United States Department of the Interior
BUREAU OF RECLAMATION

PETROGRAPHY AND ENGINEERING PROPERTIES OF IGNEOUS ROCKS

by Richard C. Mielenz

Denver, Colorado
October 1948
(Revised September 1961)
95 cents

United States Department of the Interior

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Bureau of Reclamation

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Engineering Monograph

No. 1

PETROGRAPHY AND ENGINEERING PROPERTIRES OF IGNEOUS ROCKS

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ENGINEERING MONOGRAPHS are published in limited editions for the technical staff of the Bureau of Reclamation and interested technical circles in Government and private agencies. Their purpose is to record developments, innovations, and progress in the engineering and scientific techniques and practices that are employed in the planning, design, construction, and operation of Reclamation structures and equipment. Copies may be obtained from the Bureau of Reclamation, Denver Federal Center, Denver, Colorado, and Washington, D. C.

Excavation and concreting of altered zones in rhyolite dike in the spillway foundation, Davis Damsite, Arizona-Nevada.

Frontispiece

CONTENTS

INTRODUCTION

Rocks are important to engineers. Most modern hydraulic structures rest upon rock foundations, some rest laterally against rock abutments, and essentially all are composed, at least in part, of rock material. Consequently, the design of engineering works and methods of construction depend to a great extent on the properties of rocks--their strength, elasticity, permeability, durability, density, volume change, and solubility. It follows, then, that adequate engineering investigations of rock should be made to reveal these properties and their effect on construction.

The properties of rocks depend upon their mineral composition, texture, and structure. Mineral composition controls such properties as hardness, density, and solubility. Texture and structure comprise the fabric in which the individual components of the rock are arranged; they control the properties of the rock as a whole, such as strength, permeability, and durability.

When we think specifically in terms of the properties of the rocks at a site or of the rock materials to be used in the construction, rules for rock classification and nomenclature might seem to be irrelevant. On the contrary, petrographic classification of rocks is based upon composition, texture, and structure--the same characteristics upon which the rock properties depend. Therefore, petrographic examination and identification will indicate the properties to be expected in the rock.

Petrography is being applied increasingly to engineering problems. All concrete aggregates and riprap materials to be used in construction of Bureau projects are examined and evaluated petrographically. Samples of rock as well as earth materials are analyzed and tested petrographically in connection with planning, design, construction, and maintenance problems. For example, during the past 10 years 282 samples of riprap and 1,078 samples of concrete aggregate were examined and evaluated for engineering use.

Because of the increasing application of petrography for engineers a greater number and variety of rock names are appearing in construction and feasibility reports on engineering problems. Moreover, rock names are strange to most engineers, and they are far from self-explanatory. As a result, many questions have been directed to the Petrographic Laboratory regarding the basis and method of petrographic classification. This monograph has been prepared to answer these questions, and to bring to the engineer a summary view of the range of rock composition, texture, and structure, and the relationship of these to rock properties.

GENERAL BASIS OF CLASSIFICATION OF ROCKS

Rocks, as a whole, are divided into three classes: igneous, metamorphic, and sedimentary. Igneous rocks originated through solidification of molten material either at or below the surface of the earth. Igneous rocks comprise such types as the common granites which formed from tremendously large masses of molten material intruded from depths of the earth into the crust, then cooled and crystallized far below the surface. Igneous also are the lavas poured from volcanos, and those which did not quite reach the earth's surface but froze at small depths as small intrusive masses, such as dikes and sills.

Metamorphic rocks were formed through recrystallization, in an essentially solid state, of igneous or sedimentary rocks subjected to high temperature, high pressure, or high shearing stresses within the crust of the earth. They include slates, schists, phyllite, gneisses, marbles, and many other less common rock types.

Sedimentary rocks originated through deposition and consolidation of materials weathered and eroded from the earth's surface. The decomposed and broken material after being transported over the earth's surface by water, wind, gravity, or ice was deposited in valleys, lakes, or along the margins of the oceans. Subsequently, they may have been tightly or loosely cemented by mineral substances precipitated from groundwater, or they may have been more or less indurated by compaction due to the weight of overlying materials or as a result of earth stresses. The process of consolidation may have proceeded rapidly or slowly depending upon many factors, such as the composition of the interstitial groundwater, the clayey, sandy, or gravelly character of the sediments, and the weight of overburden.

Because of the great variety of textures, structures, and compositions occuring in rocks of each of the three classes, subclasses or families of rocks can be distinguished. Thus, sedimentary rocks composed of grains 2 mm to 0.05 mm in diameter cemented by substances in the intergranular spaces are called sandstones, whereas sedimentary rocks composed of mineral and rock grains less than 0.05 mm in diameter are called siltstones. Sedimentary rocks composed of clay are called claystones, if they are massive: shale, if they are characterized by a flaky or platy structure. Rocks composed by calcium carbonate are called limestones, if fine-grained: marbles, if medium or coarse-grained. With incipient metamorphism, a sandstone is designated a metasandstone, but with recrystallization and development of new minerals, the rock may be changed to a mica schist, which is a metamorphic rock possessing a strong planar structure. A metamorphic rock composed of alternating schistose zones and massive granular zones is called a gneiss.

Although the threefold classification of rocks is based upon their origin, so perfectly is the mode of origin related to the composition, texture, and structure that a petrographer can almost always determine the origin of the rock and hence classify the rock from the characteristics determinable in the hand specimen. Consequently, rocks could be fitted into a threefold classification merely on the basis of composition, texture, and structure, without primary consideration of origin. In fact, the petrographer ordinarily must determine whether a rock is sedimentary, metamorphic, or igneous by examination of individual fragments, for the circumstances under which the rock formed usually no longer exist, but the large-scale geologic relations of the rock formation commonly are now known.

Certain textures, structures, and compositions are typical of each petrographic classification because they are controlled by the physical and chemical conditions of formation. Thus, sedimentary rocks are formed by grain-by-grain accumulation of small or large, angular or rounded particles, subsequently compacted or cemented together, creating a fabric in which the grains are not interlocked or keyed together at their margins, but which are knit by secondary cementing substances or by adhesive or cohesive forces. Stratification, the most typical structure of sedimentary rocks, represents discontinuities in the conditions of formation, such as change in composition of grain size of the sediments deposited, or in the type of mineral substances deposited interstitially by groundwater. Metamorphic rocks develop from originally igneous or sedimentary rocks subjected to temperatures, pressures, and shearing stresses so high that the components are crushed and recrystallized, commonly with development of new minerals. The recrystallization proceeds without fusion, by progressive dissolution of the old and precipitation of the new minerals, the mass of the rock being essentially solid throughout the process. Metamorphic rocks such as schists and slates which formed under conditions of high shearing stress are characterized by planar internal structures, being composed in part of platy minerals like mica, or prismatic minerals like the amphiboles which develop in response to the stress conditions. Metamorphic rocks such as granulites and some marbles formed at elevated temperature and pressure but with little shearing stress are massive in structure and are characterized by a tightly knit interlocking equigranular texture.

Igneous rocks, more so than sedimentary or metamorphic rocks, lend themselves to classification on a fundamental basis, since they are formed in a relatively narrow range of physical-chemical environments, and because they represent the solidified phase of siliceous melts typified by chemical compositions which vary within comparatively narrow limits. Igneous rocks differ from one another because of variations in environmental conditions of formation and variations in chemical composition. Environmental conditions include (1) the temperature of the melt (magma), (2) the rate of cooling, (3) the pressure, and (4) the viscosity of the melt. The chemical composition of a magma may control many of its physical-chemical properties, such as melting point and viscosity. The most important aspects of chemical composition are silica content (which ranges from 45 percent to 77 percent in common igneous rocks) and the content of gases and vapors occuring within the melt. Viscosity increases with silica content; whereas viscosity is decreased, and ease of crystallization, at any given temperature below the melting point, is increased by increasing content of volatile constituents.

Igneous rocks are classified through the simultaneous consideration of two factors: (1) the texture and structure of the rock, and (2) the chemical and mineralogic composition. Textures and structures of igneous rocks are controlled by the physical-chemical conditions existing within the magma during solidification. In turn, these conditions are most strongly influenced by the depth at which solidification took place (which controlled the rate of cooling and the hydrostatic pressure) and the physical characteristics of the melt itself (mainly temperature and viscosity). The mineralogic composition of igneous rocks is largely controlled by chemical composition of the magma; but in part the minerals which develop are determined by the environmental conditions of solidification.

For example, volcanic rocks which are characterized by rapid cooling commonly are crystallized only partially, since some of the melt was congealed as glass before crystallization was completed. The minerals which exist in equilibrium with half-crystallized melt may be different from those which would exist in equilibrium with the last residues of the melt. Thus, a basaltic magma, the mineral olivine, forms early in the progressive crystallization. But, if the melt is comparatively rich in silica, the olivine may subsequently be converted through reactions with the melt to pyroxene. The final completely crystallized rock could be designated as gabbro and would be completely free from olivine; yet the partially glassy basalt which could be formed by quick chilling of the partially crystallized magma would contain crystals of olivine. Comparable progressive changes occur in all igneous melts, especially the plagioclase or soda-lime feldspar which becomes increasingly sodic and less calcic during crystallization.

Thus, an engineering classification of igneous rock must use the mineralogic composition as a basis. A knowledge of the chemical composition is valuable for correlation of, for instance, separate but adjacent masses, or where the minerals are not determinable microscopically. However, the rocks can be adequately classified according to this scheme only after chemical analyses have been performed. This is an expensive and time-consuming process.

RELATION OF THE PETROGRAPHIC CHARACTER TO THE ENGINEERING PROPERTIES OF ROCKS

The properties of rocks depend upon their texture, structure, and composition; consequently, when these factors are precisely evaluated, the physical and chemical qualities of the rocks can be predicted. However, this prediction cannot be made from determination of the petrographic identity alone, even though petrographic identity is established from texture, structure, and composition. Texture, structure, and composition can be changed by secondary processes, and the innate properties of the rock thus caused to vary significantly. An originally weak rock may be strengthened by slight metamorphism. An originally strong rock may be weakened by weathering or hydrothermal alteration; or an originally massive rock may be rendered pervious by fractures resulting from geologic processes. To the extent that rocks are altered, decomposed, or fractured, they partake more and more of properties typically related to rocks of other origins. Thus, with increase in content of clayey decomposition products, and breakdown of the original internal texture and structure, igneous and metamorphic rocks progressively will approach the sedimentary clays and shales in their properties. Therefore, determination of petrographic identity of a rock is merely the first step in the application of petrography to engineering.

Texture, structure, and composition of rocks are determined by petrographic methods, comprising microscopical examination, microchemical analysis, X-ray diffraction analysis, and certain physical tests. With skill, experience, and good judgement, the engineering petrographer can anticipate the degree to which the observed characteristics will be reflected in adverse properties of the material. With continued research, the correlation between the petrographic characteristics and the engineering properties will be improved further. By his examination, analyses, and semiquantitative tests, the petrographer establishes the need for detailed testing of materials. He must determine the probability that the stratification, schistosity, or fractures will reduce critically the strength, durability, or impermeability of the material, the degree to which the expansive potentialities of clay constituents will deleteriously affect the engineering properties, and the engineering significance of other physical and chemical attributes of material.

Many examples of the interrelation of petrographic character and engineering properties of materials can be cited. Petrographic examination of schists from the foundation of Hiwassee Dam, North Carolina, demonstrated that schistosity, stratification, and microscopic fractures in quartz grains were present. It was anticipated that these internal structures would control the failure of specimens in compression. Subsequent tests corroborated this prediction. Portions of the shore of Lake Roosevelt, Washington, are composed of the Nespelem formation known to contain a series of stratified silts and clays having petrographically unstable characteristics. As a result of wetting by the reservoir waters, the strata of clay softened and became so unstable that extensive sliding occurred, involving areas extending as much as 1,000 feet back from the shoreline. Apparently insignificant variations in composition of rocks actually can cause great changes in properties. At a proposed dam site on the Colorado River in Utah, the great decline in strength of sandstones as a result of wetting was found to correlate with variations in the amount of determinable interstitial clay, which in no case constitutes more than 5 percent of the rock. Petrographic examination of the claystones and shale forming the foundation of the Malheur River Siphon, Owyhee Project, Oregon, would have revealed their potentialities for expansion with wetting, a process which within 8 years raised the siphon supports more than 1 foot in some places.

ENGINEERING PROPERTIES OF IGNEOUS ROCKS

Plutonic rocks

Igneous rocks which form in the so-called plutonic, or deep, zone of the earth's crust are characteristically medium-to-coarse-grained in texture and massive in structure. The series of rocks from granite through monzonites, quartz monzonites, granodiorites and quartz diorites, to gabbros include by far the most common types. When encountered in place, plutonic igneous rock bodies are usually large and may be regarded as extending indefinitely in depth. For example, the sites of Grand Coulee, Arrowrock, Kortes, and Anderson Ranch Dams lie entirely within granite.

The individual crystals or grains composing plutonic igneous rocks usually range from about 1 millimeter to 1 centimeter in size; although considerably larger crystals do occur in some less common types (e.g., the pegmatites). Because some of the minerals precipitated from the melt crystallize early and others late, granites are characterized by a poorly interlocked texture with the last crystallized minerals being molded against the essentially smooth surfaces of the early formed crystals. However, in gabbros, the main constituents, plagioclase feldspars and pyroxenes, develop simultaneously. Consequently, gabbros typically possess a well-interlocked internal texture. As a result of the poorly interlocked texture, granites tend to disintegrate with weathering, impact, or abrasion to their granular components. The excellent service of granitic rocks as road aggregate relates in part to the ease with which disintegration occurs, as a consequence of which a uniformly graded road metal is produced by traffic and natural weathering. Conversely, gabbros characteristically are tough and disintegrate less readily, their average Young's modulus of elasticity being about 1.7 times that of granite.

Because the plutonic igneous rocks develop by slow and complete crystallization of the molten magma, porosity and permeability of the igneous rock masses are typically low. However, jointing and fracturing of plutonic masses are commonly sufficient to permit localized passage of groundwater. The fracturing and jointing are unusually abundant because the originally massive structure precludes local and progressive release of earth stresses. At Kortes Damsite, Wyoming, intense hydrothermal alteration controlled by jointing has produced zones of decomposed granite as wide as 7 inches in which the rock contains secondary montmorillonite-type (bentonitic) clay and is so weakened as to yield to granulation in the hand.

In the granite-gabbro series the content of quartz and alkali feldspar (such as orthoclase) decreases and the content of basic soda-lime (plagioclase) feldspars and of dark-colored minerals increases as the silica content decreases. The basic plagioclase feldspars and the dark-colored minerals are more susceptible to weathering or hydrothermal alteration. Consequently, diorites and gabbros are more likely to exhibit local or general decomposition than are granites and monzonites. However, all primary constituents of plutonic igneous rocks are sufficiently stable to withstand chemical attack by the alkalies released during hydration of portland cement, and even if calcined and pulverized, they produce inferior or worthless pozzolans.

Despite their chemical stability, even some unaltered granitic rocks may contribute to poor durability of concrete. For example, the bond of cement paste onto the smooth, impermeable surfaces of the large exposed crystals of quartz and feldspars may be inadequate, or, because of the poorly interlocking texture of typical granites, the grains may be loosened by even moderate weathering, thus decreasing strength, elasticity, and durability of the rock. Large crystals possessing adverse properties may affect the quality of the aggregate. For example, orthoclase and microcline crystals whose thermal coefficient of expansion differs markedly from that of the cement paste may contribute to rupture of bond and distress of the enclosing mortar. These feldspars are characterized by a thermal coefficient of 0 to 0.6×10^{-6} per degree F. With changes in temperature of concrete, severe stresses arise in the cement paste, bond between aggregate and cement fails, and consequent overall deterioration of the concrete may occur. No deterioration of this kind is known to be associated with diorites or gabbros, probably because the plagioclase feldspars possess a thermal coefficient of expansion considerably greater than that of the alkali feldspar and because the individual grains of these rocks are more firmly interlocked.

Other granitic aggregates are connected with inferior quality of concrete. For example, granitic aggregates from near Anderson Ranch Dam, Idaho, and Vallecito Dam, Colorado, produce concrete of satisfactory durability only if special care is used in its manufacture. Extensive investigations have shown that only by the addition of crushed limestone gravel is it possible to obtain good concrete with the apparently sound, highly granitic sand-gravel aggregate of the Kansas-Nebraska Area. Natural granitic aggregates in the vicinity of Denver, Colorado, produce satisfactory but not superior concrete only with adequate control of mixing, placing, and curing.

With weathering or hydrothermal alteration, plutonic igneous rocks may produce compounds which themselves contribute to reduced quality of concrete. For example, an altered anorthosite from Soledad Canyon, California, containing the zeolite laumontite (or leonhardite) is known to have caused rapid deterioration of cast stone and stucco in the vicinity of Los Angeles. An apparently sound, crushed granodiorite containing a zeolite is associated with surface scaling and efflorescence of concrete on the downstream face of a dam in Southern California.

At Green Mountain Dam, Colorado, it was noted that a small number of boulders in stockpiled riprap had weathered to a rubble. The rock had been identified petrographically as monzonite porphyry. Examination of the excavation from which the rock had been obtained revealed shear zones along which the rock had lost its physical coherence by deep-seated alteration. The rock was in sound physical condition except along these zones. Exposure of the rock to natural weathering resulted in rapid disintegration of the altered material. Examination during 1959 of the riprap that had been placed on the dam about 18 years previously showed that the small number of contaminating boulders had completely disintegrated by exposure to the weather while the sound rock remained unaffected.

These comments in regard to the quality of plutonic igneous rocks should not be taken to imply that granitic rocks in general invariably contribute to inferior quality of concrete. On the contrary, plutonic igneous rocks, or sands and gravels containing particles of plutonic igneous rocks, have been widely and successfully used as concrete aggregate. It is to be anticipated that adverse qualities will be reduced by (1) decreased grain size of the crystals composing the rock, (2) increased interlocking of the grains, such as will accompany metamorphism under high pressure and temperature, and (3) decreased content of orthoclase and microcline, the feldspars characterized by very low thermal coefficient of expansion.

Hypabyssal rocks

Igneous rock solidified at moderate depths in the earth's crust (the so-called "hypabyssal" zone) are characterized by textures, structures, and composition intermediate between those of the plutonic and volcanic rocks. Consequently, their physical and chemical properties are likewise intermediate. Because of the high viscosity of highly siliceous melts and the common association of abundant gases and vapors with the more siliceous magmas, rocks of the granite-rhyolite family exhibit a very close relation between environment of solidification and internal texture and structure. Rocks of the gabbro-basalt family do not demonstrate a comparably close relation of this kind; thus the characteristics of the rocks may not always reveal the mode of occurence of the igneous bodies.

Hypabyssal igneous rocks occur as comparatively small bodies, which are called "dikes" if they are thin and tabular in form and cut across the structure of the country rock, or "sills" if they are thin and tabular in form and intrude along structures (such as stratification) of the country rock. Hypabyssal intrusions of irregular or lenticular shape, such as laccoliths, are less common than are dikes and sills.

Because of their small size, these intrusions typically constitute merely a portion of large construction sites. If they are exploited as sources of construction materials, only small quantities may be available. For example, an andesite intrusion occurs at the left abutment of Palisades Dam site, Idaho, but the remainder of the site is underlain by sedimentary rocks. Because the competence of the igneous rock and the increased strength of the sedimentary rocks indurated under the influence of the heat of the intrusion, the left abutment was selected by the designers as the site of the spillway structure. Unfortunately, close jointing in the andesite restricted use of the rock as riprap because of the limited quantity of larger sizes available. At Davis Damsite, Arizona-Nevada, granite and granite gneiss constituting the greater part of the foundation and the abutments are cut by rhyolite dikes deeply altered (even to clay) along contacts. Because of this incompetence, these zones, in some places more than 10 feet in width, required excavation to good rock prior to construction. Basalt dikes cutting the foundation were strong and competent, and presented no design problems. Rock of suitable size, quality, and gradation for slope protection could not be obtained from the excavated rock; therefore, a quarry was opened at some distance from the dam.

Along the Feeder Canal, Columbia Basin Project, Washington, sills and flows of basalt were involved in ancient landslides and possibly in renewal of sliding of the shales and siltstones of the Latah formation. These slides greatly impeded progress of construction.

Volcanic rocks

Igneous rocks which form at or near the surface of the earth are characteristically very fine-grained or partially to completely glassy. They may be massive, or they may contain few or many vesicles owing to release of gas from the melt, or they may be banded as a result of flow of the plastic lava. Thus, the structure of the volcanic rock may be massive, vesicular, pumiceous, or flow-banded. Comparable to the granite-gabbro series is the rhyolite-basalt series of volcanic rocks.

Lava flows are sheet-like in form; that is, the area which they cover is large compared to their thickness. Because of their greater fluidity, basic lavas, such as basalt, commonly extend over large areas even though the flows are thin. Acidic lavas, such as rhyolite, usually are limited in area and typically are thicker for a given distance of flow. Because of their small thickness or limited areal extent, lava flows are likely to underlie merely a portion of a large construction site.

Lava flows are commonly interbedded with tuffaceous or other fragmental volcanic material blown from the volcano. Also, particularly in the basic (basaltic) lavas, tunnels or tubes may occur wherever the still fluid lava flowed out from beneath a hardened surface crust. These zones of fragmental material--the lava tunnels, the fractured zones, and to some extent, the vesicular zones--contribute to the characteristically high permeability of thin bedded lavas. Because of the higher viscosity and commonly higher contents of gases and vapors of acidic and intermediate lavas, rhyolite, dacite, and andesite tuffs and agglomerates are considerably more common and widespread than tuffs and agglomerates of basaltic composition.

The crystals composing the greater portion of volcanic rock types are minute, usually being invisible to the unaided eye. Typically, volcanic glass, representing the uncrystallized residue of the melt, is present constituting in some instances, merely interstitial segregations, in others, virtually the entire rock. Most volcanic rocks are porphyritic; i.e., embedded within the fine-grained or glassy groundmass of the rock are crystals which are considerably larger than those in the groundmass. Rhyolites commonly are highly glassy because of the high viscosity of the melt, whereas basic volcanics, such as basalt, usually contain merely small amounts of glass held interstitially in the groundmass. Because of the content of glass, volcanic rocks are usually hard and brittle, rhyolites typically being the most brittle because of their greater glass content.

Volcanic glasses are unstable chemically, and are therefore decomposed easily by weathering or hydrothermal activity. Consequently, during examination of volcanic formations to establish their structural stability, diligent investigations should be made to assure that all zones of alteration are discovered. For example, along some sections of the Main Canal, Deschutes Project, Oregon, locally intense alteration of andesite and rhyolite tuffs to bentonitic clays is responsible for drastic instability of cut slopes and displacements in the canal section. Because of their chemical properties, glassy rhyolites, andesites, and dacites are deleteriously reactive with the alkalies released during hydration of portland cement. As a consequence of their widespread occurrence, these rocks are by far the most important rocks participating in cement-aggregate reaction. In addition, because of their chemical activity, acidic, intermediate, and alkaline volcanic rocks and tuffs are excellent sources of pozzolans for use in concrete.

Basalts also are susceptible to decomposition by weathering and hydrothermal action. But, because basalts typically contain less glass than rhyolites and andesites, equivalent alteration ordinarily impairs the structural quality of basalts less than it impairs the quality of rhyolites and andesites. On the other hand, the decomposition of the glass in the basalt can decrease critically its durability and soundness. For example, an altered dolerite proposed for use as concrete aggregate on a project in Oregon was found to contain about 30 percent of the clay mineral nontronite, formed by alteration of interstitial glass and minerals. Tests of concrete proved that this rock caused rapid freezing and thawing breakdown of concrete when used as aggregate, even though the crushed rock passed tests of soundness. The deterioration of the concrete was determined to be caused in part by large volume changes of the dolerite.

The occurrence of montmorillonite clay in basaltic fine aggregate at Prineville Dam, Oregon, caused premature stiffening of the concrete to such an extent that another aggregate had to be substituted. Deposits of highly basaltic sands and gravels near Pasco, Washington, which are satisfactory sources of concrete aggregate, are underlain by deeply weathered sands and gravel but of similar composition. Because of the susceptibility of basalt to weathering, the older portions of deposits have been rendered unsuitable for use. Exploration must be conducted to determine the extent and depth of the satisfactory aggregate to prevent contamination by the unsound material. Also, because of the ease with which basalts are decomposed by groundwater, basaltic sands and gravels commonly become coated with opal, which represents the silica leached from the basalt pebbles. These opal coatings are deleteriously reactive with cement alkalies.

Although basaltic glasses are not resistant to weathering they are not deleteriously reactive with cement alkalies. Their innocuous character apparently relates to the low content of silica and the high content of magnesium and calcium. Because of their toughness, strength, and a surface texture conducive to good bond with cement, basalts as group constitute one of the best sources of concrete aggregate.

APPLICATION OF PETROGRAPHY TO ENGINEERING PROBLEMS OF THE BUREAU OF RECLAMATION

Petrography serves the engineer in various ways: First, detailed petrographic study of rocks assists the engineering geologist in establishing the geologic structure and interrelation of formations at construction sites. Second, petrography assists in determination of the engineering properties of the rock materials in place at the site and of materials to be used in the construction.

The engineering geologist requires application of petrography to obtain the maximum geologic information from limited exposure or relatively few drill cores so that preliminary estimates will be as valid as possible and so that future explorations might be the most appropriate. For example, the geologist may wish to know if the alteration observed at the surface was caused by weathering and hence is limited in depth, or by hydrothermal processes and is likely to continue downwardly. The decision would greatly influence preliminary estimates of exploration and construction costs, for if hydrothermal, deep-seated alterations were indicated, the advisability of extensive preconstruction exploration would be established. At Anderson Ranch Dam site, intense hydrothermal alteration rendered the granite incoherent to depths in excess of 300 feet below the original surface, and serious landsliding occurred during excavation of the site.

Precise description and identification of rock formations aid the geologist in problems of correlation. Thus, the presence or absence of zones of shearing and faulting can be established by correlation of strata across the site. For example, at Canyon Ferry Damsite the sedimentary formation constituting the foundation and abutments contained thin sills of altered andesite, distinguishable only after petrographic analysis, whose continuity proved the absence of significant faulting beneath the river alluvium.

Petrography is a valuable tool for determination of the properties of rocks, either when applied independently or as a means to select those quantitative tests necessary to measure specific properties. The latter function is the more important. Most tests to measure properties of rock materials are expensive and time-consuming, and they usually require carefully selected samples so protected that at the time of test they truly represent the character of the rocks and materials in place, especially with regard to moisture content and fractures. Consequently, it is wise to determine the necessity for certain tests before they are requested. For example, testing the quality of an aggregate by performing tests of concrete containing the aggregate may be avoided by application of physical and chemical tests and petrographic examination of the aggregate. Tests of concrete need be performed only when the results of the physical and chemical tests of the aggregates are anomalous, or if the petrographic examination indicates adverse properties not evaluated by the aggregate tests. Determination of volume increase of rock materials with wetting is significant only if clay minerals of the montmorillonite type (bentonitic) are present. The presence and abundance of these clays can be determined quickly by petrographic and X-ray diffraction analysis. If the number of samples available for test is so great as to preclude testing of all, petrographic examination to select specimens representative of the group frequently will simplify the test program without sacrificing significance of the results.

Engineering petrography and engineering geology in coordination serve to relate the properties of individual specimens subjected to laboratory tests to the properties of the rock formations in place. For example, the petrographer and geologist may be called upon to decide: To what extent should the fractures, joints, and planes of shear in the rock in place be cause for reducing, below the measured strength of rock specimens, the strength of the rock mass; or to what extent might the swelling clays remain stable by virtue of their impermeability; or to what degree would discontinuities, such as joints, bedding planes, and faults, augment the known permeability of the rock itself. Not infrequently, the results of tests of rock specimens, however selected, may be more deluding than instructive. Only experience, geologic and petrographic skill, and good judgement will permit adequate translation of test results into the data required for engineering design.

The petrographer can assist the engineer in design, construction, and maintenance problems. By working with the engineering geologist, the petrographer facilitates selection, exploration, and subsurface investigation of construction sites. Through application of petrography to materials testing, specific tests to be applied and samples to be tested can be selected with minimum hazard of inefficiency. Petrography is effective in predicting the engineering properties of rocks because those properties are determined by the rocks' texture, structure, and composition, characteristics which can be discerned by petrographic methods.

A MINERALOGIC AND TEXTURAL CLASSIFICATION OF IGNEOUS ROCKS

On the basis of mineralogic composition and internal texture and structure a chart has been prepared which illustrates the characteristics of all widespread igneous rocks.* This chart, which appears following page 10, may be used for systematic classification of described rocks if all pertinent mineralogic and textural data are known; or definitions of rock types can be obtained from the chart. It is to be noted that many of the rocks shown in the chart can be identified only after microscopic examination; thus adequate facilities for preparation and examination of specimens are necessary for complete petrographic analysis. The organization of the chart is described below.

Textures

Rocks shown in the same vertical column are similar in chemical and mineralogic composition. For example, except for some natural glass which may occur in the rhyolite, granites and rhyolites are essentially the same in composition. However, as is noted in the column headed "Typical Textures," the characteristic texture and structures of the rocks in any given vertical column are different. Rocks which solidified at comparatively great depths in the earth are characterized by completely crystalline, fine- to coarse-grained textures. These rocks are shown in the bottom lines of the chart. They possess textures similar to granite and represent igneous bodies which solidified in the so-called plutonic zone of the earth's crust.

In the four rows of boxes above the bottom two rows, the rocks are generally completely crystalline, but they are fine-grained or porphyritic, since they commonly represent small, rapidly cooled igneous bodies, such as dikes. They formed in the so-called hypabyssal zone at moderate depths in the earth.

The three rows of boxes at the top of the chart represent rocks which solidified at or near the surface of the earth and which are therefore exceedingly fine grained or are partially or completely glassy. These rocks are generally related to volcanism. The topmost row represents fragmental materials thrown from volcanic vents. At the extreme left side of the chart a note has been added to describe the interrelation of occurrence, chemical composition, and texture of igneous rocks.

Mineralogic Composition

Along any horizontal row the rocks are different in chemical and mineralogic composition, and therefore are classified differently even though they may have originated in precisely the same physical situation. Feldspars are the most abundant minerals in the crust of the earth, and they occur in most igneous rocks. Therefore, igneous rocks are classified on the basis of the kind and relative abundance of the feldspars. Feldspars may be classified as alkali feldspars which are of the potassium or sodic aluminum silicates, and plagioclase or soda-lime feldspars, which represent an isomorphous series between $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$. Alkali feldspars predominate in igneous rocks which are rich in alkalies (e. g., phonolites) or high in silica (e.g., rhyolites), whereas plagioclase feldspars occur in small or large proportions in virtually all igneous rocks. A note concerning the relation of chemical composition to mineralogy of igneous rocks may be found at the bottom of the rock chart.

A horizontal row in the upper part of the chart indicates the range of silica content characteristic of the various groups of rocks. It is to be noted that these proportions represent SiO_2 determinable only by chemical analysis, as distinguished from silica crystallized as quartz.

Boxes within the chart which are empty represent exceedingly rare types of classifications not exemplified by described rocks.

*Expanded from charts prepared by J. F. Kemp, A Handbook of Rocks for Use without the Petrographic Microscope, D. Van Nostrand Company, P. 46; and G. D. Louderback, Index Table of Igneous Rocks, Mineralogic and Textural Classification.

A MINERALOGIC AN…
OF IG…

Modified after J.F. Kemp and G.D. Louderback

MINERAL NAME	COMPOSITION: Albite Molecule	COMPOSITION: Anorthite Molecule
Albite	100 to 90 %	0 to 10 %
Oligoclase	90 to 70 %	10 to 30 %
Andesine	70 to 50 %	30 to 50 %
Labradorite	50 to 30 %	50 to 70 %
Bytownite	30 to 10 %	70 to 90 %
Anorthite	10 to 0 %	90 to 100 %

		ALKALI FELDSPARS PREDOMINATE			ALKAL… FELDS…
ESSENTIAL MINERALS (Minerals essential to classification of rock). FELDSPARS: Alkali feldspars include: orthoclase, microcline, albite, anorthoclase, perthite, sanidine (in volcanics). Soda-lime feldspars (plagioclase) are an isomorphous series of minerals $NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	CHIEF FELDSPARS IN ROCK				
	Ratio of alkali to soda-lime feldspars.	100/0 to 67/33 If soda-lime feldspars comprise <5% prefix "alkali" used		Not critical	
	Soda-lime feldspars in normal rock	OLIGOCLASE TO ANDESINE (WHERE ALBITE IS PRESENT, PREFIX "ALKALI" IS USED)		ALBITE	OLIG…
Other minerals whose presence is necessary or whose virtual absence is characteristic. +Signifies presence in significant amounts. -Signifies virtual absence.		+ QUARTZ (> 5%)	- QUARTZ (or < 5%)	NEPHELINE or LEUCITE (-QUARTZ)	+ QU… (>…
CHARACTERIZING ACCESSORIES	One or more characterizing accessories may be present. If present in significant proportions, mineral is included in rock name.	BIOTITE HORNBLENDE Diopside (Alkali pyroxenes and amphiboles characterize "alkali" types)		ALKALI PYROXENE or AMPHIBOLE, MICA Sodalite, Cancrinite	B…
Percentages of SiO_2 in normal types.		77 % to 65%	68% to 55%	60% to 50 %	75%…
Frequency of occurrence of granitic types and lavas		Very common	Common	Rare	Com…

	TYPICAL MODES OF OCCURRENCE	TYPICAL TEXTURES				
VOLCANIC	Uniform or irregular beds, deposits, or accumulations of volcanic ejectamenta.	Fragmental, coarse blocks, or fine ash, cemented or loose, stratified or massive.	RHYOLITE ASH, BRECCIA, TUFF, OR AGGLOMERATE	TRACHYTE ASH, BRECCIA, TUFF, OR AGGLOMERATE	PHONOLITE OR LEUCITE PHONOLITE, ASH, BRECCIA, TUFF, AGGLOMERATE	QUART… (DELLEN… BRECCI… OR AGGL…
VOLCANIC	Surface flows; shallow, small intrusives.	Glassy (vitreous or hyaline) crystals absent or nearly so. (Identified chemically or by optical properties)	ACIDIC GLASSES AND RARE PHONOLITIC GLASSES: OBSIDIAN —	PERLITE —	PUMICE —	PITCHS…
VOLCANIC	Surface flows, shallow dikes, sills, sheets, marginal zones of hypabyssal intrusives.	Porphyritic with aphanitic (felsitic), microcrystalline, or glassy groundmass. Phenocrysts may be sparse or absent. Diabases have diabasic texture.	RHYOLITE (FELSITE)	TRACHYTE (FELSITE)	PHONOLITE or LEUCITE PHONOLITE (FELSITE)	QUART… LAT… (DELLE…
HYPABYSSAL	Hypabyssal and shallow dikes, sills, laccoliths, interiors of thick surface flows.	Porphyritic with abundant phenocrysts held in dense aphanitic, microcrystalline or partly glassy groundmass. Diabases are rarely porphyritic.	RHYOLITE PORPHYRY GRANOPHYRE (QUARTZ PORPHYRY)	TRACHYTE PORPHYRY	PHONOLITE PORPHYRY or LEUCITE PHONOLITE PORPHYRY	QUART… POR… (DELL… POR…
HYPABYSSAL	Deep-seated dikes and laccoliths as well as border zones of larger intrusive masses. Composition same as that of related granitic rock.	Porphyritic; phenocrysts constitute over 50% of rock. Groundmass aphanitic or fine-grained. Granophyres may have graphic intergrowth of groundmass quartz and feldspar.	GRANITE PORPHYRY GRANOPHYRE	SYENITE PORPHYRY	NEPHELINE SYENITE PORPHYRY or LEUCITE SYENITE PORPHYRY	QUART… MONZ… POR… (ADAME… POR…
HYPABYSSAL	Deep-seated dikes, in part hypabyssal (esp. lamprophyres). Acidic and basic differentiates (segregations) from parent magma. Mainly associated with granites, syenites, monzonites and diorites.	Fine-grained, rarely porphyritic. Dark colored minerals less abundant than in related granitic rock. — APLITES (Acidic segregations)	APLITE	SYENITE APLITE BOSTONITE	NEPHELINE SYENITE APLITE	QUART… MONZ… AP… (ADAME… APL…
PLUTONIC	(same)	Fine-grained equigranular or porphyritic. May contain some glass. Dark colored minerals abundant — LAMPROPHYRES (Basic segregations)		MINETTE VOGESITE		
PLUTONIC	Deep-seated dikes and irregular masses of all sizes, related to large intrusive bodies, where concentrations of gases and vapors were present during solidification.	Very coarse-grained, including spectacular occurrences of giant crystals. Rapid changes in granularity. Rare elements and minerals may be present.	GRANITE PEGMATITE	SYENITE PEGMATITE	NEPHELINE SYENITE PEGMATITE	QUARTZ… PEGMA… (ADAME… PEGM…
PLUTONIC	Large deep-seated intrusives, such as: batholiths, stocks, laccoliths, and dikes.	Fine to coarse-grained, granitic textures. Commonly massive, but some original banding or gneissosity may be present.	GRANITE	SYENITE	NEPHELINE SYENITE (FOYAITE) or SODALITE SYENITE (No plutonic leucite syenite has been found)	QUARTZ… (ADAM…

← GENERAL INCREASE OF …

The depth at which the intrusives lie influences the rate of cooling and hence of crystallization of igneous masses, greater depths allowing decreased rates of cooling, and hence more coarsely crystalline textures. Textures of the acidic igneous rocks reflect the depth of solidification quite strongly. But the textures of basic and ultrabasic rocks are not so strongly controlled by the rates of cooling, so that plutonic rocks are commonly not distinguishable in terms of texture from hypabyssal types, and hypabyssal rocks may have the same textures as volcanics.

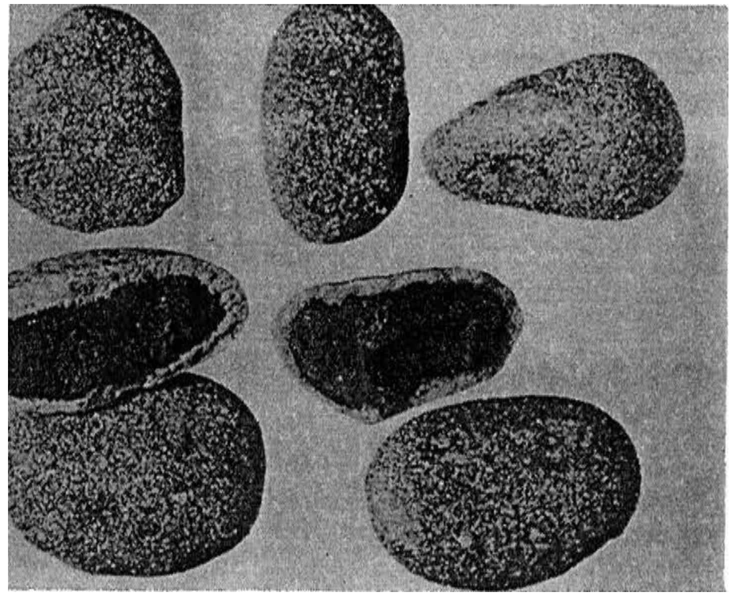
NOTE: The distribution of rocks in the horizontal direction is controlled in this classification by the proportio…
progressively decreasing proportions of alkali feldspars and concomitantly increasing proportions …
absent from the ultrabasic rocks, classified in the last two columns. These mineralogical changes ar…
chemical composition, so that from left to right in the granite-gabbro series and into the ultrabasic r…
syenites, quartz monzonites, and granodiorites are called "acid" igneous rocks; diorites and chemically …
"ultrabasic." Because of normally high contents of Na_2O and/or K_2O, rocks containing the feldspathoids

CLASSIFICATION
KS

Compiled by R.C. Mielenz

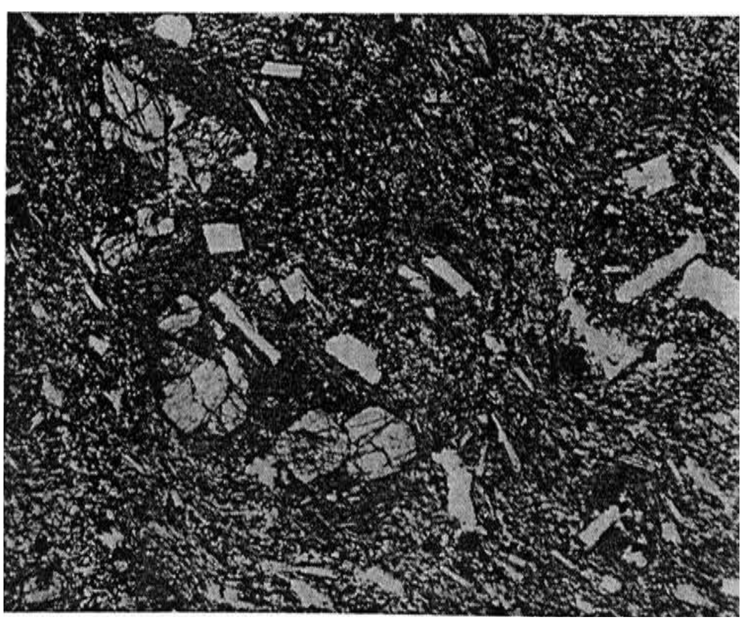
SODA-LIME FELDSPARS PREDOMINATE					FELDSPARS ABSENT (Or nearly so)		
13/87 to 0/100		Potash feldspars are rare; but albite is not uncommon in altered basalts, eg. spilite		Small proportions of potash feldspar	Some alkali feldspar may occur		
GOCLASE AND ANDESINE		LABRADORITE, BYTOWNITE AND ANORTHITE		ANDESINE TO BYTOWNITE	SOME SODA-LIME FELDSPAR MAY BE PRESENT	SOME SODA-LIME FELDSPAR MAY CONSTITUTE UP TO 10% OF ROCK. LABRADORITE TO ANORTHITE	
QUARTZ (>5%)	-QUARTZ (or -5%)	-OLIVINE	+OLIVINE	+LEUCITE or +NEPHELINE	+NEPHELINE or +LEUCITE	-NEPHELINE -LEUCITE -OLIVINE +PYROXENE or +HORNBLENDE	-NEPHELINE -LEUCITE +OLIVINE +PYROXENE
BIOTITE HORNBLENDE DIOPSIDE AUGITE HYPERSTHENE		PYROXENE Hornblende		AUGITE, ALKALI PYROXENES and AMPHIBOLES	AUGITE ALKALI PYROXENE MICA	MICA	HORNBLENDE MICA
% to 62%	65% to 50%	60% to 50%	55% to 45%	50% to 40%	50% to 40%	55% to 43%	45% to 30%
common	Very common	Very common	Very common	Very rare	Very rare	Rare	Uncommon
ACITE , BRECCIA, UFF, OR LOMERATE	ANDESITE ASH, BRECCIA, TUFF, OR AGGLOMERATE	BASALT ASH, BRECCIA, TUFF, OR AGGLOMERATE	OLIVINE BASALT, ASH, BRECCIA, TUFF, OR AGGLOMERATE	TEPHRITE OR BASANITE ASH, BRECCIA, TUFF, OR AGGLOMERATE			
'ATE GLASSES E, SCORIA		BASIC GLASSES SCORIA, VARIOLITE, TACHYLITE			ULTRA BASIC GLASSES		
ACITE	ANDESITE	BASALT If diabasic texture: DIABASE	OLIVINE BASALT OLIVINE DIABASE	-Olivine TEPHRITE +Olivine BASANITE	-Olivine NEPHELINITE LEUCITITE +Olivine NEPHELINE BASALT LEUCITE BASALT	AUGITITE	LIMBURGITE +Basic soda-lime feldspar PICRITE PICRITE BASALT +Melilite MELILITE BASALT
CITE 'ORPHYRY	ANDESITE PORPHYRY	DIABASE (Rarely porphyritic) DOLERITE	OLIVINE DIABASE	THERALITE ESSEXITE			
RTZ 'ORITE PORPHYRY ALITE ORPHYRY)	DIORITE PORPHYRY	DIABASE (Rarely porphyritic) DOLERITE	OLIVINE DIABASE	THERALITE ESSEXITE	-Olivine IJOLITE Rarely porphyritic +Olivine MISSOURITE	PYROXENITE HORNBLENDITE	PERIDOTITE +Basic soda-lime feldspar PICRITE DUNITE
ALCHITE	DIORITE APLITE	GABBRO APLITE NORITE APLITE BEERBACHITE	OLIVINE GABBRO APLITE				
RTZ RSANTITE SSARTITE	KERSANTITE SPESSARTITE CAMPTONITE	KERSANTITE SPESSARTITE ODINITE	OLIVINE KERSANTITE OLIVINE SPESSARTITE				+Melilite ALNOITE
'TZ DIORITE GMATITE ALITE GMATITE)	DIORITE PEGMATITE	GABBRO PEGMATITE NORITE PEGMATITE	OLIVINE GABBRO PEGMATITE				
QUARTZ DIORITE (TONALITE) ldspars:)	DIORITE	+Augite or Diallage GABBRO +Hypersthene or Enstatite NORITE -Pyroxene ANORTHOSITE	+Augite or Diallage OLIVINE GABBRO +Hypersthene or Enstatite OLIVINE NORITE -Pyroxene TROCTOLITE	THERALITE ESSEXITE	-Olivine IJOLITE +Olivine MISSOURITE	PYROXENITE HORNBLENDITE	PERIDOTITE DUNITE
F SiO_2			GENERAL INCREASINGLY DARK COLOR →				

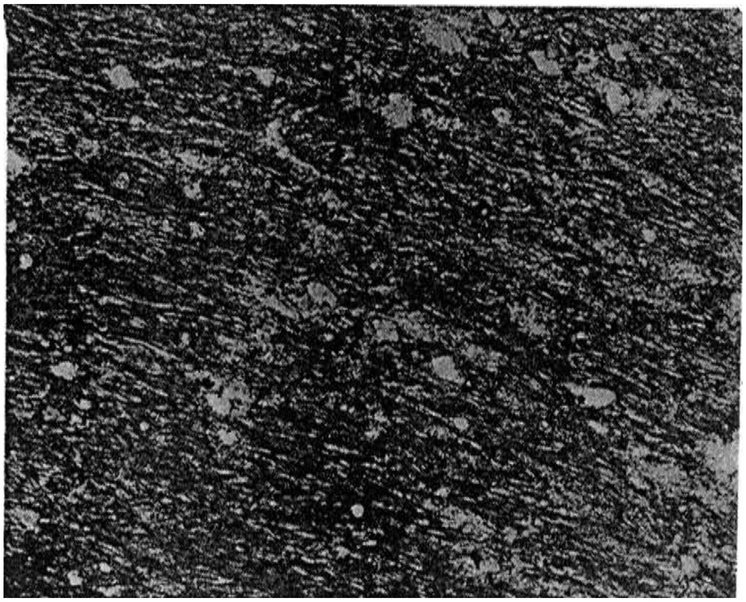
may be present. The series granite-syenite-monzonite-granodiorite-diorite-gabbro is characterized by imultaneously become less sodic and more calcic in their isomorphous series. The feldspars are essentially ied by increases in the proportions of dark colored minerals. The mineralogic changes are caused by differing crease and the proportions of MgO and, to some extent, of CaO increase. Rocks related in composition to granites, termediate". "Basic" igneous rocks include gabbros and family. Feldspar-and feldspathoid-free rocks are called lesignated as "alkaline" types.



Deeply weathered pebbles of basalt selected from physically unsound gravel in a deposit near Pasco, Washington. The gravel and sand greatly reduce the freezing and thawing durability of concrete when used as aggregate. Natural size.

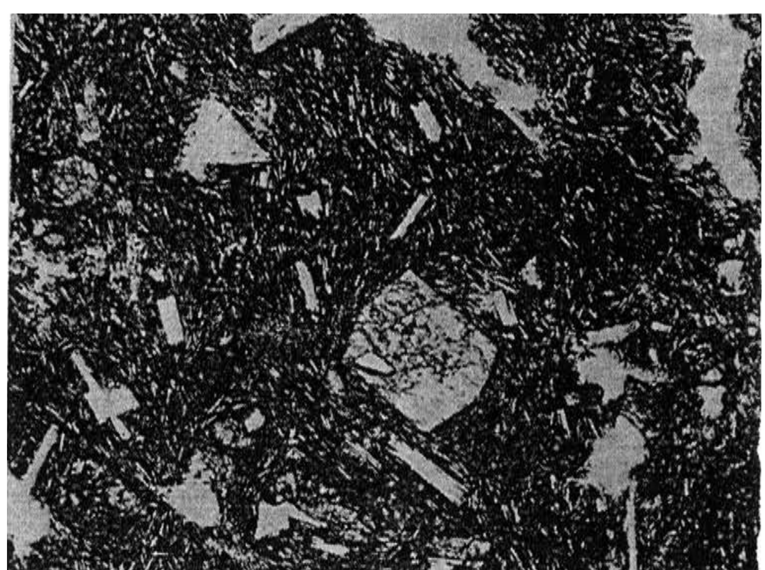
Photomicrograph of pyroxene andesite. Crystals of pyroxene (gray) and laths of plagioclase feldspar (white) are held in a groundmass composed of minute crystals and glass. The sample was obtained from the proposed Chiflo Damsite, New Mexico. Magnification X 28.

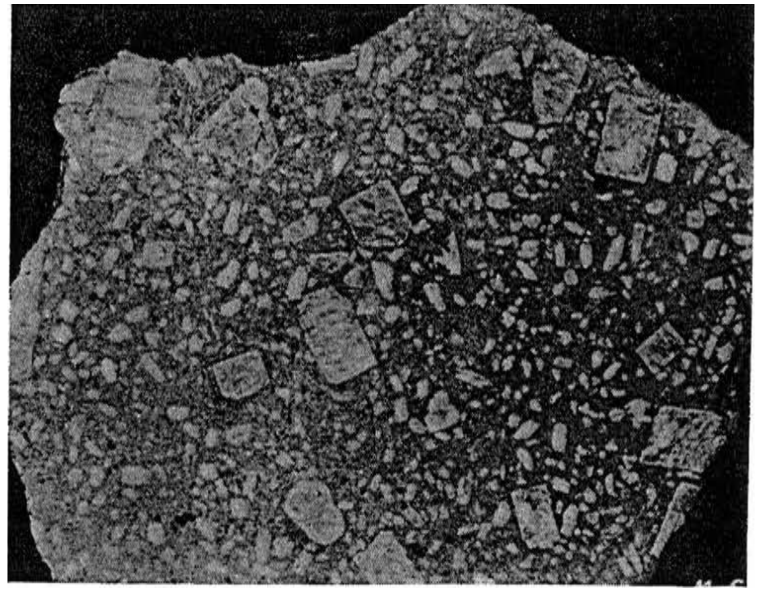




Photomicrograph of rhyolite showing marked flow-banding. The rock is composed largely of glass (cloudy) containing scattered minute crystals and vesicles (white). The rock was investigated as a source of riprap for Ochoco Dam, Oregon. Magnification X 28.

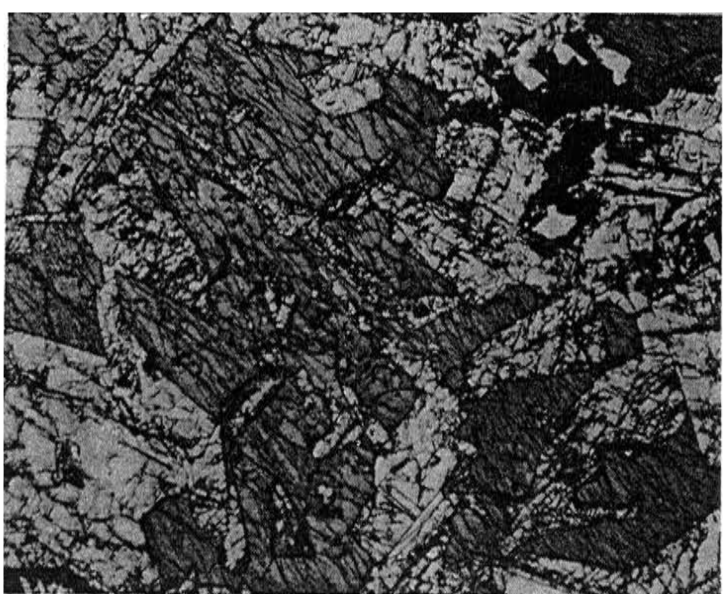
Photomicrograph of vesicular basalt composed of pyroxene crystals (gray) and laths of plagioclase feldspar (white, elongated) held in a groundmass composed of minute crystals and glass. Vesicles (voids) are irregular in shape and appear white. The rock was obtained from the proposed Chiflo Damsite, New Mexico. Magnification X 28.



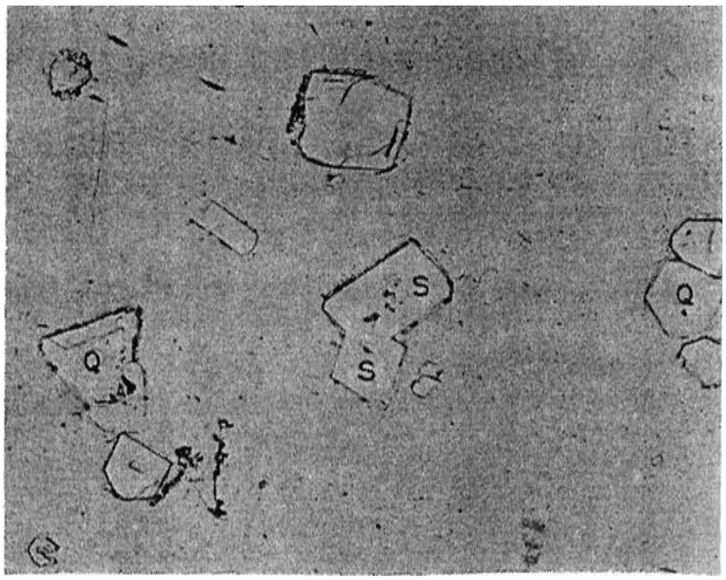


Monzonite porphyry constituting the right abutment and powerhouse foundation, Green Mountain Dam, Colorado. The large crystals (phenocrysts) are anorthoclase feldspar and the smaller crystals are plagioclase feldspar. The groundmass is composed of exceedingly minute crystals. About natural size.

Photomicrograph of gabbro showing typical well interlocked texture and massive structure which are conducive to high strength and elasticity. The rock is composed of augite (gray) and plagioclase feldspar (white). Magnification X 12

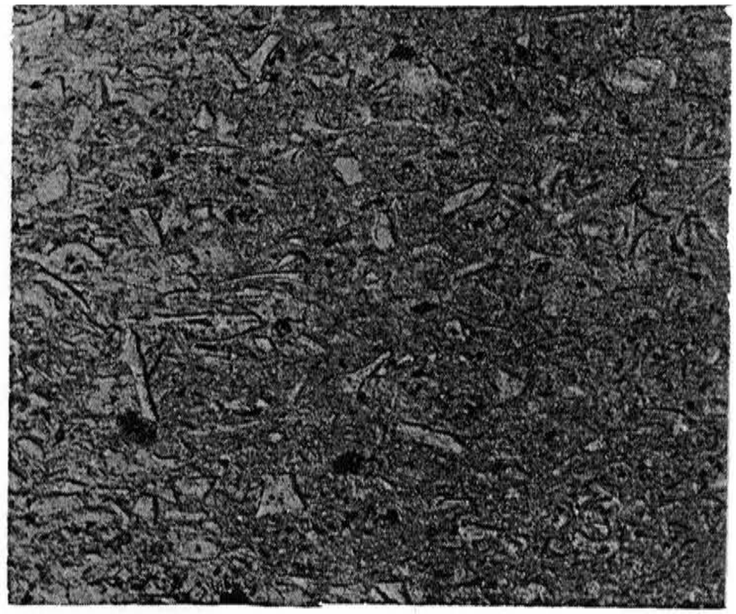


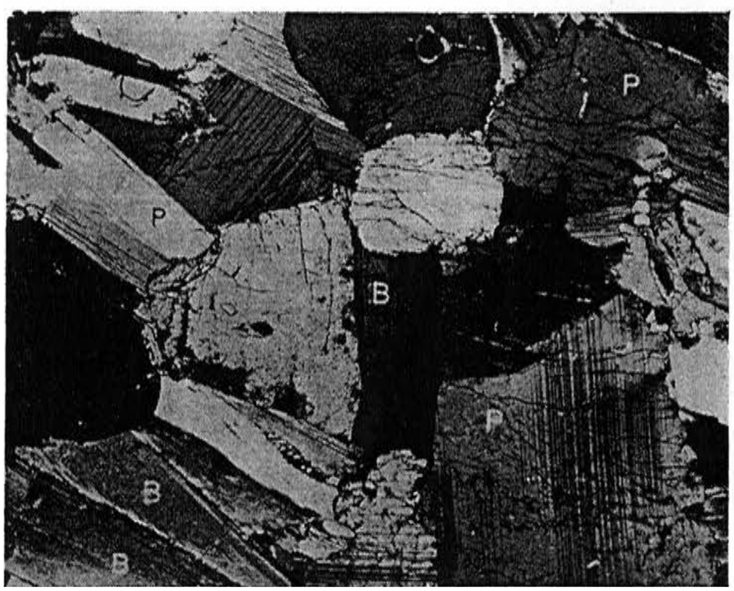
Photomicrograph of obsidian showing well-formed crystals of quartz (Q), and the alkali feldspar sanidine (S) embedded in a glassy groundmass. The rock is deleteriously reactive with cement alkalies when used as a concrete aggregate. The sample was obtained from near Georgetown, Colorado. Magnification X 28.



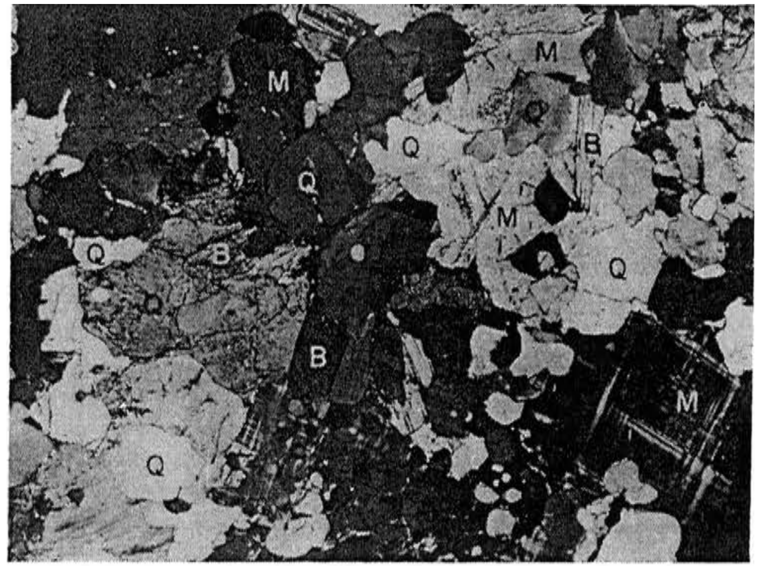
Photomicrograph of typical granophyre showing microcrystalline internal texture and massive structure composed of intercrystallized quartz and feldspar. The rock is a deleterious constituent of the aggregate used in construction of Stewart Mountain Dam, Arizona. Magnification X 13.

Photomicrograph of altered rhyolite tuff showing irregular fragments of glass embedded in a fine-grained matrix composed largely of the clay mineral beidellite. When pulverized and calcined at 1400° F., the material produces a satisfactory pozzolan. The sample was obtained near Wagon Wheel Gap, Colorado. Magnification X 90.



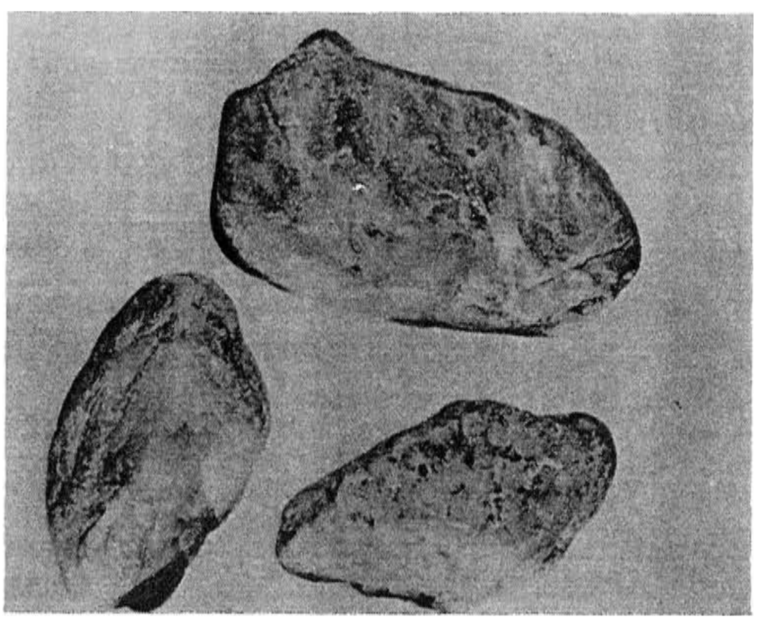


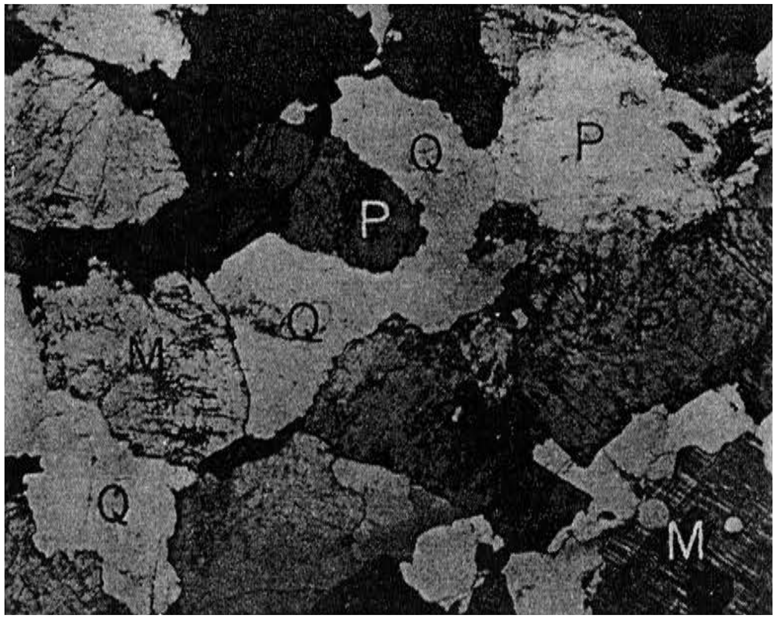
Photomicrograph of biotite diorite, showing typical moderately well interlocked texture and massive structure. The rock is composed of plagioclase feldspar (P), showing well-developed internal twinning, and biotite (B). Nicol prisms in crossed position. Magnification X 13.



Photomicrograph of biotite granite gneiss, a rock of metamorphic origin similar to a granite in composition. The rock is composed of microcline feldspar (M), quartz (Q), and biotite (B). The well interlocked texture contributes to high strength and elasticity. The rock was encountered in the excavation of Ramshorn Tunnel, Colorado-Big Thompson Project, Colorado. Magnification X 28.

Individual crystals of microcline feldspar constituting whole pebbles in the 1-1/2- to 3/4-inch gravel used as aggregate in deteriorating pavements at Kimball, Nebraska. The feldspars reduce the durability of concrete because of their abnormally low coefficient of thermal expansion, and their poor bonding characteristics. Natural size.





Photomicrograph of a granite showing typical poorly interlocked texture and massive structure. The rock is composed essentially of quartz (Q), plagioclase feldspar (P), and microcline feldspar (M). The rock was investigated as a source of riprap for Heart Butte Dam, Missouri Basin Project, North Dakota. Magnification X 16.