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A STUDY OF THE EFFECTS OF HEAT ON MISSOURI GRANITES

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ASSISTED BY

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A STUDY OF THE EFFECTS OF HEAT ON MISSOURI GRANITES

INTRODUCTION

Experience has shown that when certain of our building and ornamental stones are subjected to high temperatures, as in the burning of a building, they are very seriously damaged or are entirely destroyed. The extent to which each is damaged depends upon the mineralogical and chemical composition and upon the physical properties of the rock.

The studies which are described in this bulletin were undertaken with the object of determining the factors involved in the changes during which a given stone is damaged. Since all rocks consist of one mineral or an aggregate of minerals, the disaggregation of the rock under high temperatures should depend upon the physical properties of each of the minerals in the rock and upon their relations to each other. The best means of studying the internal structure and changes in a rock are with a petrographic microscope, and these investigations include a careful microscopic examination of the rocks studied.

For our work we used Missouri granites because they are usually very badly damaged in a fire. Furthermore their mineralogy is more complex than that of most of the common building stones and this gives a wider field for study. Another reason for using this stone is that there is no definite proof as to the cause of the disaggregation of granites under conditions of high temperatures and it was hoped that evidence bearing upon this might be obtained. As the results of the work show, we have been generally successful in getting this evidence.

The experiments consisted of heating prepared cubes of the granite to a very high temperature, cooling them under various conditions and determining their strength. The material was carefully examined before and after heating and the effect noted. Thin sections of the fresh rock and the heated rock were studied with the microscope and any changes in the minerals of the rock were noted. By this method we were able to definitely locate the cause of the disaggregation.

A general series of tests were run at various temperatures in order to determine, if possible, the point at which the granite first began to weaken. The major part of the tests were upon sets of cubes, one part of the set being heated to 500° C (about 950° F) and the other to 750° C (about 1400° F). These temperatures were chosen because they are closely related to certain physical properties of one of the constituent minerals of the granite. This mineral was regarded as the most important in causing the damage, as will be discussed later.

These results are of importance in showing, not only that granites should not be used where they might be exposed to high temperatures in a fire, but that in such a case they will not support a very heavy load.

The writer has been ably assisted in this work by Mr. L. M. Neumann, Research Assistant in the Engineering Experiment Station of the University of Missouri. He did all the heating and testing of the strength of the materials and wrote the descriptions of the physical tests.

PREVIOUS WORK

Rock has been one of man's most important building materials ever since he first began to provide shelter for himself. Since most buildings are constructed of stone and wood, and the latter, and most of man's household goods are very inflammable, fires are of all too frequent occurrence. Fire resisting materials were sought for long ago, and experiments as to the fire resisting qualities of various rocks used were begun about eighty or ninety years ago. These early tests usually consisted in heating various stones to a high temperature (either in a specially constructed furnace or in a temporary structure built for that purpose), and in noting the effect upon them. As water is generally used at a fire, the heated stones were treated to a sudden bath by plunging them into water or throwing a stream of water upon them and noting the results.

Thus it was early learned that while granite is a very durable stone and retains a polish longer than most common building stones, it was less resistant to fire than limestone or sandstone.

Some of the more important experimenters along these lines may be mentioned briefly.

H. A. Cutting was probably the first to test a series of various building stones with high temperatures.[1] He found that granite became worthless at 1000° F. He ranked the stones he tested as follows; (the most resistant first), marble, limestone, sandstone, and granite.

J. A. Dodge, about the same time, tested a series of building stones for the Minnesota Geological Survey.[2] He heated them to a dull red in a muffle furnace and plunged them into water. His results are

1. Cutting, H. A., Am. Jour. Sc. series 3, 21: 410: 1881.
2. Dodge, J. A., Minn. Geol. Sur. Vol. 1: 168.

not given comparatively, but they indicate that coarse grained rocks are more injured by high heating than fine grained ones. Most of his tests were upon syenites.

That fine grained rocks are more resistant is also shown by the results of Jackson on some California granites.[3]

E. R. Buckley carried out a rather extensive series of tests upon Wisconsin building stones, and later, while State Geologist of Missouri carried out similar tests on Missouri building stones.[4] Rocks of even grain and simple mineralogical composition were found to be the most resistant, and fine grained rocks were far more so than coarse grained, the latter being a very poor fire resisting rock. Most of the granites could easily be crumbled in the hand.

Probably the most complete series of tests that has been made up to date are those of W. E. McCourt for the New Jersey Geological Survey.[5] His tests were made on three-inch cubes, some of which were heated in a muffle furnace to 550° C. (1022° F.), and were cooled in air and water, and others were heated to 850° C. (1562° F.) and cooled the same way, while still others were heated in an open flame. He regards the last temperature as about that of a fire. His conclusions were similar to those of the preceding men. The coarse grained rocks were more damaged than the fine, and sudden cooling in a stream of water was very injurious, usually destroying the stone. The granites were ranked last at the lower temperature, and the coarse grained ones nearly last at the higher temperature; the fine grained being more resistant.

R. L. Humphrey heated some building blocks of granite to a temperature of about 1700° F. for about two hours, then turned a stream of cold water upon them while still hot.[6] The granite spalled off over one-fourth the area exposed to the flame to a depth of one to one and one-half inches. After their removal from the panel where they were heated, it was found that all the blocks were badly cracked and broken up into fragments about four by eight inches. The major cracks were across the stones and in a plane parallel to the face exposed to the flames. All were easily broken.

While the experiments carried out by these men are of interest in showing the relative durability of the stones, none of them carried the studies far enough to find out the cause of the disruption of the granite, although suggestions were made by some of them. Likewise no strength determinations were made before and after heating. Buckley in both his Wisconsin and Missouri reports recognizes that such

3. Jackson, 8th Ann. Rep. State Min. of Calif., 1888.
4. Buckley, E. R., "Building Stones of Wisconsin," Bull. IV. Wis. Geol. and Nat. Hist. Survey, 72 and 385.
Buckley, E. R., and Buehler, H. A., Mo. bur. Geol. and Mines, 11 (2): 49.
5. McCourt, W. E., Ann. Rep. State Geol. 1906: 19-77.
6. Humphrey, R. L., Bull. 370, U. S. G. S.

tests would be of value. Many of the earlier experimenters subjected the rocks they were testing to conditions which were really far more severe than the stone would probably ever undergo, their results showing that the stone was almost completely destroyed. After the tests they were often able to crush the rock in the hand, hence they did not recognize the need of testing the strength.

VIEWS HELD AS THE CAUSE OF THE DISAGGREGATION OF GRANITE

Two views are held as to the cause of the disaggregation of granite. Both are mentioned in the literature on granite. The one which seems to be regarded as most important, at least by some of our leading geologists, is as follows. The quartz in granite has long been known to contain cavities which are very minute, and are usually more or less filled with a gas, or liquid, or both, and more rarely with some solid. Water is the most common in them, but carbon dioxide has frequently been found, as well as a few other substances. On heating the granite, this water is thought to be converted into a gaseous state, and, as at high temperatures its expansive force is very great, it bursts open the small cell it is in and thus fractures the mineral and, of course, the rock. These cavities are found only in the quartz and not at all in the feldspar or the other minerals of the granite.

The other view holds that the expansion of the minerals, when highly heated, disrupts the rock. The major mineral constituents are known to have different rates of expansion and this would produce stresses which would differ in different directions in the rock and would thus cause its disruption. What may be regarded as merely a larger application of this view is held by some men. According to them the outer portion of the rock on being highly heated expands more than the cooler interior and thus tends to pull away from it. If water were thrown upon this highly heated outer portion, it would contract very suddenly and this shell would scale off from the rock. As stated above, we believe we have definite proof as to which one of these views is the more correct and these proofs will be presented in a later chapter.

CHAPTER I

DESCRIPTION OF THE GRANITES TESTED

The material for our tests was obtained from the various quarries in southeastern Missouri. There were four quarries in more or less active operation at the time of our visits to them. At least one set of six cubes each was obtained from each of these quarries and a set was also obtained from the Gilsonite quarry near Knoblick, Missouri, because of its marked difference from the other granites of Missouri. This quarry was not operating at the time of our visit. Several sets were made of the material from the A. J. Sheahan Granite Company's quarry at Graniteville, Missouri. This company is one of the most important producers of granite for building material at the present time. The Schneider Granite Company's quarry is located about one quarter of a mile north of Graniteville. Two sets were obtained here, one from their building material, and the other from their paving block material.

Milne and Gordon, and the Missouri Granite Company are operating quarries near Knoblick, Missouri. The quarry of the former is about two miles west of Knoblick, and produces monumental and building material. The Missouri Granite Company's quarry is about three miles southwest of Knoblick. They produce mainly crushed granite and paving blocks. The material was prepared for testing by A. Allen at Graniteville.

Sheahan Granite Company's Quarry.—This granite is a pinkish red to dark red rock, varying from medium to coarse-grained, with an occasional phenocryst of feldspar an inch or so in length. It consists of feldspar and quartz with minor amounts of biotite (partly altered to chlorite), muscovite, magnetite, hematite and several grains of pyrite. A grain of fluorite may be seen occasionally. An estimate of the relative proportions of the major constituents made according to the Rosiwal method gave 31.3 per cent for quartz and 68.7 per cent for feldspar.[7] All other constituents were less than two per cent and were not measured in getting the percentage of the quartz and feldspar.

The feldspar varies from pink to dark red in color. The crystals average about one-fourth of an inch in diameter, with an occasional phenocryst up to one and a quarter inches long. Zonal banding

7. Bulletin 313, U. S. Geol. Sur. p. 173.

occurs in some of the larger crystals. Considerable chlorite has developed in some of the feldspar, giving it a marked green color. The phenocrysts very frequently show Carlsbad twinning. Some plagioclase feldspar can be detected in a few cases, but most of the feldspar appears to be orthoclase.

The quartz occurs in crystals which are up to about three-eighths of an inch in diameter. When the thickness is sufficient the quartz has a dark, translucent appearance, when thin, it is transparent, save for a slight white cloudiness. This cloudiness was found, upon examination with the microscope, to be due to very minute inclusions of various minerals and cavities containing liquid and gas. The crystals less than one-eighth of an inch in diameter are usually transparent and an area of four square inches will often show six or eight crystals that have all or part of the crystal faces developed. Both pyramidal and prismatic faces occur. The angles are usually sharp, but occasionally one is seen that is slightly rounded. The remainder of the quartz crystals are irregular in outline. These two modes of occurrence indicate that there are two generations of quartz, the earlier one having the crystal faces. All the larger crystals of quartz have several cracks in them, as may be seen in figures 1a and 2. Some hematite occurs in these cracks. The quartz and feldspar are very intimately intergrown, and have crystallized at about the same time. Biotite and magnetite are present in small amounts. The biotite is black to brown in color, but is more often greenish brown from the chlorite into which it has altered. The magnetite is nearly always found in the biotite as irregular grains, rarely ever with crystalline faces. The muscovite occurs as small hexagonal books or crystals, rarely larger than one-eighth of an inch in diameter. The grains of fluorite are very rarely large enough to be seen with the naked eye, and are usually associated with the biotite. They are purple in color. The grains of pyrite are often one-sixteenth of an inch in diameter.

The microscope shows that the feldspar is orthoclase in part only. Microcline may exceed the orthoclase in amount and plagioclase may also. But on the whole, the orthoclase is the more abundant and the microcline and plagioclase are nearly equal in amount. The plagioclase varies from oligoclase-andesine to andesine. All the feldspars are kaolinized. Many contain as inclusions, other minerals, such as magnetite and hematite grains, some biotite (now largely chlorite) and fluorite, with very rarely a crystal of apatite. These inclusions are usually more abundant in the plagioclase than in the other feldspars, but this does not always hold.

The quartz is the interesting mineral in the rock because it is the mineral which should contain the fluidal cavities, if the view which holds them to be the cause of the breaking up of the stone is correct.

As a rule the quartz is clear and transparent. Cracks may be seen running in various directions. Occasionally some are seen which are parallel, suggesting that they are along the cleavage lines of the quartz. (Quartz is usually stated as having no cleavage, which is generally correct as far as can be seen in most specimens. It does have an imperfect cleavage parallel to the pyramidal face *r*.)

Running in various directions through the quartz may be seen more or less sinuous lines of inclusions. There is a strong suggestion that these lines are parallel to the crystal faces of the quartz in some crystals. The lines are very small and are not closely spaced. This is evident from the fact that the quartz is transparent to translucent. Not all the inclusions are in lines or rows. Many are scattered through the quartz, often aggregated in clouds, but usually disseminated. These inclusions are very minute. Measurements on a great many gave diameters from .005 mm. to .00027 mm., the average being about .0025. The inclusions consist of grains of fluorite, magnetite, apatite, a greenish colored material which is believed to be a greenish biotite or chlorite, and the fluidal cavities. The cavities, chlorite, and fluorite are the most abundant, and in the order they are mentioned. The chlorite is in irregularly shaped grains, which are usually the largest of the inclusions. They do not show the arrangement into lines that the other inclusions do. The fluorite occurs in shapeless grains and also as small crystals, showing the characteristic square outline. They may have, even in the very small grains, a purplish color like the larger grains, but the majority are colorless. They show a tendency to arrange themselves into lines, as though they had been pushed along by the growing crystal. This is not a marked feature, however.

The fluidal cavities are of particular interest. They are all very minute, the diameters given above applying to them, as well as to the other inclusions. On the whole, however, the cavities are smaller than the largest size given, i. e., 0.005 mm. They are irregular in shape but many are oblong in outline. Sometimes these cavities contain a small bubble of gas or air. This bubble is in motion in about one-third of the cavities, but occasionally nearly every cavity has one, which constantly moves from one part of the cavity to another. They are called "moving bubbles." The diameter of one of the largest seen was estimated to be 0.00009 mm. It was in a cavity 0.0027 mm. in diameter. Some of the cavities probably contain air or gas alone and some liquids alone, but it is not possible to distinguish between them unless they contain a bubble. These fluidal cavities show the same tendency, as does the fluorite, to be arranged in wavy lines or rows, although many are scattered throughout the quartz crystal. The more cloudy quartz crystals contain the inclusions in this disseminated manner. The relative abundance of the fluidal inclusions is a fact which our problem demands but it was found impossible, however, to make a quantitative determination. Seen megascopically, or even with a binocular magnifying twenty-five times, the inclusions appear very numerous. This appearance is misleading, however, and is due to the reflection of the light from each one, giving to the quartz the cloudy appearance, and so this cannot be relied upon as an indication of the abundance of the cavities. The inclusions make up about one per cent of the quartz. The fluidal cavities comprise about fifty to seventy-five per cent of this one per cent or from one-half to three-fourths of one per cent. This is merely an estimate and may be too low, but is thought to represent the amount fairly well. On the whole, we see that they comprise a very small part, indeed, of the quartz. It might be noted here, that this is the conclusion of other men who have studied the inclusions of rock sections. The minute size of the fluidal cavities, and their rarity, are facts which should be kept in mind.

The other constituents of the granite make up but a small percentage of the rock. Biotite, magnetite, and muscovite are the most important. The biotite is usually more or less altered to chlorite. The biotite shows some pleochroism but is usually green in color and the pleochroism is not marked. Magnetite, some original and some secondary after biotite, is very common in the biotite. It also occurs in the other minerals. The chlorite is in shreds which are usually radiating and it shows the characteristic interference tints. It has replaced the biotite, or at least, partly so. The muscovite shows the usual interference tints and was one of the later minerals to crystallize.

The only common accessory mineral, aside from magnetite, is fluorite. Large grains and crystals of this mineral, usually a deep purple in color, but also colorless, were seen in all the sections made from this granite. Usually it is found near the biotite, but this is not a necessary mode of occurrence. Some of the crystals showed the characteristic square section of fluorite, and showed also the cleavage lines of fluorite. The presence of fluorite as one of the inclusions in quartz has already been noted. It also occurs abundantly as inclusions in the feldspar. It should be noted in this connection that large grains of fluorite were found in the small veins in the granite in Sheahan's Quarry. Some sections were made of the quartz taken from these veins and it was found to contain much fluorite as one of the inclusions. The inclusions were very commonly crystals. Rarely, a small rod of apatite was seen. In two cases a minute garnet was observed. Hematite was seen in various minerals, but usually in cracks in the quartz, and in the feldspars.

A. J. Sheahan Granite Company, Old Quarry.—This quarry was formerly operated by this company and lies a short distance to the west of Graniteville.

The granite is a dark red color, but of a lighter shade than that at their present quarry. The color and texture vary in different parts of the quarry. It consists essentially of orthoclase and quartz with small amounts of biotite, chlorite, magnetite, hematite, muscovite, and fluorite. The estimate of the orthoclase and quartz gave 67 per cent and 33 per cent respectively. The crystals of orthoclase are from about one-fourth inch down, with the exception of the phenocrysts, which may be nearly an inch in diameter and show Carlsbad twinning. A pink plagioclase, in grains the size of the orthoclase, can be recognized. The quartz occurs in crystals three-eighths of an inch or less in diameter. It is more or less transparent to translucent, except for some which has crystalline faces developed, and this has a dark, smoky appearance. All the larger crystals are full of cracks. Some of the orthoclase contains small quartz crystals. The few flakes of biotite are black, save where they are altered to chlorite and magnetite or more rarely to hematite. Magnetite and hematite are very common all through the rock, occurring in small grains. Most of the magnetite was derived from the biotite which seems to have been iron rich but some of it has crystal faces, thus indicating a different origin. Only a few flakes of silvery, white muscovite occur. There is also a grain or two of purple fluorite.

The microscope shows that the rock consists of plagioclase, microcline, orthoclase, and perthite, (in the order named) with quartz and some minor constituents. The feldspar is kaolinized and contains inclusions of chlorite and fluorite. The plagioclase contains most of the fluorite and also appears to have crystallized out before the other feldspars. The quartz contains numerous cracks and inclusions of chlorite, fluorite, and fluidal cavities. The inclusions are arranged in sinuous lines or rows which were observed to cross from one grain to another in some of the crystals. The inclusions are in the quartz which crystallized out last. The fluidal cavities are very minute but numerous, as in the other granite. A great many moving bubbles occur. The biotite, muscovite, and chlorite present the usual characteristics as described above. The magnetite and hematite were derived, in large part, from the biotite. The fluorite occurs as inclusions in the feldspar and quartz.

Schneider Granite Company's Quarry.—Megascopically this granite is a coarse-grained, slightly porphyritic rock of a dark red color. The feldspar crystals are three-eighths of an inch in diameter or less, while the phenocrysts are about three-fourths of an inch in length. Carlsbad twins are common. Both orthoclase and plagioclase can be recognized, the latter usually having a lighter shade of red. Some of the crystals contain chlorite, especially in the interior, and this gives them a greenish color. The estimate of the relative percentage of feldspar and quartz showed 72.5 per cent of feldspar and

27.5 per cent of quartz. The quartz occurs in translucent to transparent crystals three-eighths of an inch or less in diameter. The smaller crystals show some crystal faces which are sometimes pyramidal, and these crystals are usually of a slightly smoky color. All of the larger quartz crystals are badly cracked and shattered, and some of them show a slight cloudiness. Biotite is quite common, but is much altered to chlorite, magnetite, and hematite. The magnetite is in grains one-eighth of an inch across. A few flakes of muscovite occur. Pyrite crystals one-sixteenth of an inch in diameter are very common and are usually associated with the chlorite.

Under the microscope the rock is seen to consist of feldspar, microcline, plagioclase, and orthoclase in order of their abundance. Quartz, with some 3 to 5 per cent of minor minerals, makes up the remainder of the rock. The feldspars are all kaolinized to a certain extent, and also contain numerous inclusions of chlorite and fluorite. The former is in rods and shreds, some .182 mm. in length but most of them about .02 mm. The fluorite is in crystals and grains which are smaller than the chlorite, on the average. The quartz is full of cracks and contains many inclusions of which fluorite in grains as small as .00026 mm. is common. There are a few grains of other minerals, among them a very minute garnet. The fluidal cavities are very abundant and only a few bubbles were recognized. The biotite is largely altered to chlorite and the iron oxides. The latter are so abundant as to suggest that the biotite was iron rich. No large grains of fluorite or muscovite were seen.

Paving-block material from Schneider's Quarry.—No slide was made of this rock as such material is not used in building operations. Megascopically, this rock might be called a granite-porphyry. The ground mass is crystalline and fine-grained but the constituents can be recognized. The phenocrysts rarely exceed five-eighths of an inch, and consist of feldspar, which is often idiomorphic, and of quartz. The feldspar phenocrysts are lighter colored than the feldspar in the ground-mass, which is a dark pink. They show a zonal arrangement, and usually contain considerable chlorite which stains the mineral green. They occasionally contain unaltered biotite. The quartz rarely exceeds three-eighths of an inch as phenocrysts, and averages about one-eighth of an inch. Crystal faces are common, both pyramidal and prismatic faces occurring. Only the larger crystals are cracked, the smaller ones, one-eighth of an inch or less in size, are usually translucent to transparent, with the same tendency to a smoky tint observed in the other rocks. The ground mass contains some small grains. Biotite is much more abundant in this rock than in any of the above. It is scattered throughout the rock in sufficient amount to give it a grayish tinge. Chlorite and the iron oxides are formed when it is altered. A few small grains of pyrite occur.

Missouri Granite Construction Company's Quarry.—This quarry is located three miles southwest of Knoblick, Missouri. The granite is a medium-grained, slightly porphyritic rock, of a light red color, consisting of feldspar, quartz, and biotite, with phenocrysts of orthoclase, and quartz. The feldspar varies in color from pink to red. The quartz is in rounded grains, which usually have a milky, translucent appearance. Cracks are common in it. The biotite is dark green to black. An estimation of the percentage of the constituents is as follows: 5 per cent of the biotite and its alteration products, chlorite and the iron oxides, 69.4 per cent of feldspar, and 25.6 per cent of quartz. This is the lowest percentage of quartz in any of the granites of which an estimate was made.

The microscope shows that the feldspar is orthoclase and plagioclase and that both are strongly kaolinized. The plagioclase is more altered than the orthoclase. It is of interest to note that there is no microcline in this rock and that the plagioclase is a basic variety, probably labradorite. The feldspar contains many inclusions of chloritic and other material. The quartz is very commonly idiomorphic. The angles between the faces are sometimes rounded, but they still possess their six-sided character, which indicates that they crystallized out early in the solidification of the rock. It contains many inclusions which are usually of some mineral, but are so small that the mineral could not be determined. The inclusions are often in rows, parallel to the pyramidal faces of the quartz, indicating that they were pushed along by the growing crystal. When not so arranged they are scattered through the crystal. Many fluidal cavities, containing liquid or gas or both, can be seen. Few bubbles are moving. Some cavities contain minute crystals. The biotite is largely altered to chlorite and magnetite. Many rods of apatite were found in this rock.

Milne and Gordon Quarry.—This quarry is about two miles west of Knoblick, Missouri, and near Syenite postoffice. The rock is a reddish to grayish, medium-grained granite consisting of orthoclase, quartz, and biotite. The feldspar varies in color from pink to red, and the larger crystals show a zonal structure. The quartz is in smaller crystals than the feldspar, but is usually very much shattered. the feldspar is 29 to 71. The biotite makes up only a very small It is transparent to translucent. The ratio between the quartz and percentage of the rock. It is altered to chlorite and magnetite.

Under the microscope the rock is seen to consist mainly of orthoclase and quartz, with a small amount of basic plagioclase and minor minerals. The orthoclase and plagioclase are very much altered to kaolin. The quartz crystallized last as it fills in the space between the feldspar. Mortar structure occurs. The quartz is full of inclusions of cavities, fluorite, mica, and some indeterminate grains. Some of the liquid and gas inclusions are very large and occasionally are arranged in lines. They contain some very large bubbles. Biotite presents its usual alteration products.

Gilsonite Quarry.—The granite from this quarry is dark gray in color. At a distance it has a bluish cast and is known as the blue granite. It is medium-grained with an occasional phenocryst of white, gray, or reddish feldspar. Scattered through the rock are segregations or "knots" of the dark mineral biotite and sometimes of hornblende. These knots are sometimes an inch or two in length. The rock consists primarily of feldspar, biotite, and some quartz, with magnetite and pyrite, the latter being very abundant.

The microscope shows that the feldspar is largely orthoclase, with some plagioclase, both being altered to kaolin. The orthoclase shows zonal banding. The quartz is in small crystals with part of the faces well developed. It contains a few inclusions of liquid or gaseous cavities and some other material (not determined) arranged roughly in lines. The biotite is abundant and is altered, as usual, to chlorite and magnetite. There is much apatite throughout the slide. There is a small amount of hornblende in the segregations. The other minerals in them are feldspar, biotite, some quartz grains, apatite, and magnetite.

CHAPTER II

PHYSICAL TESTS

A series of tests were made to determine the crushing strength, the effect of heat on the crushing strength, and the amount of expansion when heated.

The compression tests were made with a 150,000 pound Reihle testing machine. The blocks to be tested were approximately two-inch cubes, polished on the two opposite faces, which were as nearly parallel as possible. (See figures 1a, 2, and 4a.) The other four sides were rough. (See fig. 1b.) The blocks were crushed without being bedded in any material. The polished faces were placed on the steel head block of the testing machine, the lower block being rotated in such a manner that the bearing could be brought upon the entire surface of the block, if the faces were not exactly parallel. In most cases only two blocks from each quarry were tested for the compressive strength before heating, and the average of the two was taken.

There was considerable variation in the crushing strength of some of the blocks, which was, in some cases, probably due to defects produced by trimming while they were being made, and in others, because the bearing surface was uneven. The blocks failed with a loud report and the fragments flew in all directions. The cones which were obtained were slender and long; in fact, there was no prominent, central cone, but a number of sharp splinters. (See fig. 3.) After the blocks were heated they failed with less violence and much better cones were obtained. (See figures 8a and b.) The crushing of the various granites is shown in table 1.

Four blocks from each set were tested to determine the effect of heat on the crushing strength. The temperatures were measured with a La Chatelier thermo-couple, which would read to 1600° C. It was found rather difficult to hold the temperature at 500° C. and 750° C. respectively for thirty minutes; in fact, a few degrees, two to four, up or down was as near as could be gotten to the two temperatures mentioned. This variation or even a larger one would have no effect on the results, as the temperatures were not near enough to the inversion temperature of quartz to affect it, even if it were probable that they would. It would not be possible to control the temperature in an actual fire, and our working temperatures were arbitrarily chosen with regard to certain physical properties of the quartz, as will be explained later. The tests were made in a Denver Fire Clay Company gas furnace, number 12. The four blocks were placed in the furnace

TABLE 1. THE CRUSHING STRENGTH OF THE UNHEATED GRANITE.

Quarry and Locality	Number of set	Number of block	Area of crushing surface	Crushing strength	Strength per square inch	Average crushing strength	Remarks
A. J. Sheahan Granite Co., Graniteville, Mo.	I	4	4.00	80,400	20,100	26,030	Explosive break.
	I	5	4.24	123,890	29,220		
	I	6	4.07	116,090	28,530		
	II	3	4.10	107,750	26,280		
A. J. Sheahan's Old Quarry, Graniteville, Mo.	III	6	4.17	113,530	27,225	27,000	Explosive break.
	III	4	3.98	106,600	26,780		
Schneider Granite Co., Graniteville, Mo.	IV	3	4.00	125,170	31,290	31,290	Explosive break.
	V	3	4.12	151,000	36,650	34,960	Paving block material.
	V	7	4.14	138,000	33,330		
Missouri Granite Construction Co., Knoblick, Mo.	VI	8	4.10	133,380	32,530	28,845	Explosive break.
	VI	11	3.95	99,400	25,160		
Milne and Gordon, Syenite, Mo.	VII	2	3.95	102,200	25,900	25,100	Explosive break.
	VII	6	3.95	96,000	24,300		
Gilsonite Granite Co., Knoblick, Mo.	VIII	5	4.10	149,650	36,500	34,875	Explosive break.
	VIII	6	4.00	133,000	33,250		

at the same time, and the temperature was gradually brought to 500° C. where it was held for half an hour. Two of the blocks were then taken out and one was allowed to cool in the air, while the other was cooled in a stream of water. The temperature of the furnace was then raised to 750° C., where it was held for half an hour again. The remaining two blocks were then taken out and cooled in the same way as the others. The polished surfaces of the blocks were studied before and after heating, with the results given in chapter III. There were usually cracks, which could be seen with the naked eye. (See figures 4b, 5a and b, 6 and 7.) When the blocks were heated the feldspar lost some of its red color and the quartz became more or less milky white. (See figures 5b, 6 and 7.) These blocks were then crushed; the difference in crushing strength between them and the unheated specimens is given in table 2. The heated blocks had a much greater crushing strength than it was expected they would have.

The results of these tests are shown by the accompanying curves (fig. 9). The curve includes the strength of the unheated specimens of the same rock, and all the curves show the marked decrease in the strength of the granite. The difference is greater between the unheated specimen and the average of those heated to 500° C., than between those from 500° C. to 750° C. The average strength of all the unheated or fresh granite was 29,260 pounds per square inch and that of the blocks heated to 500° C. was 18,610 pounds, or a difference of 10,650 pounds. The average strength of the blocks heated to 750° C. was 10,990 pounds per square inch, or a difference of 7620 pounds. The total average loss of strength was 18,270 pounds per square inch. Such a loss of strength becomes a serious matter wherever the granite so heated supports a large load. These averages, plotted as a curve, show the decrease at a glance. (See the curve for the average of all the sets, fig. 9.) Two of the sets were heated only to 700° C., but the results differ but by a few pounds from those heated to the higher temperature. The results obtained from the tests of the material from the Milne and Gordon quarry are very unsatisfactory, as the cubes crumbled while yet in the furnace, and there is a very wide difference in the strength of the two specimens heated to 500° C.

Another interesting feature brought out by the tests is that the sudden cooling by plunging into water is not as damaging to the stone as it has been thought to be. In four of the sets the water-cooled cube showed greater strength than the four cooled in air. One of these was from Graniteville and the others were the three sets obtained from the vicinity of Knoblick. On the whole, the last three were finer-grained than the Graniteville material, but even one of the sets from there showed this variation; hence the cause is not

TABLE 2. CRUSHING STRENGTH AFTER HEATING.

Quarry and Locality.	Number of set	Number of cube	Temp. at which the cube was held for 30 minutes	Cooled in	Area of crushing surface	Total crushing strength	Crushing strength per sq.in.	Remarks
A. J. Sheahan Granite Co., Graniteville, Mo.	I	1	500°C	air	4.0	61,280	15,320	
		11	500°C	water	4.0	78,000	19,500	
		7	750°C	air	4.0	44,000	11,000	
		9	750°C	water	4.1	33,300	8,120	
A. J. Sheahan Granite Co., Graniteville, Mo.	II	1	500°C	air	4.0	81,000	20,240	
		6	500°C	water	4.1	59,610	14,540	
		2	700°C	air	4.0	44,250	11,060	
		5	700°C	water	4.0	32,130	8,030	Only one face polished.
A. J. Sheahan Granite Co., Graniteville, Mo. Old Quarry.	III	3	500°C	air	4.2	90,800	21,640	
		1	500°C	water	4.0	60,560	15,140	
		5	700°C	air	4.0	32,000	8,000	
		7	700°C	water	4.0	42,120	10,530	
Schneider Granite Co., Graniteville, Mo.	IV	4	500°C	air	4.1	84,160	20,500	
		1	500°C	water	4.0	70,810	17,700	
		5	750°C	air	4.1	49,300	12,020	
		2	750°C	water	4.1	49,660	12,110	

TABLE 2. Continued.

Quarry and Locality.	Number of set	Number of cube	Temp. at which the cube was held for 30 minutes	Cooled in	Area of crushing surface	Total crushing strength	Crushing strength per sq.in.	Remarks.
Schneider Granite Co., Graniteville, Mo.	V	1	500°C	air	4.2	95,740	23,280	Paving block material.
		2	500°C	water	4.1	86,040	21,000	
		6	750°C	air	4.1	61,300	15,000	
		8	750°C	water	4.1	64,380	15,700	
Missouri Granite Construction Co., Knoblick, Mo.	VI	1	500°C	air	4.0	86,860	21,715	
		2	500°C	water	4.0	88,480	22,120	
		4	750°C	air	4.1	67,490	16,460	
		3	750°C	water	4.0	62,370	15,590	
Milne and Gordon, Knoblick, Mo.	VII	4	500°C	air	4.0	38,700	9,675	
		5	500°C	water	4.1	66,400	16,200	
		1	750°C	air	----	------	-----	Fell to pieces in the furnace.
		3	750°C	water	----	------	-----	
Gilsonite Granite Co., Knoblick, Mo.	VIII	1	500°C	air	4.1	94,580	23,070	
		2	500°C	water	4.1	107,140	26,130	
		3	750°C	air	4.1	73,610	17,980	
		4	750°C	water	4.0	57,020	14,255	

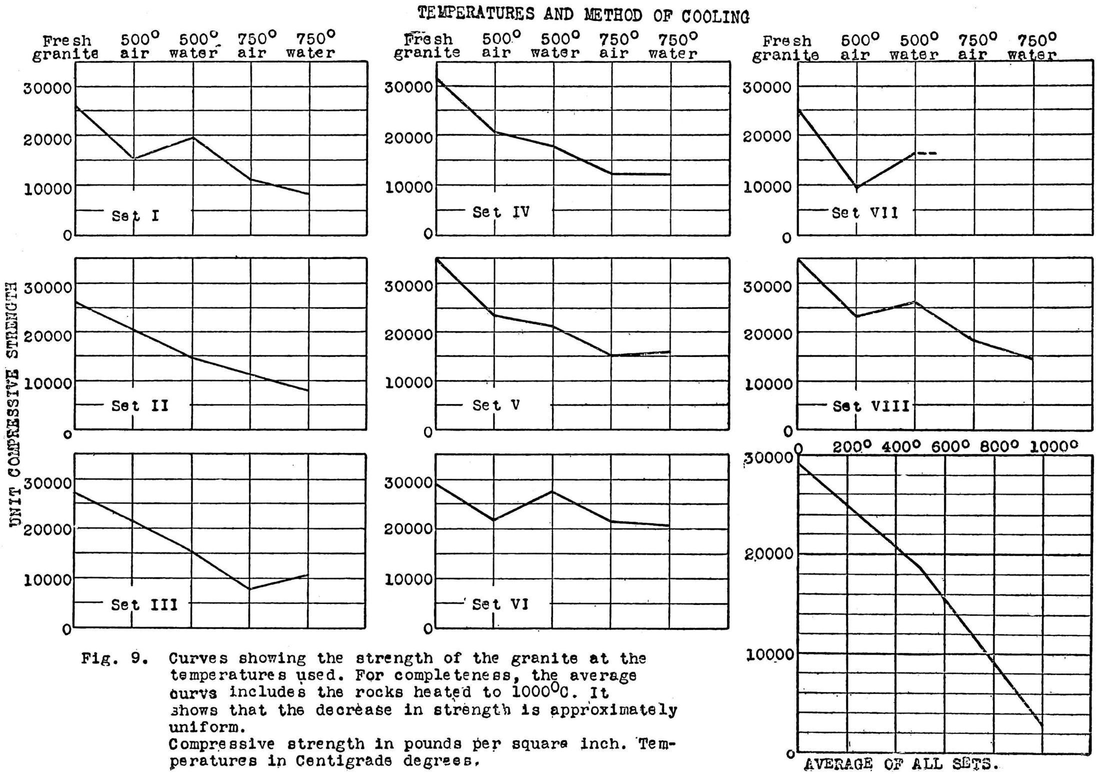


Fig. 9. Curves showing the strength of the granite at the temperatures used. For completeness, the average curve includes the rocks heated to 1000°C. It shows that the decrease in strength is approximately uniform.
Compressive strength in pounds per square inch. Temperatures in Centigrade degrees.

wholly the difference in texture. The mineralogical composition probably plays a part, and defects in the cubes may also be an explanation. The average excess strength of those which are stronger after cooling in air is 4320 pounds, while the excess for those cooled in water is 3540 pounds, so the difference is very little. The strength of those specimens heated to 750° C. and cooled in air is on the average about 1000 pounds higher than when they were cooled in water, though slightly favoring the slower air-cooling. Remembering that we are dealing with only eight sets, a tentative conclusion would be that the water bath is not as damaging as it has usually been thought to be.

Tests were made on a series of blocks to determine at what temperature the heat caused the block to lose its strength. The following tables show these results (tables 3 and 4). The first series consisted of unpolished blocks, from Sheahan's Quarry at Graniteville, which had to be imbedded in plaster of paris for crushing. These blocks were very weak, for the unheated blocks that were crushed were only half as strong as the unheated, polished blocks, and there was greater fluctuation of the crushing strength. The difference was no doubt due to the fact that the blocks were injured

TABLE 3. CRUSHING STRENGTH OF A SERIES OF POLISHED BLOCKS HEATED TO VARIOUS TEMPERATURES. COOLED IN AIR. THE MATERIAL WAS FROM THE MISSOURI GRANITE CONSTRUCTION CO., KNOBLICK, MO.

Number	Temperature for 30 min.	Area of crushing surface.	Crushing strength (total)	Crushing strength per sq. in.
1	250°C	4.0	116,210	29,050
2	300°C	4.0	87,000	21,750
3	350°C	4.0	93,420	23,355
4	400°C	4.1	93,971	22,920
5	450°C	4.05	79,600	19,900
6	500°C	4.00	86,860	21,700
7	750°C	4.1	67,490	16,460
8	800°C	4.0	34,660	8,665
9	850°C	4.0	45,600	11,400
10	900°C	4.1	27,120	6,600
11	1000°C	4.0	16,040	4,010

in roughing them out and this was increased by the imbedding. The temperatures used were from 250° C. to 1000° C., starting at 250° C. and increasing from 25° C. to 50° C. at a time. The blocks were left in the furnace thirty minutes at the desired temperature and were cooled in air. A shortage of polished blocks caused some of the intermediate temperatures to be left out. However, the results are not affected by this. Curves showing the various strengths are shown in figure 10.

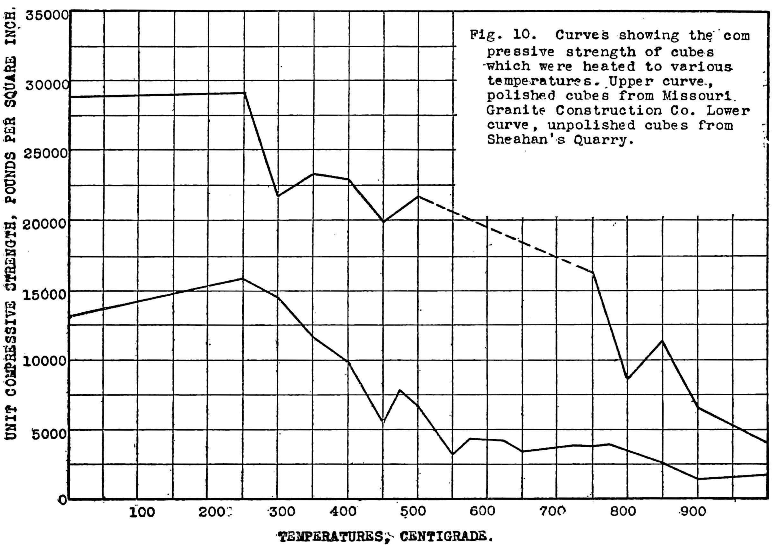


Fig. 10. Curves showing the compressive strength of cubes which were heated to various temperatures. Upper curve, polished cubes from Missouri Granite Construction Co. Lower curve, unpolished cubes from Sheahan's Quarry.

It is to be noticed that the strength of the granite declines rapidly from the very first. The loss between 250° C. and 500° C. in the series from the Missouri Granite Construction Company at Knoblick, Missouri (Table 3) is 7350 pounds, and for the unpolished series from Sheahan's Quarry, Graniteville, Missouri, the loss is 9140 pounds. Unfortunately, the total loss of the granite cannot be obtained from these data because of the undoubtedly erroneous values of the strength of the unheated specimen. However, the same information is given in the sets of blocks, and for the Sheahan's Present Quarry the loss on heating to 500° and cooling in air is 8250 pounds, while for the Missouri Granite Construction Company the loss was 7130 pounds. Comparing these figures, and remembering that they are based on the tests of a few blocks, we see that the granite is not greatly affected at 250° C. The decline in strength is almost linear and rather

TABLE 4. THE CRUSHING STRENGTH OF A SERIES OF UNPOLISHED BLOCKS OF GRANITE HEATED TO VARIOUS TEMPERATURES. COOLED IN AIR. MATERIAL FROM SHEAHAN'S QUARRY, GRANITEVILLE.

Number	Temperature for 30 minutes	Area of crushing surface	Crushing strength (Total)	Crushing strength per sq. in.	Remarks.
1	20°C	4.0	52,320	13,080	Average of two blocks.
2	250°C	4.0	63,560	15,890	No change.
3	300°C	4.0	58,140	14,530	Slightly bleached.
4	350°C	4.0	46,840	11,710	Slightly bleached.
5	400°C	4.0	39,830	9,960	Slightly bleached.
6	450°C	4.0	21,930	5,480	Cracks in feldspar and quartz. Quartz whitened. The
7	475°C	4.0	31,000	7,780	Cracks in feldspar and quartz. remainder of the series
8	500°C	4.0	26,990	6,750	Small crack across the face. ring on scratching.
9	550°C	4.0	12,070	3,020	Number of small cracks.
10	575°C	4.0	17,400	4,350	Number of small cracks.
11	625°C	4.0	16,950	4,240	Cracks readily visible to eye.
12	650°C	4.0	13,960	3,490	Cracks larger. Light pink.
13	725°C	4.0	15,750	3,940	Cracks large. Pink.
14	750°C	4.0	15,330	3,830	Many small cracks.
15	775°C	4.0	15,960	3,990	Several large cracks.
16	850°C	4.0	10,250	2,560	Several large cracks.
17	900°C	4.0	5,960	1,490	Cracks large and numerous. Much shattered.
18	1000°C	4.0	6,700	1,670	Shattered. Ferromagnesian minerals fused to a slag and the feldspar fused to small drops of glass.

rapid to 500° C. or 600° C. but from this point to about 800° C. the rock is rendered worthless, retaining only ten to fifteen per cent of its crushing strenth.

While there does not appear to be a definite point at which the strength suddenly fails, a rock heated to 500° C. or 600° C. loses the greater part of its strength and is unfit to bear a very large load. At 1000° C. the rock is completely destroyed and can be crumbled in the fingers.

Tests were made for the expansion, at 500° C. and at 750° C., on blocks approximately seven and one-half inches long and two inches square. Three blocks were measured and then placed in the furnace and the temperature gradually brought to 500° C., where it was held for thirty minutes. They were then taken out and measured and allowed to cool in the air. The other three blocks were treated in a like manner except the temperature was 750° C. The table given later shows the results (table 5). The average permanent expansion per inch as shown by the table is .00483 for the temperature of 500° C. or .000,966 for one degree, and .01299 for the temperature of 750° C., or .000,017,3 for one degree. These values are about the same as those of previous determinations.

Four paving blocks, which were about five by seven by twelve inches, were tested to find the effect of heat on larger blocks. Two of these blocks were brought to 500° where they were held for thirty minutes. One of the blocks was allowed to cool in air, the other was cooled in water. The other two blocks were subjected to the same treatment at a temperature of 750° C. Cracks which ran in all directions were developed in these blocks. Those which had been heated to 750° were fractured more than those at 500°. A fairly large piece split off the block which had been heated to 750° and cooled in water.

CHAPTER III

THE EFFECTS OF HEATING ON THE GRANITES

Before the crushing strength of the heated cubes of granite was determined, each one was carefully examined and the effect of the heat and the subsequent treatment noted. These observations thus indicate in a general way what the resulting effect would be if the granite were exposed to the heat of a conflagration, which McCourt regards as being about 843° C. or 1550° F. The temperatures in some fires no doubt go higher than this.

After a careful study had been made of the blocks, they were crushed and slides were made of some of the sets to determine what effect, if any, the heat had upon the inclusions in the quartz, especially the liquid and gaseous inclusions. As far as the writer is aware this is the first time slides of the rock tested have been made before and after heating, and the results are of interest in throwing light upon the oft repeated statement that the liquid and gaseous contents of the cavities are a probable factor in the disruption of the granite.

EXAMINATION OF THE HEATED CUBES, MEGASCOPICALLY AND WITH A BINOCULAR MICROSCOPE

The polished faces of the cubes lend themselves, especially, to the study of heat effects, as they show the cracks beautifully. All observations made were made upon these faces. It was found that a Leitz Binocular microscope with magnifications of from twenty to fifty-five times was a very valuable aid in the study. It enabled one to see the cracks in their true relationship to the inclusions, and other physical properties of the minerals.

Set I. Sheahan's Present Quarry.

Number 1, 500° C., air-cooled.

The original dark red color of the granite was bleached to a pink during the heating. Many small cracks were developed, the largest being .05 mm. in diameter, while a given crack is usually largest near the edge of the cube. (See fig. 4b.) There are usually only one or two large cracks on the side of a cube and these are near the center, and run more or less parallel to the sides. The cracks usually pass around the quartz grains which are less than 1.5 mm. in diameter, but cross all larger quartzes and also the other minerals. They follow the cleavage and twinning planes of the feldspar, and as the plane of contact of two minerals is a plane of weakness, a crack usually develops there also. These last mentioned cracks are especially noticeable at the contact where a thin fragment of a quartz grain lies upon the surface of the cube.

The larger grains of quartz became a more or less milky white in color. The smaller ones remained clear and transparent. This change of color is due to the development of numerous cracks which are roughly parallel, or make a slight angle, with the surface of the cube. The binocular showed that the numerous cracks were developed without regard to the lines of inclusions in the quartz. The cracks may parallel a line of inclusions for a short distance, then turn and cross it. It is rather surprising that so few follow the lines of inclusions, for theoretically, these should be lines of weakness and thus should be followed for this, if for no other reason. No cracks could be observed which passed from the lines of inclusions to the surface of the quartz. A comparative study of the quartz in the fresh and heated granite showed that the lines of inclusions were the same in both.

The cracks in the feldspar followed the cleavage or the twinning planes. They are especially noticeable when these planes are at an angle of forty-five degrees or less to the surface. Often the crack along a cleavage plane intersects another crack, and then the fragment of the mineral drops out entirely. The biotite usually expands quite markedly and so projects a little above the surface.

That the stone as a whole is rendered more porous as the result of heating is shown by the peculiar, ringing sound emitted by it on being scratched. Buckley has compared this sound to that observed on scratching a brick. The sound is due to the state of tension which the mineral particles are in, because of the permanent expansion from the heating. Each one acts like the string of a musical instrument, picking up the vibrations produced by the scratching and intensifying it, aided by the increase in pore space from the development of cracks.

Number 11, 500° C., water-cooled.

The color was about the same as that of No. 1, but the more prominent cracks appeared to be larger and slightly more numerous. (See fig. 5a.) The most marked difference was in the cracks in the quartz which were very numerous but were, for the most part, perpendicular to the polished surface. This distribution of the cracks is to be noticed, for in the specimen cooled in air the cracks were not prominent unless more or less parallel to the surface. Not only were these perpendicular cracks found in the quartz, but also in the feldspar to a certain extent. They did not have any recognizable relation to the lines of inclusions in the quartz, and were largely unaffected

a

b

Fig. 1. Sheahan's Quarry.
a. Polished face of granite cube.
b. Rough face of granite cube.
About 1.5 times actual size.

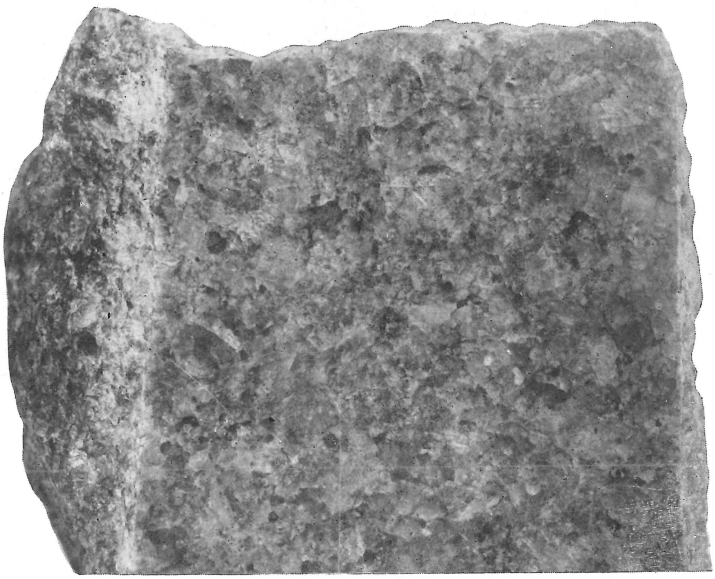


Fig. 2. Fresh granite. Sheahan's Quarry. Note the numerous cracks in the quartz. About twice natural size.

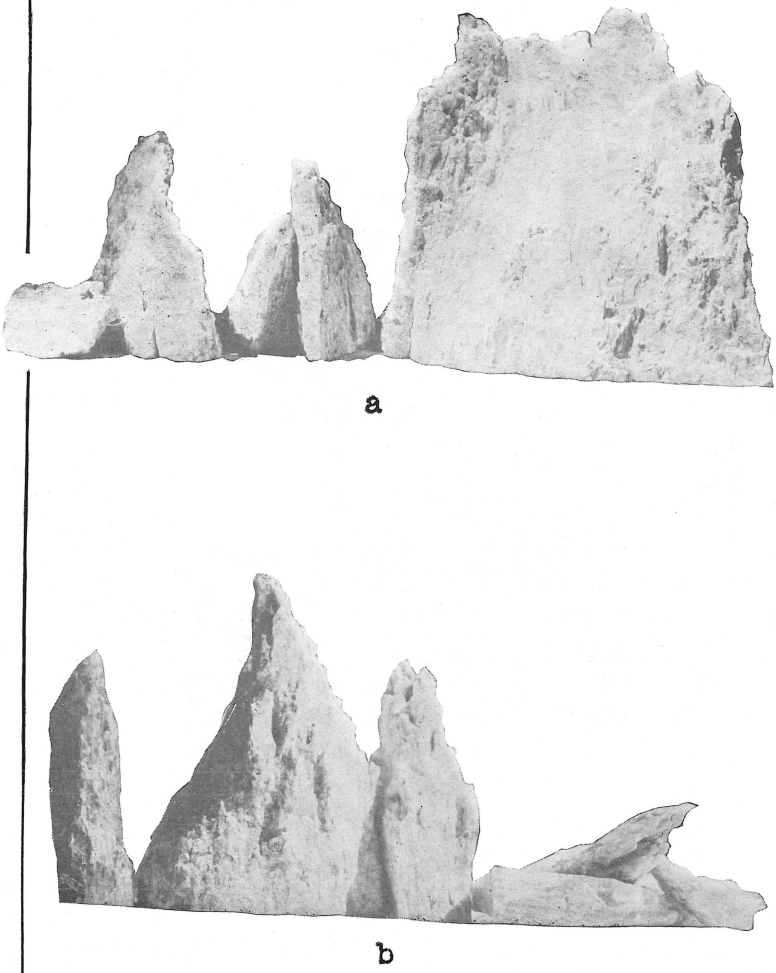
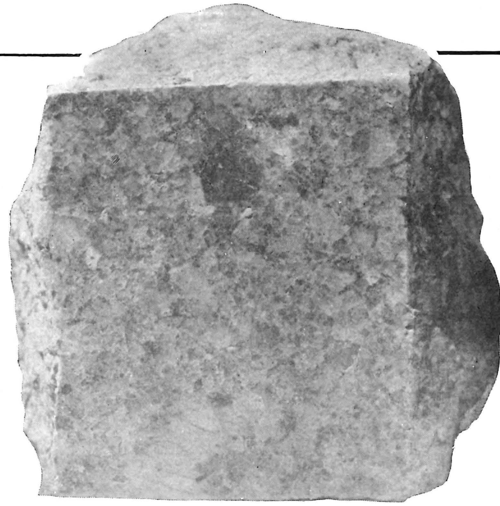
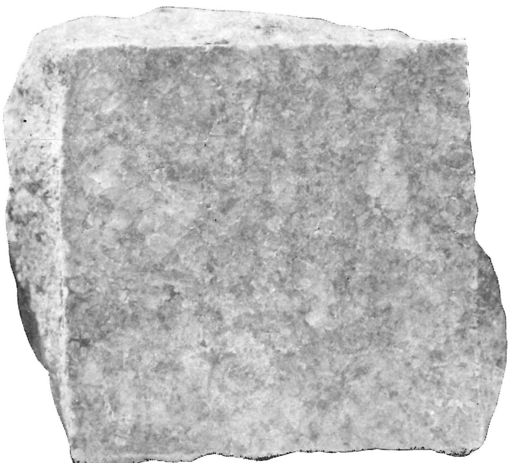


Fig. 3. Shape of fragments after crushing unheated cones.

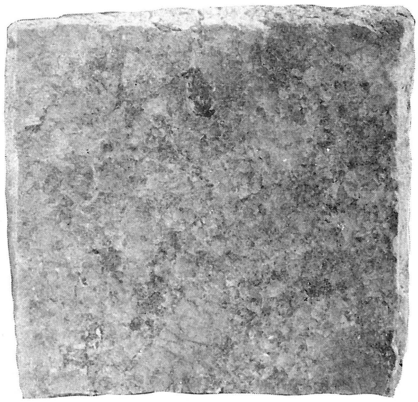


a

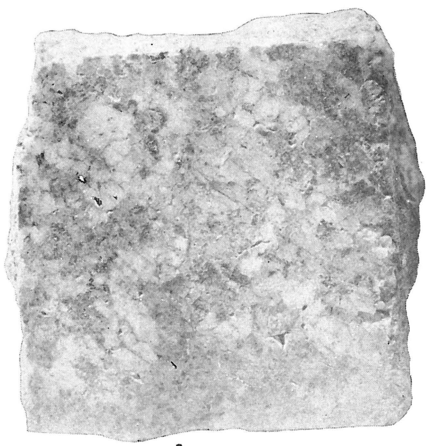


b

Fig. 4. Granite from Sheahan's Quarry.
a. Unheated.
b. Heated to 500°C. air cooled.



a



b

Fig. 5. Granite from Sheahan's Quarry.
a. Heated to 500°C. water cooled.
b. Heated to 750°C. water cooled.

The quartz in b is white, due to the shattering by the water. Note the small holes where fragments have dropped out.

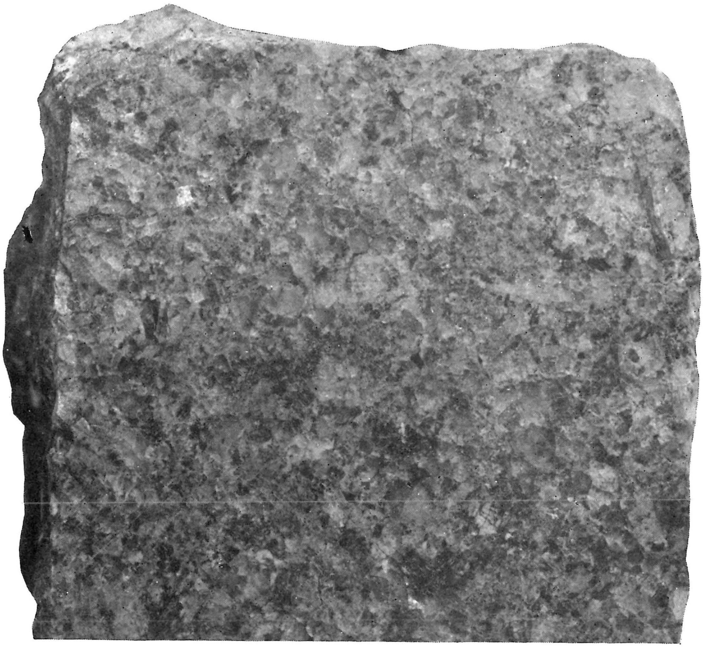


Fig. 6. Heated to 700°C.air cooled.
Sheahan's Quarry.
About 1.5 times actual size.

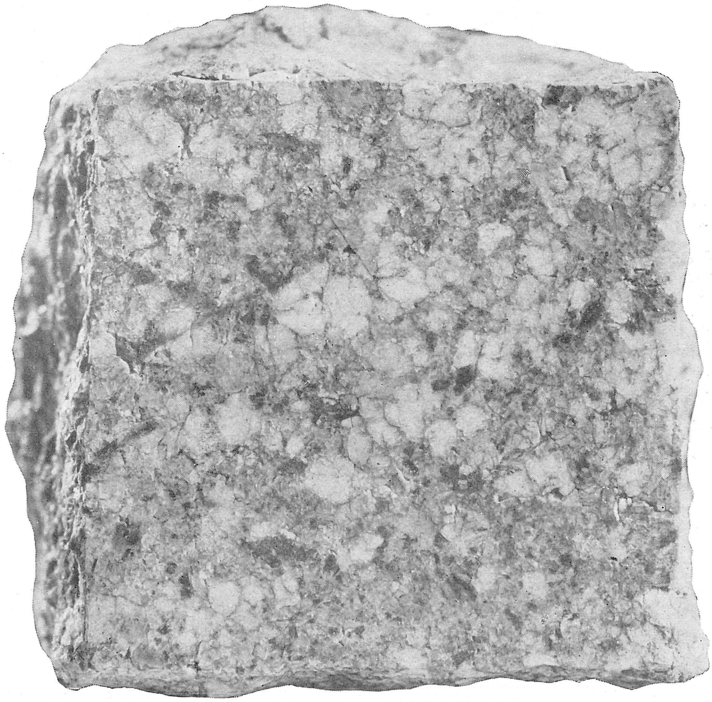
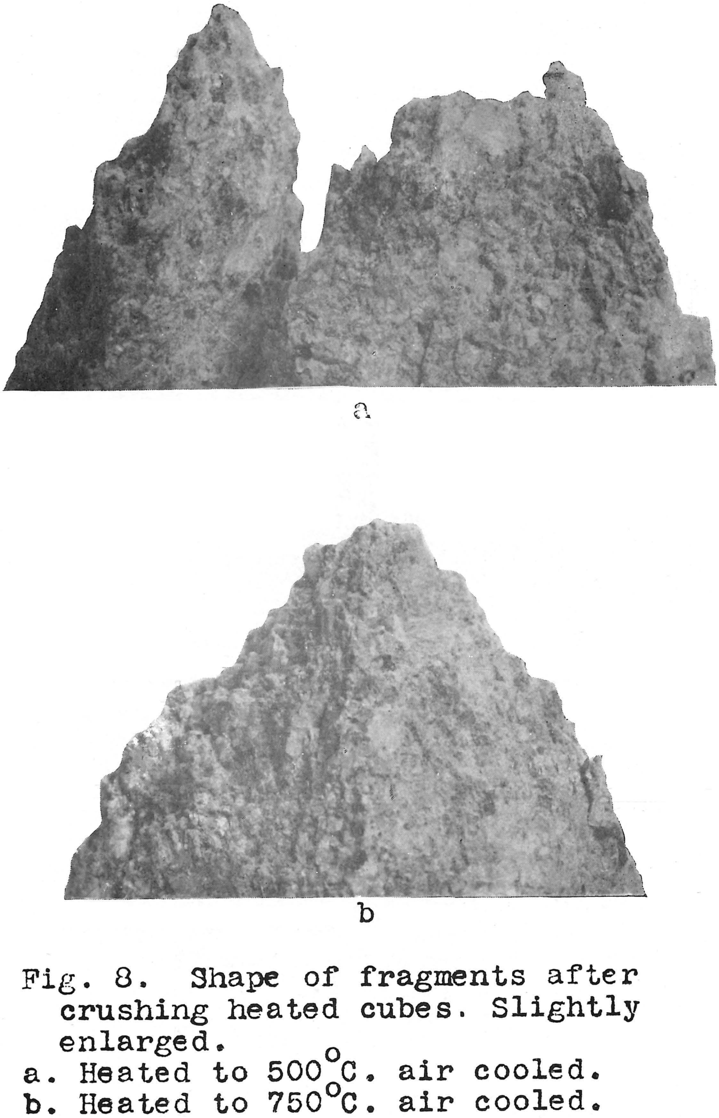


Fig. 7. Heated to 750^{o}C. water cooled.
Sheahan's Quarry.
Note the white color of the quartz in this figure. Compare with Fig. 6, which was air cooled.
Enlarged nearly twice.



a

b

Fig. 8. Shape of fragments after crushing heated cubes. Slightly enlarged.
a. Heated to 500°C. air cooled.
b. Heated to 750°C. air cooled.

TABLE 5. EXPANSION OF GRANITE. MATERIAL FROM SHEAHAN'S QUARRY, GRANITEVILLE, MISSOURI.

Number	Temperature Centigrade.	Length before heating. inches.	Length while hot inches.	Length when cooled. inches.	Expansion while hot. inches.	Permanent expansion. inches.	Average permanent expansion. in. for 500°C	Average permanent expansion for one degree in inches.
1	500°	7.6719	7.7188	7.7031	0.0469	0.0312		
2	500°	7.6250	7.6875	7.6719	0.0625	0.0469	0.00483	0.000966
3	500°	7.5625	7.6250	7.5938	0.0625	0.0313		
4	750°	7.6562	7.7812	7.7656	0.1250	0.1094		
5	750°	7.5938	7.7188	7.6875	0.1250	0.0937	0.01299	0.0000173
6	750°	7.5938	7.7188	7.6875	0.1250	0.0937		

by the cleavage planes in the feldspar. These cracks appear to owe their origin to the strains set up in the surface by the rapid cooling in water, for they do not extend very deep, only about one millimeter in the specimens heated to the higher temperature.

The biotite was bleached to a brown color. The twinning lines of the plagioclase are often seen in the heated specimen, and are probably due to the accentuation given them by the heating. The surface has a peculiar shagreened appearance and the cube emits the ringing sound when scratched.

Number 7, 750° C., air-cooled.

The rock was bleached to a lighter pink than either of the cubes heated to 500° C. The surface was roughened by the unequal expansion of the various minerals, and the rock is more friable than the others. The cracks were larger and more numerous than in the other cubes, likewise, the smaller cracks appear more numerous in the quartz than in the feldspar. They are about one millimeter long and one-fourth millimeter in diameter, thus having the appearance of slender rods.

As to the relationship of the cracks to the inclusions in the quartz nothing could be seen. They were in quartz grains which were perfectly free from inclusions, as well as in those which contained the inclusions scattered through the grain, rather than in rows. Often they were more numerous around the borders of the larger crystals than in the inclusion-filled, central parts. Many small quartz grains were free from cracks.

Number 9, 750° C., water-cooled.

The surface of the specimen was roughened, and the cracks developed were about the same as the last specimen described. (See fig. 7.) When scratched it emitted a marked ring which sounded as though the minerals were loosely held together. Further evidence of this friable character is found in the numerous small chips that come off the sides by handling. The color is the same as in No. 7.

Nearly every grain of quartz is white because of the innumerable small cracks which fill it. (See fig. 7.) It is completely shattered, the cracks being about roughly perpendicular and about a millimeter in depth. The resulting particles were about .05 mm. in diameter. The shattering was caused by the sudden immersion of the quartz in water. The cleavage lines of the feldspar are more prominent than they were in the previous specimens. The color of the biotite was changed to a golden brown, and the crystals were permanently expanded so that they projected above the surface of the cube.

Set II. Sheahan's Present Quarry.

Number 1, 500° C., air-cooled.

The original dark red color was bleached to a pink. Two rather large, prominent cracks were developed on each face, one being larger than the other. Many cracks were developed around the minerals of the rock. The surface was slightly roughened from their permanent expansion, especially from that of the feldspar crystals.

The quartz was slightly whitened from the incipient cracks which were developed in it. They are found in the crystals that are free from inclusions as well as in those filled with them, showing that the inclusions are not essential to their formation. The cracks resemble those developed in the specimens heated to 750° C., and are mostly perpendicular to the surface. The feldspar has cracks along the cleavage and twinning planes, as usual.

Number 6, 500° C., water-cooled.

The color and roughened surface are about the same as in No. 1. There was a large crack on the face which rested upon the bottom of the muffle in the furnace and a smaller one on the top face. These run roughly parallel to the sides of the cube. The cracks around the grains are smaller and more numerous than in number one. This is due to the sudden cooling.

The cracks in the larger quartz crystals, which are of a marked whitish color are very abundant and produce a series of polygonal rods of more than a millimeter in length. The small, thin grains of quartz, less than .5 mm. in diameter, which lie on the surface have pulled away, developing a crack behind them. The cracks are present, irrespective of any inclusions and do not appear to be in any way connected with them. The feldspar has the usual fractures along the cleavage planes.

Number 2, 700° C., air-cooled.

The color of this specimen did not become paler at the higher temperature as in the first set. (See fig. 6. Compare with fig. 7.) The surface was very much roughened and had the appearance of being shattered, the cracks bearing this out, for they were larger than in the other specimens of this set but no more numerous. Four fairly large cracks developed on the base and only one small one on the upper surface. This was due, no doubt, to the floor of the muffle being hotter. The cracks around the grains were no more numerous but were larger than in those at the lower temperatures.

The quartz contains the usual inclusions in clouds and lines, but those crystals which were free from inclusions were as full of cracks as those with them. They were perpendicular to the surface and formed small parallel, polygonal rods. The feldspar was much shattered in the same manner as in the other cubes.

Number 5, 700° C., water-cooled.

The color and surface were the same as the other specimen heated to 700° C. There were several prominent cracks on the base and some small ones on the top, and there were many small cracks around the grains.

The quartz was completely shattered and its color was white. The cracks were perpendicular to the surface and the result was a series of polygonal rods. Cracks in the feldspar followed the cleavage planes, but it was no more shattered than in the specimens heated to 500° C. The cracks in the quartz show no relationship to the inclusions.

Set III. Sheahan's Old Quarry.

Number 3, 500° C., air-cooled.

This rock was coarse-grained, slightly porphyritic and of a dark red color. It was bleached to a pale, pinkish red. It appears to have been the least affected of any of the sets. There are no large cracks, and only one small one on each face. There are many small ones around the crystals. The surface is not roughened to any extent. The quartz, on the whole, is clear and transparent and is not greatly affected with cracks, probably because of the smaller average size of the quartz grains in this rock. They are more or less incipient cracks, nearly perpendicular to the surface and resemble lines of inclusions, in fact, some may be along such lines. The feldspar was affected as in all the other specimens. There does not appear to be much difference in the effect of heat on the feldspar. It cracks along lines of weakness at either of the temperatures used.

Number 1, 500° C., water-cooled.

This granite was bleached as was number 3, but it does not show any large cracks. The usual cracks at the contacts of the minerals are larger than in number three, probably because of the cooling in water.

The quartz in small grains, those less than 1 mm. in diameter, is very clear, with only an occasional incipient crack. The larger crystals are very much shattered. Evidence which shows that the cracks are not related to the inclusions was found in this specimen. The cracks were very numerous and were parallel. In a basal section of quartz they were parallel and inclined, suggesting that they were produced along the cleavage lines of the quartz. The quartz which showed this was clear and transparent, indicating the absence of inclusions. Cracks were just as abundant in the clear quartz as in that with inclusions.

Number 5, 700° C., air-cooled.

The color produced by the heating was a pinkish red. A few medium-sized cracks developed on the surface, while there were a great many around the minerals, especially the larger ones.

Many incipient cracks were developed in the quartz, parallel to each other even in the smaller crystals. They were often inclined, but were also perpendicular to the surface. Occasionally these cracks are at an agle of 120° to each other, which is significant, in view of their being along the cleavage lines of the quartz. Other quartz grains show the numerous small rods, developed by the cracks being perpendicular to the surface. Some of the small, transparent crystals show incipient cracks. The feldspar is cracked as usual.

Number 2, 700° C., water-cooled.

The color produced was a reddish pink, and the surface was rough from the varying expansion of the crystals. Some large prominent cracks pass through the cube, passing around or cutting through the crystals.

The quartz was completely shattered, and consisted of a mass of small rods, as in the other specimens heated to this temperature and cooled in water. The rods are from .1 mm. down, usually less than .05 mm. The feldspar was affected as usual.

Set IV. Schneider's Quarry.

The fresh, unheated specimen was a coarse-grained, dark red rock. Incipient cracks appeared at the contact of the various minerals, while the quartz was very much shattered, especially the larger pieces. The feldspar, also, contained some cracks.

Number 4, 500° C., air-cooled.

The rock was bleached to a dark pink. Some small, rather prominent cracks developed on the polished face, otherwise the cracks are hardly more numerous than they are in the fresh rock. The cracks at the contact of the minerals are larger, and the slight movement from the expansion at these places has fractured the minerals so that they appear white from the reflected light from each small particle. Much of the quartz is greatly shattered, but this was the case in the fresh specimen. The inclusions are abundant in some crystals. The feldspar, also, was cracked.

Number 1, 500° C., water-cooled.

The color was the same as in No. 4, but the cracks were larger and more numerous than in the air-cooled specimen. The quartz was badly shattered, largely by cracks which are perpendicular to the surface and which produce polygonal rods. This is especially true of the thin fragments of quartz lying upon the surface. The cracks in the quartz are not related to the inclusions. The feldspar is cracked as usual.

Number 5, 750° C., air-cooled.

The rock was bleached to a pale pink. It contains many large, prominent, and quite numerous cracks. The specimen emits the characteristic sound when scratched, and the surface is slightly roughened from the unequal expansion of the various minerals. The cracks in the quartz are perpendicular to the surface and are very numerous. Many cracks were observed which crossed the lines of inclusions and possibly some are along these lines although this cannot be affirmed. The feldspar is cracked as it is in the other specimens.

Number 2, 750° C., water-cooled.

As in all the specimens heated to the higher temperatures, the quartz was completely shattered. It was composed of small rods arranged perpendicular to the face. The feldspar was expanded and split along the cleavage planes. There are some large cracks which cross each other at about right angles, while the surface is rough. Several fragments, small and thin, spalled off the sides.

Set V. Paving-block Material from Schneider's Quarry.

This material was fine-grained and porphyritic. It was brownish red to pinkish red in color. The largest phenocrysts of feldspar were not over one and half centimeters in length, while the largest crystals of quartz did not exceed one centimeter in length.

Number 1, 500° C., air-cooled.

This specimen was bleached to a pink red. There were three prominent cracks on one face and one on the other. The fine-grained ground-mass appears to be full of cracks, largely along the contract of the minerals. Some of the quartz has a milky color, apparently due to inclusions. Nearly all the crystals of quartz are cracked, some with incipient cracks only. They appear in those with inclusions and in those that are clear. Many are parallel and often inclined to the surface, probably along the cleavage lines of the quartz. The feldspar has many cracks.

Number 2, 500° C., air-cooled.

The color is the same as in No. 1, and the surface is roughened from the permanent expansion of the minerals. One very large crack goes through the center of the cube and there are also several prominent ones, all of which pass straight through every mineral. The large quartz phenocrysts are shattered and even the smaller crystals have a great many cracks. Most of the cracks are perpendicular to the surface, while occasionally they are parallel and inclined. Only a few of the quartz grains contain inclusions and all are shattered, even the small ones with perfect faces.

Number 6, 750° C., air-cooled.

This specimen was bleached by the heat to a lighter shade of pink than was No. 2. The surface was roughened and shows one or two rather marked cracks and several small, minor ones. It emits a ring on being scratched. Some of the larger quartz crystals contain inclusions, but all are shattered, the larger ones especially so. The cracks in the feldspar are along the cleavage planes.

Number 8, 750° C., water-cooled.

The color is the same as that of No. 6, and the surface was roughened. There are a few fairly prominent cracks which are usually in the center. All the quartz is completely shattered by the usual, perpendicular cracks. Some appear to be parallel to cleavage cracks. The feldspar is badly cracked also.

Set VI. Missouri Granite Construction Company.

Number 1, 500° C., air-cooled.

The color of this specimen after heating is a light pink. A few cracks developed along the edges of the cubes but they are not large. Some occur around the minerals. The most prominent are those along the cleavage planes of the feldspars. There are many cracks in the quartz and many beginning to develop. They run in all directions and some of the cloudiness of the quartz may be due to the incipient cracks.

Number 2, 500° C., water-cooled.

The color produced is the same as in No. 1, but the cracks are larger, extending nearly across the cube. The surface is roughened considerably. All the quartz is very much shattered by perpendicular cracks, and many incipient cracks add to the milky white color caused by the inclusions. The former are not related to the inclusions, but the latter may be.

Number 4, 750° C., air-cooled.

The color produced is the same as that of No. 2, but the surface is rougher. There are two large cracks which pass partly through the specimen on one face, and there are several small ones on the other face. The cracks in the quartz are slightly more numerous than in specimen number 2, but are of the same general character. There is no evident connection with lines of inclusions. The biotite is a deep brown.

Number 3, 750° C., water-cooled.

The color and surface are the same as those of No. 4. The cracks in the interior of the face are better developed. There are no large cracks. The quartz and feldspar are full of cracks, as usual. The former is greatly shattered and cracks are no more numerous in those with inclusions than in those without.

Set VII. Milne and Gordon Quarry, Syenite, Missouri.

Number 4, 500° C., air-cooled.

The color caused by the heating is a pale grayish pink, grayish because of the biotite it contains. Only one polished surface shows any cracks, and but three of these were very prominent. This same face had many small cracks well developed, but there were only a few incipient ones on the other face. The quartz shows a great many inclusions scattered throughout the crystal but not arranged in lines. The cracks in it are numerous and perpendicular, but some may be parallel to the surface. The feldspar is cracked along the cleavage planes.

Number 5, 500° C., water-cooled.

The color of this specimen was the same as that of No. 4, with several prominent cracks in the middle of the face. There are numerous small cracks around the grains and they are more abundant in the bottom face, that is, the one that rested on the bottom of the muffle. The quartz does not appear to be more cracked than in the air-cooled specimen. The specimen appears firm, and emits a ringing sound when scratched.

Numbers 1 and 3, 750° C.

These speciments fell to pieces in the muffle when they were touched with the tongs to remove them. The fragments were about an inch square and one was curved so that one edge was one-fourth of an inch higher than the other. The quartz was full of cracks. The probable cause of the disruption of the specimens was the expansion of the biotite books or crystals, which were very numerous in the rock. They were greatly expanded.

Set VIII. Gilsonite Quarry, Knoblick, Missouri.

Number 1, 500° C., air-cooled.

The original color of this granite was gray but it was bleached to a pinkish gray. There was one large crack and one or two small ones. The quartz grains are small and all are more or less cloudy, although only the larger ones are cracked. Incipient cracks appear at the contact of the minerals. There are cracks in the feldspar. The quartz and feldspar are cracked especially around the numerous basic inclusions, where these have well defined borders.

Number 3, 750° C., air-cooled.

The color produced in this specimen is the same as that of No. 1. A very large crack runs through the center, and there are also a few small ones; otherwise the specimen is the same as No. 1.

Number 3, 750° C., air-cooled.

The color is a lighter, pinkish gray than that of No. 2. One fairly large crack was developed on each face. The binocular showed many small cracks which appear to be at the surface. The quartz is much shattered but the cloudiness of the inclusions is still preserved.

Number 4, 750° C., water-cooled.

The color produced in this specimen is the same as that of No. 3, all the feldspar having a pink color. There was a slight roughening of the surface. One very large crack runs through the cube. The large quartz crystals were completely shattered, but the smaller ones being already very small do not show the water-effects. The quartz is clear save for cracks and inclusions. The chloritic green of the feldspar was changed to a yellowish brown color.

SUMMARY

The study of the heated specimens shows that the granites from each locality are more or less affected by the high temperatures. The material from one of the quarries is not on the market at the present time, but it was included in the series tested, because of its fine-grained texture and slightly different mineral composition; thus giving the results a wider application.

The original color in all the granites was changed to a lighter shade by the heating. The feldspar became a lighter pink and the quartz usually a milky white, while the biotite changed from black to golden brown.

The rock became more porous as is shown by the sound emitted on scratching the specimen, by the roughened surface due to permanent expansion of the different minerals, and by the cracks. All the specimens were cracked to a certain extent. The size and continuity of the cracks vary with the texture of the rock, being much less well defined in the coarse-grained ones. Also the higher temperature of the bottom of the muffle often caused more cracks to develop there than on the top. In the coarse-grained granites the stresses produced by the heat found relief by developing cracks around the larger crystals of rock. Such cracks are very common in all the rocks of this texture. The larger cracks usually pass through all minerals alike, unless the crystals of the minerals are small. They follow the cleavage and twinning planes of those minerals that have them, but go straight across those that do not have these planes of weakness well developed. Since feldspar has two good cleavage directions and is very often twinned it is full of cracks of all sizes. The cleavage planes make all kinds of angles with the surface and when these are small and intersect cracks fragments of the mineral fall out on handling them.

The quartz is the most interesting of the minerals, for it contains the inclusions which are supposed to aid in disrupting the rock. The study shows that there is no connection between the inclusions and the cracks which cross the quartz. The mere presence of a series of inclusions in a line, whatever they were, would make the plane that contained the line a plane of weakness, and one which a crack produced by relief of stresses in a strained mineral would be likely to follow. As far as can be seen by using the binocular microscope this has probably been the case in some instances, yet the great majority of the cracks are not related in any way to the inclusions of the quartz. They may cross them or be parallel to them in any position.

On the whole, the temperatures used are detrimental to the granite. The strength is decreased in all of the granites, and very decidedly so in some of them. The rock is made more porous, which renders it especially liable to attack by air and water.

RESULTS OF MICROSCOPIC STUDY OF THE HEATED GRANITE

Slides of the heated rocks were made for microscopic study, as was stated above. The study was especially valuable in showing the changes which were produced in the internal structure of the component minerals of the rock. The results cannot be tabulated, hence a brief description of the slides by sets will be given. Much repetition will be saved by stating certain facts which were common to all the slides.

As the material from which the slides were made was very friable, in making the thin sections of the rock required for microscopic work, the minerals were pulled apart along the more prominent lines of weakness, especially along the cracks developed in the heating. However, for the most part, the separated pieces preserve their positions relative to each other, so that no difficulty was found in studying the character of the line of separation.

The composition of the rocks is, of course, the same as that of the original specimens, so the description given above applies to the slide of the heated rock as well. The feldspars which were very much altered to kaolin are much darker in all the slides of the heated rock. The feldspar shows a slight widening along the cleavage planes, due to the expansion. The biotite, especially the brown colored variety, usually became darker. The iron oxides were not changed save for the development of a little more hematite than the original rock contained. The other minerals, with the exception of the quartz, are very few and are not noticeably changed. The quartz was very carefully studied, of course, and will be fully described in the following pages.

The study includes the size, kind, and arrangement (whether in lines or disseminated) of the inclusions, the size and continuity of any cracks which are in the quartz and their relationship, if any to the inclusions.

Material from Sheahan's Quarry, Graniteville, Missouri

500° C., air-cooled.

The smaller grains of quartz (those under one millimeter in diameter) are often completely shattered, the cracks producing roughly polygonal areas, usually less than .026 mm. in diameter. Rarely, there are some lines of inclusions in these smaller crystals. The larger ones, with many inclusions, are only slightly shattered. In some of the crystals there are numerous, parallel, incipient cracks that are inclined to the surface. These were very frequently noted in many of the slides and are believed to be cracks just beginning to develop along the cleavage planes of the quartz. They may or may not be near or cut across a cavity containing liquid or gas. When they do cut such a cavity there is no change in it. The inclusions consist largely of cavities which contain some liquid and gas, and small grains of fluorite and other minerals. Just what the material in the cavities is, is not known, but it is probably largely water or water vapor and in small part, carbon dioxide which is quite common in such cavities.

It is an interesting fact that not a single moving bubble could be identified in any of the slides of the heated rocks. On the other hand, the cavities are more prominent and easily recognized in the heated specimen than in the unheated rock. They are darker and the borders of the inclusions are broader, in fact, they appear to be gaseous rather than liquid. Occasionally the inclusions are in well defined lines, more or less wavy, but the cracks which are developed, cross them at various angles or run parallel to them. There is no apparent connection between the two.

500° C., water-cooled.

Cracks do not appear to be more numerous in this specimen than in the one cooled in air. The effect of the water has been to produce, either large cracks which pass entirely through the block, or very small ones on the surface. The slide was made of material taken from the interior, hence no marked increase was to be expected. The inclusions are similar in amount and arrangement to those in the air-cooled specimen. The cracks are not related to the inclusions.

750° C., air-cooled.

The slide contains a great many cracks, and the minerals are shattered, the quartz especially so. Some of the crystals of the latter are free from inclusions of gases and liquids and yet are full of cracks. Others contain many lines of inclusions, but they are not genetically related to the cracks. No moving bubbles were found. Under crossed nicols the quartz shows a shadowy strain effect, but it is very poorly developed.

750° C., water-cooled.

On the whole this block is more shattered than the air-cooled one. The quartz shows this especially well. It is full of inclusions, arranged in lines and disseminated, but the cracks it contains are not necessarily controlled by their position except when the inclusions are very abundant and in a line, in which case the crack may follow them a short distance. They run in all directions.

Material from the Missouri Granite Construction Company, Knoblick, Missouri

500° C., air-cooled.

The quartz contains a great many inclusions, usually in nearly straight lines. The lines of inclusions in adjacent crystals are sometimes parallel. The inclusions are mainly of liquid and gas. The cracks cross them at all angles and are not genetically related to them.

500° C., water-cooled.

The quartz, especially that of the larger crystals, contains a good many cracks. Occasionally one is along the lines of inclusions, of which the mineral contains a great many, but the majority of the cracks do not follow such lines of inclusions. Some of the quartz contains some very small, parallel, incipient cracks. These may or may not cut through the inclusions. Occasionally they make an angle of 120° with each other. The inclusions are largely gaseous, with some liquid ones. No moving bubbles could be found.

750° C., air-cooled.

All the minerals on the slide are greatly shattered. The feldspar shows a widening along the cleavage planes. The quartz is especially shattered. It usually contains many inclusions in rows, some as broad, heavy lines. Cracks follow these larger lines of inclusions but they change their direction without regard to the line of inclusions they may be following. The cracks are just as numerous in those crystals of quartz which do not contain inclusions or in which they are disseminated. Many broad lines of inclusions are free from cracks entirely. The incipient, parallel cracks are larger and more abundant than in the block heated to 500° C. They are as common in areas free from inclusions as in those which contain them.

750° C., water-cooled.

The quartz of this specimen contains the usual amount of inclusions, both in lines and disseminated. There are some grains quite free from scattered inclusions. The cracks run in all directions and may follow a row of inclusions or may cross it at all angles. Incipient, parallel cracks are developing in some of the crystals of quartz. They may cut across a cavity, for they are often in quartz which is full of inclusions. The inclusions do not appear to be changed by the crack.

Material from the Milne and Gordon Quarry, Knoblick, Missouri

500° C., air-cooled.

A slide of the material from the outside of the block and one of the material from the interior were made from this specimen. The quartz is quite full of dark inclusions, in rows and scattered, which are largely gaseous, but some liquid, and some mineral inclusions occur. The quartz shows only a few cracks and these have no relation to the position of the inclusions.

500° C., water-cooled.

The quartz contains as many inclusions as there are in the above slides, but it is very much shattered in this one. The cracks run in all directions and are not connected genetically with the inclusions.

750° C., air-cooled.

The two cubes heated to 750° C. fell to pieces when touched with the tongs to remove them from the furnace muffle. Both were air-cooled. Slides were made of the outside and inside material, but there is no difference between them. The quartz contains many inclusions, the majority of which are gaseous or liquid, with some mineral inclusions. There are some parallel, incipient cracks in quartz which is with or without inclusions. Some of these cracks are very well developed, in fact, better than in any of the slides. The larger cracks sometimes follow the inclusions but they also cross them.

Material from the Gilsonite Quarry, Knoblick, Missouri.

This material was tested because it was fine-grained. Only two slides were made.

500° C., water-cooled.

All the minerals in this specimen are very small. The quartz contains only a few inclusions, which are disseminated and in rows. Cracks are fairly numerous but they cut across or around the grains. They usually do not follow the lines of inclusions.

750° C., water-cooled.

The inclusions in this specimen are the same as in the above slide. The cracks are about the same, save a majority of them go around the grains rather than through them.

Material from Graniteville, Missouri

The following slides were made from some fragments of the Graniteville granite. It was not intended that slides should be made of them when they were heated, but the temperatures were carried to 850° C. and 900° C., so it was decided to do so, to compare the results with those obtained from heating to lower temperatures.

850° C., air-cooled.

The quartz contains the usual inclusions, gaseous and liquid with some mineral ones, arranged in rows or disseminated. The cracks are very numerous, but their directions are not controlled by the lines of inclusions. They pass in all directions through the quartz. A very interesting feature, seen for the first time in this slide, is the wavy extinction of the quartz and feldspar. It is wonderfully well developed in the quartz, and fairly well in the feldspar. It is due to the strains produced in the mineral by the high temperature.

850° C., air-cooled.

The wavy extinction seen in the slides described above, occurs in this one also. The inclusions are the same as usual. The quartz is much more shattered than in any other slide studied. The fragments range in size from .078 mm. to .266 mm. or larger. Probably from fifteen to twenty-five per cent of the cracks follow the lines of inclusions. This is to be expected for the quartz is broken up into smaller fragments than has been heretofore seen. The feldspar shows cracks developed along the cleavage lines. The cracks become very irregular when they are in a feldspar crystal that is much altered to kaolin.

900° C., air-cooled.

The wavy extinction and shattering are prominent features in this slide as they were in the last one described. The quartz is very much granulated, and even the feldspar is so, along its contact with other minerals. While the minerals are shattered, only a part of the cracks follow the rows of inclusions.

900° C., water-cooled.

This slide shows essentially the same features as the other one which was heated to 900° C. Inclusions are the same as in the other rocks, and are not genetically related to the cracks.

SUMMARY

The microscopic study of thin sections shows that the moving bubbles have disappeared in the heated sections, and that the inclusions which contained gases and liquids, are darker and have broader margins. The cavities which contain liquids and gases are just as numerous as in the unheated specimen and are arranged in the same way. They do not show cracks associated with them. The quartz shows many cracks which run through it in various directions but which may or may not follow the lines of inclusions. Incipient, parallel cracks have developed in the quartz. They are probably along the cleavage lines of the quartz. They often cut through an inclusion but do not produce a change in it. Both of the above types of cracks are just as common in the quartz which does not contain any inclusions as in that which does.

CHAPTER IV

THE CAUSE OF THE DISAGGREGATION OF THE GRANITE

That there was a great loss of strength, when the granite was heated to high temperatures, is indicated by the tables and the curves, which show the results of the strength tests. The decrease in strength was greater up to 500° C. than afterwards, but the rock was completely destroyed at 1000° C. The greatest resistance to high temperatures was shown by the fine-grained granites, while the coarse-grained ones, like the Graniteville granite, was the least resistant. An apparent exception to this statement is the granite from the Milne and Gordon Quarry, which was destroyed at 750° C.

Further evidence of the disaggregation is found in the cracks and fractures which are developed by the heating. Some of the cracks are large and continue entirely across the face of the cube, while others are not so prominent, being only an inch or so long. Many cracks are developed at the contacts of the minerals with each other, and there are some which are confined to the individual minerals. These last are usually small, and take advantage of the planes of weakness already existing in the mineral on account of its molecular structure, such as cleavage and twinning planes. While the unheated rock shows a few cracks they are not nearly so numerous as in the heated ones. The quartz in the fresh rock is usually more shattered than the feldspar, although this may not be really the case, as the cracks are readily seen in the quartz, and with difficulty in the feldspar. The quartz in the water-cooled cubes is nearly always greatly shattered on the surface. This shattering is not so prominent in the quartz in the interior of the cube, which points to a probable connection of the cracks with the sudden cooling by the water.

Another evidence that the rock is weakened by heating is the strained condition that is indicated by the wavy extinction of the quartz and feldspar in the specimens heated to 850° C. or above. While this feature is not shown by those heated to 750° C. or less, it is evidence that the heat was probably producing similar strains at lower temperatures, and thus aiding in weakening the rock. The ringing sound emitted when the heated cube is scratched is believed to show the tension, due to permanent expansion, under which the minerals exist in the heated specimen. The sound has a marked ringing note in those specimens which contain numerous small cracks, but is dull in those where larger ones have developed. Some of the cubes heated to the higher temperatures are so friable that they can be crumbled with the fingers.

The results of the tests indicate, then, that the granite cannot withstand more than a moderate heat without becoming weakened.

While it is always necessary to have various tests made on rocks used for building and structural purposes in order to determine their various physical properties, the results of the data so obtained are subject to interpretations which depend upon the completeness of the data. In the series of tests and studies described in this bulletin, data as to the cause of the marked loss of the strength of the granite on heating was sought. The data which was obtained is given above. As stated in the beginning of this paper, the cause must lie in the individual mineral components of the rock, and in their relationship to each other. It becomes necessary to evaluate each factor, and to determine whether the real cause lies in the individual and in their relationships, or whether the results are the cumulative effects of the individual minerals uniting in the whole effect.

The Effect of Molecular Structure

This study is simplified by having only two minerals, quartz and feldspar, to deal with in most of the rocks. The minerals are all more or less cracked, as a result of the heating, as is shown by the study of the heated blocks, and by the microscopic study of the slides. In the feldspar the cracks are controlled by the molecular structure of the minerals, such as the cleavage, twinning planes, etc. When it is altered to a mass of kaolin, the cracks are no longer controlled by the molecular structure. As feldspar has good cleavage in two directions, the cracks would be expected to be rather abundant, and they are found to be so.

Quartz, on the other hand, is usually regarded as being massive, but it does have a very good cleavage parallel to the pyramidal face *r*. This cleavage face is very rarely seen. (The writer remembers having seen a large crystal of quartz, which had been heated, that showed cracks which were parallel to the face mentioned above.) The incipient, parallel cracks, that have been mentioned in the description of nearly every slide, and also in the description of some of the cubes, are interpretated to be along the cleavage lines. They were more prominent and larger on the surface of some of the cubes, because there, when the quartz crystal was lying with its long axis parallel to the surface, the cleavage planes would make an angle with the surface which was favorable for the expansion of the mineral. This expansion probably developed the cracks.

Besides this cleavage in one direction, there is no other physical property of quartz which would control the direction of a crack or fracture. There is another factor here, however, which must be recognized, and that is the presence of inclusions in the quartz. They consist, as has been stated above in the descriptions of the Missouri granites, of various minerals in small amounts, and of numerous cavities, which contain liquids and gases. The most common of these are water and carbon dioxide, both of which may exist in the quartz in a liquid or a gaseous state. These inclusions were incorporated in the quartz at the time of its solidification. They may be scattered throughout the quartz, or they may be in lines or rows which are usually more or less curved. A few of these lines were found to be approximately parallel to the cleavage direction of the quartz mentioned above. Occasionally they cross from one grain to another, which probably means that the two grains were formerly part of a single crystal. The inclusions vary greatly in size. The study with the binocular microscope showed that the inclusions were really in planes.

Since this is the case, these planes of inclusions should be planes of weakness, and the cracks should follow them, whenever their position or direction was such as to enable them to take advantage of the plane. Not only should the planes be weaker because of the presence of the inclusions, but it has been suggested, that those which contain liquids and gases, under high temperatures would exert a very great pressure upon the walls, (great enough to burst them, according to some men), and this pressure should aid in weakening them. Any other inclusions present are not believed to play a very important part in the weakening effect, although any expansion they undergo will help.

Laying aside for a time the question of the effectiveness of the materials in the cavities, we must consider whether there is a relationship between the cracks, as observed in the quartz, and the lines of inclusions. The answer must be largely negative. The great majority of the cracks cross, at any angle, the lines of inclusions which they encounter, in fact, they are often parallel to the cracks, and but a fraction of a millimeter away. It must be understood, however, that while this is true of a majority of the occurrences there are cracks which follow the lines of inclusions, often for several millimeters. This was noticed especially in the case of a few of the large lines. The more numerous the cracks, the more apt they were to follow the lines. In view of the fact that the line of inclusions should be expected to be a line of weakness in the quartz, it is surprising how many of the cracks cut across them. In many crystals of quartz there were no lines or rows of inclusions; they were disseminated throughout the crystal. These crystals were cracked just the same as those with the inclusions in lines, the cracks running in any direction.

The above facts show that the lines of inclusions do not influence the position of the cracks but what is even stronger evidence, although negative in character, is that the quartz which is free from inclusions contains just as many cracks, and of the same general character, as those in the inclusion-rich quartz. This would indicate that the cracks could develop independently of the inclusions. Another feature along these lines was the presence of small radial cracks often only a millimeter or less in length, along the margin of the quartz grains. They did not reach the lines of inclusions on the interior. They were seen only on the polished surface, and probably owe their origin to the expansion and contraction of the quartz while cooling.

The conclusion must be, therefore, that the molecular structure of the mineral largely determines the direction of the cracks developed in it and that the lines of inclusions are very minor factors in the location of the cracks.

The Effect of the Fluidal Inclusions

The presence of gases and liquids in the cavities of the quartz has been noted above. They are very minute, rarely over .02 mm. in diameter and usually much less. One was measured which was .0027 mm. in diameter. Hull estimates that the cavities in some quartz crystals are so small that from 1 to 10,000 million could be contained in a single cubic inch of space.[8] The "moving bubble" which is found in so many of them is, of course, much smaller. The total amount of the inclusions of all kinds in the quartz is estimated to be about one per cent, which may be incorrect fifty per cent either way. From fifty to seventy-five per cent of the inclusions are fluidal cavities so their amount is very small. It is the opinion of other men who have studied them in other rocks, that the inclusions comprise a very small percentage of the quartz. Quantitatively, then, the effectiveness of the included gases and liquids would be small, even when heated to very high temperatures.

It has been stated above that not a single moving bubble was found in the heated granite, so we must consider what became of them. There are two possibilities: one, that the gas in the bubble has escaped, and the other, that the liquid in the cavity with the bubble has been converted, in part at least, into a gas. In either case the "moving" bubble would disappear.

For the gas to have escaped it would be necessary for it to rupture the confining walls. If it had force enough it might do this, or it might be aided by the development of a crack by outside agencies, the crack penetrating its walls. The contents of those inclusions along the cracks have escaped, as a matter of course, but the vast majority of the cavities show absolutely no sign of a crack, or even a strain.

8. Hull, E., Bldg. and Ornamental Stones, 1872, p. 30.

effect in their walls or near them. This, then, is taken to mean that the gaseous bubble has not escaped; it has not burst its walls, thus shattering the quartz, and hence the granite.

As to the second possibility, it has been mentioned in the descriptions, that the cavities are darker in all the heated specimens, and that their margin is broader. This is a characteristic of gaseous inclusions, and it is believed that part of the liquid may have been converted wholly, or in large part, into a gas by the high temperature, and that liquifaction has not yet resulted, if, in fact, it ever does. The boundaries of the cavities are as distinct as they were before heating, and many of the larger cavities still retain a large, immovable bubble.

Hence the conclusion is, that the liquid and gaseous inclusions in the quartz have no influence on the development of the cracks, and thus on the consequent disruption of the granite.

The Effect of the Unequal Expansion of the Minerals.

The above discussion has shown that the granite is greatly weakened by heating, and that the development of numerous cracks has been the chief physical change. The cracks were controlled mainly by the molecular structure of the given mineral and only to a very minor extent by the inclusions. The character of the inclusions had no influence on the direction of the cracks. The cause that produced the cracks was undoubtedly the unequal expansion of the different minerals in the rock. Clarke gives the cubic expansion of quartz as .000036 per degree, and of feldspar as .000017.[9] Thus quartz has more than twice as great an expansion as feldspar and consequently very unequal stresses are set up when a rock which contains these two minerals is heated to high temperatures. The linear expansion of minerals is unequal along the different axes in the same mineral. Clarke gives the following values for quartz. On the c-axis the expansion is .000008073, along the a-axes it is .000015147, the ratio being nearly 1:22. For feldspar (adularia, a transparent variety of orthoclase) the values are different along the three axes at right angles to each other and have the following values: .000015687, .000000659, and .000002914, the ratios being 23.6:1:4.4. Thus we find that the feldspar expands nearly twenty-four times as much along one axis, as along that of the least expansion, and 4.4 times as much along another. Here there is a source of great tension which will produce severe strains in the minerals and the rock. If the rate of expansion holds

9. Clarke, F. W., Smithsonian Miscellaneous Collections., Vol. 14, No. 289, p. 17.

for the higher temperatures, the amount of cubic expansion at different temperatures for the quartz and feldspar are as follows:

	500° C.	750° C.	1000° C.
Quartz	.018	.027	.036
Feldspar	.0085	.0128	.017

Likewise, if the same rate of linear expansion holds at the high temperatures, the values for the different temperatures for quartz and feldspar are as follows:

		500° C.	750° C.	1000° C.
Quartz				
	c-axis	.004	.006	.008
	a-axes	.0076	.0114	.0152
Feldspar				
	Three axes	.0078	.0118	.0157
	at right	.00033	.0005	.0007
	angles.	.0015	.0022	.0029

These figures are regarded as being of value only in indicating the general character of the amount of expansion. They show that the heating must produce very severe strains in the rock, which find relief in fracturing the rock and thus causing it to become weakened. The permanent expansion of the rock indicates the same result. The average permanent expansion in a block about seven and one-half inches long, heated to 500° C. is .00483 inches, and for a similar block heated to 750° C. it is .01299 inches.

The effect of sudden cooling by plunging in a stream of cold water was felt primarily on the exterior of the block, and only secondarily on the interior. The rapid cooling of the outside caused it to contract more than the hot interior, and thus developed the cracks in the outer part. The size of the crystals in the rock would become a factor here, the fine-grained rock transmitting the heat faster than the coarse-grained. This may be a partial cause of the greater strength and resistance of the fine-grained rocks.

On the whole it is seen that the heating must produce strains in the rock which find relief in fractures. These strains vary in different directions in the minerals and thus intensify the effect. The result is a series of cracks and fractures along lines of weakness in the minerals themselves at their contacts with each other and through them in any position. This greatly weakens the rock and may destroy it.

There is still another factor which may aid in the disaggregation of the rock. This is the property of quartz to change into another form at certain temperatures. Quartz, which has solidified at a temperature less than 575° C. is called alpha-quartz, and on being heated above this temperature changes into beta-quartz. This change is accompanied by a permanent expansion of the mineral and by a shattering. Further heating to 870° C.,[10] in the presence of a suitable flux, slowly changes the quartz to tridymite but if no flux is present it does not change until 1400° C.,[11] or higher, is reached.

As most granites are thought to have cooled at temperatures above 575° C., the lower change is not probable in our study, and the temperature necessary for the last change was not reached in our series, save in the case of the Graniteville material. The other condition, that is, the necessary flux, was lacking also. The strain effects noted at the higher temperatures are not due to the tendency of the quartz to invert into another form, for they are in the feldspar as well as in the quartz.

When the study was begun it was decided to use temperatures of 500° C. and 750° C. in order to remain below these inversion points. These temperatures are sufficiently high to greatly weaken the stone, and so are believed to be satisfactory. The changes which the quartz undergoes at these temperatures are those due to its unequal expansion, just as are those in the feldspar. Hence the change of quartz into another form is not believed to be influential. The expansion of the rock as a whole produced numerous strains between the cooler and the hotter portions, and aided in the development of the larger cracks. It is these larger, cumulative strains that produce the spalling off of fragments from larger blocks. This spalling was very noticeable in the large blocks used in Humphrey's fire tests for the government.[12]

10. Wright and Larsen, Am. Jour. Sc. 4th series, 27: 421: 1909.

11. Fenner, Wash. Acad. Sc. 1-2: 472: 1911-12. Johnston, John, Jour. Geol. 21: 497: 1913.

12. Humphrey, R. L., Bull., 370, U. S. G. S.

CONCLUSIONS.

The loss of strength by the Missouri granites, on heating, is due to the differential stresses that are set up in the individual minerals, because their expansion differs widely along the crystallographic axes. To this is added the strain due to varying temperatures in different parts of the block.

The presence of numerous inclusions, especially liquids and gases, in the quartz is regarded as not having any effect upon the resulting disaggregation, except in so far as a series of inclusions of any nature arranged along a plane in a mineral would make that plane a line of weakness in it.

The temperature is not high enough to cause the quartz to invert into another form, hence the physical change involved in this inversion is not a factor in the disaggregation of the granite.

CHAPTER V

PRACTICAL CONSIDERATIONS

The studies that are described in this bulletin are of practical value in several ways. The most important of these is the determination of the loss of strength on heating to high temperatures. At the same time, it was of value to determine the effect of various temperatures upon the granite. The tests give the strength of several more granites than have been available heretofore. The effects of slow cooling in air and sudden cooling by water are also noted. The practical application of these various tests will be discussed.

Since all structures utilized by man in his home and industrial life are in danger of fires it is of value to know something of the fire resisting properties of the materials used in the structures and whether they are active members of the structure or are merely ornamental. In the former case it is expedient, because that material should be used which is least liable to be completely destroyed or seriously damaged; in the latter case, if the material is seriously damaged, there is a total loss.

Granite is used extensively in all building operations, but not so extensively for ornamental purposes, largely because it costs much more to prepare it for the desired use, than it costs to prepare marble or serpentine. This is because of the greater hardness of the granite. There are many granites on the market today that are far more beautiful than some of the marbles used for interior decoration, and they would doubtless be used for this purpose if it were not for their higher cost.

Other men have usually stated that granite is not very fire resistant and that it is seriously damaged, if not totally destroyed, by even a moderately hot fire. While the tests described here were not made as a comparative study, they indicate that granite does lose a large part of its strength at comparatively low temperatures, about 36.4 per cent below 500° C. and 62.4 per cent below 750° C. The effects of the tests made are not so severe as they would be if larger cubes had been used. It is the minerals which are affected, rather than the cube as a whole, for the larger cracks are produced by the cumulative stresses developed by the minerals. In the small cube these mineral stresses were relieved by the expansion of the cube as a whole, for it soon became heated throughout, while in a larger block some portions would be at a different temperature for a longer time so that larger stresses would develop between the cooler and hotter portions and find relief by fracturing the rock. This might occur during the heating or afterwards during the cooling. Spalling is especially liable to develop under these conditions. If the fire lasts for a considerable length of time, the spalling would completely destroy a granite column. Therefore, when the marked loss of strength in the cubes, due to heating, is applied to larger sized material, the damage would probably be much greater. Even if the damage in a larger block was no greater than in the small cubes the results indicate that the stone would be made worthless.

The texture of a stone is of importance in resisting the damage, due to the heat. The fine-grained rocks in the sets are the most resistant, showing the highest crushing strengths after heating. Other investigators state that the coarse-grained rocks are less resistant.

The mineral composition is not so very important. The Missouri granites consist mainly of quartz and feldspar, with small amounts of other minerals. In general, the coarse-grained granites contain the most quartz, averaging about four per cent more than the fine-grained ones. However, the size of the crystals of each of the minerals is far more important than their relative numerical proportions. McCourt (Op. cit.) found that a syenite with very little quartz was as badly injured as were the gneisses that he tested. The texture of the rocks was more important. Dodge tested some Minnesota syenites and found that all were damaged but that the coarse-grained ones suffered the most.[13] The conclusions, resulting from this study, which maintain that the inclusions in the quartz do not affect the strength of the granite and are not a factor in its disaggregation, are supported by these facts.

The crushing strength of seven different Missouri granites was determined. These values are higher than those of the three different granites given by Buckley and Buehler in their report on the quarrying industry of Missouri.[14] This is due mainly to the fact that the cubes used in our tests were more perfect than the ones they used. The average of the crushing strengths of all the cubes tested in our work is 29,260 pounds per square inch. The minimum crushing strength is 25,100 pounds per square inch, and the maximum is 34,960 pounds. These values, especially the average, are well above the values of Wisconsin, Minnesota, and Washington granites given by the above authors on page 323 of their report. These values are fully equal to the average strength of the granites in the eastern part of the United States. The results show that, in respect to their crushing strength, the Missouri granites are the equal of any in the United States, and

13. Dodge, J. A., Minn. Geol. Sur. Vol. I, : 186; 1882.
14. Buckley and Buehler, Mo., Bur., of Geol. and Mines, II, 2d series: 313.

are suitable for usage where the rock is required to support great weight.

The effects of cooling in air and in water indicate that the damage to the granite by cooling in water is not so serious as is generally thought. Some of the sets cooled in water showed greater strength than those cooled in air, as is shown above on page 22. The damage to large blocks, however, would be far more serious than in the small cubes on which these tests were made.

High temperatures are found to be very damaging to the Missouri granite, its strength at 750° C. being only about two thirds of what it is in the fresh granite. Mineralogical composition has little effect on the resulting loss of strength, but the texture is very important, the fine-grained varieties being the most resistant to heat. The average strength of the several Missouri granites is high.

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