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ROCK-BURSTS IN THE GRANITE QUARRIES AT BARRE, VERMONT

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By

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INTRODUCTION

During the last few years the quarrymen of Barre, Vermont, have been troubled by rock-bursts in the granite. Partly freed blocks develop fractures at oblique angles to the natural partings of the rock, and much stone is thereby lost. Preliminary study of the problem indicates that the fractures are caused by expansion of the rock as it is freed. Probably little can be done to reduce the pressure [1] of this expansion, but certain modifications of quarrying practice should reduce the number of destructive fractures.

The writer spent eight days in a preliminary field study of the problem in November and December, 1944. In the limited time available no quantitative study of the rock expansion and bursting was made nor was an exhaustive study of the literature of rock-bursts attempted. Preparation of this report was delayed by more pressing wartime duties. All conclusions and recommendations are tentative, and point to the need for quantitative measurement of the factors involved.

[1] The word "pressure", as used in this article and by the quarrymen concerned, refers to the force generated by elastic expansion of the granite, a force that causes drill holes to close, displaces large blocks of granite, and causes rock-bursts.

The writer is grateful to the management and quarrymen of the Barre quarries visited for their interested cooperation and many courtesies extended. Preliminary observations and notes on the rock-bursting by M. P. Billings and A. E. J. Engel of the U. S. Geological Survey have proved most helpful. Previous geologic studies in the Barre area by R. H. Jahns and the writer provided a background knowledge of the regional geology. The writer is much indebted to L. W. Currier and R. H. Jahns of the Geological Survey and Prof. Francis Birch of Harvard University for critical review of the manuscript.

GEOLOGY

A preliminary map of the Barre granite area (fig. 1) made by the writer in July 1940, shows the distribution and shape of the granite bodies. They are narrow tabular bodies, more or less parallel with the enclosing rocks ("slates") on a regional scale, but sharply crosscutting in detail. The bodies strike north-northeast to northeast and probably dip (slope) steeply northwest. The rocks have undergone very little deformation since the granite was intruded.

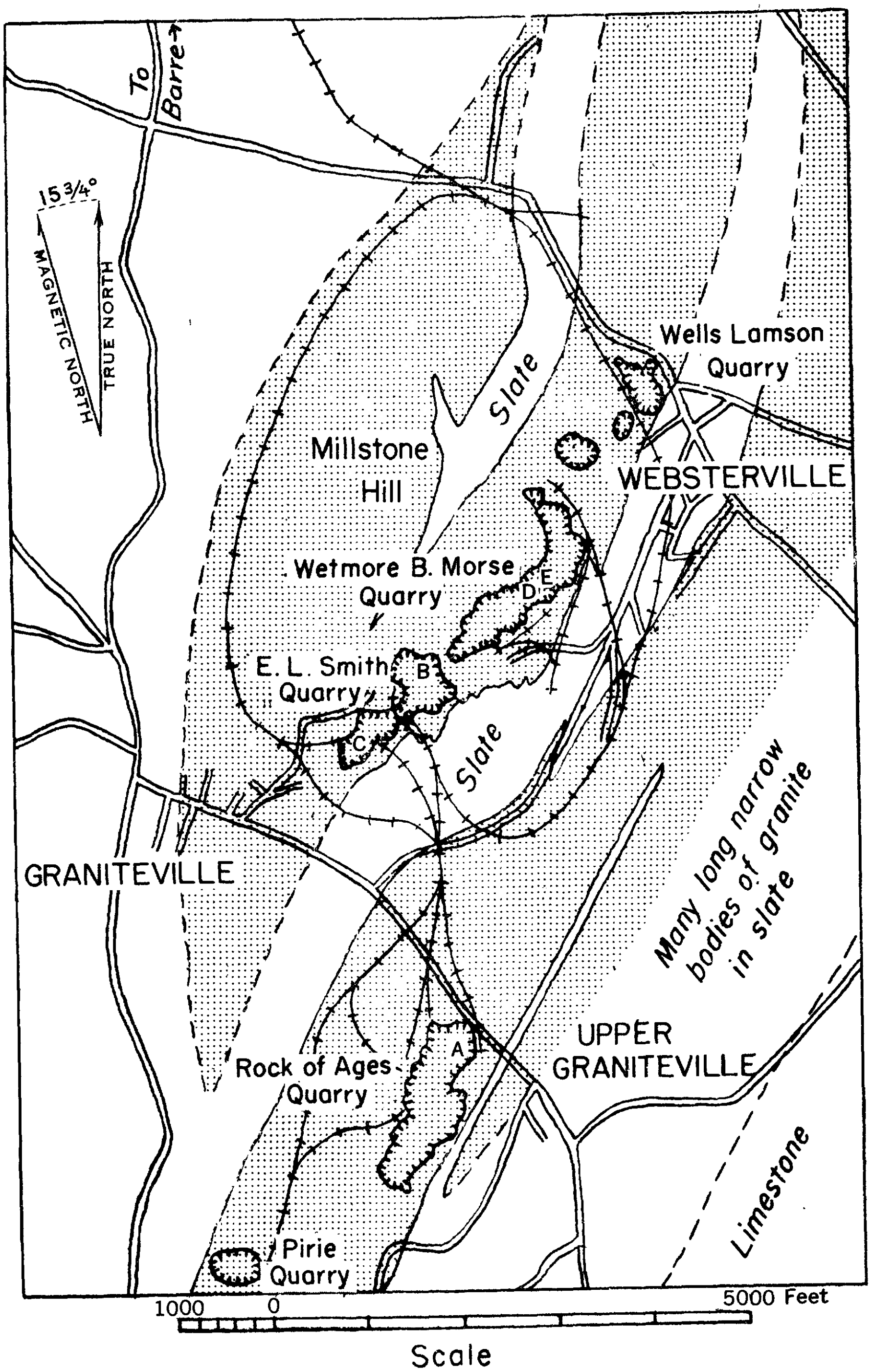

Figure 1. —Index map of Barre granite area. Shaded area is underlain by granite. Letters in quarries give location of views in plate 1.

The granite has been described in detail by several writers. [2] It is a medium- to fine-grained rock, ranging in composition from granodiorite to granite. Most of the granite in the quarries is massive and lacks a conspicuous linear or platy arrangement of minerals; schlieren (streaks of black mica) are very rare. Balk[3] found that where foliation and linear elements are present, they lie in planes more or less parallel with the boundaries of the granite bodies. The principal joints also strike parallel to the boundaries, but dip steeply southeast. Persistent joints or groups of joints, called "headers" by the quarrymen, generally have this orientation.

The rift, or direction along which the granite splits most easily, trends northeast and dips steeply southeast to vertical. It is nearly parallel to the principal joints, or "headers", and may be closely related to them in origin. The hardway, or direction of most difficult splitting, is also vertical and trends across the granite bodies at right angles to the rift. The lift, which is intermediate between the rift and the hardway in ease of splitting, is essentially horizontal.

In most of the quarries the granite is fractured into sheets, or "beds", that lie more or less parallel to the surface of the ground. The sheeting, or "bedding", is horizontal near the tops of hills; on the sides, it slopes in the same direction as the surface of the ground, but generally less steeply (fig. 2). Most sheets exposed at the natural surface of the ground are a foot or less in thickness; sheets 200 feet below the surface may be as much as 30 feet thick. There is practically no sheeting in the northeast part of the Rock of Ages quarry. Sheeting is generally attributed to upward and sideways expansion of the granite as the overlying rocks are gradually eroded away. [4] This belief is confirmed by the fact that the pressure due to rock expansion (see below) is small or absent in highly sheeted granite near the surface on hills. The sheets have probably already relieved the pressure by expanding sideways in such a way as to spread the hill a few inches or feet. Slight arching and lateral movement of wedge-shaped sheets in the direction of taper may also afford local relief of pressure.

ROCK-BURSTS

Relation of cracks to geologic features of the granite

Plate 1 contains five oriented sketches, drawn in isometric projection, showing cracks that formed during or following quarrying operations. The cracks slope in all directions and may be gentle or steep. It is clear, therefore, that they have no consistent relationship to the natural parting directions, sheeting, planar structures, and boundaries of the granite, all of which have a more or less constant orientation throughout the district.

[2]Balk, Robert, A contribution to the structural relations of the granitic intrusions of Bethel, Barre, and Woodbury, Vermont: Vermont State Geologist, Ann. Rept.for 1925-26, p. 50-72, 1927.
Dale, T. N., U. S. Geol. Survey, Bull. 738, p. 121-143, 1923.
Finley, G. I., The granite area of Barre: Vermont State Geologist, Ann. Rept. for 1901-02, p. 46-60, 1902.

[3]Balk, R., op. cit., p. 60 and map, p. 52.

[4]For discussion and bibliography, see Jahns, R. H., Sheet structure in granites; Jour. Geology, v. 51, p. 71-81, 1943.

Relation of cracks to quarrying

The cracks have a very consistent relationship to the shape of the part of the quarry in which they lie; without exception they slope towards the deepest adjacent opening or high free face. They are certainly the result of the tendency of the granite to expand into the quarry opening. The cracks are a product of "exfoliation", a name that geologists have given to a process common in nature. Blocks of massive rock, like granite, in the course of time almost invariably tend to fracture in such a way that corners and sharp angles are broken off.

Cause of rock expansion

When the granite was formed by the cooling of molten liquid millions of years ago, there were several thousands of feet of rock above the present surface of the land. Since that time the land surface has been worn down to its present level, and the compression caused by the weight of this overlying rock has been removed. Just as certain deep-sea fish expand or even burst when brought to the surface, the granite, which was originally deep and greatly compressed, now tends to expand in all directions because of the removal of the overlying rocks.

All the pressure phenomena observed at Barre can be attributed to expansion after compression. The quarrymen understandably refer to the weight of rock in hills behind quarries or in high walls as the source of the pressure, but pressure generated in this manner is probably negligible.

Amount and force of expansion

A distinction must be made between the amount of expansion and the force of expansion ("pressure"). The amount is small and the force relatively large.

The amount of expansion depends upon the size of the mass of granite that is expanding and on the amount a unit mass expands upon being freed. Dale[5] found at Stone Mountain, Georgia, and Westford, Massachusetts, that blocks expanded about 0. 1 percent, that is, a block that was 1, 000 inches long before quarrying would be 1, 001 inches long after being freed. At Barre, masses of rock have locally been displaced 2 or 3 inches; this indicates that the mass of rock that is expanding is well over 100 feet long in the direction of expansion. At many such places the granite in the quarry walls must be expanding into the quarry.

The force of expansion is tremendous, as any quarryman can testify. This force amounts to many thousands of pounds per square inch before quarrying begins, and is often sufficient to crush the "cores". [6] But as quarrying proceeds, and the rock expands into the new opening, the pressure disappears rapidly. As described in the preceding paragraph, the expansion in a quarry required to reduce the pressure to zero may amount to 2 or 3 inches, but at most places may not be readily detected by visual examination.

Apparently the expansion is not everywhere uniform. Channels parallel to the rift are more commonly closed up than hardway channels at the E. L. Smith

[5]Dale, T. N., op. cit., p. 30.

[6]A "core" is the rock left between two adjacent drill holes in a channel.

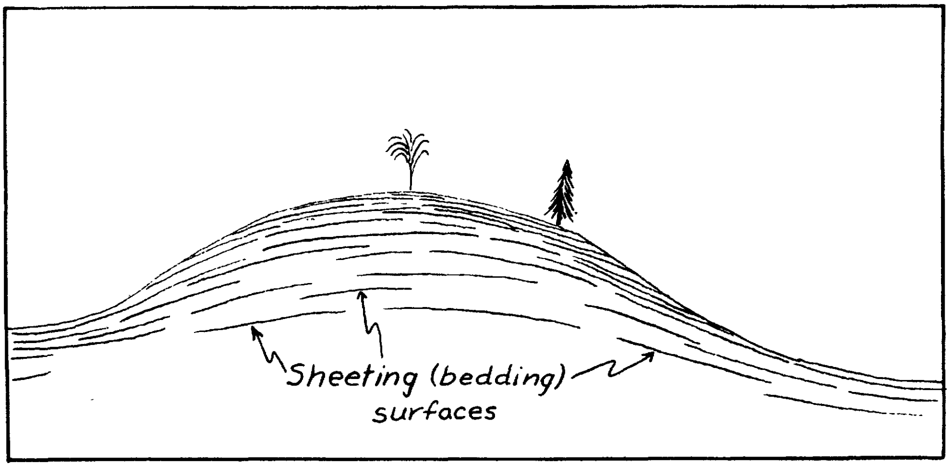

Figure 2. —Cross section of a granite hill, showing sheeting nearly parallel to slope of hill. Sheeting (bedding) probably forms by upward and outward expansion of granite.

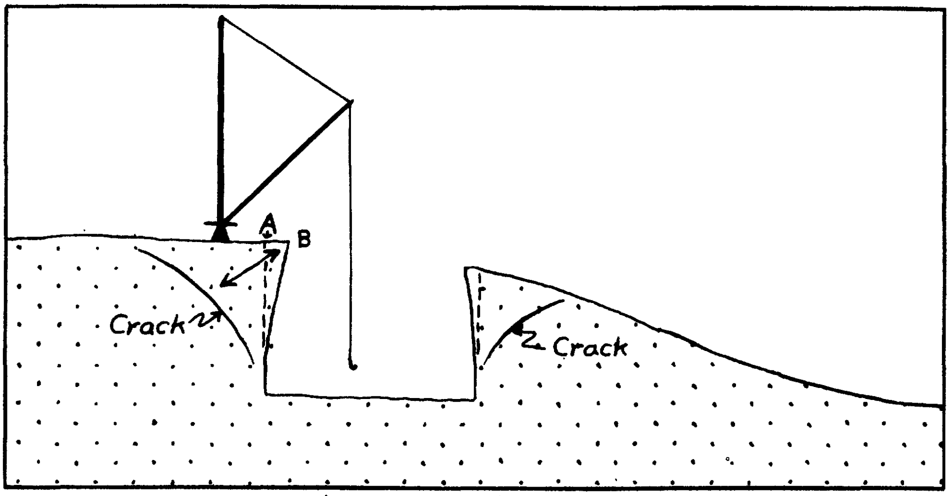

Figure 3. —Cross section of a newly opened quarry in unsheeted granite, showing how granite expands. Dashed lines represent original position of rocks that now form walls. Amount of expansion greatly exaggerated. Double arrow is axis of maximum stretching.

and Wetmore & Morse quarries. Vertical expansion of the granite is probably negligible, because near the surface of the earth the rocks have already expanded upwards. This universal upward expansion has undoubtedly contributed to the formation of the sheets or "beds" in the granite. The following discussion of the localization of rock-bursts is limited largely to consideration of the effects of sideways expansion; furthermore, the differences in the amount of expansion in different horizontal directions are neglected for lack of quantitative data.

Results of rock expansion

Expansion of the granite results in movement of rock toward available open spaces and, indirectly, to the distortion and fracture of rock masses that resist this movement. This distortion may take place in the walls or floor of a quarry, or in partly detached blocks within the quarry. The rock at the top of a typical quarry may be several inches nearer the center of the quarry than it was before the opening was made. As indicated above, the amount that the walls must move inward to dissipate the force of expansion is relatively small. But until dissipated by this small movement, the force is tremendous, and more than adequate to distort or break large blocks of granite that resist it.

Rock movement is aided by the bedding or sheeting typically present in the Barre quarries. If no sheets were present, inward movement of the top of quarry walls would be resisted by the strength of the granite beneath. The sheeting, however, permits greater freedom of movement, and individual sheets can slide a little over underlying sheets that have not yet been freed. To some extent, therefore, quarry walls are like the sides of a deck of cards rather than like the sides of a block of wood. The analogy is imperfect, however, because sliding on the sheeting surfaces is strongly resisted by friction and by the many interlocking projections and hollows that characterize these surfaces. The typical nature of the rocks lies somewhere between the examples of a deck of cards and a block of wood. To simplify the descriptions and illustrations that follow, sheeting is for the most part neglected; in deep quarries there is more movement, and hence more rock-bursting in sheeted than unsheeted granite, but the types of bursts are the same. In a quantitative study, sheeting would require far fuller consideration.

Another factor that undoubtedly influences the expansion, and therefore the results of expansion, is the jointing (headers), so common in the Barre quarries. Where joints are common in the granites of other regions, sheeting is generally rare or absent, and most geologists accept this fact as evidence that the force of expansion in the rock has been dissipated by slight movements on the joint planes.[7] The absence of sheeting in the north part of the Rock of Ages quarry, close to a large header, is very suggestive in this connection. There are, however, rock-bursts in this part of the quarry, which is ample evidence that the force of expansion there is still large. Furthermore, joints or headers are fully as abundant in the well-sheeted rock of the E. L. Smith quarry as in the unsheeted granite of the Rock of Ages quarry. The prominent joints throughout the district dip (slope) steeply, and probably permit very little sideways expansion of the granite. For the present the writer proposes to omit consideration of the role played by joints in reducing the pressure of expansion within specific blocks of ground, but such a role must certainly be investigated in a more detailed study.

Rock-bursts occur when the sideways movement of rock toward an opening operates to distort a block of granite beyond its breaking point. Blocks may be distorted in at least three ways, and the resulting fractures are of three types. The commonest type is illustrated diagrammatically in figure 3. The walls, pressing inward, move point A sideways to a new position at B. The axis of maximum stretching is shown by the double arrow, and cracks form perpendicular to this line. It should be noted that these cracks slope toward the nearest free face. Most of the cracks indicated in the diagrams of plate 1 are of this type. If the rock at the bottom of the vertical face were as free to move inward as the rock at the top, because of slip on sheeting surfaces, no such fracture would form. The fact that most of the rock-bursts at Barre take place along this type of fracture, rather than along the type described in the following paragraph, is clear evidence that slip on sheeting surfaces is of minor importance.

The second type of fracture is nearly vertical (pl. 1E, behind derrick 5A) and is found only where a sheet has been freed to slide over the underlying sheeting fracture. The fracture passes completely through a sheet and does not affect the sheet below. Its origin may be visualized by regarding figure 3 as a map rather than a cross section. This type of fracture is rare, but the common fractures in which corners are broken off may be combinations of types 1 and 2.

The third type of fracture is flatter, and appears to have formed where very little sideways yielding was possible, and the rock could only expand upward. Such fractures are not common and generally release only a thin slab.

All the fractures represent the results of expansion into the nearest open space. Viewed very simply, they represent new sheeting or bedding fractures that originate when man changes the topography of the surface of the earth. And like the natural sheeting fractures that faithfully follow the slopes of hills and valleys, but with more subdued contour (fig. 2), these new fractures slope toward the new man-made valleys, the quarries (fig. 3). And also like the natural sheeting fractures, the new fractures tend to form in such a way that corners are broken off.

Brief mention should be made of the fact that some blocks, apparently intact when freed, subsequently develop cracks. The writer was not present when such a crack developed, but a possible explanation was suggested by observations on cracks in blocks that had not yet been freed. A large number of cracks that were observed in one face do not persist to the corners that bound adjoining faces. The crack, which may be very obvious and large enough to accommodate a knife blade in the middle of a face, disappears when followed towards an adjacent face. This fact suggests that there may be cracks within a block that do not extend to the faces, and subsequent splitting or handling of the freed block may cause these cracks to open up to the outer surfaces.

[7] Jahns, op. cit., p. 75. Gives bibliography.

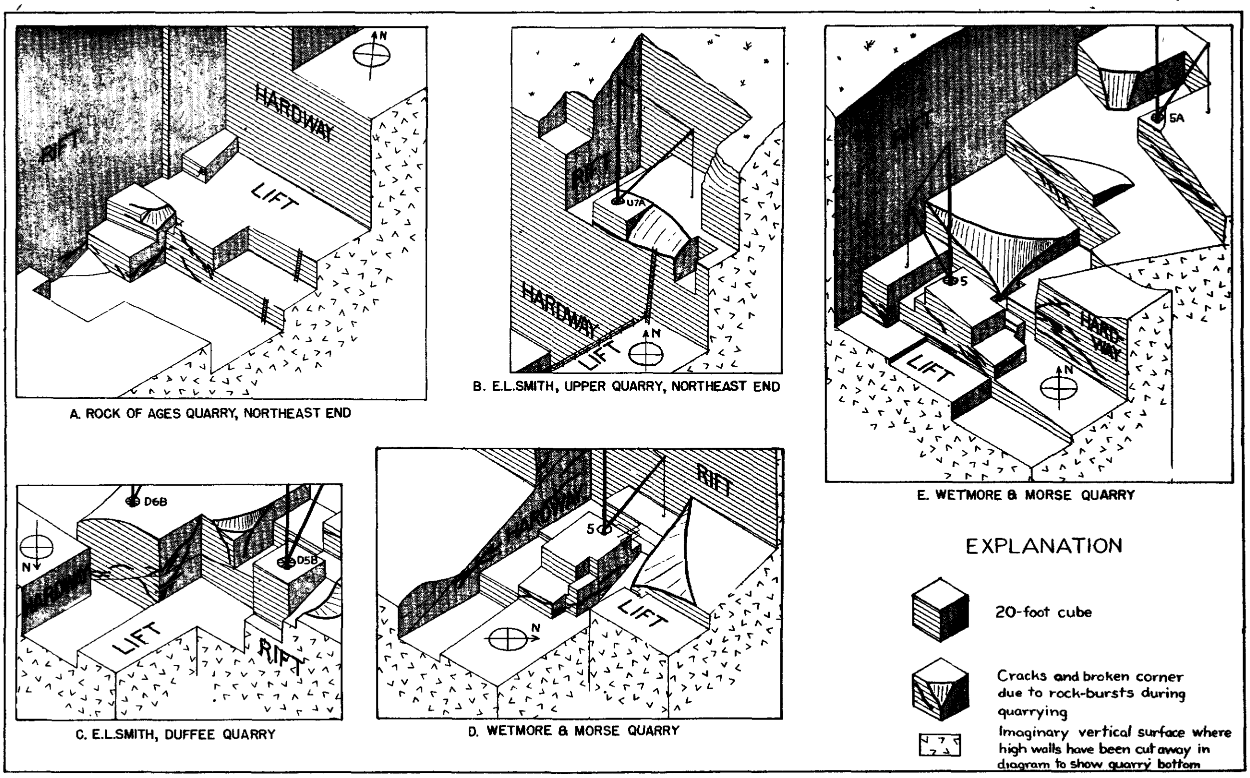

Plate 1. —Diagrammatic views of Barre granite quarries, showing cracks due to rock-bursts.

Factors controlling rupture of distorted blocks

As suggested above, partly freed granite blocks will crack when the amount of distortion or extension at any point exceeds some allowable quantity. Therefore any factor that limits the amount of distortion is an important control of rupture. The two factors that appear most significant are (1) the size, shape, and support of a given block, and (2) the extent to which the strains and movement in the rock are permitted to be concentrated at certain points within a quarry. Sheeting has an important bearing on the second factor. Proper control of these factors should substantially reduce the number of rock-bursts at Barre.

Size, shape, and support of blocks. —A simple example will demonstrate that the shape and size of a block control the amount of distortion. The end of a 10-foot diving board is depressed less than half as much by its own weight as the end of a 20-foot board would be. In the same way, a point at the top of a 40-foot vertical wall in unsheeted granite, under constant pressure from within the wall, can move more, in proportion to its height, than a point at the top of a 12-foot vertical wall under the same unit pressure. Distortion is therefore greater, and with it the chance of fracture.

The manner in which lateral support may offer resistance to bending and reduce distortion is illustrated in figure 4, a plan and section of a part of a hypothetical quarry, closely resembling the situation in plate 1B. When the block to the right of line DE (fig. 4A) was removed, expansion of the granite caused point B to move to B'. This distortion may or may not have caused a crack, but if a crack formed, it would cut the surface of the block along the heavy black line. If no fracture formed and a channel were cut from F to D, point D would expand to D'. The distance D-D' is considerably larger than B-B'. The bending of boards offers a comparable example; a heavy diving board, free at one end, bends down farther than the same board would bend if it were supported at both ends. The fracture that would form after the channel is cut at DE would follow the dotted line EF. The removal of lateral support by the cutting of channel DF permitted the distortion that broke the block.

It is clear, therefore, that, other things being equal, blocks with extensive free faces are more apt to break than small blocks, and blocks are most apt to break when lateral support is removed. The size of blocks that can be freed on two or more sides without breaking is not everywhere the same, and depends on lateral support, local distribution of pressure within the sheets and perhaps, to a less extent, on variation in the tensile strength of the granite. But observations in the Barre quarries visited suggest that where 2 or 3 free sides of a block are over 20 feet high, there is great danger of breaking, particularly where one fixed side is against a main quarry wall; blocks in any location with 2 or 3 free sides 40 feet high are almost certain to burst. Blocks with only one free vertical face, like that shown in figure 4A may burst where the supporting walls at the sides are more than 75 feet apart.

Concentration of pressure and movement. —With modern quarrying practice, pressure is concentrated at certain points within the quarry, and the walls are fairly free to move inward. The reasons for this concentration can be made clear by two examples. If two sealed, hollow tin cans, one oblong in shape and the other spherical, are carried to great depth in water, the oblong can will collapse at much shallower depth than the spherical one; hence the spherical design of the bathysphere. Similarly, an arch has much greater load capacity than a span bridge of equal weight. In both the sphere and the arch, there is relatively uniform distribution of pressure throughout the structure, and maximum use is made of the compressional or crushing strength of the material to prevent inward movement. In certain materials, including granite, the crushing strength far exceeds the tensional or bending strength. Modern quarries resemble the oblong can or the span bridge.

Before the advent of the compressed air drill, maximum use was made of joints and other natural breaks in the rock to loosen blocks with a minimum of drilling. The shape of blocks was of less importance than the ease with which they could be loosened, because it was cheaper to shape the stone by splitting and throw away a large proportion than to attempt to cut out blocks with squared faces. This practice resulted in essentially bowl-shaped or oval quarries (fig. 5), because all projecting masses of rock were easily attacked and therefore were generally removed. These bowl-shaped quarries favored a relatively uniform distribution of the pressure due to expansion of the rock, and reduced the amount of distorting inward movement of the walls to a minimum. In such quarries the force that can be concentrated at any one point is probably rarely adequate to break much stone, because the rock at any one point is prevented from moving inward by the rock beside it, as in an arch (fig. 5A). As the diameter of the quarry decreases downward, the amount of inward movement is progressively less. In figure 5B, the dashed line represents the original position of the rock that now forms the walls, and their present position is shown by a solid line. The distance between these lines is, of course, tremendously exaggerated. The gradual downward decrease in the distance between the dashed and solid lines, however, suggests the uniform downward decrease in the amount of inward movement, and indicates the manner in which distortion is evenly distributed through the whole quarry wall. A bowl shape can be considered a "natural" shape in contrast with a rectangular shape, because, in nature, exfoliation tends to eliminate corners.

In modern quarrying with compressed-air drills, most of the cost of the operation is in channeling, for the removal of large squared blocks permits a big saving by substantially cutting down the amount of waste. It generally results, however, in rectangular openings. The amount of distortion and inward movement of the walls in a rectangular quarry are very uneven, and permit the concentration at certain points of forces that are capable of breaking the stone. The ideal distribution of these forces is somewhat different in sheeted and unsheeted granite.

In well-sheeted granite, inward movement of the walls is almost as great at the bottom of the quarry as at the top, and is restricted only by the friction between sheets or beds and by the support of the other walls in corners (figures 6B and 6C). It will be noted in figure 6A that angles in the four corners of the quarry that were

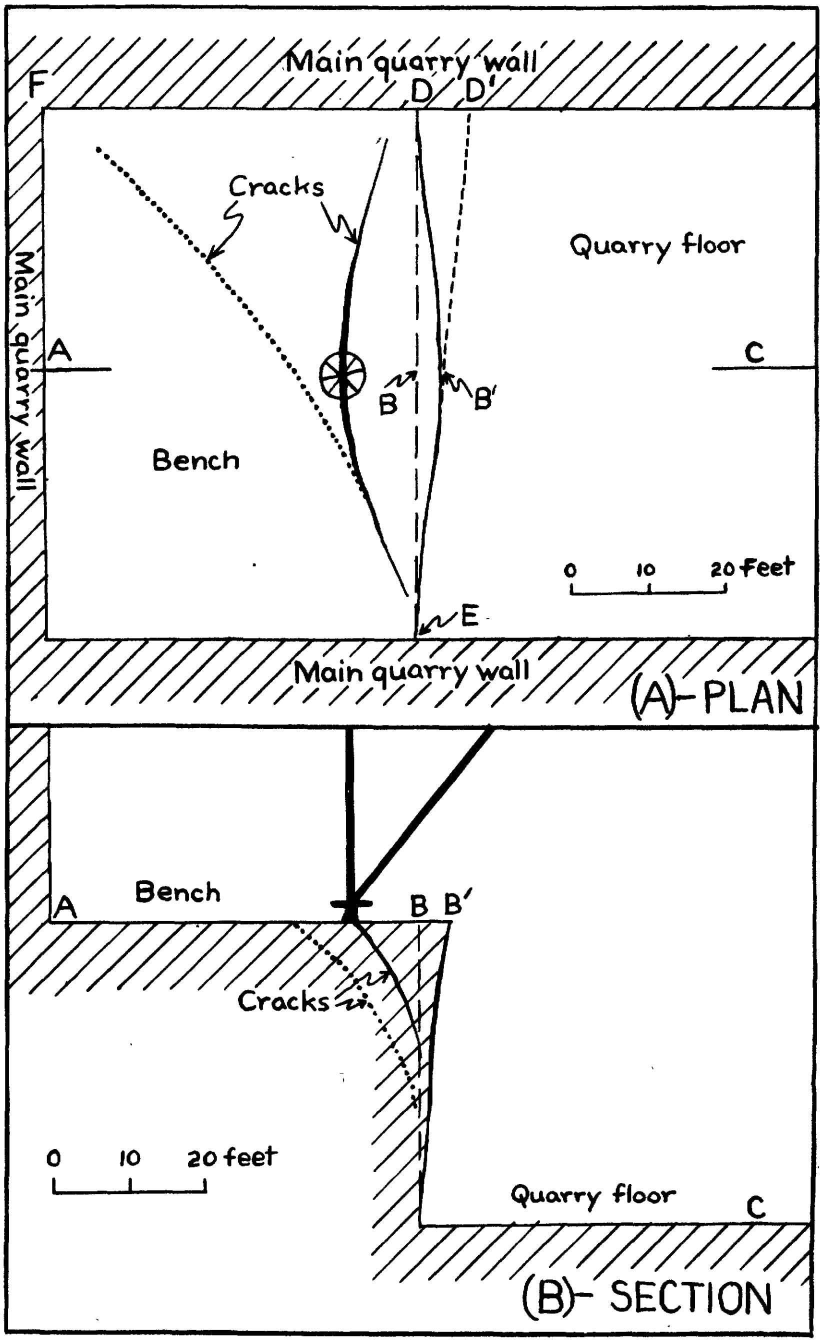

Figure 4. —Plan (A) and section (B) of part of a quarry. Section is drawn along line AC of (A). Dashed line DE represents original position of rock at edge of bench before rock to the right of DE was removed. Dashed line B'D' represents edge of bench after cutting of channel DF. Amount of distortion greatly exaggerated.

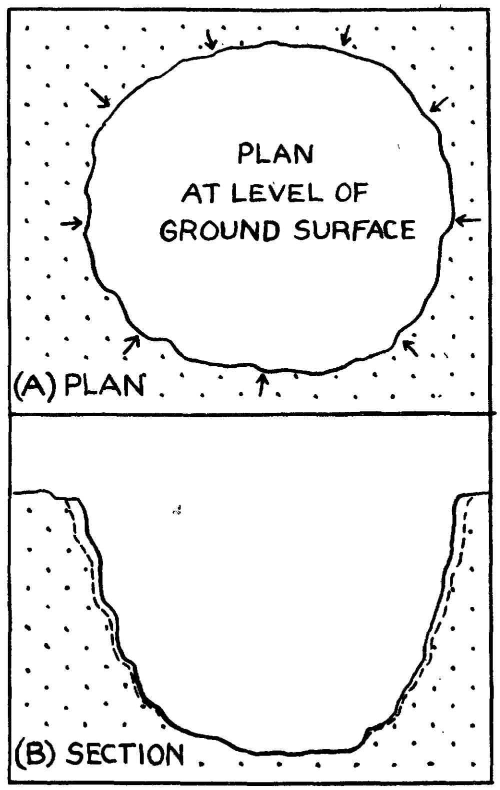

Figure 5. —Even distribution of pressure and distortion in bowl-shaped quarry. Dashed lines represent original position of rock that now forms walls of quarry. Amount of distortion greatly exaggerated.

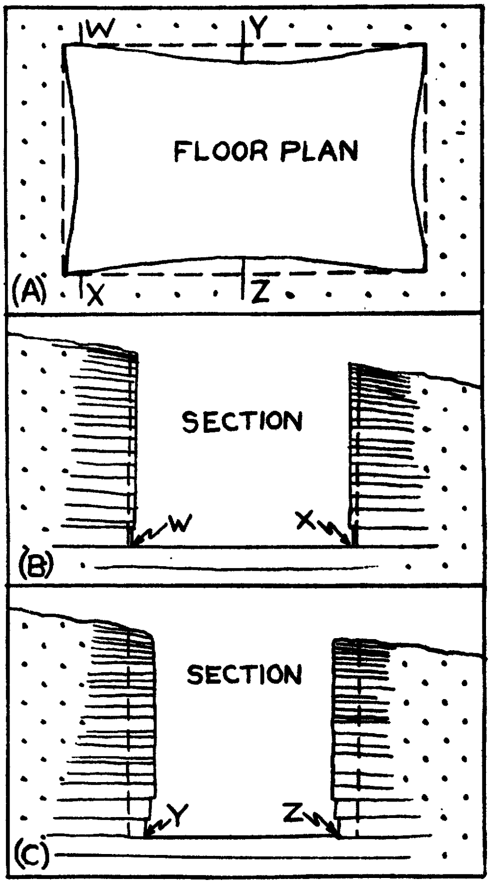

Figure 6. —Distortion in rectangular quarry in sheeted granite. Section in (B) is drawn along line WX of (A) and section in (C) along line YZ. Dashed lines represent original position of rock that now forms walls of quarry. Amount of distortion greatly exaggerated.

formerly right angles are now acute. Blocks of granite that remain unquarried in these corners are squeezed into a diamond shape, and their fracture is almost inevitable after the rock in the middle of the quarry has been removed. In one such corner in the Wells-Lamson quarry, the rock is under such great distorting pressure that practically every channel drilled in the bottom is accompanied by bursting. Along the sides, the rock is pushed inward with even greater force, but will not fracture if it is free to slide over the sheeting surface beneath it. Any block that resists the inward movement of the sides, however, will probably fracture.

In unsheeted granite, there is very little distortion of the shape of the floor of the quarry, particularly in corners, because the floor and the walls are part of the same unit of rock, and brace each other (fig. 7A). But along the sides, particularly at the center, the walls are bent inward above the floor level, and the original right angle between the wall and the floor is made acute (fig. 7C); the upper surface of any block remaining unquarried in this angle is pushed toward the opening farther than the attached lower surface, and the block will fracture. In plate 1A, a view of unsheeted granite, it is clear that most of the fractures are located along the side of the quarry at some distance from the corner.

As stated above, the friction between sheets or beds makes the behavior of most of the granite at Barre lie somewhere between the ideal behavior of sheeted and unsheeted granite. Therefore fractures occur along the sides as well as in the corners of quarries in sheeted granite.

Where the sheets or beds are not horizontal, the maximum pressure is exerted in a direction parallel to the sheets rather than horizontally. In the bottom of the northeast Wetmore & Morse quarry, movement of one sheet over another has formed openings along an irregular sheeting surface. In this place (upper right-hand part of pl. 1E), where the sheeting dips (slopes) 25° to 30° SE, expansion within a single sheet has formed cracks which have different orientations on opposite sides of a removed block. Both types of cracks can be found in this quarry, and they are diagrammatically illustrated in figure 8. If the sheeting were flat, the cracks would presumably slope at about the same angle but in opposite directions. This special occurrence is mentioned for its possible usefulness.

RECOMMENDATIONS

The following recommendations for local modifications of quarrying practice are based on a purely qualitative consideration of the factors involved in rock-bursts. Specific figures are avoided, in general, because no actual measurements of rock expansion were made, and because in the time available it was not possible to isolate and evaluate the relative importance of all the contributing factors at the points of observation. The recommendations are made with full knowledge that it would be uneconomic to follow them faithfully because (1) the shapes of present openings are largely fixed by past operation; (2) it is impractical to quarry a lot of unmarketable stone for the purpose of avoiding a few cracks in the part of the quarry that produces marketable stone; (3) it may be cheaper, in general, to sacrifice a little stone to rock-bursts than to adopt a more costly improvement of method and save the stone; and (4) adoption of some of the recommendations would require abandoning parts of some quarries, such as the south end of the Wells-Lamson quarry, with consequent loss of investment in derrick location and completed channels. The recommendations are made in the hope that where several methods of cutting out a given mass of stone are similar in cost, or where other considerations permit a choice in location of a new operation, the recommendations will be helpful in showing which choice is best from the point of view of avoiding rock-bursts.

Avoidance of extensive free faces

Except near the surface in hillside quarries, wide and high vertical or bedding surfaces, particularly near main quarry walls, generally lead to rock-bursts. Where two sides of a block are free to expand into an opening, and these sides are as much as 40 feet high and long, bursting appears to be almost inevitable. Deep keyways[8] are almost everywhere accompanied by cracking of the blocks at either side. A method of quarrying by which such bursts can generally be avoided is as follows:

In figure 9, a cross section of a hypothetical keyway, the solid line represents a keyway about 36 feet deep and the dotted lines the blocks at either side. The heavy lines represent cracks that formed during the cutting of the lowest block (block 6). The high vertical walls have permitted sufficient distortion of the blocks on either side to cause bursting. Viewed more simply, it is quite clear that no rock would have been present to burst next to the keyway if the granite had been quarried as a series of blocks 12 feet thick and 24 feet wide in the order of the numbers in figure 9.

Distribution of pressure in quarries

Modern quarries permit a concentration of pressure in corners, and this unequal distribution can be corrected only by development of bowl-shaped quarries (fig. 10). Such an extreme shape is clearly impractical for many reasons, notably the shape of present openings, the distribution of good stone, and maximum utilization of hoist capacity. It requires that a bowl shape, once attained, must be preserved by an equal rate of deepening of all parts of the quarry as operations proceed. Although a bowl shape can only be considered as ideal, the principle involved should be followed wherever there is a choice of two or more locations for a new operation within a quarry. Overdeepening of large holes and deep narrow cuts with vertical walls like the northeast end of the Rock of Ages quarry (pl. 1A), should be avoided whenever possible. Where it is necessary to make such holes or cuts, an attempt should be made to keep the bottom in a series of steps about 12 feet high and 25 feet wide with the lowest step or level in the middle of the cut. It is doubtful, however, that even this procedure would have prevented all the cracks shown in plate 1A; the cut is too narrow and the large, high rift face too long and straight. A broad flat bottom will cause extreme wedging of tolls in channels, and new cuts into the floor of the quarry will generally permit rock-bursts.

[8] A keyway is the first cut from a lower bench into higher bench, and frees the second side of the two blocks it separates. See opening behind Derrick 5A in plate 1E.

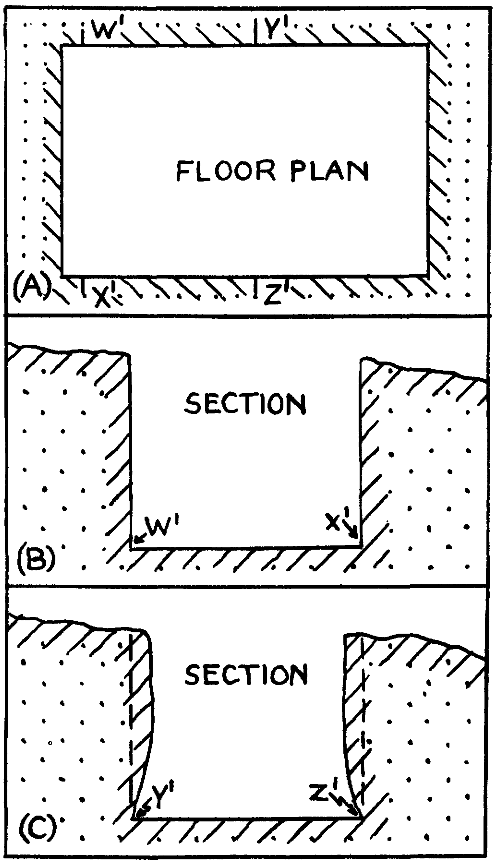

Figure 7. —Distortion in rectangular quarry in unsheeted granite. Section in (B) is drawn along line W'X' of (A), and section in (C) along line Y'Z'. Dashed lines represent original position of rock that now forms walls of quarry. Amount of distortion greatly exaggerated.

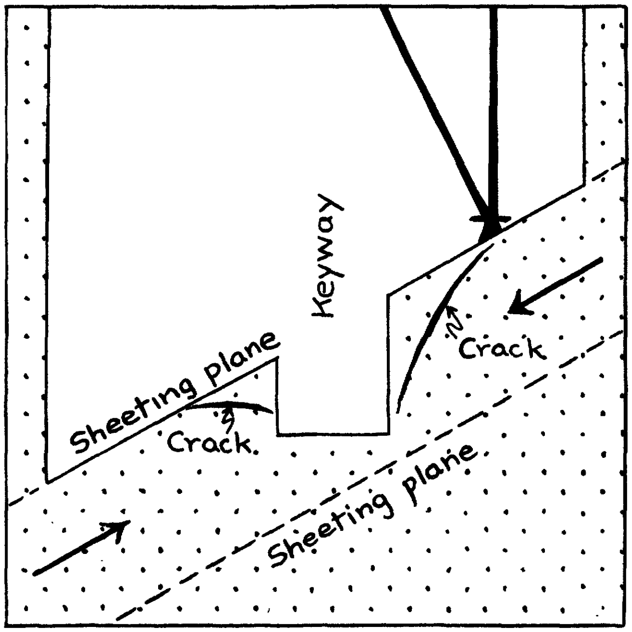

Figure 8. —Section showing cracks next to keyway in steeply sloping sheet (bed). Large arrows show direction in which maximum pressure is exerted.

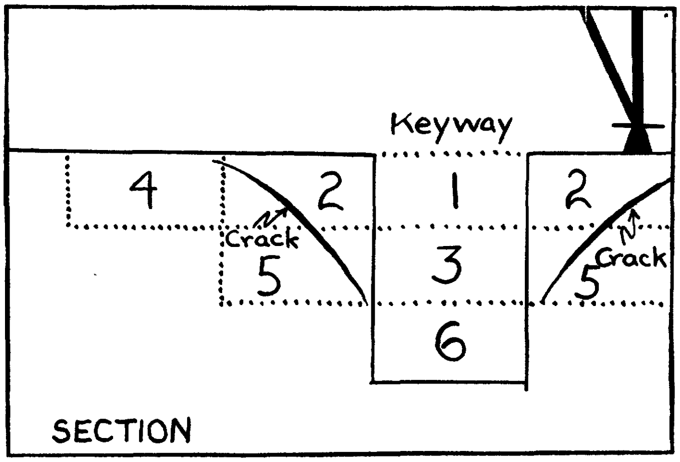

Figure 9. —Diagram comparing present method of cutting keyway with recommended procedure. Solid line shows a keyway as cut at present. Numbers in blocks bounded by dotted lines give order of cutting blocks in recommended procedure.

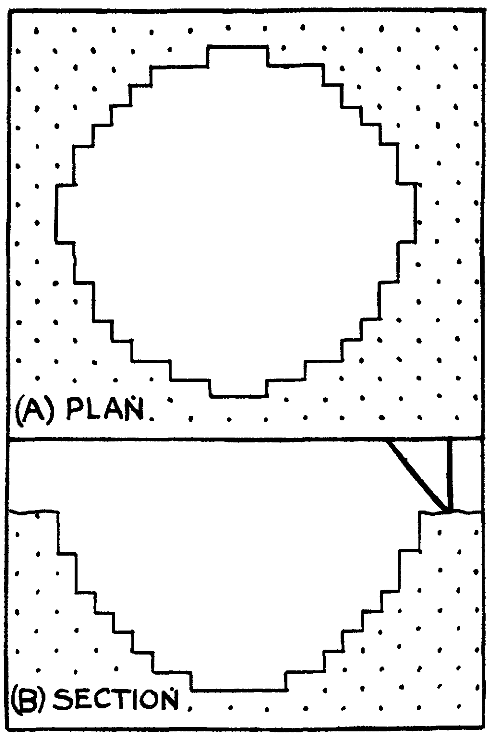

Figure 10. —Plan and section of ideal bowl-shaped quarry. Bowl shape is preserved by quarrying in benches and avoiding long straight faces. Quarry is 80 to 100 feet deep.

In addition to reducing rock-bursts, the ideal bowl-shaped quarry or its modifications would present fewer difficulties of closing of channels by lateral pressure.

Sloping sheet fractures

In figure 8, the cracks to the right of the keyway have destroyed some stone, but those to the left are more or less parallel to the "lift", and little if any stone is lost. It is immediately apparent that if the keyway had been cut next to the main quarry wall on the right, most of the cracks that formed during quarrying would be useful rather than destructive. Use of this principle can be made where the sheeting slopes steeply at the Whetmore & Morse and E. L. Smith quarries.

Quantitative measurement of expansion

The maximum size of free faces and the optimum slope and curvature of quarry walls to reduce rock-bursts to a minimum are functions of (1) the amount a unit of granite expands upon being freed (this may vary with depth and direction), (2) the size of the mass of granite that contributes to displacement at a given point, (3) the forces that resist expansion, particularly the rigidity of large masses, and the friction between beds and the interlocking of beds, (4) the ratio of vertical to lateral (bedding plane) expansion, and (5) time. All these factors except the first are interdependent. Vertical expansion is resisted by bending strength, but the bending caused solely by vertical expansion is probably far less than that necessary to rupture the rocks except possibly at the base of high vertical quarry walls.

The relative importance and quantitative values of these various factors are not known, and can be found only by careful and detailed measurement of the movements that take place as a block is quarried. Such measurements should be made over an area of several hundred feet under different quarrying circumstances, and for as long a time as is necessary to make significant observations.

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