MODE OF EMPLACEMENT OF THE BARRE GRANITE, VERMONT

Thesis by

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ABSTRACT

The Barre granite district, three to six miles southeast of Barre, Vermont, covers an area of less than thirty square miles. The main quarries were mapped on a scale of 200 feet to the inch, and an areal geologic map was prepared on a scale of 1500 feet to the inch.

This region is underlain by phyllites, impure limestones, impure quartzites, and calcareous mica schists of the Waits River formation, at least a portion of which is Ordovician in age. The Barre granite, probably of late Devonian age, cuts these metasedimentary rocks. It is a fine to medium-grained gray granite with two distinct phases; the earlier of these, the "dark Barre", occupies the southern part of the exposed granite masses; the later phase, the "light Barre", is slightly lighter in color, and is a co-magmatic member of the sequence. It occupies the bulk of the exposed granite masses.

Previous workers have ascribed the emplacement of these plutons to forceful injection. Results of the present investigations suggest that a large portion of the space required for the pluton probably was gained by stoping processes. The factors which support this conclusion are: the small amount of doming in the granite, the small expansion across the schistosity, the uniformity of schistosity in the country rock, the complete removal of a large portion of the metasedimentary section by the granite, and the lack of orientation of inclusions in the granite.

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INTRODUCTION

General statement

The Barre district has yielded commercial granite for more than a century. In 1833, ox teams moved blocks of Barre granite to Montpelier for use in the construction of the State Capitol. An order for ten million paving blocks for the city of Troy, New York (15,p.59)* helped stimulate the budding industry so that by 1907, seventy-four years after the initial exploitation, there were fifty-six active quarries on and near Millstone and Cobble Hills (12,p.121). Subsequently many of the quarries either were closed or were so much further developed that they coalesced with adjoining ones. Most of the individual quarries have been purchased by the Rock of Ages Corporation, which now plays the dominant role in production of raw stone in the district. The only other important quarry operators are the Wells-Lamson Company and the Pirie Estate.

At present, all the production from the district is used for memorials and monuments in practically every country in the world. Approximately eighty percent of all the rock handled is rejected at the quarry as not

* - Numbers in parentheses refer to references listed at the end of the paper.

fully suitable for processing. None of the granite is now used for building materials, as the companies believe it would have a deleterious effect upon the sales of their monuments.

Location and size of area

The center of the Barre granite district lies three miles southeast of Barre, Vermont, and ten miles southeast of Montpelier, the state capital. The small quarry towns of East Barre, Websterville, Lower Websterville, Graniteville, and Upper Graniteville lie within the area.

The rectangular area mapped is approximately seven miles long and four miles wide. The granite itself occupies about ten square miles in the central part of the mapped area. Almost the entire quarry district is in the southeast portion of the township of Barre. Only a few quarries, notably the Pirie and the southern portion of the Rock of Ages, are in the township of Williamstown, the town immediately to the south of Barre. All of the quarry towns named are in the township of Barre.

Ready access to the area is supplied by a network of surfaced and unsurfaced roads. U. S. Highway 302, in the valley of the Jail Branch, transects the district from east to west. The Barre and Chelsea Railroad, with some of the steepest grades in the country, connects the quarries with the city of Barre. In Barre the stone is cut to size, polished, and ornamented, and then sent out to all parts of the world.

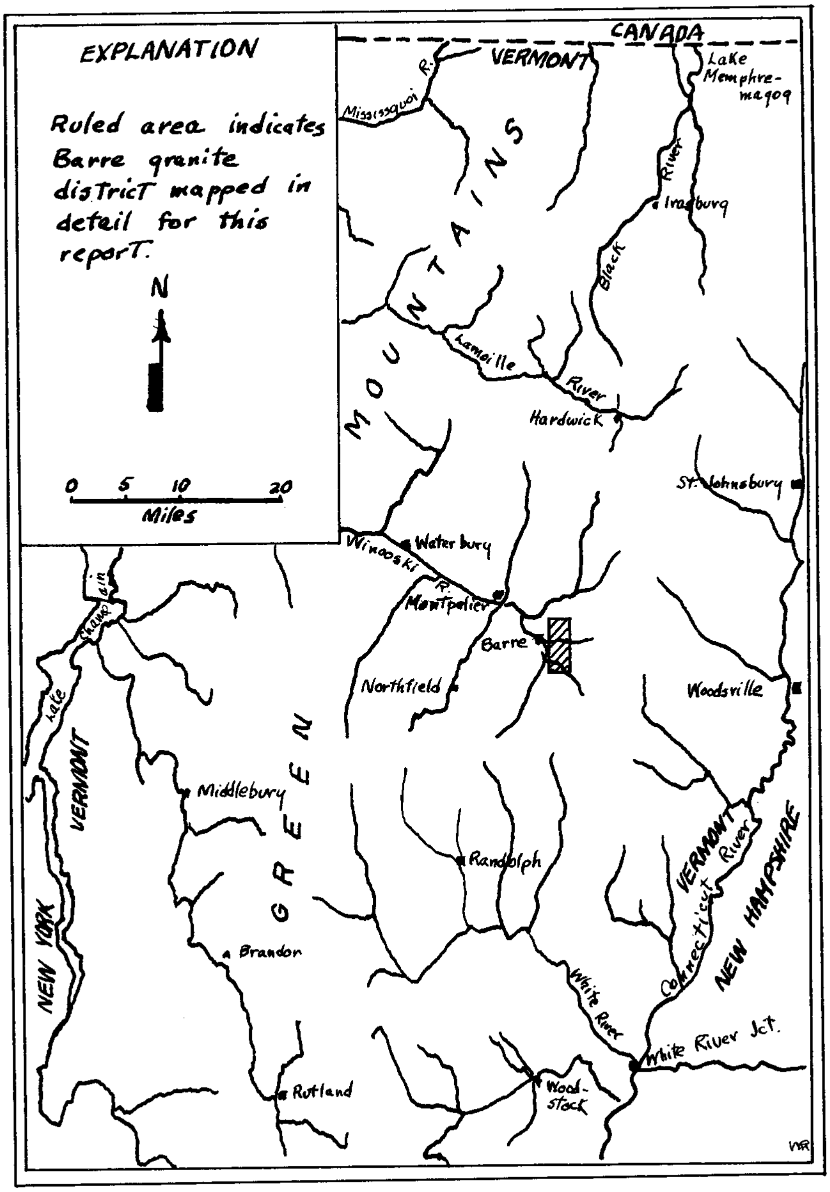


Figure 1 - Index Map

Purpose and scope of investigation

The prime purpose of the investigation was to determine the distribution, occurrence, and structural features of the granite, mainly by detailed and accurate mapping. The major portion of the writer's time was devoted to studying the mode of emplacement of the granite. This was accomplished by detailed mapping of the country-rock structures, the primary structures within the granite itself, and the granite-country rock contacts. This entailed mapping the whole district on a scale of 1200 feet to the inch, with subsequent reduction for publication to a scale of 1500 feet to the inch. The base map was obtained by photographically enlarging appropriate parts of the Barre and East Barre quadrangles from their scale of one mile to the inch. A stereoscopic-pair of aerial photographs was used to transfer accurately the locations of quarries to the enlarged topographic map. In addition, detailed plane-table maps, at a scale of 200 feet to the inch, were made of the Wells-Lamson, Wetmore and Morse, E. L. Smith, Rock of Ages, and Pirie quarries.

The tracing of contacts in the country rock was extremely difficult, as all the metasedimentary contacts are gradational. As a result, all of these contacts are dashed where located within 50 feet and dotted where buried or otherwise obscure. The granite, on the other hand, consistently has sharp contacts where exposed.

A total of twenty-eight man days was spent in the area by R. H. Jahns and the writer during August and September, 1948. This work was a part of the final mapping of the Barre quadrangle for the U. S. Geological Survey. The project had been started in 1937 and continued until 1940, when the war interrupted work until the summer of 1948.

Acknowledgments

The writer gratefully acknowledges the invaluable assistance of Dr. R. H. Jahns during the field work, with his innumerable suggestions and excellent field mapping techniques. Also during the writing of this report, the discussions, guidance, and the use of manuscripts prepared by Jahns were extremely valuable to the writer. Thanks also are extended to Dr. J. A. Noble for the use of his unpublished manuscript on mechanics of intrusion in the Lead district, South Dakota, and for his critical suggestions on the writer's problems, and other areas that have direct bearing on this problem. Thanks are also due to Miss Sally Provine for the typing of the first draft, and to Mrs. L. A. Norman, Jr. for the typing of the final draft of this manuscript.

GEOGRAPHY

The total relief in the district is little more than a thousand feet, but the hills have very steep slopes. Some are difficult to negotiate even on foot, and some require mountain-climbing equipment. The highest point in the area, with an altitude of 1776 feet, is the summit of the hill east of Cobble Hill. The lowest point is on the Jail Branch at an altitude of 752 feet.

The area is characterized by till-covered slopes and terraces, with bedrock hills protruding here and there from the almost continuous glacial cover. The most prominent of these bedrock hills are Cobble and Millstone Hills and Mt. Pleasant. The Jail Branch was filled during the Pleistocene epoch with till and glaciofluvial sands and gravels, but the stream has since cut a canyon more than two hundred feet deep. Much of this canyon is bottomed in glacial deposits.

Owing to the humid climate of the region, all uncultivated regions are covered with dense growths of pine, spruce, and several varieties of hardwoods. The damper regions develop a dense maze of underbrush which impedes foot travel and frequently prevents the geologist from determining his exact location.

Rock outcrops are fairly scattered for detailed mapping, although the quarries provide excellent exposures of the granite and some of its contacts with the country rock. Conversely, the huge waste piles conceal significant relations in some areas. The thick till blanket in the Jail Branch obscures much bedrock geology in a wide strip across the area.

REGIONAL STRATIGRAPHY

Much of central Vermont is underlain by metamorphosed sedimentary rocks of Cambrian and Ordovician age. All these rocks are earlier than the principal orogeny which probably is Acadian (28,p.26). Billings states (28,p.26) that it is "later than early Devonian and earlier than Triassic and antedated the intrusion of the igneous rocks that are probably Mississippian". He also indicates (28,p.8) that,

> "All of the stratified rocks and some of the igneous rocks have been metamorphosed. The metamorphism has been both dynamic, as shown by widespread foliation with oriented micas, and thermal, as revealed by porphyroblastic growth of high-temperature metamorphic minerals."

All the metasedimentary beds in the Barre district trend consistently N 30° E to N 40° E, and dip steeply west. The attitude of cross-bedding and gradation of size within beds has shown that all these beds are overturned, so that they are progressively younger from west to east. They constitute a part of the east flank of the great Green Mountains arch, whose axis is essentially parallel to the crest of the Green Mountains.

All of the stratified rocks in the Barre district are a part of the Waits River formation. According to White and Jahns (28,p.16), this formation consists of approximately 20,000 feet of

"interbedded impure limestones, calc-mica-schists, phyllite, quartz-mica-schist, and platy impure quartzite. The interbedding of calcareous and noncalcareous rocks occurs on all scales, and beds and groups of beds range in thickness from a fraction of an inch to many tens of feet. Some sections several hundred feet in apparent thickness are dominately calcareous, whereas the others contain little or no carbonate minerals."

That at least the lower part of the Waits River formation is Ordovician in age is shown by the discovery in 1947 of Ordovician tetracoralla by W. M. Cady near East Montpelier Center. C. H. Doll (28,p.25), however, reports fossils of lower Devonian age in the Waits River formation. In discussing the significance of his findings, White and Jahns (28,p.25) state,

"The organic origin of these forms has been doubted by some geologists, despite the arguments put forward by Doll and others, and for this reason the consequent age assignments should be viewed as tentative, pending the discovery of better preserved material."

Lying conformably beneath the Waits River formation is the Northfield slate, which consists of about 4,000 feet of interbedded slate and subordinate limestone. The limestone interbeds contain crinoid stems that are mid-Ordovician in age or younger (28,p15).

Unconformably beneath the Northfield slate is the Shaw Mountain formation. In most places it is less than 100 feet thick, and it marks the boundary between the calcareous-argillaceous section just discussed and an arenaceous-argillaceous section to the west. It has been traced by several geologists from the Canadian border of Vermont southward to the Vermont-Massachusetts state line. C. H. Richardson termed the base of the formation the "Cambrian-Ordovician boundary" and considered what has subsequently been named the Shaw Mountain formation to be the basal member of the Ordovician sequence. Subsequent work, however, has shown this formation to be distinctly younger than previously believed.

REGIONAL STRUCTURE

The metamorphic rocks of central Vermont have been affected by four major periods of deformation. The dating of these deformations is largely by long-distance correlation with other areas because of the restriction of the geologic section in this area to lower Paleozoic rocks.

The earliest deformation apparently was in Acadian, or late Devonian time. It developed the Green Mountain arch, with numerous drag folds. The axis of the arch coincides with the main crest of the Green Mountains. Most of the rocks of the Vermont stratigraphy are involved in the arching. The east flank was overturned toward the east for an outcrop width of about fifty miles. Flow and shear cleavages were developed in the rocks, as were linear elements with gentle to moderate north plunges.

Masses of ultramafic rock were introduced in several areas, in general after the early period of deformation but preceding the second period. The second deformation, which was mainly a horizontal to gently inclined shear with a major east side up-and-north component, in general antedated the intrusion of the Barre granites. The second deformation, also, is very likely a part of the Acadian orogeny. One of its effects was development of a slip cleavage that intersects the earlier flow and shear cleavages to form linear elements that, in the Barre district, dip more gently to the north than the first deformation lineation.

The third deformation involved thrusting from the northwest. The most notable effects are small, steep-angled thrusts which occasionally break the continuity of the contacts. No dating is available for this deformation.

The fourth deformation developed a tensional force opening east-west fractures, many of which are now filled with diabase dikes. Similar dikes in the Connecticut Valley area of Massachusetts are of Triassic age and those in central Vermont may well be of that age also. Within the granite masses, these dikes commonly fill the longitudinal joints, which trend essentially parallel to the country-rock schistosity.

BARRE GRANITE

Previous Work

C. H. Hitchcock (18,map) published the first geologic map of Vermont in 1861. His work is the first to discuss the origin of granite in Vermont. He believed in an "igneo-aqueous theory", in which he melts heated sediments at depth in water and thus forms igneous rocks. Hitchcock also pointed out that the Barre rocks form a part of a belt of granitic rocks that extends north from Barre through Plainfield, Marshfield, Calais and Woodbury.

G. I. Finlay (15,pp.46-60), in 1902, published a map that shows the granite as a single unit intruded into the schist country rock.

T. N. Dale (12,pp.121-143) spent four weeks in the district during 1907, when he studied the granites as part of a broad project on the granites of New England. He was primarily concerned with the economic aspects of the districts, but also included much information of purely scientific value. The writer has used many of these data in the present study.

Robert Balk mapped the Barre district in 1925, using the methods of granite tectonics to establish the probable mode of intrusion (1,pp.50-72). He considers the outcrops to represent a series of individual plutons, each of which has come from a common reservoir but has reached its present position by individual action. He mapped arched flow structures in these plutons, which indicate expansion in a northeast-southwest direction. He states (2,p.76) that the "independent arches of the flow lines render impossible any assumption that some such process as piecemeal stoping may have carried the granite to the now-exposed level".

The following quotation from White and Jahns (28,pp.27-28) represents the most recent view on this question:

> "The granitic rocks are believed to have been forcefully injected into the schists that now enclose them. All contacts are sharp. Highly feldspathized schist or other hybrid contact rocks are rare, and are distinctly localized in all areas studied in detail. The composition of the rocks intruded into calcareous schists does not differ from that of those intruded into noncalcareous schists. There is abundant local evidence that, on a small scale, the intrusives made way for themselves by forcing apart the schist walls, and in places the schists are bulged out on a larger scale around the areas of intrusion. Some of the plutons differ from those emplaced wholly by stoping (Billings,1942,p.293) in their elongate form, their concordant and subconcordant relations with the wall rock, and the scarcity of inclusions with random orientation.
>
> Though broadly concordant with the bedding or schistosity of the enclosing rocks, the plutons of Barre granite locally transect the structural features of the enclosing sediments at low or high angles. Dikes and stringers of granite or granodiorite cut across schistosity at many places, and locally cut sharply across folds in the schistosity. Inasmuch as these folds represent the last stage of major deformation in the region, the Barre granite is believed to have been emplaced during the closing stages of this deformation, or in part after the deformation had ceased. That they were not intruded long after the deformation is shown by their spatial relations to zones of metamorphism in the metasedimentary rocks."

Petrography

The Barre granite is a biotite granite of varying shades of gray, due both to differences in degrees of kaolinization and micacization of the orthoclase and to variations in content of biotite. The so-called "dark Barre" granite is finer grained than the light and medium grades; its darkness is due to a bluish cast in the feldspar, and to a higher content of biotite than is found in "light Barre" granite. "Light Barre" granite is the dominant type and is found north of an east-west line near Upper Graniteville. "Dark Barre" granite formed the initial intrusion as it is replaced and partially assimilated by the "light Barre" type. The contact between the "light Barre" and the "dark Barre" is very irregular. Portions of "dark Barre" are now found as rounded, partially assimilated inclusions in the "light", tongues of "light" intrude the "dark" and in some portions the contact fades out and an almost insensible color variation is found between true "light" and true "dark Barre" granite. Plates II- B, III-A, and III-B illustrate the types of relations found.

The constituents in the average of Barre granite, in decreasing order of abundance (12,p.124) are: potassium feldspar, mostly orthoclase, some microcline; light smoky quartz, which is strained and has fluid inclusions and rift cracks; a plagioclase that ranges from oligoclase-albite to oligoclase-andesine; biotite, some of which is chloritized; very little muscovite that may be bleached biotite; and such accessories as pyrite, magnetite, titanite, allanite, apatite, zircon, rutile; secondary minerals include calcite (abundant in the orthoclase), sericite, epidote and chlorite.

A micrometric analysis of "dark Barre", quoted by Dale (12,p.124), has the following percentages: feldspar 65.5, quartz 26.6 and mica 7.9. Finlay (15,p.56) lists the following micrometric analyses:

	I	II	III
Microcline	47.9	56.8	38.4
Orthoclase	7.5	2.1	8.9
Plagioclase	15.1	1.3	3.7
Quartz	26.0	28.5	18.4
Biotite	----	10.2	26.1
Muscovite	3.3	.1	.2
Titanite	----	.6	2.6
Magnetite	----	----	1.0
Apatite	----	----	.5
Total	99.8	99.6	99.8

I----Acid granite, south end of Millstone Hill.
II---Granite, medium stock, east slope of Millstone Hill.
III--Basic segregation, granite, north slope of Millstone Hill.

Fracture systems

Balk (2,pp.1-155) discusses all the possible joint systems that can be found within a pluton. The primary joints are cross joints, longitudinal joints, marginal upthrusts, diagonal joints and primary flat joints. All of these types occur in the Barre district, and most are iron-stained.

Cross joints, which are among the earliest fractures to form, are generally perpendicular to flow lines (2,p.27 They are tensional in origin and form at right angles to the elongation of the intrusive mass (6,p.303).

Longitudinal joints may well be caused by contraction of the cooling granite (2,p.41). They are ordinarily steep, and trend about 45 degrees from the strike of the lineation (6,p.303). They are interpreted as shear fractures.

Secondary joints may be developed in the frozen pluton by regional tectonic stresses or by exfoliation. Regional stresses may either cause movement on already existing fractures or develop fracture sets of their own. In contrast are large-scale exfoliation joints, thought to be caused by release of pressure due to erosion. Individual sheets are essentially parallel to the ground surface, except where unusually rapid, specifically directed erosion has occurred(6,pp.128-129; 20,pp.71-98). The sheets are a foot or so thick near the surface and thicken to tens of feet in depth.

Joint sets

T. N. Dale (12,p.126) records ten different joint sets found in the district. These have widely differing attitudes. Only five sets are quantitatively important, each of the other sets having been noted in only a few quarries. In order of numerical importance, the five sets as summarized by Dale are as follows:

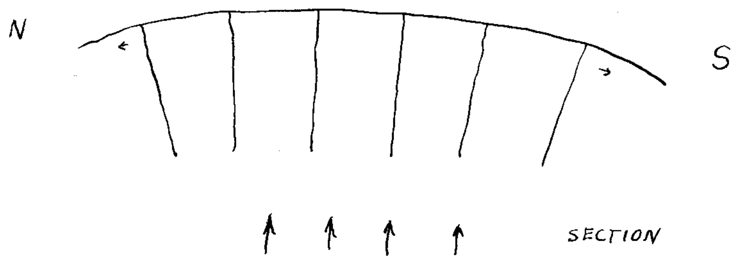
1. N 30-40°E, found in 21 quarries
2. N 70-90°E, found in 18 quarries
3. N 60-70°E, found in 10 quarries
4. N 30-40°W, found in 10 quarries
5. N 10-25°W, found in 8 quarries

Each of these sets dips steeply to the east or the west. The work of Jahns and the writer supports these observations, except that joints striking N 45-55°E are almost as important quantitatively as the dominant two sets listed by Dale. Due to curving of the joints, the longitudinal joint set comprises both the N 30-40°E set and the N 45-55°E set, as well as the intervening strikes.

1. The dominant set trends N 30-40°E and also has members that trend N 45-55°E. It corresponds to the longitudinal joints, to the trend of bedding in the country rock, to artificial rift planes in the granite, and to linear parallelism of minerals in the granite. These probably are due mainly to the contraction of the cooling granite. Many extend from the contact with the country rock, and die out within the granite. These may also be partly due to the last stages of tectonic activity during the second period of regional deformation previously described.

2. The dominant cross-joint set is the N 70-90°E set, that has allowed expansion for the final doming of the

upwelling magma, as can be illustrated by the sketch below.



The granite body dips steeply north-northwest, so that these joints are essentially perpendicular to both the direction of intrusion and the flow lines. These dikes are frequently filled with pegmatites and aplites and must have been open tension fractures to receive these injections of materials.

3. The N 60-70°E set may also be due to this tension, as many of these are filled with pegmatitic and aplitic material. Some additional joints may have been formed by tectonic processes associated with the third deformation, which was later than the granite intrusion. It was characterized by thrusting from the north-northwest. This may account for some of the reverse faulting within the pluton.

4 and 5. The N 30-40°W and the N 10-25°W sets are complementary to sets 2 and 3 (N 70-90°E, N 60-70°E). When doming occurs in a mass, two sets of tension fractures form approximately at right angles to each other and perpendicular to the direction of intrusion, thus allowing expansion of the partly cooled mass. These sets

ordinarily curve around the ends of the intrusive mass, and therefore have a wide latitude in strike. This probably also accounts for the other, subordinate sets of fractures.

Marginal upthrusts

Along the granite-country-rock contacts are several marginal upthrusts, the granite being forced up with respect to the walls. Balk found a maximum of nine feet upthrust. These marginal upthrusts are parallel to the longitudinal joints, and many are coated with aplites and quartz veins. Balk also states that these upthrusts are more numerous along the northwest than along the southeast contacts, which possibly indicates that these movements are related in part to regional thrusting. However, he further states that none of these upthrusts displaces the country-rock contact. Therefore, these structures must have developed before final consolidation of the granite.

Sheet structure

Sheeting is a phenomenom that has been observed in most areas of granitic rocks. Sheeting is the sets of joints that are essentially parallel with the configuration of the surface of the ground. The formation of these sheets is commonly ascribed to a release of internal stresses caused by erosion and removal of hundreds and thousands of feet of the overlying rock. The sheets become progressively thicker in depth, near surface sheets being only a few feet thick and increasing in thickness to fifty feet or more several hundred feet in depth. If the granite mass has a well-developed joint set to relieve internal stresses, the sheeting is correspondingly poorly developed.

Sheet structure has been used by Jahns in northeastern Massachusetts (20,pp.71-98) for estimating minimum depth beneath the pre-glacial surface of individual sheets. Thus, a minimum depth of glacial erosion can be measured. Using the correlations of Jahns on the Barre district, it can be shown that the entire Barre district has undergone glacial erosion to a depth of at least fifty feet, and some portions to one hundred feet or more.

Sheeting is developed over Millstone and Cobble Hills and forms a dome over them. Much of the district has been so deeply glaciated that only a few thick and irregular pre-glacial sheets remain. A few thin post-glacial sheets have developed on the glacially-modified surface. These sheets are only a few feet deep and each individual sheet is only a few inches thick. On the south side of Cobble Hill severe glacial plucking has oversteepened this face. Parallel to the old contours of the hill and now projecting out from the south face are the thick pre-glacial sheets. Superimposed on this and parallel to the present surface are a set of post-glacial sheets. These two sets of sheets intersect at a high angle and this structure is known as double sheet structure.

Number of units involved

Balk distinguishes at least eight separate plutons in the district. Each of these is presumed to be a dynamically independent unit (2,p.76). Field work by Jahns and the writer indicates that all the individual plutons of Balk are interconnected, and hence, that they are parts of one major intrusive mass. Intrusive relations between "dark Barre" granite and "light Barre" granite show that in reality two intrusions exist. The "dark Barre" granite was still partially liquid when the "light Barre" granite was emplaced. In some places, the contact between "dark" and "light Barre" granite fades out into areas where there is an almost insensible variation in color from the dark to the light. The successive emplacement of these intrusions suggests that the "light Barre" is a slightly later differentiate from the parent magma.

MODE OF EMPLACEMENT

General statement

There has been advanced a number of modes of intrusion that are theoretically possible for an intrusive pluton. These hypothetical types will be discussed in the following order:

1. Granitization; although, admittedly is not a mode of intrusion, but is a mode of <u>formation</u> of plutons, will be discussed here as a possibility.
2. Pure melting and assimilation.
3. Forceful injection, involving expansion in all directions.
4. Pushing upward of a block, by cone-sheet or bysmalith mechanisms.
5. Differential expansion, involving expansion in given directions.
6. Dropping downward of blocks, by stoping or by related processes.

<u>Granitization</u>

Grout (16,pp.1525-1576) has published a detailed critique of metasomatic replacement as a mechanism for forming "igneous-looking rocks". Metasomatic origin, according to Jahns (19,p.341) involves the "quiet replacement of preexisting bedded and foliated rocks by invading fluids of magmatic derivation". Grout has presented a very detailed list of criteria necessary to prove replacement. The Barre granite pluton does not support most of the criteria presented.

Lack of evidence that the magma has crowded or displaced its walls is the most frequently advocated proof for granitization (16,pp.1541-1543). In the Barre pluton, there has been displacement of the walls by measurable amounts. Also, the quartzite septum on Millstone Hill and the quartzite-phyllite septum near Websterville have been wedged to the southeast by the granite mass. This is clearly indicated by the swing in direction of schistosity near Lower Websterville, and by the displacement of a well-marked quartzite-phyllite contact near Websterville.

A complete gradation along the strike from undoubted country rock to undoubted igneous rock is probably the best evidence for granitization. The Barre granite has extremely sharp contacts with the country rock. Finlay (16,p.51) states that "contact effects are everywhere light......rarely greater than one centimeter in width". Dale (13,p.85) mentions the Anderson quarry as rather exceptional in showing a wide contact zone. The under surface of the schist is coarsely serrate. The granite is darkened for a space of twenty-five feet from the schist, with pieces of mica schist scaled off and carried a few inches into the granite.

The textural and mineralogic uniformity of the granite where it trends across the strike of varying country-rock lithology is another argument against granitization. The "dark Barre"-"light Barre" contact trends in general at right angles to that of the country-rock bedding, perpendicular to the direction needed for metasomatic replacement. Another point of the mineralogical discontinuities between granite-country rock is the following from Dale (12,p.25) : "Sheets of cavities (rift and grain) in the granitic quartz stop abruptly at the contact with the quartz of inclusions or the country rock".

The quotation from White and Jahns (28,pp.27-28) previously made, also has bearing on this point. A portion is here repeated:

> "Though broadly concordant with bedding or schistosity of the enclosing rocks, the pluton of Barre granite locally transects the structural features of the enclosing sediments at low or high angles. Dikes and stringers of granite and granodiorite cut across schistosity at many places; and locally cut sharply across folds in the schist."

The very minor deuteric or metamorphic effects usually found within the granite, as well as in the adjacent country rock, also point away from metasomatism and toward true magmatic intrusion.

Fine and medium-grained textures also assist in disproving granitization, according to Grout (16,pp.1541-1543). Barre granite is a fine to medium-grained granite.

It is the belief of the writer that there has been very little metasomatism involved in the Barre granite intrusion.

Pure melting

Harker (A. Harker, The Natural History of Igneous Rocks, New York, 1909, p.338, as quoted by Daly (14,p.290)) states that "at a deep level in the Earth's crust, where solid and liquid rocks are in approximate thermal equilibrium......extensive melting may be conceded, and, indeed, must be postulated." Daly observes that field observations seem to prove a relative insignificence for post-Archean assimilation as compared with Archean assimilation (14,p.294). Once the crust attained a sufficient thickness to prevent foundering, the thermal gradient was shallow enough to cool any intruding mass fast enough to prevent much shallow depth assimilation and melting of the country rocks.

Regional metamorphism has attained the biotite zone in the Barre district. Superimposed in this district are the high-temperature thermal zones of garnet and, in places, staurolite.

The fracturing of the country rock and subsequent dike-filling by the intrusive granite, the very limited zone of contact effects on the country rock by the pluton, the scarcity of hybrid rocks and feldspathized schists, and the sharp boundaries of inclusions suggest very little melting of the country rock. These same facts indicate the present outcrop is in the zone of fracture and therefore we are not "at a deep level in the Earth's crust". Thus, essentially pure melting might well be eliminated from consideration as a mechanism for emplacement of the Barre pluton.

Forceful injection

Forceful injection requires an expansion of the country rock and consequent disturbance of its structures by the intruding magma. It is not necessary that any internal structures of importance be developed within the magma. Thin marginal bandings approximately an inch wide are the only internal structures found in the forcefully intruded dikes of the Homestake region, Lead, South Dakota.(24) The surrounding schists can be shown to have been forcibly thrust aside in the Homestake region.

The measurable separation of wall-rock units that flank the Barre granite accounts for only a small fraction of the space occupied by igneous rock. The great masses of quartzite and phyllite that are missing must have been forced upward or dropped downward. Further discussion of this point is deferred for later sections of this report.

The fairly consistent dips and strikes of schistosity, as well as the uniform dip of the lineation, indicates very little disturbance of the country rock.

Forceful injection was, undoubtedly, a factor in the deep zones in forcing the magma upward. However, it has had a small effect in the section of the stock now exposed.

Pushing block up

Raising blocks by either bysmalith or cone sheet mechanisms necessitates at least one and probably a series of concentric faults. It would also be logical to expect a circular or oval intrusive mass, even in schistose country rocks. Bysmaliths are a special variety of laccolith which are found doming and faulting flat-lying sedimentary rocks. However, the area involved has steeply dipping schistose rocks; therefore, bysmaliths can be eliminated from the discussion.

The recent detailed mapping has not disclosed faults of large magnitude in the vicinity of the intrusive. It must be admitted that many small faults could have escaped attention in areas of poor exposures. Moreover, any faults parallel to the structures of the country rock would be extremely difficult to find or trace.

Doming of the overlying country rock has occurred, as shown by Balk's maps (2,p.75) of the Barre granite district. According to his published sections, using linear flow structures, doming amounts to less than three hundred feet in all of his plutons. Planar flow structures mapped by Jahns and the writer are largely restricted to the western side of Millstone Hill, where they dip steeply west. These structures are essentially parallel to the presumed contact along this border of the intrusive. Except for this small doming, there appears to have been very little uplift of blocks.

Differential expansion

Expansion in any given direction is limited, as indicated by the present contact relations. Across the strike of the country-rocks, the displacements of the intraformational country-rock contacts is less than two thousand feet. Balk's flow lines and graphs (1,p.59) indicate stretching parallel to the schistosity rather than across it. This may indicate a greater expansion along the strike rather than across. In any event, the expansion is still much less than the space requirements of the presently exposed level of the stock.

Stretching of the granite parallel to the country-rock schistosity should involve shortening of the meta-sedimentary section by crumpling and/or bedding-plane faults. Crumpling was not observed, as the schistosity and lineations are uniform on all sides of the intrusive. Bedding-plane faults, as already noted, could easily have been overlooked in this terrain of very discontinuous outcrops.

Expansion of the roof of country-rock above the granite, and the expansion across the schistosity would aid in setting up tensions in the crust and allow the formation of the dike intrusions so well developed in the southeast portion of the district.

Differential expansion is necessary as one of the mechanisms needed to provide the space required for the Barre pluton.

Stoping

Balk, in referring to the Barre pluton, states (2,p.76): "Independent arches of the flow lines render impossible any assumption that some such process as piecemeal stoping may have carried the granite to the now-exposed level." In contrast to this, it is the contention of the present writer that stoping processes played an important role in the emplacement of the Barre pluton, and that forcible injection does not automatically exclude stoping as an associated process.

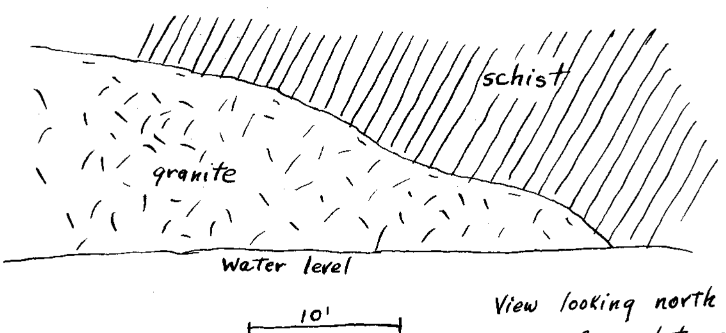
Balk notes that the Barre district contains at least eight separate plutons, each dynamically independent during intrusion (2,pp.74-76). The present mapping consists of numerous dikes and a single, perhaps composite, pluton. All of Balk's plutons are now known to be interconnected. The doming mapped by Balk probably indicates the final upbowing in individual parts of the main intrusive mass.

The White Mountains of New Hampshire present numerous examples of intrusives formed mainly by stoping mechanisms,(5,pp.40-68). The various techniques of ring-dikes, cauldron subsidence and piecemeal stoping are recognized (7,pp.1059-1100; 9,pp.502-530; 24,pp.1185-1932) by the workers in this region.

Mt. Ascutney, Vermont, is the area where the process of piece-meal stoping was first set forth by Daly to explain igneous intrusions (13,pp.1-122). Subsequent remapping, however, seems to indicate that cauldron subsidence (8,pp.191-212) was more important here than piecemeal stoping. Even if wholly correct, this reinterpretation does not nullify the concept of stoping, as it has been adduced in many places throughout the world.

A section through the Barre intrusive across Millstone Hill and Websterville shows that more than one-third of the quartzite originally present, and almost all of the originally 1200 foot thick section of phyllite, has been removed. The quartzite, because of its more massive nature, breaks into large pieces, as the septum on Millstone Hill indicates. The phyllite, being more schistose, is more easily broken into slabs and displaced. The dike area near Upper Graniteville illustrates the early stages of the removal of the phyllite in long, thin sheets. The amount of material missing from this section cannot be accounted for by expansion of the walls, and therefore, must have been stoped downward.

The small quarry east of Cobble Hill exposes an undisturbed capping of schist, as shown in the sketch section below.



View looking north
Sketch from photograph by R.H. Jahns

The sharpness and gentle dips of the contact, as well as its westward continuation over Cobble Hill, would indicate a possibility that some such large-scale process as cauldron subsidence may have played a part in the emplacement of this portion of the pluton. The schist capping on Cobble Hill is an indication of the flatness of this contact over a considerable area, and could conceivably represent the upper surface of the fracture from which a large block subsided. This surface has subsequently been modified by removal of small blocks by stoping and small dike intrusions of granite, thus developing the ragged edge now presented by the Cobble Hill capping. This capping, also, has been tilted somewhat, and the schistosity now is essentially vertical over most of the hill.

If forceful injection were the only mechanism for intrusion of the Barre pluton, as advocated by Balk (1,p.267), most of the inclusions should be oriented parallel to the flow lines. Some of the inclusions are parallel to these lines, but this may well be only accidental. The work of Dale (12,p.64), Balk (2,p.106) and the writer shows a striking lack of orientation of these inclusions or of the schistosity within them.

The septa of Millstone Hill and Websterville have schistosities that are almost identical with those of the undisturbed country rock. These septa have been wedged southeastward by the intruding magma. To have preserved their orientation requires that these septa were disconnected from the overlying schists and shoved or floated horizontally. These would then be bounded above by sub-horizontal fractures much like the Cobble Hill contact. These septa may represent the initial steps in foundering great blocks of the crust. ~~by cauldron subsidence methods~~.

Summary of the intrusion

Initially, the "dark Barre" granite worked its way upward by slight expansion due to upward forces and stoping. This expansion caused tension cracks to form in the surrounding country rock. The cracks were filled with granite, thus loosening blocks of wall rock and allowing them to sink in the magma.

While the earlier "dark Barre" granite was still, in part, liquid, the "light Barre" was intruded into it. The "light Barre" intrusive was on a larger scale and displaced a volume of country-rock several times that of the "dark Barre". The main mass bulged the walls and roof, shouldered the septa of Millstone Hill and Websterville to the southeast, opened fractures for subsequent granite-dike formation in the region north of Upper Graniteville, and stoped out the remaining country rock to aid in making space for the intrusive.

All of this stoping and shouldering occurred during the final spasms of the second regional deformation. This tectonic action aided in forming the uniform rift as well as probably giving the mass its upthrust action and causing the final doming.

In the last phases of solidification of the intrusion came the injection of the aplite, quartz and pegmatite into the joints of the granite and the fractures in the surrounding country rock.

While cooling and consolidation were proceeding, the small amount of remaining magmatic juices within the mass worked their way to the top of this tilted, elongate, lathlike mass and caused the greater kaolinization of the feldspars, as well as the more pegmatitic facies of the Cobble Hill region of the pluton. The chlorite and iron oxides were formed along many of the joint surfaces at this time.

After completion of crystallization, thrusting from the northwest probably formed some of the minor joints within the main mass. Finally, in Triassic time, the north-south tension developed (the fourth regional deformation) accompanied by diabase dike filling. These dikes filled east-west fractures in the country-rock and some of the northeast-southwest trending longitudinal joints within the granite.

Thus ended the structural deformations of the Barre granite. Long-continued erosion since then has brought the Barre granite to the present topographic surface.

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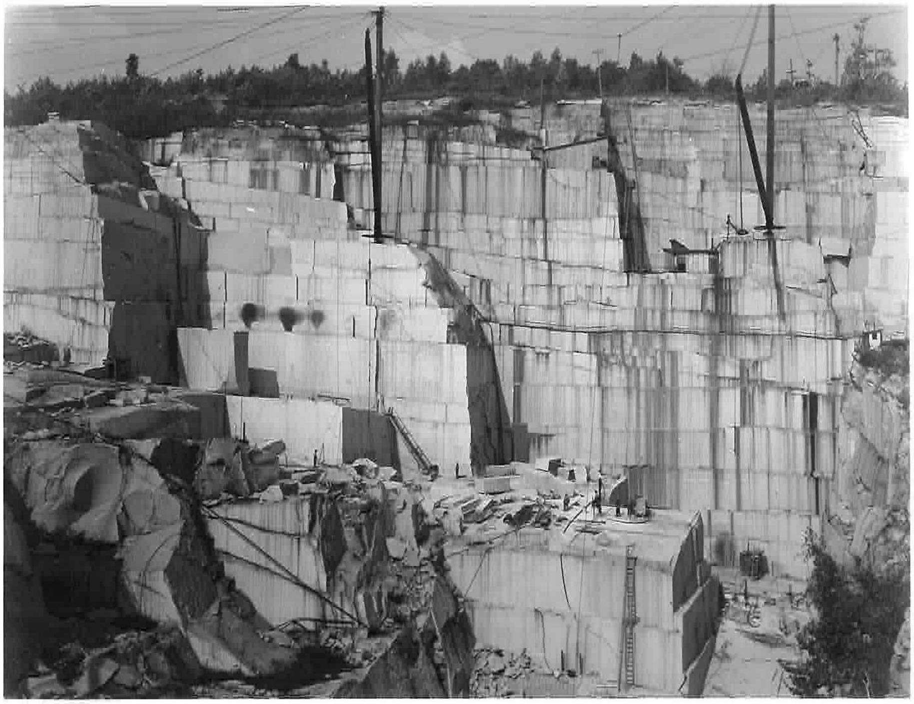
Plate I

A. West face of the Wetmore and Morse quarry. Shows fairly well-developed thin post-glacial sheets near the surface and the much thicker pre-glacial sheets in the main part of the quarry. Note that the sheets are least well developed near primary joints. Note the transverse joints in the lower left part of the view. Note also the lenticularity of the sheets.

B. General view of south end of Millstone Hill, showing the E. L. Smith quarry and the southern end of the Wetmore and Morse quarry. View looking north.

PLATE I



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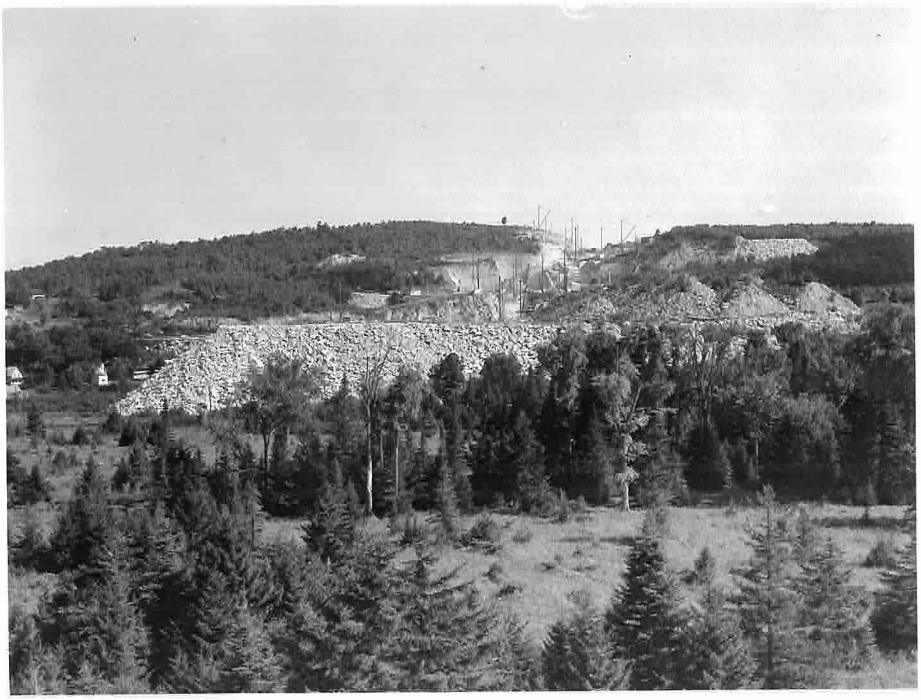

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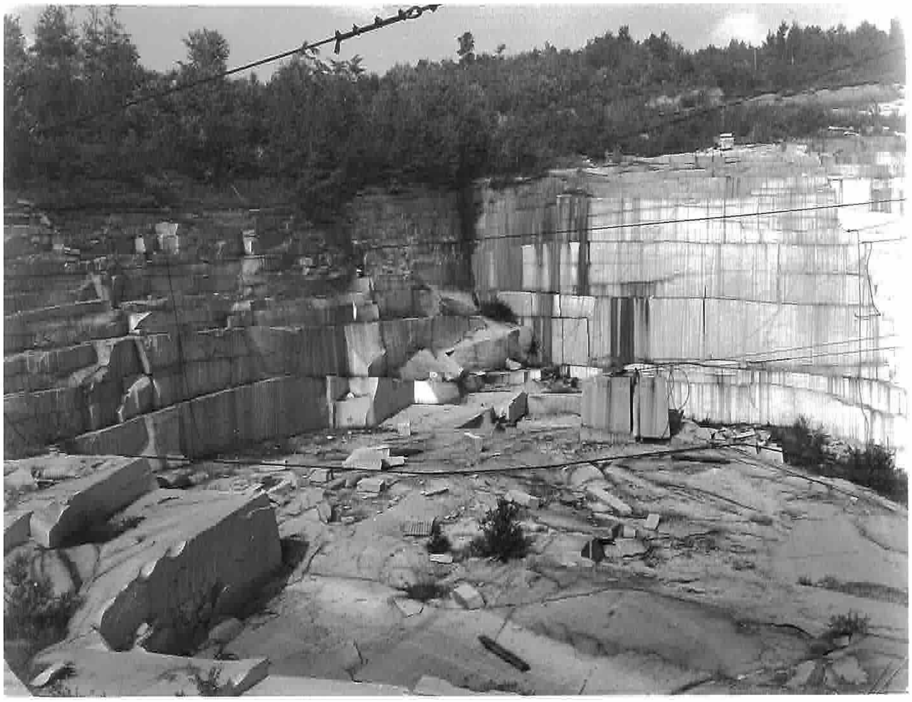
Plate II

A. Abandoned quarry west of the E. L. Smith quarry. Illustrates the well-developed sheet structure in this portion of the district.

B. "Light Barre-dark Barre" granite intrusive contact, illustrating typical fading out. Circular mass of "light Barre" in right center is interpreted as a tongue protruding toward the observer and is connected in the third dimension to the main mass of the "light Barre" granite.

PLATE 2



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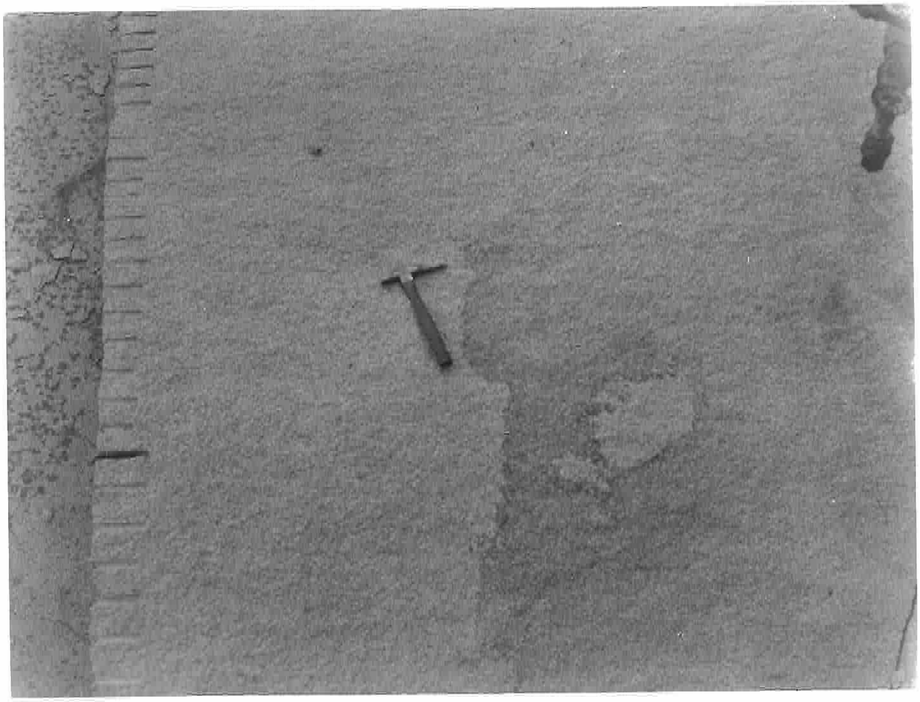


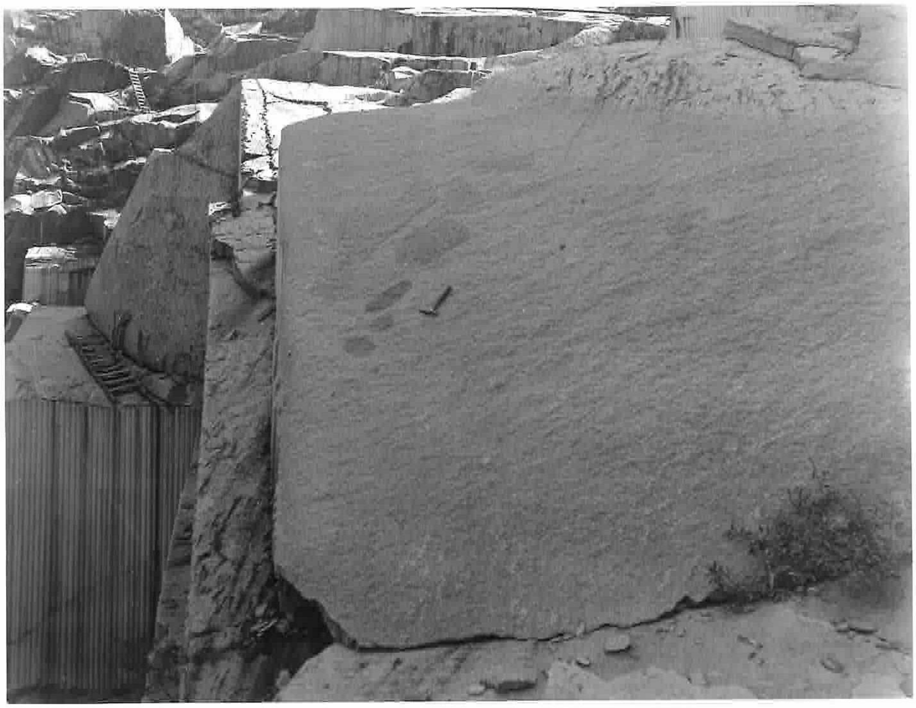
B

Plate III

A. Partially assimilated inclusions of "dark Barre" granite in "light Barre" granite. In Pirie quarry.

B. Block from the School quarry showing "light Barre" granite intruding "dark Barre" granite.

PLATE 3



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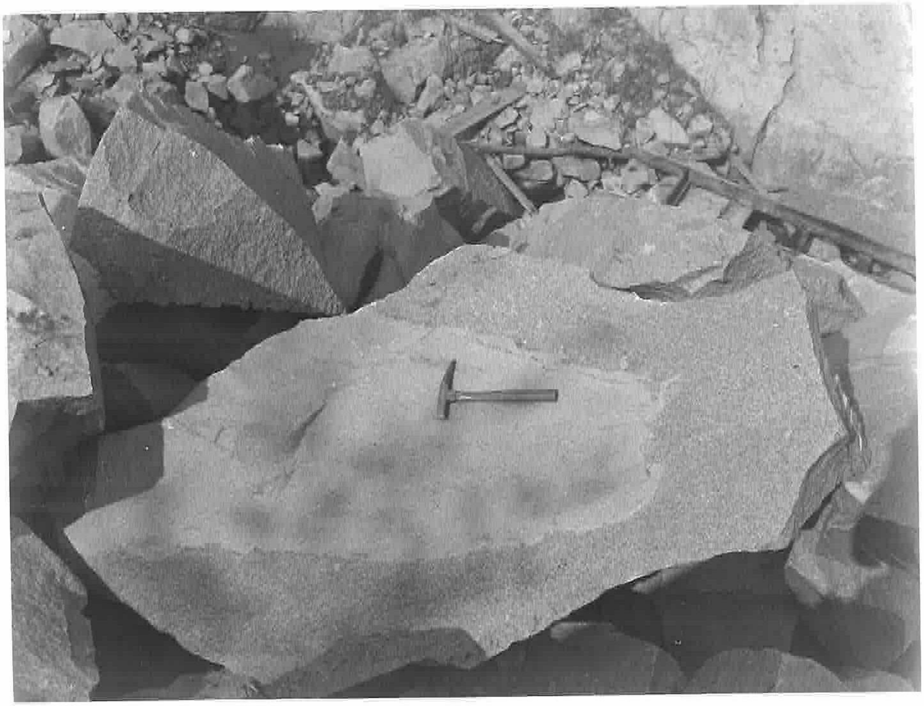

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Plate IV

A. Corner of the Pirie quarry. Illustrating the well-developed, iron-stained longitudinal joints trending N. 30-40° E. Height of face approximately 150 feet.

B. View west across central portion of the Rock of Ages quarry showing sharp walls of schist xenoliths in right foreground, well-developed longitudinal joints in left middle-ground, and some of the smaller piles of "grout", or waste, in the background.

PLATE 4

A

B