Termier's statement (1903, page 581) that "dynamic metamorphism . . . does not exist" depends on an arbitrary and hardly defensible definition of the term. Grubenmann's objection to it loses weight if it be recognized that "metamorphism" itself implies the activity of solutions; the idea that pressure alone is involved in the dynamic phase is automatically excluded. The objections by Van Hise and Zirkel, founded on a too inclusive use of the word "dynamic," have already been discussed; all progress in classification is impeded if the meaning of adjectives or noun be fixed by literal etymology.

How far such a technical expression as "dynamic metamorphism" bears its meaning on its face depends on the meaning to be assigned to its correlative or negative in scientific classification—in this case, "static metamorphism." In the mind of the average geologist using both terms is a more or less distinct picture of the thing which "moves" or "stands." That thing is the earth's crust. One set of metamorphic conditions accompanies strong movements of the crust. Another, not necessarily quite different, set controls regional metamorphism in the absence of strong crustal movements. These two conceptions, ruling in the geological profession, together suggest the definition of dynamic metamorphism as *metamorphism which is induced in rocks because of their deformation, the crustal movement being of the orogenic type.*

The proposed definition has the advantage of not being too intensive for general acceptance. It does not state the physical chemistry involved. It does not presuppose an increase of temperature, however general such increase may be during mountain-building. It does not presuppose an enforced, special circulation of water or other fluids; nor does it by any means cover all instances where the changing rocks have undergone crushing or mere increase of pressure. The one essential, and perhaps the only unassailable criterion, for dynamic metamorphism is its genetic relation to *orogenic* movement, the transfer of large masses of the earth's crust. According to the suggested definition, the mental picture called up by the use of the term is a geological picture, as it should be. The single genetic condition emphasized is in ultimate control of the reactions leading to chemical equilibrium in the rocks; but it is also the supreme fact for the general geologist who is studying the given region or is reading the reports of others about that region. So restricted, the name "dynamic metamorphism" may be saved for science and serve as a perfect counterpart of that other most useful name, "static metamorphism."

DEFINITION OF STATIC METAMORPHISM

Judd (1889, pages 243-246) introduced the expression "statical metamorphism" to designate the rock changes resulting from "chemical and crystallizing processes which certainly go on at great depths, and under enormous pressures, even when the rock-masses do not yield to the pressures and thus become subjected to the movements which result in dynamo-metamorphic action. Such changes, resulting from pressures that do not affect movements in the rock-masses, may be appropriately called 'statical metamorphism.' . . . The most potent agency by which change is effected consists in the penetration of the whole mass of the rock by various liquid or gaseous solvents. It is for the whole group of such changes—of which 'schillerization' is a conspicuous example—that I propose to employ the term *statical* metamorphism." He noted that statical metamorphism may either precede or follow dynamic metamorphism, and that the latter is much less important than was generally thought at the time of his writing.

Dana (1895, page 440) described "statical metamorphism" as that "dependent on heat of a statical source—the earth's mass and the vapors about it."

Geikie (1903, page 805) speaks of the "statical phase" of regional metamorphism as that connected with "enormous pressure leading to little or no molecular crushing, but with some shearing movement in the rock." He remarks that it "does not produce such striking results as the . . . dynamical phase."

Van Hise (1904, page 47) wrote: "Metamorphism by molecular movement has generally been called static metamorphism."

Ries and Watson (1915, page 204) note simply that static metamorphism refers to "quiescent conditions."

Here, again, there is no consensus of opinion. Judd specified that "the rocks do not yield to the pressures [exerted by thick covers]." Geikie assumes such yielding, for there is "some shearing movement in the rock," though he makes the cryptic remark that the pressure leads to "little or no molecular crushing." Judd stressed the work of fluid solutions. Dana stressed the influence of the earth's internal heat. Van Hise regards molecular movement as the essential feature.

Solutions, heat, molecular movement, and some yielding to pressure are necessary characteristics of all kinds of metamorphism. The residual condition, which may be taken as a workable criterion, is the absence of deformation of the orogenic type. Accordingly, as already implied, static metamorphism may be defined as *that phase of regional metamorphism which is not induced by orogenic deformation.*

Contact metamorphism is usually, in a literal sense, also "static," inasmuch as alterations by magmatic heat and gases are not conditioned by crustal deformation. The proposed restriction of meaning for "static" is therefore arbitrary, but no published name other than "static metamorphism" so well expresses the required negative of "dynamic metamorphism," just delimited. As a couple the two definitions are logical, and the corresponding terms can directly tell what the geologist most needs to know concerning the principal condition for the regional alteration of rocks.

PHASES OF STATIC AND DYNAMIC METAMORPHISM

Supported to a considerable extent by traditional usage, one may thus divide all metamorphic processes into two primary classes, symbolized by the expressions "regional metamorphism" and "local metamorphism"; and also divide regional metamorphic processes into secondary classes, symbolized by "static metamorphism" and "dynamic metamorphism." Further logical subdivision is not so well guided by the principle of long usage and is intrinsically more difficult. Nevertheless, more intensive terms are urgently needed to portray the existing state of knowledge and to provide for the description and discussion of metamorphism in the future.

All metamorphism is due to the activity of solutions. Hence the factors to be used in distinguishing ternary and still lower classes of metamorphic processes may well be of physico-chemical nature. If these finer subdivisions can be so made, the more purely geological factors appearing in the primary and secondary categories, a full genetic scheme is possible.

The march of crystallization in a rock depends on temperature, pressure, the presence of liquid and gaseous solvents, and the chemical composition of the rock as a whole; for none of these factors are the quantitative data sufficient to allow its rigorous application to the present problem, and it is hopeless to expect an adequate collection of the data for generations to come. The vocabulary of metamorphism is poverty-stricken for a very good reason. It lacks in names for the respective subdivisions of dynamic, static, contact, or load contact metamorphism, if made on the basis of any one of the four physico-chemical factors; nor is there at present any apparent need of spinning the web of classification so elaborately. Nevertheless, the content of either static metamorphism or dynamic metamorphism is so huge that their further subdivision is already advisable.

In the present state of knowledge temperature may be assumed as the most appropriate factor for the ternary, genetic subdivision. The static metamorphism of rocks situated at comparatively small depths takes place *at low temperature and is possible only in the presence of water or other fluids with low freezing-points.* Cementation or lithifaction, when dependent on new crystallizations, is metamorphism of this sort. It may be designated as *hydrometamorphism* (see Harker, 1889, page 15; Merrill, 1897, page 161; Lindgren, 1905, page 124), if the name be understood as applying to changes in rocks not subjected to orogenic stress during the metamorphism. This use of the word is arbitrary, inasmuch as certain hydrous formations have been partially recrystallized during their deformation yet without the development of high temperature. No unequivocal synonym has been found in print. To supply one, the expression *"stato-hydral metamorphism"* has been coined.

The corresponding alteration *under dynamic conditions, but at low temperature,* may be called *"dynamo-hydral metamorphism."* A simpler name might be *"slaty metamorphism,"* since certain slates have been so developed. However, other slates have been formed at temperatures that can not be called low; hence this adaptation is not wholly satisfactory.

The analogous term *"stato-thermal metamorphism"* has been coined to mean *regional alteration under static conditions and at high temperature.*

Its simpler synonym is Milch's *"load metamorphism."* "Load metamorphism" directly connotes vertical stress, but just as truly also high temperature. New crystallization controlled by dead weight can not take place except at deep levels, where the rocks feel strongly the internal heat of the earth. This type of alteration has been perhaps the most important of all; yet recent writers, over-enthusiastic about dynamic metamorphism, have strangely overlooked it or else left it without due emphasis. Hence a following section of this paper is specially devoted to load metamorphism.

The fourth member of the ternary series may bear the name *"dynamo-thermal metamorphism."* This is regional metamorphism *under dynamic conditions and at high temperature.* A simple synonym is hard to find, but Gosselet's (1883, page 202) term *"friction metamorphism"* might be revived for the purpose. It should, however, be used symbolically, with proper guarding, for friction is clearly not the sole cause for the high temperature so often operative in purely dynamic metamorphism.

The suggested ternary subdivision is imperfect. It depends on a distinction between "low temperature" and "high temperature"—one that can not yet be made, in practice, on a quantitative basis. Nevertheless, there is some advantage in so enlarging the vocabulary of metamorphism that temperature control may be, at least approximately, indicated in accounts of recrystallized rocks.

DEFINITION AND SANCTION OF "LOAD METAMORPHISM"

Geology owes to Milch (1894, page 121) an important paper, in which two kinds of regional metamorphism are described and named. The first is called "Dislocationsmetamorphismus," Lossen's old name for what most geologists call dynamic metamorphism, originating in pressure directed tangentially with respect to the earth's curved surface. The second is called "Belastungsmetamorphismus," with the exact English translation, "load metamorphism." This type originates in "verticale Belastung." Milch holds that load metamorphism "is represented in the development of every rock; it changes every rock which is not in process of destruction by weathering agents."

Milch points out that dynamic and local metamorphism result in very similar or identical kinds of mineralogical composites, because each phase may entail the same physico-chemical conditions underground. Through load metamorphism he explains the ubiquity of the "Grundgebirge" and the very common parallelism between original stratification planes and schistosity planes in metamorphosed sediments. He believes also that in some instances load metamorphism can induce planes of schistosity crossing the bedding of sediments which had been upturned before their final recrystallization was completed.

In a later paper (1910, page 44) Milch shows the likeness between load metamorphism and the "normal metamorphism" of de Beaumont and the "regional metamorphism" of Daubrée.

Brauns (1896, page 278) adopts "Belastungsmetamorphismus," giving "regional metamorphism" as synonym; he notes the strong contrast of both to "dynamic metamorphism" in meaning.

After many years of field-work in the older Precambrian (Shuswap) terrane of British Columbia, G. M. Dawson (1901, page 64) concluded that "the foliation of the Shuswap rocks may have been produced rather beneath the mere weight of superincumbent strata than by pressure of a tangential character accompanied by folding." In his summary of British Columbia geology, he continues with the remark: "In the Archean of eastern Canada, foliation still nearly horizontal or inclined at low angles often characterizes considerable areas and appears to call for some explanation similar to that above suggested [for the Shuswap rocks]."

While mapping the later Precambrian (Beltian) formations of southern British Columbia and Alberta, the present writer independently came to the view that load metamorphism is of superlative importance. Later work in the Shuswap terrane itself confirmed that conclusion, in which the writer found he had been anticipated by Dawson, as well as by Milch, who first gave this general process its name.[3]

In eloquent addresses to two international congresses, Termier (1903, 1910) uttered timely protests against exaggerated claims for dynamic metamorphism. His reasoning was based on his experience in the western Alps. Translated, his words (1903, page 580) are: "Wide areas of the Alps seem to have enjoyed relative tranquillity and, in any case, to have undergone neither intense folding, nor crushing, nor cleaving. . . . And, nevertheless, the metamorphism of the crystalline terranes is as intense as elsewhere." He believes their rocks had already become crystalline schists before the great foldings and overthrusts characteristic of the Alps took place. The relations are like those observed in nature by Dawson, Milch, and others; but Termier preferred to use, in explanation, the older term "regional metamorphism" to Judd's "statical metamorphism" or Milch's "load metamorphism." In fact, Termier emphasizes the rise of juvenile gases with the consequent heating of geosynclinal strata, rather than vertical stress, as the controlling condition of the recrystallization.

[3] See summary reports of the Geological Survey of Canada, 1911, page 168, and 1912, page 159; also memoirs of the Geological Survey of Canada, number 38, 1912, page 172, and number 68, 1915, page 44.

In spite of the clear announcements of the principle by Dawson and Milch, many geologists of the present day are still far from sympathetic with the idea of load metamorphism. Very rarely is it even mentioned in works on rock changes or on the crystalline schists. Of the few authors who have considered vertical stress in relation to the development of schistosity, a number like A. Geikie, Van Hise, and Pirsson express doubt that there is any important positive relation between them. For these reasons a sketch of the field facts, suggesting the reality and great significance of load metamorphism, may not be without warrant. The value of a classification of the phases of metamorphism really depends in no small part on a wise decision in this matter.

A strong, perhaps the strongest, argument for load metamorphism is expressed in the foregoing quotations from Dawson and Termier. Extensive areas in western Canada, eastern Canada, and the western Alps, though underlain by typical crystalline schists, display no evidence of ever having been greatly affected by crustal deformation. Bedding is perfectly preserved in the sedimentary members of the crystalline groups of rocks. The dip is characteristically low, even nearly horizontal, over wide stretches. The structure is that of a plateau, a somewhat broken plateau.

Besides the examples in the Belt terrane and Shuswap terrane of the American Cordillera, in Ontario, and in the Alps (compare Lory, 1888, page 87 ff), many others are on record. In this list of regions are notable tracts in Labrador (Low, 1895, page 199); the Adirondacks (Cushing, 1914, page 30; W. J. Miller, 1914, page 59, and 1916, page 587); Greenland (A. Heim, 1911, page 180); the Gföhl gneiss of the Lower-Austria Waldviertel (Becke, 1910, page 617); the Erzgebirge (Lepsius, 1903, pages 89, 99, 108); the Schwarzwald (Schwenkel, 1912, pages 139 and 253); the Oban-Dalmally district of Scotland (Kynaston, 1908, page 21); German East Africa (Schmidt, 1886, page 451, and Bornhardt, 1900, page 459); Rhodesia, Congo State, and Uganda (Mennell, 1913, page 205).

With a few exceptions, the authors mentioned do not consider in print the cause of the plateau structure in the respective gneisses and schists. The extreme advocates of dynamic metamorphism would find it in "rolling-out," "overturning of folds," "multiple thrusts," or intense horizontal shearing. In the fields studied by the writer none of these explanations can be admitted. As Dawson clearly saw, the only feasible explanation of the schistosity in the flat-lying Shuswap rocks is dead-weight stress controlling their recrystallization. Supported also by the opinions of Milch, Termier, Lory, Becke, and Schwenkel, it is not altogether rash for one to assume that load has been a main factor in the metamorphism of many of the plateau terranes listed.

Again, for some schistose formations which have been greatly dislocated, there is good evidence that the principal metamorphism was accomplished before the main foldings or faultings. An unusually vivid instance is found in the British Columbia Shuswap terrane. On its gneisses and schists rest, in nearly perfect structural conformity, the extremely thick Beltian sediments. These, nearly or quite conformably, pass upward into the Cambrian series. All three rock groups have been upturned in post-Cambrian time. Some of the Cambrian beds, much of the Beltian series, and almost all of the Shuswap sediments and eruptives had been thoroughly recrystallized before the upturning. That deformation caused new, *quite local* dynamic metamorphism, but left the original schistosity largely unchanged. The post-Cambrian orogeny seems to have had nothing to do with the principal schistosity.

A similar relation prevails in the Erzgebirge, Vogtland, the Fichtelgebirge, and East Thuringia, where the "Archean" gneisses and schists pass up, concordantly, into thick phyllites, and these up into fossiliferous Cambrian sediments (Credner, 1897, page 396; Lepsius, 1903, page 108; Rosenbusch, 1910, page 577).

Lory (1888, page 87) described it in the Monte Rosa district of the Alps.

A third reason for crediting the great efficiency of load metamorphism is the exceedingly common parallelism between foliation or schistosity and the stratification. This fact is abundantly illustrated in the Canadian shield, in the Adirondacks of New York State, and in the Precambrian of the North American Cordillera, Scotland, Scandinavia, Finland, etcetera. Löwl (1906, page 50) has given a good statement of it in the following passage (translated): "The great majority of the crystalline schists are foliated, not across the bedding, but parallel to it. Their parallel texture must have been developed when the rocks lay undisturbed, and thus only because of the downward pressure of the overlying rocks, exactly as in the case of shale and most clay-slates, among which, indeed, transverse cleavage is not the rule, but the exception. It is not merely a case of the condensation of the buried rock by the dead weight of its cover. The load also causes foliation. Its effect is not hydrostatic, but, even if there be pressure on all sides, the pressure in the vertical direction is the strongest. Lateral thrust may develop still greater inequality of pressure, especially at small depth; yet an essential difference between the effects of load and lateral thrust is not to be assumed."

Parallelism of schistosity and bedding, to the degree observed in the crystalline schists, is truly inexplicable by pure dynamic metamorphism. The parallelism is found, whether or not the dips are persistently low or high or persistently changing across-country. Since new metamorphic minerals seem to be regularly elongated at right angles to the metamorphosing stress, the schistosity produced by intense orogenic movements (tangential force) will be parallel to bedding only in comparatively rare and narrow belts. Prevailing parallelism in a terrane of variable dip is therefore a good indication that dynamic metamorphism has not controlled the recrystallization. Elementary as it is, this principle has been wonderfully neglected in most of the recent discussions of regional metamorphism.

A fourth argument, connected with the last, has independent power. In the Shuswap terrane, in the Precambrian of eastern North America, and in many other schist areas the crystallinity or degree of metamorphism is, to a large extent, not directly related to the amount of crustal deformation. Many vertically dipping schists are practically identical in habit, including size of grain, with neighboring, little-deformed schists of the same chemical composition. For this fact the assumption of load metamorphism, active before the mountain-building, offers the only explanation yet proposed.

Of course, a rock series already recrystallized by load metamorphism may be affected by later alterations of dynamic origin. Beautiful examples are visible among the Shuswap rocks (Daly, 1915, plate 21). Such superposition of metamorphisms may thus obscure the whole problem of origins. In fact, its solution has doubtless been retarded because special students of metamorphism have so largely worked in fields where schists and gneisses happen to have been much dislocated since the recrystallization of those rocks. Most workers have not sufficiently canvassed the question as to what was the condition of each rock formation *before* upturning. The proof of recrystallization in zones of intense dynamic stress has too easily led to generalizations as to the genesis of the rest, often the greater part, of the same terrane, where crustal deformation has been less or where its causal connection with the visible metamorphism can not be demonstrated.

Finally, the fully significance of load metamorphism is not understood until its relation to the doctrine of uniformitarianism has been made out. Koenigsberger (1910, page 651) and Ries and Watson (1915, page 203) deny that deep burial has caused regional metamorphism, on the ground that many Paleozoic and younger strata, though once covered by thousands of meters of rock, have not been changed to crystalline schists. The present writer (1912, page 479) has observed a nearly complete absence of recrystallization in the Lower Cretaceous arkose and shale of the Pasayten series in British Columbia. Yet those beds were formerly beneath younger Cretaceous sediments probably more than 8,000 meters thick. A similar condition is reported for the basal beds of the Cretaceous geosynclinal of northern California, where the thickness of cover was likewise colossal.

Such examples do show the subordinate importance of load metamorphism in later geological time. To a somewhat smaller extent the Paleozoic geosynclinals fail to exhibit recrystallization in their lower strata. The pressure has been high, the water content considerable, the composition of the sediments appropriate, the deep burial of long duration; and yet metamorphism has been partial or nil.

The latest Precambrian (Beltian) strata, on the other hand, are largely recrystallized at horizons which have never been buried deeper than those reached by the non-crystalline Mesozoic and Paleozoic sediments just mentioned. The pre-Beltian stratified formations, from bottom to top, the world over, have been almost entirely recrystallized.

From Clarke's (1916, page 30) calculation of the whole amount of rock that has ever been decomposed by the weather it is easy to form a rough idea of the total volume eroded in geological time. But a fraction of this total can be assigned to Precambrian time. Of that fraction only a part represents the covers that lay on the surfaces of unconformity between the later Precambrian series and the older complexes of crystalline schists. The complexes were highly metamorphic before the ancient denudation corresponding to each of the unconformities. The combined areas of the known complexes form a vast total. Much greater is the total area of similar Precambrian terranes, reasonably supposed to underlie the existing Paleozoic and younger sediments. It seems safe to hold that the average cover on the complexes at the time of their recrystallization was far less than 5,000 meters in thickness. Hence, if that change were induced by vertical stress, the conditions must have been quite different from those which have ruled since the beginning of the Paleozoic.

Assuming a steeper thermal gradient for the earth in the pre-Beltian era, as well as load metamorphism under a moderate cover, the ancient recrystallization of the Shuswap terrane has been explained. In somewhat less concrete form the idea is found in writings as old as Hutton's. It has been lost to sight by too many of the modern advocates of dynamic metamorphism. A speculation involving the conception of an earth originally very hot near the surface is no more dangerous than the fashionable explanation of all, or nearly all, regional metamorphism by orogenic movements. More probably than any other, the conception of load metamorphism affords a useful starting-point in the problem of the Precambrian crystalline schists.

The five arguments outlined are of unequal strength, but their cumulative power is great. In any case it seems eminently wise to provide load metamorphism a place in a general classification of rock changes, if that classification is to meet the needs of geologists who have to deal with the Precambrian formations.

DEFINITION OF "DYNAMO-STATIC METAMORPHISM"

A special combination of static and dynamic conditions is worthy of recognition. A rock formation which has become *covered by a thick overthrust mass may itself not be crushed or otherwise deformed and yet may be recrystallized because of the new load on it.* If so, the temperature being necessarily high and the pressure on the recrystallizing rocks being vertical, the process is an example of load metamorphism, while the special inciting cause is dynamic. To distinguish such a case, the name "dynamo-static metamorphism," symbolizing a third principal subdivision of regional metamorphism, may be employed.

DEFINITION OF CONTACT METAMORPHISM

Contact metamorphism comprises all metamorphic changes due to contact with or proximity to any body of eruptive (igneous) rock, the new crystallizations not being definitely directed by dead-weight stress. This definition, adapted from Geikie (1903, page 766), is that generally followed by geologists.

Certain authors have tried to restrict the term to mean the effects of mere heating by eruptive magma. Thus de Lapparent (1893, page 1402) used "métamorphisme périphérique" to symbolize the metamorphism induced by gases and liquids emanating from magma and included it with "métamorphisme de contact" in a dichotomous division of "métamorphisme d'influence." Haug (1907, page 176) appears to agree in this usage. Von Wolff (1914, page 240) makes "contact metamorphism in the narrower sense" a synonym for this purely thermal contact action.

On the other hand, Boeke (1915, page 384) reverses the definition and regards "Kontakt-Metamorphose" as that due to the recrystallizing influence of magmatic fluids on the invaded rocks, while his "Thermometamorphose" is that induced when high temperature plays the chief rôle at igneous contacts.

Inasmuch as it is, in many instances, impossible to distinguish the effects of mere heating from those of gaseous emanation, most geologists have been right in refusing to use either principle as a criterion for contact metamorphism, and, expressly or tacitly, have used the name with the broad meaning given above. Their view is reflected in the definitions given in the geological manuals of Dana, Geikie, Tornquist, Pirsson and Schuchert, Cleland, and many others. The term is thereby made essentially synonymous with the French "métamorphisme d'influence" and with the older names "abnormal metamorphism" and "accidental metamorphism."

Barrell (1907, page 116) separates contact metamorphism from contact metasomatism. The former is described as "taking place without addition of materials and resulting in a crystallization of the wall rocks." The changes are "those of volume and not of mass." Contact metasomatism "indicates a mass change in the composition of the rock other than the elimination of gases involved in simple metamorphism. The action takes place through magmatic emanations." These usages conflict with the definition of metamorphism here proposed and also with definitions of contact metamorphism by the majority of writers (for example, Grubenmann, 1910, page 70), who regard magmatically controlled metasomatism as a true metamorphic phenomenon.

V. M. Goldschmidt (1911, page 119) describes a mere recrystallization of the country rock, without the addition of material to it from the magma, as "normal contact metamorphism," and describes alteration of the country rock through such addition of material as "pneumatolytic contact metamorphism." Von Wolff (1914, page 240) adopts the latter name with Goldschmidt's definition.

Bunsen's (1851, page 241) "pneumatolytic" referred to sublimations from truly volcanic masses. Brögger (1890, page 213) enlarges its meaning so as to take in all the metamorphic changes due to magmatic gases in general. Barrell (1907, page 117) suggests that "contact metasomatism may be divided into pneumatolitic (sic) and hydrothermal metasomatism, according to whether the magmatic emanations are above or below 365° C. and 200 atmospheres pressure—the critical temperature and pressure of water." In principle Irving (1911, page 298) follows this usage. It raises the question whether the field of contact metamorphism might be divided into three parts: *thermal-contact* metamorphism, covering rock changes due to mere heating; *hydrothermal-contact* metamorphism, covering rock changes involving magmatic fluid emanations at temperatures less than 365° C.; and *pneumatolytic-contact* metamorphism, involving gases at temperatures above 365° C. This query seems best answered in the negative. First, because present knowledge does not permit the distinction in practice on the basis of the given temperature; secondly, because the exclusion of many reactions, controlled by vapors and true gases, from the domain of pneumatolysis causes a highly arbitrary and apparently quite unnecessary departure from the literal meaning of "pneumatolysis"; lastly, because connate fluids of the country rock, which have metamorphic effects very similar to those exerted by magmatic emanations, are not considered in the subdivision.

According to another conceivable classification, "*hydrothermal-contact* metamorphism" might be defined as metamorphism controlled by water and its accompanying vapor, while "*pneumatolytic-contact* metamorphism" includes the types of contact metamorphism controlled by other volatile substances. "*Thermal-contact* metamorphism" would be defined as before. This scheme also is hard to apply in nature, and it does not agree with the concept of pneumatolysis which, vague as it is, now rules in the minds of most geologists.

In the present connection it should again be noted that existing criteria do not in many cases suffice to distinguish, practically, "thermal-contact" effects from those controlled by gases and vapors.

In fact, the writer has been unable to find in the literature any suggestion of a satisfactory subdivision of the contact-metamorphic processes. The importance of the subject in the theory and description of ore deposits is manifest. Perhaps the group of economic geologists will yet develop a truly scientific classification, with corresponding definitions, for the phases of contact metamorphism.

DEFINITION AND SANCTION OF "LOAD-CONTACT METAMORPHISM"

Extensive masses of the older Precambrian rocks are composites of sediments or surface volcanics with injections of igneous material. Generally granitic in composition, the intrusives commonly favor the form of the sill or laccolithic sheet. So numerous are these bodies that their total contact-metamorphic effects are profound. In some cases the changes wrought are those of pure contact-metamorphism. In very many others the recrystallization of the invaded formation has been simultaneously controlled by the weight of its cover. *The influences of vertical stress, of the earth's general heat, and of the injected magma are thus concurrent. New crystallizations in the country rock are caused by a combination of causes which may be called "load-contact metamorphism."*

The writer first began to appreciate this compound type while studying the Shuswap terrane of British Columbia, with which a comparison of Precambrian rocks in Ontario was later made in the field. Where the siliceous sediments, limestones, and basic volcanics of the western terrane are not charged with igneous injections in great number, the rocks are seen to have been recrystallized by pure load-metamorphism. In other areas, where the same formations were split by many granitic sills, the invaded rocks have quite different habit. The grain is characteristically much coarser. The mineralogical composition is somewhat unlike that observed in the sill-free parts of the terrane. Nevertheless, the invaded rocks are usually schistose in high degree; the planes of schistosity are here, also, sensibly parallel to bedding planes, and the directing influence of overlying load is as clear as elsewhere. The sediments appear to have been recrystallized by pure load-metamorphism before the epoch or epochs of sill injection. If so, this is another instance of superposed metamorphisms. However, the evidence for a combination of contact and load influences in the later metamorphism of the sill-charged strata is clear. In fact, load metamorphism continued after the freezing of the sills, for most of these are now orthogneisses, with schistosity planes parallel to the sill contacts and to the planes of bedding in sediments and volcanics. An influence which so fully controlled the recrystallization of a comparatively stable assemblage of minerals, like granite, could not fail to direct the recrystallization of the strata alternating with the sills.

The writer suspects that load-contact metamorphism is largely responsible for the development of Precambrian gneiss-schist complexes in general. The sanction for the new term and for its definition depends in part on the strength of the reasoning by which belief in pure load-metamorphism has been won. Using both principles, or at any rate keeping an open mind on the question of their validity, one is better equipped for an attack on the problem of the crystalline schists.

PROPOSED CLASSIFICATION

The following table gives the suggested division of metamorphic processes, each name bearing the preferred definition:

A. Regional metamorphism (not caused by eruptive bodies).
- I. *Static metamorphism* (orogenic movement not a causal condition).
  1. *Stato-hydral* metamorphism or *hydrometamorphism* (low temperature).
  2. *Stato-thermal* metamorphism or *load* metamorphism (high temperature).
- II. *Dynamic metamorphism* (orogenic movement a causal condition).
  1. *Dynamo-hydral* metamorphism or *slaty* (?) metamorphism (low temperature).
  2. *Dynamo-thermal* metamorphism or *friction* (?) metamorphism (high temperature).
- III. *Dynamo-static metamorphism* (load metamorphism in rocks lying beneath overthrust masses).

B. LOCAL METAMORPHISM (caused by eruptive bodies).

I. *Contact metamorphism* (magmatic influence in control).

II. *Load-contact metamorphism* (combination of load and magmatic influences).

ATTEMPT AT AN ALTERNATIVE CLASSIFICATION

With this scheme in mind, the ground for the exclusion of pure volatilization from the list of metamorphic processes may again be profitably considered. The question is whether it is expedient to regard as technically metamorphic rock changes that are typified by the conversion of soft coals into anthracite and by the mere expulsion of water from buried mud. In order to discuss this enlargement of the conception of metamorphism, a special name for changes through pure volatilization is desirable. The expression "alembic metamorphism" is suggested for the purpose.

Pure distillation takes place under the conditions of static, or dynamic, or contact metamorphism. In a similarly tentative way, let these phases of pure volatilization be called, respectively, "stato-alembic," "dynamo-alembic," and "contact-alembic." To fit into the classification so far given, "stato-alembic metamorphism" must be rigorously distinguished from "stato-hydral metamorphism"; "dynamo-alembic metamorphism" from "dynamo-hydral metamorphism," and "contact-alembic metamorphism" from the purely thermal phase of contact metamorphism as the cause of new crystallizations. None of the three distinctions seems possible in practice. Nor has there been better success in attempting a workable dichotomous division of regional metamorphism and then contact metamorphism, each pair of subdivisions consisting of a class of rock changes induced by pure volatilization and a class induced by other causes, with or without volatilization.

In short, the inclusion of pure distillation in metamorphism seems inevitably to lead to excessive complication and to the abandonment of the effort to give strict definition to such established terms as "dynamic metamorphism," "static metamorphism," "load metamorphism," "local metamorphism," and "contact metamorphism." It is simpler to make new crystallization the criterion for metamorphism and to describe rock changes through pure volatilization by some such expression as *"alembic* (French, "alambic;" German, "Alembik") *transformation."*

FAVORED CLASSIFICATION IN ACTUAL PRACTICE

As far as possible, terms already in use have been preferred in building the classification. The violence done to existing definitions of the adjectives "regional," "dynamic," "static," and "contact" generally consists in lessening the intensiveness of each. The prevailing conflicts of definitions threaten to destroy these terms as practical aids in geology. To save them, no better course offers itself than to seek the factor common to the largest number of definitions for each of the words. With that common factor in supreme control of the definition, the word loses depth of meaning, but, as a rule, gains breadth and, above all, capacity for logical, clean-cut description and usage.

The four compound names—"stato-hydral," "stato-thermal," "dynamo-hydral," and "dynamo-thermal metamorphism"—are directly founded on root words already familiar and are mnemonically easy to locate in the scheme. They are, however, somewhat cumbrous and barbarous in form; synonyms of simpler make would, therefore, be welcome. The suggested equivalents, respectively, "hydro-," "load," "slaty," and "friction metamorphism" are arbitrarily defined from the standpoint of the literal meaning of each adjective. "Slaty" and "friction" have been adapted for the present purpose with some misgiving. The writer has not yet been able to find adjectives that might immediately suggest the ideas involved; more than usually in the proposed system, the technical names are here figurative rather than fully connotative. In practice the geologist seldom needs to distinguish under separate names "dynamo-hydral" and "dynamo-thermal" metamorphism.

The adjectives most likely to be useful in the future are "regional," "local," "static," "load," "dynamic," "contact," and "load-contact." The sanction of each of them is founded on theory of origins. General agreement in definition is bound to be indirectly proportional to the respective amounts of theory implied in these seven words. For the student of post-Cambrian rocks, the terms "regional metamorphism," "local metamorphism," "dynamic metamorphism," and "contact metamorphism" may be in constant use; "static metamorphism" is likely to be less in demand; "load metamorphism" and "load-contact metamorphism" are still less in active demand. For the student of the Precambrian complexes, all seven phases need expression, but he should feel the special need of "load metamorphism" and "load-contact metamorphism." Until the peculiar conditions of Precambrian time have been sensed and compared with later conditions, it is impossible to make a permanent definition of metamorphism or a universally acceptable classification of its phases.

The problem of metamorphism thus remains, where it has always been, chiefly in the hands of workers specializing in the Precambrian terranes. Intensive research on younger formations and laboratory experiment are both extremely valuable, but the field investigator of the Precambrian rocks must make his unique and first-rank contribution to the necessary sum of facts. To him especially the writer offers definitions and classification. In many instances the Precambrian specialist has gone into the field with too much reliance on single principles affecting rock alteration. He has overemphasized dynamic action, or the efficiency of vadose waters, or the purely thermal effects of burial, or the power of hot gases rising from the earth's interior. Preconceptions have thus too often prevented workers from observing critical facts in the field. Some of these geologists have preached false doctrines, not because they were too theoretical, but because they were too little theoretical and did not apply thoroughly the principle of multiple hypotheses. Scarcely one fundamental modern idea on metamorphism was not foreshadowed by writers in the heroic age of geology. Field men stumble, teachers are puzzled, and students are worried because the geological profession has not insisted on the maximum possible completeness of a systematic, rigorous classification of principles suggested long ago. Though but a report of progress and thus unfinished, such a classification serves as a means of expression and, yet more valuably, as a stimulus to further correct observation in nature.

The writer does not, of course, pretend to have formed definitions or classification which will satisfy geologists in general. He merely offers a scheme for criticism and *then improvement.* It may be pointed out that all names used in classification are either now represented in the leading languages of Europe or are capable of ready translation. The proposed scheme thus follows a peremptory rule in building a scientific system and specially invites international cooperation for its bettering.

Additional descriptive Terms

Since 1833 many words, other than those embodied in the present classification and yet denoting aspects of metamorphism, have been coined or adapted. Some have permanent value as aids to the description of metamorphic rocks, when the causes of their alteration are only partly known.

If one wishes to emphasize pressure as a leading physico-chemical condition in a given case, the term *pressure metamorphism* might be used. If so, the context should clearly indicate that its employment is due to a lack of knowledge as to the source of the pressure itself, whether primarily an incident of mountain-building or the effect of simple burial. If the choice between these alternatives is possible, then "dynamic metamorphism" or "load metamorphism," as the case may be, should be preferred.

The development of schistose structure in a rock is a stress phenomenon. That change might be called *stress metamorphism,* if the observer has not the data for assigning it to either static or dynamic metamorphism and yet wishes to contrast the type of recrystallization with that yielding a massive rock, such as common marble.

Properly guarded, *thermal metamorphism* might signify changes effected by high temperature. The use of this expression would, however, imply that the field observations do not suffice to make clear what is the source of heat—mere burial, dynamic action, or igneous intrusion. If water and high temperature had essentially cooperated, and again, if outcrops failed to show the source of heat, *hydrothermal metamorphism* might similarly be employed.

Katamorphism and *anamorphism,* denoting contrasted phases of rock alteration in general, seem likely to persist as useful descriptive terms. They represent a problem in the classification of processes which is quite different from the problem attacked in this paper, and the favored definitions of "metamorphism" and its subdivisions do not conflict with those of the two key words employed by Van Hise or Leith and Mead.

H. C. Sargent (1917, page 59) has proposed *"auto-metamorphism"* as a name for the intense decomposition of spilite, "due to retention of volatile constituents resulting from the physical environment of a submarine flow."

Finally, if a formation has been recrystallized more than once, it may be said to have undergone *superimposed metamorphisms,* or, more compactly, as suggested by Teall (1888, page 8), *superposed metamorphisms.* An adjective proposed by Koenigsberger (1910, page 670) suggests *polymetamorphism* as a synonym.

ULTRA-METAMORPHISM

Sederholm (1907, page 102) has called the complete remelting of a rock *anatexis.* With him one may describe anatexis as a phase of *"ultra-metamorphism"* (Holmquist, 1909) without running counter to the proposed definition of metamorphism. The course of the melting-up may be purely thermal or it may be hydrothermal. Sederholm (1907, page 102) makes the emanation of gases and heat from the general subcrustal region of the earth responsible for the *palingenesis* (rebirth) of Pre-cambrian granitic magma *in situ.*

Several French geologists, including Termier and Haug, still believe that the rise of hot gases from the earth's interior has generated the post-Cambrian batholiths from geosynclinal sediments. This extremely doubtful thesis regarding the geological efficiency of "colonnes filtrantes" is a matter relating to ultra-metamorphism rather than to metamorphism.

"Roches d'imbibition" result from contact metamorphism. They may graduate into complexes developed by lit-par-lit injection, which is commonly simultaneous with regional metamorphism and also a cause of contact metamorphism. But several considerations forbid belief that any voluminous granitic magma of post-Cambrian age has been at once cause and effect of gas-thermal alteration. On the other hand, conditions special to the earlier Precambrian may, as Sederholm suggests, have caused palingenesis in the older terranes, through the cooperation of heat and rising gases. In fact, there is some ground for the hypothesis that the earth's original crust was changed by load-contact metamorphism, palingenesis, and lit-par-lit injection *during* its original, slow formation. The geology of the Precambrian complexes seems to indicate for the original crust: (*a*) an average chemical composition like that of common granite; (*b*) a general gneissic structure, due to load metamorphism in the presence of abundant water and a steep thermal gradient; and (*c*) injection of countless granitic sills along the new planes of foliation, followed by more or less perfect load metamorphism of the sills themselves. A very thin surface shell of massive granitic or rhyolitic rock may have covered the thickening crust, but, below the depth of a few hundred meters, that crust would be a composite, as described. Perhaps Sederholm (1910, page 134) is right in assuming the possibility of actual representation of the original crust in the older Precambrian formations of Fennoscandia and Canada.

Certain pegmatites and perhaps certain veins of aplitic constitution may have been formed by the "selective solution" (Lane, 1913, page 704) of some components of a rock-mass which has undergone ordinary, though intense, metamorphism, dynamic or static.[4] Small bodies of such new magma, forced out of the parent formation and injected into other rocks, may cause a little contact metamorphism, but the magmatic bodies themselves are by-products of regional metamorphism and belong to the field of ultra-metamorphism.

According to the proposed definition, *exomorphic* changes, leading to new crystallizations near igneous contacts, must, as usual, be treated under metamorphism, while *endomorphic solution* of country rock is another example of ultra-metamorphism. Thus hybrid rocks properly fall in the igneous rather than the metamorphic class.

Summary

The problem of rock alteration below the earth's shell of weathering is immeasurably complex. The kinds of change are many. The necessity of their indefinitely detailed discussion is one of the most insistent duties of a field geologist. Fruitful discussion depends on names and definitions. The most used and most important name is "metamorphism," the

[4] Since this paper went to press, Holmquist's 1916 article on the Swedish Archean has come to America. Holmquist (page 141) there clearly states his belief in the ultrametamorphic origin of many Archean pegmatites and aplites.

history of which shows a very notable failure of unanimity in usage. A review of the older definitions has led to one which is verbally new, but covering essential ideas underlying Lyell's use of "metamorphic," and is nearly the same as Harker's (1889, page 15) formal definition.

The expediency of that definition appears clearer after meanings have been properly assigned to such expressions as "regional," "local," "dynamic," "static," and "contact" metamorphism. Some of their respective published definitions can not be fully adopted without logical conflict with the preferred definition of metamorphism itself; yet the necessary departures from authority are, in general, not any more serious than if one tries to use these older terms in any other systematic, logical subdivision of metamorphic processes as now understood.

The existing terminology does not suffice to cover all the categories. Thus static metamorphism includes what are here called "stato-hydral metamorphism" or hydro-metamorphism, and "stato-thermal metamorphism" or load metamorphism. Dynamic metamorphism is divided into "dynamo-hydral metamorphism" and "dynamo-thermal metamorphism." Metamorphism of rocks, produced by their burial under overthrust masses, is called "dynamo-static metamorphism." Metamorphism by a combination of igneous injection and deep burial is distinguished as "load-contact metamorphism."

The question whether pure volatilization is technically a metamorphic process seems to be best answered in the negative.

How the proposed scheme may meet the needs of working geologists is a question briefly discussed. Those occupied with the Precambrian complexes are apt to find the expressions "load metamorphism" and "load-contact metamorphism" at least as useful as "regional metamorphism" or "dynamic metamorphism." The classification is fairly elaborate, but it will seldom be incumbent on the field investigator to consider the subdivisions of dynamic metamorphism or to apply the term "dynamo-static metamorphism." The memory must, however, be somewhat burdened in the use of any workable classification.

The suggested scheme does not interfere with the employment of certain descriptive words, which for various reasons have no place in it. Those appearing in the table of classification have been systematized in meaning, with a double object: first, to express the just conclusions of the present day as to genetic conditions; secondly, to furnish a scheme elastic enough to admit further discoveries about the origin of the crystalline schists, without seriously dislocating the partial classification so far erected.

The relation of metamorphism to "ultra-metamorphism" has been considered. Load metamorphism, load-contact metamorphism, and possibly the ultra-metamorphic processes of anatexis and palingenesis—all supplemented by dynamic metamorphism—appear to have been the principal phases under which the Precambrian rocks became crystalline schists.

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