PETROLOGY

by

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Dean Emeritus, College of Engineering

THE ARIZONA BUREAU OF MINES

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CONDENSED AND SIMPLIFIED

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GURDON M. BUTLER, for forty years a teacher and administrator at the University of Arizona, has spent a long and productive life in the study of geology, mining engineering, and precious gems. Dr. Butler served as director of the Arizona Bureau of Mines for nearly a quarter of a century. Dean of Arizona's College of Mines and Engineering from 1915 to 1940, he then became dean of the College of Engineering, retiring from formal academic duties in 1954.

FOREWORD

This Bulletin 166 of the Arizona Bureau of Mines, was published originally in 1959 not long before the author's demise and, thus, so far as is known, it represents the last technical treatise written by the late Dr. G. M. Butler. For this reason, therefore, that it is Dean Butler's last scientific expression, as well as for the fact that the journal contains much useful information, it is considered fitting that the bulletin should be reprinted in 1967 so as to be available to the people of Arizona on a continuing basis.

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J. D. Forrester, Director
Arizona Bureau of Mines
October, 1967

PETROLOGY

THE STUDY of rocks without the aid of a compound microscope or chemical analyses constitutes the science of petrology. The usual aim of a student of this science is to classify or assign names to rocks in the field. All that is said herein applies to what may be seen in rocks by the use of no aid to the eyes but a hand lens.

Rock identification thus attempted is not as easy or conclusive as are most instances of mineral identification inasmuch as all rock species except most chemical precipitates, later discussed, are transitional by imperceptible degrees into other species, and many are so fine-grained that their constituents cannot be determined even with a hand lens. Alteration that results from exposure to atmospheric agents at or near the earth's surface may also make identification uncertain.

Nevertheless, it is highly desirable for geologists and mining engineers to be able to attach names to rocks they encounter, even if many of these names must be considered tentative — subject to correction after later detailed laboratory study. Fortunately, a skilled petrologist will find that a large majority of his tentative identifications will not have to be then changed.

CLASSES OF ROCKS

Three distinctly different classes of rocks, based on their mode of formation, are generally recognized, namely: igneous, stratified, and metamorphic.

1. IGNEOUS ROCKS

Igneous rocks appear to have been formed by the solidification of once molten earth material — magma. Undoubtedly, most of them were so formed, but, in some instances, great pressure and the heat that results from compaction and movement under pressure, may change rocks into pasty, but per-

haps not completely fluid or molten, masses in which molecular rearrangement occurs, and on cooling, the resulting rocks cannot be distinguished at sight from species once perfectly fluid.

Most igneous rocks, except porous varieties, are very hard when fresh. Three subdivisions or classes of such rocks may be recognized, namely: plutonic, minor intrusive, and extrusive.

Plutonic Rocks

Such igneous rocks have usually cooled far below the earth's surface where reduction of temperature is extremely slow, and the pressure is very great. They ordinarily occur in huge, rather irregularly shaped masses called batholiths (appear to have melted or fluxed their way into overlying rocks), laccoliths (masses with roughly plane bottoms that while molten appear to have lifted overlying rocks so that layers, if present, are elevated (folded up) into rough domes), bysmaliths (appear to have punched their way up through overlying rocks, and are bounded by faults), etc. Plutonic rocks may occasionally occur as relatively narrow dikes (tabular masses that cut across other earth materials) and, more rarely, as sills (tabular masses forced while molten between layers of earth materials). Some plutonic sills are hundreds of feet thick.

Plutonic rocks are dense (not porous), are composed principally of interlocked grains most of which are large enough to be seen with unaided eyes, which consist of two or more minerals that can usually be identified readily by a mineralogist, and, with rare exceptions, the large and more plentiful constitutents do not occur as well-formed crystals.

Minor Intrusive Rocks

Such igneous rocks are formed from magmas that have risen toward the earth's surface through cracks that have broken across earth materials (forming dikes) or the magmas have spread between layers of earth materials (forming sills or laccoliths).

It is usually true that, before the upward movement began, one or two minerals started to crystallize out of the magma, and since the process took place very slowly, there was ample time for molecular orientation, and the crystals grew to considerable size. They were suspended in the liquid and carried

along with it as it moved upward, but the still molten portion of the magma, coming in contact with relatively cool earth material above, would be forced to crystallize more rapidly. Such comparatively rapid crystallization produces small crystals, or glass if the cooling is sufficiently rapid. Consequently, the minor intrusive rocks show typically well-formed crystals (phenocrysts — evident crystals) of one or more minerals imbedded in a finer grained groundmass. An examination with a compound microscope of a thin section of such a rock will show that the groundmass contains some of the material present in the phenocrysts, but as a whole is usually less basic. Phenocrysts of one or more minerals imbedded in a notably finer grained groundmass of somewhat similar composition constitute what is known as porphyritic texture. If a magma cools sufficiently for phenocrysts to develop at very great depth, and then rises a considerable distance where somewhat more rapid cooling occurs, and it remains in the new position a relatively long time, another series of phenocrysts, somewhat smaller and, often a little less basic, may develop. If, then, the magma rises still further to where it is forced to cool with relative rapidity, there will be two sets of phenocrysts of two different average sizes imbedded in a finely crystalline or glassy groundmass.

Because formed under considerable pressure, minor intrusive rocks are as dense and hard as plutonic rocks, but feldspar (discussed later) phenocrysts may be decidedly altered and softened even when the groundmass remains hard.

Extrusive Rocks

Such igneous rocks have solidified on or relatively near the surface of the earth, and occur typically as surface flows, volcanic necks, and dikes. Otherwise, much that was said about minor intrusive rocks applies to extrusive rocks, but the latter are much more frequently composed of lava glass (obsidian), are frequently porous (and consequently light in weight and soft), and they are sometimes made up of thin, alternately dense and porous layers which somewhat differ in color (flow texture). Moreover, feldspar phenocrysts are entirely glassy in fresh specimens (although they sometimes look like crackled glass under a hand lens) so often appear to be much harder than a porous groundmass.

Identification of Igneous Rocks

In order to name a specimen of igneous rock, it is necessary to decide to which of the three classes mentioned it probably belongs and the more prominent minerals (at least) that it contains. The distinctions between the three classes recognized have been given. They include manner of occurrence and textural features that result from the varying conditions under which these classes were formed. A summary of these features is given below.

Plutonic	*Minor Intrusive*	*Extrusive*
1. Occur typically in batholiths, laccoliths, bysmaliths, dikes, etc.; more rarely in sills.	1. Occur typically in dikes, sills, and laccoliths.	1. Occur typically in surface flows, dikes, and volcanic necks; much more rarely in laccoliths.
2. Dense (very rarely contain large cavities lined with crystals). Comparatively heavy.	2. Dense and comparatively heavy.	2. May be porous, and the pores may be large or microscopic. When pores are numerous and small, may be light enough to float on water, as is true of the species of these rocks called pumice.
3. Coarse grained; practically all ingredients visible to the unaided eyes.	3. Fine grained except for phenocrysts.	3. Fine grained except for phenocrysts.
4. Never glassy.	4. Rare minor instrusive glass (pitchstone) contains a comparatively large percentage of water and has a greasy lustre.	4. Rocks made up of glass, with or without phenocrysts, are common. This glass has a vitreous to dull lustre.
5. Never show flow texture.	5. Flow texture rarely evident to the naked eye.	5. Flow texture commonly visible to the naked eye.

6. Phenocrysts very rare (but very large when present), so very rarely porphyritic. If phenocrysts are present, they are imbedded in granular material, most of which is coarse enough to be readily identifiable.	6. Phenocrysts common, so usually porphyritic. Nature of groundmass usually indeterminate.	6. Phenocrysts common, so ordinarily porphyritic. Nature of groundmass usually indeterminate.
7. Feldspars usually stony (translucent to opaque).	7. No entirely glassy (transparent) feldspars. The outer parts or all portions of feldspar phenocrysts are stony.	7. Some or all feldspars are entirely glassy, but may appear rather dull to the naked eye because full of closely spaced cracks. Their glassy nature is then evident under a hand lens.
	8. Feldspar phenocrysts are often softer and apparently more altered than the groundmass.	8. Groundmass is often apparently softer and more altered than feldspar phenocrysts.

Identification of Mineral Constituents

Having decided on the bases of occurrence and texture to which of the three classes a specimen of igneous rock belongs, it is next necessary to identify the more plentiful mineral constituents if it is plutonic, and the phenocrysts if it is minor intrusive or extrusive. Mere matching of an unidentified specimen with labeled rocks is a useless procedure since quite different rock species may look very much alike.

Scores of different minerals occur in igneous rocks, and a large number of them may be identified in plutonic rocks with a hand lens. Fortunately, few of them must be recognized in order to name a rock. If the presence or absence of a mineral does not affect the naming of a rock, it is called an *accessory* mineral. Since a few accessory minerals are commonly found in certain rocks, and may be scanty or missing in others, their recognition in a rock may make its identification easier or more certain, and it is important that a petrologist be very familiar

with them. They include hornblende, orthorhombic pyroxenes (enstatite and hypersthene), monoclinic pyroxene (diallage and augite), biotite and muscovite.

The minerals that characterize and give names to igneous rock species, called *essential* minerals, are likewise few in number if we exclude the ones that give varietal names to relatively rare species. The more important essential minerals are quartz, orthoclase (including microcline), plagioclase (all members of the plagioclase series of feldspars), nephelite, and olivine (or chrysolite).

It will be assumed that the reader is already trained in the sight identification of these minerals, or will acquire that skill before attempting to identify igneous rocks, but it seems desirable to review here the distinctions between the feldspars (orthoclase and plagioclase) and between hornblende and the pyroxenes as they occur in igneous rocks, as follows:

Orthoclase	*Plagioclase*
1. Has a tendency to occur in rather "chunky" crystals or grains.	1. Usually occurs in decidedly tabular crystals or grains, most sections of which are very long and slender — "lath-shaped."
2. The better (or rather long and narrow) basal cleavage (the result of a tendency to split easily and smoothly along one or more directions determined by the arrangement of the molecules) faces often show the effects of Carlsbad twinning (are broken longitudinally into two portions, one of which reflects light brilliantly while the other remains dull). By rotating the specimen about *60°* around an axis *perpendicular* to the longer dimension of the cleavage face, the bright half will become dull, and the dull half will reflect light brilliantly. See Fig. 1 and footnote.	2. The better (or very long, narrow) basal cleavage faces, unless badly altered, *always* show the effects of albitic twinning (are striated or striped longitudinally with bands of variable width, sometimes very narrow lines, that alternately reflect light brilliantly or fail to do so and are therefore bright and dark). By rotating the specimen less than 8° around an axis *parallel* to the longer dimension of the cleavage face, the bright bands or lines will become dull, and the dull ones will reflect light brilliantly. See Fig. 1 and footnote.

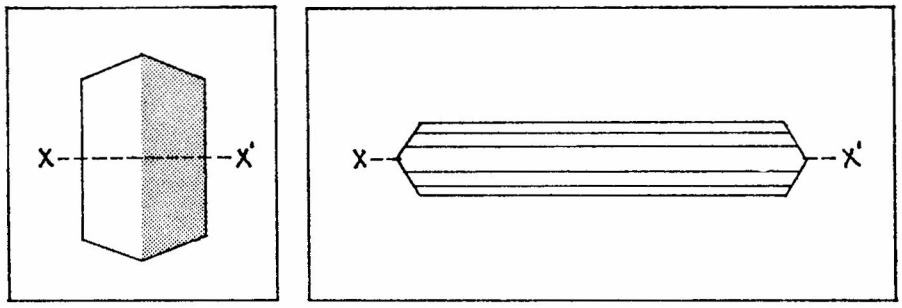
In order to see and distinguish between the effects of Carlsbad and albitic twinning, a hand-lens should be used, and the specimen should be held so that the light from a window across the room comes from the back over a shoulder and is reflected brightly from the cleaved surfaces. The effects of albitic twinning are often obscure on very fresh, glassy crystals.

3. Commonly associated with quartz.

4. Tends to weather to some shade of red, pink, flesh-colored or brown before softening.

3. Commonly not associated with quartz. If so associated, orthoclase is usually also present.

4. Tends to weather white or greenish before notable softening.



Orthoclase *Plagioclase*

FIGURE 1
Feldspar Cleavage Faces

x - x'. Axes around which crystals or grains must be rotated in order that bright parts may become dark and dark portions reflect light brilliantly.

Amphibole

1. Cleaves or splits easily and *smoothly* in two directions at angles of about *124°* or 56°. The cleavage faces reflect light brilliantly.

2. Transverse sections of crystals in igneous rocks are nearly always *hexagonal.* See Fig. 2.

Pyroxene

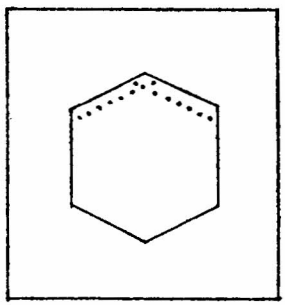
1. Cleaves or splits in two directions at an angle of about *90°*, but the cleavage faces *are not very smooth,* and reflections from them are not notably bright.

   The orthorhombic pyroxenes and diallage have an easy additional parting in one direction that bisects the cleavage angle. This parting shows up as smooth, flat surfaces on broken crystals or grains. This parting may be so well developed as to import almost a micaceous appearance to the mineral.

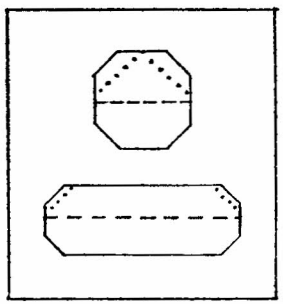
2. Transverse sections of crystals in igneous rocks are nearly always *eight-sided.* See Fig. 2.

3. May be associated with quartz.

3. Except for the soda-bearing variety acmite or aegerite, which occurs occasionally in very slender, transversely grooved crystals, pyroxene is almost never associated with quartz.



Hornblende



Pyroxene

FIGURE 2

Transverse Sections

Directions of cleavage are indicated by dotted lines, and directions of parting by dashed lines. (Note: The parting in a diallage crystal runs from front to back, not from right to left as it does in oriented crystals of enstatite or hypersthene.)

Essential Materials	*Commoner Accessory Minerals*	*Plutonic Rock Names*	*Minor Intrusive Rock Names*	*Extrusive Rock Names*	
Quartz and Feldspar (Mainly Orthoclase)	*Muscovite,* Biotite, Rare Minerals	Pegmatite[1]			Dark Mineral, Mainly Biotite
	Biotite, Muscovite, Hornblende	Granite	Granite-Porphyry[2]	Rhyolite	
Feldspar (Mainly Orthoclase); Little or No Quartz	*Hornblende,* Biotite, Muscovite	Syenite			
Feldspar (Mainly Orthoclase) and Nephelite		Nephelite Syenite		Phonolite[3]	Dark Mineral, Mainly Hornblende[7]
Feldspar (Both Orthoclase and Plagioclase)	*Hornblende,* Biotite, Pyroxene	Monzonite	Monzonite-Porphyry	Latite	
Feldspar (Mainly Plagioclase)		Diorite	Diorite-Porphyry[4]	Andesite	
				Feldspar Basalt or Balsalt Proper	Dark Mineral, Mainly Pyroxene
	Pyroxene,[5] Olivine, Magnetite, Biotite	Gabbro			
Olivine. Little or No Feldspar	*Pyroxene,* Magnetite, Chromite, Biotite	Peridotite	Peridotite-Porphyry[6]	Olivine Basalt	

IGNEOUS ROCKS

Having decided by noting how a rock occurs in the field, by observing carefully its textural characteristics, and by identifying the more plentiful or prominently developed (in the case of phenocrysts) of the mineral constitutents, a name may be assigned to it by determining to what position on Table I it should be assigned.

Notes that Apply to Table I.

(1) Pegmatite is characterized by extreme coarseness of grain. Most constituent crystals or grains are commonly more than half an inch across, and are sometimes huge. Crystals of spodumene that weighed several tons each have, for instance, been found in pegmatite. This rock occurs characteristically in dikes.

(2) Quartz, if visible, usually occurs as phenocrysts with hexagonal or nearly square sections, and a porphyry that contains phenocrysts of quartz, with or without phenocrysts of feldspar, may be called quartz porphyry.

Unfortunately, quartz, if present, is often confined to the groundmass, and cannot be identified even with a hand lens. The same statement applies to the nephelite in a minor intrusive rock. Consequently, the minor intrusive equivalents of syenite and nephelite syenite cannot be identified in the field, and, since the only recognizable phenocrysts are usually orthoclase, all must be called granite-porphyry. Because quartz, if present, is commonly confined to the groundmass, it is equally impossible to identify the extrusive equivalent of syenite (trachite) in the field, and it must be called rhyolite.

(3) Phonolite, the extrusive equivalent of nephelite syenite, can rarely be identified without the examination of a thin section under a compound microscope, and must usually be grouped with rhyolite in the field. As found at Cripple Creek, Colo., and some other places, however, it is an extremely dense rock with a somewhat greasy lustre (due to the nephelite in the groundmass). It occurs in various tints of dull green, gray, and brown, and shows few minerals easily identifiable with a hand lens. They include scanty phenocrysts of glassy orthoclase, and, sometimes, numerous tiny, slender, black crystals of segerite pyroxene.

(4) Since the field distinction between diorite and gabbro depends upon the presence and identification of the accessory

minerals hornblende and the orthorhombic pyroxenes or diallage, and since these minerals rarely appear as phenocrysts in the minor intrusive equivalents of diorite and gabbro, these minor intrusive equivalents cannot be recognized, and it is necessary to use one term, diorite-porphyry, to cover both of them in the field.

(5) The pyroxene in gabbro is enstatite, hypersthene, or diallage, while in basalt and andesite it is augite.

Not only does diorite differ from gabbro in the nature of the most plentiful accessory mineral (hornblende in diorite and pyroxene in gabbro), but in diorite there is usually more plagioclase and in gabbro less plagioclase than dark-colored minerals present.

(6) The term peridotite-porphyry cannot be used with any degree of certainty. A dense, hard, dark-colored rock that shows no feldspar phenocrysts may be so called if its manner of occurrence indicates that it was formed at considerable depth, but it may be easily confused with an olivine basalt.

(7) Not only is the pyroxene in extrusive rocks apt to be augite (or aegerite), as stated in Note 5, but there is a strong tendency for augite to occur in such rocks instead of hornblende. Augite andesites are fairly common, and can be distinguished in the field from feldspar basalt only by the relatively high proportion of feldspar in the andesite.

Identification of Minor Intrusive or Extrusive Rocks That Contain No Recognizable Mineral Constituents

The term aphanitic is applied to material the exact nature of which cannot be determined with a hand lens; it may be very fine-grained or glassy.

It is often possible to distinguish between minor intrusive and extrusive aphanitic rocks by the principles already given, but inability to identify any of the mineral constituents prevents the assignment of a name to the rock by the application of the data on Table I.

In order to apply field names to such rocks, it should be known that all igneous rocks may be divided into three classes on the basis of the percentage of silicic acid (SiO_2) present, namely, acid, intermediate, and basic rocks. The acid rocks contain more than 60 percent, the intermediate rocks about

60 percent, and the basic rocks less than 60 percent of this acid. Table I is arranged so that the acid rocks are at the top, the basic rocks at the bottom, and the intermediate rocks in the middle.

Acid and basic minor intrusive and extrusive rocks may often be distinguished by applying the following rules:

1. Acid rocks are usually light colored unless composed of compact glass.

2. Basic rocks are usually dark colored and are often black.

3. Acid glass usually has a vitreous lustre, but the rare acid minor intrusive glasses have a greasy lustre.

4. Basic glass usually has a dull lustre.

5. Flow texture is fairly common in acid and very rare in basic rocks.

6. Most rocks smell of kaolin when moistened, but that is not true of the most basic ones.

7. The cavities in porous acid rocks are usually small and very numerous, so such a rock is light in weight, and a knife blade may easily crush its way through the very thin walls between the pores, so the rock may seem very soft.

8. In the basic rocks the bubble-holes are usually comparatively large. The solid material between holes is often, but not always, thick and compact. Such a rock is relatively heavy unless the holes are very numerous.

The number of species that may be tentatively (until examined in thin sections with a compound microscope or chemically analyzed) identified by application of the facts just given is necessarily decidedly limited, but includes the ones given on Table II.

	Minor Intrusive	*Extrusive*
Acid	Acid Porphyry, Including Pitchstone	Rhyolite, Including Obsidian and Pumice
Intermediate	Intermediate Porphyry	Andesite
Basic	Basic Porphyry	Basalt

TABLE II

Brief Descriptions of Igneous Rocks Not Shown on Table I or Previously Defined

Plutonic

Alaskite: Granite that contains few or no necessary minerals. Since it is composed of almost nothing but quartz and feldspar, it is sometimes called binary granite.

Anorthosite: A variety of gabbro that is composed almost entirely of plagioclase, the name being derived from the French word for plagioclase, not from the mineral anorthite. May contain very small amounts of pyroxene and other accessory minerals.

Aplite: A fine-grained rock composed of feldspar and quartz, which occurs in dikes. Closely related to pegmatite.

Courtlandite: A very basic rock that contains hornblende and, often, a little plagioclase. Small crystals or grains of other minerals such as olivine and pyroxene may be imbedded in the hornblende.

Dunite: A peridotite made up chiefly of granular olivine, but grains of chromite are usually visible, and the rock may contain small proportions of other minerals, most commonly ilmenite and pyroxene.

Granodiorite: A rock that is intermediate between a granite and a diorite, so contains recognizable orthoclase, plagioclase, and quartz, plus accessory minerals.

Graphic Granite: A pegmatite composed of nothing but relatively large orthoclase crystals in which imperfectly crystallized quartz is imbedded. The quartz usually takes the form of portions of hollow six- and three-sided crystals. Transverse sections of these imperfect crystals appear on the fine basal cleavage of the orthoclase, and resemble the characters of some strange alphabet, hence the name.

Norite: A name used by many petrographers (users of thin sections and compound microscopes) for a gabbro-like rock that contains enstatite or hypersthene, while they limit the use of the term gabbro to a similar rock that contains diallage. This distinction cannot be made in the field, and it is best there to call all such rocks gabbros although some authorities call them gabbro-norites.

Pyroxenite: A very basic rock that is composed almost entirely of pyroxene (diallage, enstatite, or hypersthene), but very small amounts of olivine, hornblende, magnetite, spinel, plagioclase, etc. may be present.

Quartz Monzonite: Practically the same as granodiorite, q.v., but some petrographers apply the term granodiorite to rocks that resemble diorites more closely than they do granites and call rocks quartz monzonites if they are more closely allied to granites than to diorites. Such distinctions cannot be made in the field, and all such rocks should there be called granodiorite, the older name.

Troctolite (or Forellenstein): A rock composed principally of plagioclase and olivine. The latter usually occurs as dull-lustred, dark brown or green, round or irregular grains that give the rock a spotted appearance, hence the name which means "trout stone."

Minor Intrusive

Acid and Basic Porphyries: Very convenient, self-explanatory terms that must often be used in the field when mineral constituents cannot be identified. See page 12 for distinctions between acid and basic rocks.

Camptonite: A basic porphyry that shows phenocrysts of only hornblende or augite, and, rarely biotite and/or olivine.

Diabase: A fairly important and common basic rock composed of numerous rather closely crowded crystals of plagioclase embedded in a matrix of pyroxene, largely augite in most instances. The plagioclase may be included within large crystals or grains of the pyroxene, or small crystals or grains of the pyroxene may fill the interstices between the plagioclase crystals. In a given locality, the rock may often be identified by "matching" with material of known character, but usually a thin section must be examined with a compound microscope to make sure that there is little or no plagioclase in the pyroxene matrix, and the rock is truly a diabase.

Felsite: An acid rock of very fine grained or aphanitic, chert-like texture that usually has a stony lustre and is white or light gray in color. If dark colored, the sharp edges of thin chips are apt to be translucent and nearly colorless. That distinguishes this rock from more basic ones of similar texture.

Felsophyre: A felsite, q.v., that contains some phenocrysts of feldspar and sometimes quartz.

Perlite: An acid glass that contains several percent of combined water. The fact that it is a glass shows that it cooled rapidly, but the presence of the water indicates that it was under comparatively high pressure, so it is intermediate between a minor intrusive and an extrusive rock. It is white to some shade of gray in color and has an enamel-like lustre. It contains spheroids that usually vary from less than an eighth to nearly a quarter of an inch in diameter. They are made up of concentric shells (resulting from contraction while cooling) and faintly resemble pearls, hence the name.

Pitchstone: A glass with a resinous lustre, often reddish brown or dark green in color. It may contain up to 10 percent of combined water, and, like perlite, this combination of characteristics would seem to make it intermediate between minor extrusive and extrusive rocks.

Extrusive

Amygdaloid: A rock, most commonly a basalt, that contains holes, usually from an eighth to a half of an inch in longest dimensions, that are filled with secondary minerals (amygdules) such as calcite, chlorite, zeolites, etc.

Dacite: An andesite that contains quartz, but this mineral is so rarely visible with a hand lens that the term can rarely be used in the field.

Dolerite: A coarse-grained basalt that approaches a plutonic rock in texture.

Leucitophyre: A rock related to phonolite, but the nephelite is largely or entirely replaced by leucite which occurs in phenocrysts (rhombic trapezohedra) or spheroidal grains, usually of such size as to be readily identified. Glassy orthoclase phenocrysts are commonly rather plentiful.

Scoria: Basalts that contain many gas cavities that are large and very irregular in shape. The walls between cavities are thin and usually made of glass, and the proportion of openings may be so high that the rock will float on water. The color is usually black or dark red.

2. STRATIFIED ROCKS

Stratified rocks (sedimentary rocks) are composed of layers of material laid down on the bottoms of bodies of water or on land surfaces.

Based on the manner in which they have been deposited or of the material of which they are made up, these rocks may be subdivided into three classes, namely: clastics, chemical precipitates, and organic rocks. All, except accumulations dropped by melting glaciers, are characterized by the fact that they are more or less plainly stratified (occur in layers or beds that may cover extensive areas, which vary in thickness, material, color, and texture). These layers or strata are superimposed one on top of another to form series that may be hundreds and even thousands of feet thick. The beds are usually horizontal or nearly so unless they have been subjected after deposition to geological disturbances when they may be more or less complexly folded, and an individual stratum may thus resemble a dike.

Clastics or Clastic Rocks

Such rocks are composed of solid fragments of earth materials that have mechanically settled out of the water or air or been dropped by the glacial ice by which they were transported. Later such accumulations of material are usually more or less indurated or hardened by compaction under the great weight of thick overlying deposits and by being cemented with silica, calcium carbonate, iron oxide, etc.

These rocks may contain the impressions of more or less perfectly preserved remains of animals and plants (fossils), ripple-marked or sun-cracked surfaces on the planes that separate the layers, and other features described in any work on geology.

The names assigned to the different varieties of clastic rocks are based on the size, shape, and nature of the fragments of which they are composed, as follows:

The Larger Fragments are More Than Approximately an Eighth of an Inch in Average Dimension.

Breccia: The larger fragmental components, at least, are *angular* (not water-worn, and may be almost any kind of rock or mineral although often made up of hard, relatively unalterable varieties; limestone breccias are, however, not uncommon. The interstices between the larger fragments may be filled by a single cementing substance, such as quartz, or, in some instances, fine-grained igneous rock, but are more likely to contain smaller fragments and sand with more or less inconspicuous cementing material. As has already been indicated when limestone breccias were mentioned, varietal terms may be applied to breccias by prefixing the name of the material of which the larger fragments are composed, as, for example, jasper breccia, quartzite breccia, etc. Fault breccias are produced by the crushing of earth materials that often accompanies faulting under small pressure comparatively close to the earth's surface. The fragments in fault breccias have, of course, not been transported from the place where the crushing occurred.

As the size of the larger fragments decreases, breccias become transitional into sandstones.

Conglomerate: All that was said about breccia applies to conglomerate except that the larger fragmental components, at least, are *rounded* (water-worn), a cement of fine-grained igneous rock is excessively rare, and a conglomerate is never the direct result of faulting.

The Larger Fragments are Less Than Approximately an Eighth of an Inch in Average Dimension.

Sandstone: The grains may be rounded or angular, and are usually, but not always, predominantly quartz. They are more or less firmly cemented by such substances as are mentioned under breccia, or by clay. A very coarse-grained sandstone composed of angular fragments that are usually quartz is called *grit*. Sandstones often contain concretions or nodules (roughly spherical, ellipsoidal, or irregularly shaped masses) of iron oxides, or, less frequently, carbonate of lime.

Arkose: A coarse-grained sandstone that contains unaltered fragments of feldspar (usually orthoclase) as well as quartz and, often, muscovite mica. It closely resembles a fine-

grained granite, but may be distinguished from that rock with a hand lens by noting the angular shapes of the grains.

Shale: Composed of particles too fine to be seen even with a hand lens, but chemical or other laboratory methods prove it to be made up principally of kaolinite or other hydrous aluminum silicates ("clay" minerals). Shales are soft and brittle, have a strong "clayey" odor when moistened, and split readily into thin, flat fragments. Because the different thin layers of which they are composed vary in hardness and consequent susceptibility to wind and water erosion, outcrops of shales look somewhat like piles of cardboard. Shales may contain concretions of iron sulphide, iron carbonate, or carbonate of lime. Many examples are plastic when moistened especially after having been crushed to a powder.

Clay: Like shale except that it is not made up of layers; many examples are plastic when moistened.

Loess: Unstratified accumulations of wind-blown dust, which are sometimes several hundred feet thick. It is composed largely of extremely small grains of quartz and clay minerals, loosely cemented by calcium carbonate so it effervesces vigorously, but briefly, in acid. It feels like chalk, and, although soft, vertical bluffs of it are surprisingly resistant to erosion.

Limestone (in part): Composed principally of calcium carbonate so effervesces vigorously and dissolves entirely or almost so in acid. It has a dull lustre and looks much like a clay, but lacks a "clayey" odor when moistened. Eroded outcrops have a characteristic "blocky" appearance due to the deepening and widening of exposed bedding planes and joints roughly perpendicular thereto. Very dense varieties have a smoothly curving (conchoidal) fracture. Limestones may contain concretions of chert or jasper. Even when composed of excessively fine calcareous material, that substance is probably in most instances finely comminuted corals, shells, etc.

Marl: Contains a relatively high proportion of clayey material so smells like clay when moistened, yet effervesces vigorously in acid.

Tuff (often erroneously called tufa): Composed of so-called "volcanic ash" which is really lava that has been violently blown into the air while molten, finely subdivided, and rapidly

cooled as small shreds and grains of glass, often porous, which may be blown considerable distances and cover wide areas. When consolidated by pressure or cementation, the resulting tuff is a rather porous, harsh-feeling, fine grained, usually light colored rock that ordinarily contains angular fragments of rock that have been blown with great force into the air along with the "ash".

Note: Examples of any two varieties of finer grained clastic rocks that are transitional into each other may be found, and they are given self-explanatory names such as sandy clay, shaley sandstone, limey shale, etc.

Chemical Precipitates

These rocks, as the name indicates, are composed of minerals that have been chemically deposited from aqueous solutions usually by evaporation of such solutions, but sometimes by relief of pressure and, very rarely, by cooling. In a very few instances, chemical replacement of previously existing material may occur. Deposits of relatively pure minerals may be formed in this way, but, where deposited by evaporation in an enclosed basin, wind and rain may carry dust and other products of rock decomposition into the evaporating body of water, and these substances may mingle with the precipitates and make them impure, or they may form layers interbedded with the precipitates. Such association of clastic and chemical precipitate rocks is common.

Since it is assumed that the reader is already able to identify the common minerals that occur as chemical precipitates, all that will be set forth concerning them are their names and a few notes concerning the varieties that occur as such rocks, as follows:

Oxides of Iron
- Limonite — bog iron ore.
- Hematite — oolitic, earthy, and compact, all with earthy lustres, and micaceous which has a metallic lustre.

Oxides of Silicon
- Quartz — jasper, chert, and flint.
- Opal — geyserite.

Chloride of Sodium
- Halite or rock salt.

Carbonate of Lime
- Calcite — oolitic limestone, travertine, onyx and calcareous tufa.

Carbonate of Lime and Magnesium

Dolomite. Probably all rock dolomite has been formed either (1) by direct precipitation from sea water, (2) by the replacement of some of the CaO in calcareous sediments with MgO in solution in sea water before overlying beds are deposited, or (3) by the later alteration of limestone to dolomite.

Magnesian Limestone. Contains between about 5 per cent and 15 per cent MgO, so is transitional between dolomite and calcareous limestone.

Carbonate of Iron

Siderite — clay ironstone and sphaerosiderite.

Hydrous Sulphate of Lime

Gypsum — platy (selenite), scaly, and granular (alabaster); may be easily scratched with a finger nail.

Anhydrous Sulphate of Lime

Anhydrite — dense and granular like marble, but will not effervesce in acid.

Hydrous Borate of Lime

Colemanite — Cavities contain highly modified crystals, perfect cleavage in one direction, white, hardness 3.5-4.5. Usually cleavable, granular, or compact masses that look like chalk.

Hydrous Borate of Sodium

Kernite (rasorite) — Resembles cleavable gypsum but is slightly harder (2.5-3) and is soluble in water.

Sulphate of Barium

Barite — granular or platy; very heavy.

Anhydrous Sulphate of Sodium

Thenardite.

Hydrous Sulphate of Sodium

Mirabilite.

Phosphate of Lime with Chlorine and Fluorine

Apatite — phosphate rock or phosphorite; resembles limestone, but will not effervesce in acid and is slightly heavier.

Organic Rocks

Organic rocks are composed of the skeletons, shells, or other parts of animals or plants, or fragments thereof. The composition of the material may be materially changed after deposition, by replacement. Organisms often play a part in the formation of some of the rocks classed here as chemical precipitates such as, for instance, chert, geyserite, and phos-

phate rock, so such substances bridge the boundary between chemical precipitates and organic rocks.

The most important organic rocks are:

Peat: Dark brown to black, more or less compacted fragments of vegetation that accumulate in swampy areas in relatively cool climates.

Coal: Lignite, sub-bituminous, and bituminous varieties.

Diatomaceous Earth and Diatomite: Both these rocks are made up of the exceedingly minute skeletons or shells of tiny aquatic organisms (plants) called diatoms. These rocks are soft, light colored, very light in weight, and chalk-like in appearance and fuel, but are composed of opal silica, so will not effervesce in acid and are even lighter than chalk.

Both earthy and decidedly coherent varieties are called diatomaceous earth, but the term diatomite is sometimes used for the more cohesive material.

Limestone (in part): It is often difficult to decide whether a limestone should be classed as a clastic rock or an organic rock, but there are some varieties that are manifestly the work of organisms, as is the case when the rock is evidently a buried coral reef.

Chalk: Made up chiefly of the very fine plates of calcareous algae and tiny shells of foraminifera, with some silicious sponge specules and minute shells of other animals. Chalk is very soft and porous, fine grained, somewhat harsh to the feel, does not have a "clayey" odor when moistened, and effervesces very vigorously in acid.

Coquina: A very porous rock made up of relatively large fragments of shells more or less firmly cemented together.

Guano: Phosphatic and nitrogenous material composed mainly of the excrement of birds or bats. It is usually white or light gray and rather porous. In the field it may be identified by the fact that it covers the floor of a cave or occurs as a blanket that covers other rocks, sometimes to a depth of several feet, not far from large bodies of water.

Phosphate Rock: A rock rich in calcium phosphate that is usually derived more or less directly from organic remains. It occurs as strata interbedded with such rocks as sandstone and limestone, as lenses in such rocks, and as concretions. It

is usually very fine-grained and may be dense or porous. It may lie in the position originally deposited or it may have been dissolved, transported, and deposited elsewhere, perhaps as a replacement of limestone, in which case, it should doubtless be classed as a chemical precipitate rock, as should material deposited by the reaction of calcium carbonate and phosphoric acid in solution in sea water. A blowpipe test for phosphorous is often necessary to identify this rock with certainty.

3. METAMORPHIC ROCKS

Masses of earth materials that have been changed in one or more of the qualities of hardness, texture, structure, and mineralogical or chemical composition from the preexisting rock from which they were formed are called metamorphic rocks. Excluded from this term are, however, the usually softened and otherwise changed rocks found at or near the earth's surface that owe their alteration to chemical reaction with atmospheric constituents.

Two great sub-classes of metamorphic rocks are recognized, namely regional or dynamo-metamorphic rocks and contact or thermo-metamorphic rocks.

Regional Metamorphic Rocks

Regional metamorphic rocks are formed when large masses of deeply buried earth materials are subjected to enormous pressures, and, often, attacked by water or water vapor and various gases. The mere weight of later deposited material, although it may be thousands of feet thick, is not usually sufficient to do more than make some sediments very compact. Induration or hardening by cementation of some loosely coherent, deeply buried material may also occur, and limestone may recrystallize as marble.

In order to produce the profound changes that most regional metamorphic rocks have undergone, the material must have been subjected to the terrific horizontal pressures and shearing stresses, with the relatively high temperatures resulting from compaction and friction, that accompany crustal folding in mountain-making movements. Pebbles, crystals, fossils, and concretions may then be flattened and even drawn out into thin lenses or sheets. Hot water and gases may

permeate the metamorphosing material, and, under pressure, are powerful chemical reagents. They may materially change the mineral constitutents or may introduce new minerals.

Any rock may be regionally metamorphosed, and so great are the changes frequently produced that it is often impossible to decide in the field what the original, unmetamorphosed rock was. Regional metamorphic rocks are characterized by the fact that they are dense and (with the exception of quartzite, marble, some soapstone, serpentine, and argillite) have a schistose texture which means that they are composed of layers that differ more or less in mineralogical composition. Individual layers vary from a fraction of an inch to many feet in thickness, and each may be traceable for a long distance or may be decidedly lenticular (lens-shaped). The layers are frequently folded and even intricately contorted, and one layer is often easily separated from another, especially if a thin layer of mica lies between them. A small specimen broken from the inside of a relatively thick layer may show little or no evidence of banding or foliation, but some of the constituents, such as hornblende or mica, may show a rough parallelism. Even a small piece is sometimes complexly "crinkled," however, especially if composed largely of mica. The layered condition is usually very evident on field exposures except in some instances in which the rock that was metamorphosed was composed almost entirely of a single mineral such as a limestone or a nearly pure quartz sandstone.

The more important regional metamorphic rocks are:

Gneiss: Although some petrologists now use this term very loosely for any laminated rock that approximates the mineralogical composition of any plutonic igneous rock, it seems desirable to give it nearly the meaning originally assigned to it, namely a regional metamorphic rock composed essentially of feldspar and quartz. The feldspar may be orthoclase or plagioclase, or both, but is most commonly largely orthoclase, and petrographers would then call it a granite-gneiss. Muscovite is probably the commonest accessory mineral although biotite is very common, also. None of the minerals mentioned is apt to occur in well-formed crystals, but garnet in good crystals, sometimes large, is a fairly common accessory. Other accessories include hornblende, graphite, epidote, corundum, iolite, sillimanite, and tourmaline.

Mica Schist: Muscovite or biotite schists are the commoner varieties, but huge bodies of dark green chlorite schist occur in some places. Muscovite and biotite schists usually contain a large proportion of granular quartz, but the mica and the quartz are in thin alternating layers, and the rocks split along the mica layers so, when the broad broken surfaces are observed, the rock appears to be made up almost entirely of mica. It is only when the edges of the layers are inspected that the preponderance of quartz becomes evident.

Garnet is the commonest accessory mineral in mica schist, but a large number of other minerals, including such species as tourmaline, staurolite, and cyanite, are plentiful in some places, and they often occur in relatively large, well-formed crystals. Feldspar is not uncommon, but is not prominent.

Amphibole Schist and Amphibolite: Various amphiboles, including hornblende, actinolite, and tremolite, occur plentifully in some schistose rocks, associated with more or less feldspar (often plagioclase), biotite, muscovite, quartz and other minerals common in regional metamorphic rocks. If the rock is not clearly banded in a hand specimen, it had better be called an *amphibolite.*

Talc Schist and Soapstone: This greasy-feeling rock is composed principally of flakes and grains of talc, usually light colored, with a good platy cleavage. Magnetite, amphibole, micas, and other minerals common in regional metamorphic rocks are also present in variable amounts, but may not be readily seen with unaided eyes. If non-foliated, it is called soapstone.

Serpentine: Usually massive (lacks a schistose texture).

Slate, Phyllite, and Argillite: A slate is a hard, very fine-grained rock, originally a clay or shale, in which the clay particles have been flattened by pressure, so that a fine parting ("slaty cleavage") has been developed perpendicular to the direction of pressure. The direction of this parting is unrelated to the original bedding or sedimentation planes. If considerable mica, often fine-grained muscovite (sericite), is present, especially along the partings, it is called phyllite, and, if otherwise like slate, but lacking the slaty parting or cleavage, it is conveniently called argillite. Some authorities regard the terms slate and argillite as synonymous, however. Slates and argillites

are usually dark-colored – often black, while phyllite is often light colored and may have a silvery lustre.

Quartzite: A dense, hard rock, usually composed very largely of quartz, which was formed by the deposition of quartz in a sandstone so as completely to fill the spaces between the grains, or the compression and deformation of the sandstone grains until no openings between these grains remain. Quartzites still retain a somewhat granular appearance, but break through the original grains just as readily as around them. Sedimentation or bedding planes are rarely evident. The names of various impurities are prefixed to that of the rock to create varietal names, as "mica quartzite."

Marble: Fine to coarse grained *granular* limestone. It most commonly resembles lump sugar, but may be much coarser or somewhat finer (the grains barely visible with a hand lens). It is white when pure, but may be tinted rather uniformly by some impurity, or may be mottled or banded.

Anthracite Coal and Graphite: All *large* deposits of anthracite coal have been formed by the regional metamorphism of bituminous coal. If still more volatile material is expelled, the metamorphosed substance burns with difficulty, if at all, in the air, and all graduations between true anthracite and almost pure graphite, doubtless produced in this way, have been found.

Contact Metamorphic Rocks

Contact metamorphic rocks may be formed when molten material (magma) breaks through or invades solid, relatively cool rock. The changes are produced by the heat of the cooling magma and the gases or vapors and liquids (which may be conveniently termed "mineralizers") expelled therefrom. These changes are naturally most profound close to the contact of the once molten igneous rocks and the preexisting rock, but in some localities the effect of the passage of chemically active mineralizers through the preexisting rocks is evident for hundreds of feet (and even several thousand feet in some places) from a contact such as has been mentioned.

The degree to which rocks are changed by contact metamorphism varies greatly and some rocks are affected little if

at all. Acid igneous rock, breccia, conglomerate, arkose, hematite, jasper, mica and amphibole schist, serpentine, and quartzite are among the rocks that are rarely changed by this type of metamorphism.

By a process of elimination, then, it should be evident that the effects of contact metamorphism are most apt to be evident on such sedimentary rocks as shale and limestone. Even these rocks are, however, changed in ways and to degrees that vary greatly depending upon their exact compositions and the compositions and sizes of the masses of magma that invade or cut across them.

In general it is true that acid magmas contain, and expel when cooling, much larger proportions of gases (which become liquids as they cool) than do basic magmas, but that the latter conduct heat more readily than the former, cool more rapidly, and therefore heat the preexisting rocks to higher temperatures than do the former. In other words, the contact metamorphism produced by acid magmas results principally from the passage of mineralizers through the preexisting rocks, and may be evident to long distances from the contact, while basic magmas may merely heat or bake the surrounding rocks, and this effect may not be noticeable for only a short distance from the contact.

It should be evident that the larger the mass of magma, the greater the amount of mineralizers or heat that may be expelled from it while cooling. Since, then, plutonic masses average larger than any others, the most profound and extensive contact metamorphism may be expected where plutonic intrusions came in contact with clay rocks and limestones.

Surrounding large masses of acid plutonic rocks that have intruded into other rocks that are susceptible to contact metamorphism are usually found several, sometimes a half-dozen or even more, quite different zones of metamorphosed material, and each zone may be suddenly or gradually transitional into adjacent zones. The metamorphosed zone nearest the intrusion is usually the narrowest and shows the greatest amount of change. As one goes further from the contact, then, the successive zones get wider, the metamorphism becomes less evident, and eventually all evidence of it disappears.

Not only may the preexisting or intruded rock be altered by contact metamorphism, but relatively rapid cooling near the contact may make the intruding rock finer grained near

the contact than it is some distance therefrom. In some instances, the intruding and the intruded rocks may melt at the contact and become so intimately mingled that there is a complete, but rather sudden, transition from one to the other.

Because of the considerable number of factors involved, the effects of contact metamorphism are almost never exactly the same at different localities. Consequently, there are few specific names that can be applied to rocks thus formed, and the correct classification of such rocks with a hand lens in the laboratory is often difficult or impossible. It is only when the field conditions can be studied that it is usually possible to identify many such rocks with certainty, and even then there may be no specific names that are commonly applied to such undoubtedly metamorphosed material as may be found.

Most of the terms that can be applied in the field to contact metamorphic rocks are given in the material that follows.

Contact Metamorphism of Clay Rocks

When shales or slates are invaded by large masses of acid magma, such as granite, a series of zones roughly paralleling the contact are often produced, as has already been mentioned. They may number a half-dozen or more, but are not usually that numerous.

Nearest to the contact is frequently developed a dark-colored, dense, rather fine granular rock called a hornfels. Biotite in small scales is usually the most plentiful mineral present, but andalusite (of the variety called chiastolite), cyanite, staurolite, garnet, tourmaline, and other minerals may occur as crystals of fair size. *Andalusite hornfels* is probably the variety most frequently encountered.

As one gets further from the contact, other, wider zones may be found, and among them one that contains considerable tourmaline is not unusual. Still further out thick zones of *spotted mica schist* and, further out, *spotted shale or slate* are apt to occur. The spots, which are usually roughly lath-shaped, are merely aggregates of extremely fine grains of the dark-colored constituents of the rock. They gradually become less numerous, and sometimes smaller, the further they are from the contact, and finally disappear entirely when the completely unmetamorphosed shale or slate is reached.

A basic magma may fuse a shale or slate, or may bake it so that it closely resembles unglazed porcelain or chert. If white or light tinted, it is called *porcelanite*. If darker colored, it is termed *porcelain jasper*. Occasionally soft shales or clays are merely hardened and become *argillite* which may be indistinguishable from the regional metamorphic rock of the same name. Such changes may occur to a distance of only a few inches from the contact, or may extend several scores of feet therefrom.

Contact Metamorphism of Limestone

Except that basic magmas are more apt to fuse the limestone at the contact and other effects produced do not usually extend as far from the contact as when acid magmas are involved, the rocks produced by the intrusion of acid and basic magmas into limestone do not differ materially.

If the limestone is quite pure, white marble may be produced, and it is like the regional *metamorphic* rock of that name. If the limestone was slightly impure, the marble may be mottled or banded.

When calcareous or dolomitic limestone that contains more or less clayey material and other impurities is metamorphosed, a *lime-silicate hornfels* may develop at or near the contact. It is a hard, dense, very fine grained, chert-like aggregate of various anhydrous silicates of lime, alumina, magnesia, and iron, such as garnet (most commonly grossularite), vesuvianite, wernerite, diopsite, tremolite, wollastonite, and epidote. None of these minerals is visible, however, even when a hand lens is used. In nearly all instances, because some residual calcite remains in a lime-silicate hornfels, it will effervesce to some extent in acid.

Instead of the fine-grained material just described, the contact metamorphism of an impure limestone may produce a rock that is made up of one or more of the lime, magnesia, alumina, and iron silicates mentioned, in coarsely crystalline form. Garnet and vesuvianite are most apt to occur in this way, either alone, together, or mixed with other minerals, and thus *garnet rock* or *garnet-vesuvianite rock* is formed, for example. These silicate minerals may or may not be imbedded in a matrix of marble.

Sometimes the metamorphism of a magnesian limestone may produce *ophicalcite* — marble in which grains of serpentine are imbedded.

Some of the other results of contact metamorphism are given below.

Preexisting Material	*Substance Produced*
Pure quartz sandstone	Quartzite (does not differ from the regional metamorphic rock of the same name).
Bituminous coal	"Mineral coke" or anthracite coal (in limited quantities near a contact).
Limonite	Magnetite or specularite.

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SERVICES AVAILABLE FROM ARIZONA BUREAU OF MINES THE UNIVERSITY OF ARIZONA, TUCSON, ARIZONA

The ARIZONA BUREAU OF MINES was created and placed under the authority of the Arizona Board of Regents in 1915 by an act of the State legislature. The Bureau is directly charged with developing, maintaining, and disseminating to the people of Arizona information relating to geology, mining, metallurgy, and earth sciences generally. The Bureau's primary functions, therefore, are scientific investigation and public service activities comparable to those conducted by geological survey agencies and mineral experiment stations in other states. These primary functions are achieved through the following continuing programs:

1. Prepare and publish bulletins and circulars containing authoritative information on a wide range of topics of interest to prospectors, miners, and others concerned with the development of Arizona's mineral resources and industries. The bulletins are distributed free of charge to residents and at cost to nonresidents of Arizona upon request.

2. Classify mineral and rock specimens. Besides identifying rocks and giving the composition of minerals, the Bureau makes qualititative tests for important elements and answers inquiries concerning the probable market for and the economic value of material similar to samples submitted. This service is furnished free of charge providing the specimens originate within the State of Arizona; a charge of $1 per specimen is made for samples submitted from outside the State. Spectrographic analyses and detailed microscopic determinations are furnished at established rates, a schedule of which will be submitted on request.

3. Conduct laboratory and pilot-plant metallurgical testing of mineral substances in cooperation with industries and individual mine operators in the State. Such tests are conducted on the basis of nominal charges to compensate for wear and depreciation of equipment needed in the experimentation.

4. Make geologic investigations and compile geologic maps and reports. Geologic maps of each county, on a scale of 1:375,000, have been issued and geologic reports on numerous mining districts have been made available as bulletins. In addition to maps and reports on counties and mining districts, comprehensive studies of basic problems in the geology of Arizona are being carried out in order that the maximum benefits may be derived by the people of the State by having a more complete knowledge of its geologic setting.

5. Maintain a working file of statistical records of mineral production in Arizona.

6. Develop well-log storage facilities and a library of data pertaining to oil and water wells drilled in Arizona.

7. Conduct state-wide commodity studies as to modes of occurrence and potential industrial value of various mineral materials.

8. Collect and file items relating to Arizona mines and minerals that appear in Arizona newspapers and in many technical periodicals.

The basic philosophy which obtains in the operation of the Arizona Bureau of Mines is that of providing for the people of Arizona educational services in the earth sciences which cannot be readily secured elsewhere, and furnishing advice and service about mineral occurrences which cannot be obtained conveniently from commercial sources.

An inquiry addressed to: Director, Arizona Bureau of Mines, University of Arizona, Tucson, AZ 85721, will bring a prompt response if further information is desired about the services which are available.

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