THE RELATION OF CRUSHING STRENGTH TO MINERAL CONTENT IN ROCKS AT HAMILTON DAM SITE, BURNET COUNTY, TEXAS

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Dean of the Graduate School.

August 28, 1931.

THE RELATION OF CRUSHING STRENGTH TO MINERAL CONTENT IN ROCKS AT HAMILTON DAM SITE, BURNET COUNTY, TEXAS

Thesis

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MASTER OF ARTS

By

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PREFACE

This piece of research work was attempted through the suggestion of Dr. E. H. Sellards. The problem was investigated as part of the work in Geology 84, a graduate course in petrography, under the direction of Dr. Fred M. Bullard, to whom the writer is indebted for many suggestions and for encouragement to carry the work forward.

Thanks are also due Professor L. S. Brown for helpful suggestions and criticisms; The Fargo Engineering Company of Jackson, Michigan, for permission to use the cores taken from the Hamilton Dam Site; Dr. Sellards for the use of the specimens, maps, and information about the locality; and Mr. Raymond F. Dawson, Testing Engineer, Bureau of Engineering Research, University of Texas, for data on the crushing strength of the rocks.

Martin N. Broughton

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CHAPTER I

INTRODUCTION

The Problem

The purpose of this investigation is to determine in as accurate way as possible the relations that exist, if such relations do exist, between the quantitative and qualitative mineral content and resistance to pressures of rocks taken from the foundation of the Hamilton Dam; to devise means of expressing these relations; and to furnish suggestions for the pursuit of future investigations of these relations.

Location

The Hamilton Dam Site is in that part of Texas known as the Central Mineral Region. The dam, which is now[1] under construction, is located on the Colorado River ten miles due west of the town of Burnet. It is approximately one mile downstream from the right angle bend which the river makes in changing its direction from south to east. Barringer Hill, the famous rare earth mineral locality, is about four miles above the dam site. The dam extends from the north end of Long Mountain,

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1. August, 1931.

in Llano County, northward across the river to the south end of a high hill in Burnet County.[2] When completed the dam will have a length of 9,000 feet, a height of 137 feet, a bottom breadth of 210 feet, a top breadth of 36 feet, and will form a lake 36 miles long with an average width of two miles, an average depth of 28 feet, and will store 1,000,000 acre-feet of water.[3]

Geology

The rocks exposed at the Hamilton Dam Site are mapped as Valley Spring gneiss.[4] In the river valley the crystalline schists and gneisses of Valley Spring age are well exposed. A short distance upstream from the dam site is the contact between the Valley Spring gneiss and a fine-grained granite assigned by Paige to the early Archeozoic.[5]

The surrounding country is one of moderate relief and is characterized by rolling hills due to the erosion of unequally resistant schists, gneisses, and granites. Where mesquite covers the country serving as a protection against erosion, a thin surface soil covers the crystalline rocks. This surface soil ranges from a few inches to a few feet in thickness and is composed

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2. See accompanying map.
3. Personal communication from Mr. A.C.Cook, State Board of Water Engineers, August 24, 1931.
4. Paige, Sidney: U. S. Geol. Survey Geol. Atlas, Llano-Burnet Folio (No. 183), 1912, geologic map.
5. Ibid.

of arkose and arkosic clays and sands resulting from the weathering "in situ" of the underlying rocks.[6]

6. For further description of the geology and physiography of this region see Paige, Sidney: U. S. Geol. Survey Geol. Atlas, Llano-Burnet Folio (No. 183), 1912.

CHAPTER II

TECHNOLOGY

Methods and Procedure

One hundred and twnety-nine thin sections were made from the cores on which crushing strength tests had been made in connection with the investigation of the foundation of the Hamilton Dam Site. The mineral composition of these slides was determined with a petrographic microscope and determinative tables in standard textbooks[7] on optical mineralogy.

Quantitative determinations of mineral content were made according to the Rosiwal method of micrometric analysis as described by Holmes.[8] An eyepiece micrometer graduated into one-hundredths and a mechanical stage were used in addition to the regular equipment of a petrographic microscope. Several traverses were made across each thin section noting the number of divisions on the micrometer scale intercepted byneach mineral. As the micrometer is divided into one hundred lines, a count of the intercepts for each mineral gives the percentage of that particular mineral directly. In order to obtain greater accuracy, an average of several such counts on

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7. Winchell, A. N.: Elements of Optical Mineralogy, Third Edition, Part III, Determinative Tables, New York, 1928.
Weinschenk, Ernst: Petrographic Methods, Translation by Clark, R. W.: New York, 1912.
8. Holmes, Arthur: Petrographic Methods and Calculations, London, 1921, pp. 313-319.

each section was taken.

The mechanical stage was found to be advantageous in making the traverses, in that a direct line across the specimen could be followed much easier and faster than by moving the slide by hand. The use of the mechanical stage also permits the position of the stage and of the slide to be changed and moved back to the original position, a very tedious and time-consuming task if done by hand.

The accuracy obtained by the linear method of micrometric analysis is sufficient for this investigation. The linear intercept method of estimation of mineral composition depends on the principle:

> "that along any line of adequate length drawn on a plane surface--...the ratio of the sum of the linear intercepts of any given mineral to the total length measured across the rock-surface is approximately equal to the volume-percentage of that mineral in the rock".[9]

Checks on the linear method of analysis by checking several minerals against each other for the same rock and comparison with gravity separation methods of analysis, show that in the case of homogeneous rocks, a maximum error of only two to three per cent exists.[10] As the rocks investigated in this study are extremely variable in character in the same specimen, the error for these volume determinations is probably greater than in the case

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9. Ibid., p. 311.
10. Ibid.

of homogeneous rocks.

Sources of Error

No doubt many of the apparent anomalies in the relation of stress resistance to mineral content are due to the variation in the character of the rock which would induce large errors in computations of mineral content. The only way by which these errors may be reduced is by taking larger and larger numbers of traverses and computing an average. Even this precaution fails to bring the error within narrow limits in the case of rocks so variable as those from the Hamilton Dam Site. It is believed that in the case of more homogeneous rocks, more definite relations of mineral content to crushing strength could be obtained by a study of comparatively few specimens, and it is hoped that some of the suggestions set forth herein may be of use in further investigations.

CHAPTER III

THE RELATION OF CRUSHING STRENGTH TO MINERAL CONTENT OF ROCKS

Theoretical considerations

So far as the writer is aware no correlation between the crushing strength and quantitative mineral content of rocks has been attempted. Leith[11] and numerous other writers of textbooks give tables of crushing strength for granites, limestones, and other rocks, but no mention is made of the exact mineral content of these rocks. None of these tables include figures for crystalline schists or gneisses. It is obvious that any data on crushing strength of schists would need to be accompanied by at least a qualitative description of the mineral content, as the term schist includes rocks of many combinations of minerals ranging from extremely friable hornblende-mica schists with a crushing strength of 2,000 pounds per square inch[12] to very hard, quartzitic schists the strength of which would no doubt prove to be much higher than any specimens reported on in this paper. The greatest crushing strength reported is that for granite which reaches a maximum of 43,000 pounds per square inch.[13] The explanation for the great strength of granite is found in its minerals and their arrangement. Granite is composed essentially of feldspar, quartz, and mica, the mica usually

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11. Leith, C. K.: Structural Geology, Revised Edition, New York, 1923, p. 289.
12. Table 1, Appendix A, and Graph 5.
13. Leith, C. K.: Op. cit.

being present in small widely separated plates. Quartz is a hard, dense mineral and in granites is usually equidimensional and is not oriented in planes such as would form cleavage planes by parting of its crystal faces. It does not have cleavage planes within the mineral itself. Feldspar, although possessing excellent cleavage, is also equidimensional in habit and usually oriented at random. Mica is usually distributed in small flakes in the interstices between the other crystals of the rock. This combination and arrangement of minerals form an interlocking mass of substantial particles making for a strong rock. Between rocks of this type and the soft, friable, and fibrous rocks are the great majority of rocks, the stress resistances of which are determined by the character, proportions, and arrangement of the minerals of which they are composed.

The rocks cored at the Hamilton Dam Site include several representatives of a large group of rocks called schists. The term schist[14] has no relation to the specific mineral content of the rocks but is descriptive of the character of the rock. Schist is a finely banded rock produced from sedimentary or igneous rocks by dynamic

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14. Pirsson, L. V.: Rocks and Minerals, Second Edition, Revised by Knopf, Adolph, New York, 1926, pp. 376-381. Hatch, F. H., and Wells, A. K.: The Petrology of Igneous Rocks, New York, 1926, p. 385.

metamorphic processes, the banding of which is imparted by the concentration in zones of unequidimensional, tabular, platy, or easily cleaved mineral crystals whose planes of cleavage, or axes of elongation, are arranged subparallel to each other thus bringing a large number of planes of easy separation into one zone and producing a zone of weakness in the rock.[15] (See Plate III, figure 2). This tendency to part along this plane of weakness is called schistosity.[16]

The purpose of this investigation is to determine how the strength of the rocks from the Hamilton Dam Site vary, if it does vary, when the mineral content varies both qualitatively and quantitatively. That there is a relation between the mineral content and crushing strength, there can be no doubt. An examination of graphs constructed from data, admitted to have a fairly wide margin of error, shows that by taking a sufficiently large number of specimens, these data fall into groups that, even though they could hardly be called lines, are distinctly bands with fairly narrow limits and definite trends.[17] Inaccuracies and wide range of crushing strength in some of the specimens are no doubt due in large part to the extreme variability

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15. Ibid.
16. Ries, Heinrich, and Watson, T. L.: Engineering Geology, New York, 1914, p. 191.
17. Graphs 1, 2, 3, 4, and 5.

in character of the rocks within the same specimen which is to be expected of schistose rocks. In several cases more than one core for testing was made of the same specimen which showed wide differences in crushing strength and mineral content. In cases of this kind nothing but an average of figures available could be used. Cases of this kind are noted and the accuracy of data concerning them should be discounted accordingly. It is believed that averages of quantitative data from a fairly large number of specimens would result in narrower and more definite limits with much less margin of error.

A study of data obtained in the present work and principles previously laid down concerning the crushing strength of rocks suggests the following factors which control the crushing strength of rocks:

FACTORS CONTROLLING THE CRUSHING STRENGTH OF ROCKS

I. Conditions which make for strength in rocks:

1. The predominance of hard, crystalline minerals which
   a. are characterized by poor or no cleavage;
   b. are practically equidimensional and usually oriented at random;

c. although possessing good cleavage and being tabular in habit, are oriented at random, thus preventing their cleavage planes and crystal faces from forming zones of weakness in the rock; or

d. although possessing good cleavage, are equidimensional in habit and usually oriented at random.

2. The presence of secondary minerals which:

a. fill the interstices formed by recrystallization and crystal shrinkage; or

b. consolidate the rock by filling the interstices and acting as a cementing agent.

II. Conditions which weaken rocks:

1. The presence of

a. minerals possessing good cleavage;

b. unequidimensional minerals which are aggregated in planes and which are oriented with their long axes parallel; or

c. fibrous or soft minerals.

2. Alteration of minerals.

Explanation of controlling factors

I. Conditions which make for strength in rocks:-

1. The predominance of hard, crystalline, minerals which:

(a) are characterized by poor or no cleavage contribute greatly to the strength of a rock for the obvious reason that minerals of this type are strong, possess great stress resistance, and are not subject to easy parting as are mineral crystals characterized by planes of cleavage. A predominance of these minerals implies a corresponding absence of other minerals which might tend to weaken the rock as explained below. Quartz, probably the commonest of all minerals, is an excellent example of a mineral of this type. Quartz is an important constituent of granite, the strongest class of rocks for which data are available. The ratio of the greatest to the mean dimension of a crystal of quartz is 1.5:1.[18]

(b) The effects of equidimensional and irregularly oriented minerals contrast with those of unequidimensional or tabular minerals which are usually oriented in planes or zones parallel to each other thus bringing together in a plane a large number of large well developed crystal faces which separate easily from each other and from interstitial minerals. The total effect of irregularly

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18. Leith, C. K.: Structural Geology, Revised Edition, New York, 1923, p. 114.

oriented equidimensional minerals is to form an aggregate of interlocking grains which form a very substantial rock unless modified by a weakening factor. Quartz and the feldspars are both excellent examples of this type of mineral and both are principal constituents the stronger rocks.

(c) Minerals which, although possessing good cleavage, and being unequidimensional or tabular in habit are oriented at random:- Minerals of this type contribute to the strength of a rock to a certain extent in that their crystal faces and planes of cleavage are oblique to the planes of schistosity[19] and therefore do not cause a large number of planes of easy parting (cleavage planes and crystal faces) to be so arranged as to produce a plane of cleavage in the rock. Hornblende is an example of this type of mineral. Hornblende is also included in Group II as it possesses properties which are discussed under that group.

(d) Minerals of the first group, which although possessing cleavage, are equidimensional and usually oriented at random:-Minerals of this type by their arrangement and shape have the weakening effects of their cleavage planes minimized and tend to form, with grains of other minerals described under (a), an interlocking mass which makes for a strong rock. The feldspars are the

19. Ibid., p. 115.

commonest and most important minerals of this type. They possess perfect cleavage. The ratio of the greatest to the mean dimension in a typical feldspar crystal is 1.5:1.[20]

2. The presence of secondary minerals which (a) fill the interstices formed by recrystallization and crystal shrinkage and theoretically, at least, increase the strength of a rock by reenforcement of the walls of minute fractures and spaces formed by cleavage cracks and shrinking of minerals. In many cases the presence of secondary material in these cracks tends to prevent or serve as a brake to slipping along planes of schistosity. An example of this type of mineral is pyrite and other sulphides deposited from mineralizing waters in these minute spaces.

The presence of secondary minerals which (b) cement the grains of an otherwise friable rock is an obvious advantage in the reenforcement of a rock. Secondary quartz is frequently deposited in the interstices formed in the manner described under Group II (a) forming a filler for the interstices and a cement to prevent separation of loose grains and crystals. In addition to quartz, iron oxides are common examples of this type of mineral.

II. Conditions which weaken rocks:- 1. The presence

20. Ibid., p. 114.

of (a) minerals possessing good cleavage is an important factor contributing to the weakness of rocks. It is obvious that a rock with a large percentage of easily cleaved minerals would not be as strong as one made up entirely of minerals without cleavage planes unless some compensating factor were introduced to counteract the weakening effect of such minerals. The micas and hornblende are good examples of such weakening minerals as both possess good cleavage. Feldspar also possesses good cleavage but the weakening effects of its cleavage are to a certain extent compensated for by its equidimensional habit and random orientation which allows other mineral crystals such as quartz to form an interlocking aggregate with it and decrease the weakening effects of its cleavage. Actually, on account of its crystal habit and occurrence, feldspar is one of the major constituents of the stronger rocks and is therefore included in the group of strengthening factors.

The presence of (b) unequidimensional, or tabular and platy minerals which are aggregated in planes or zones and which are oriented with their long axes parallel is one of the most important factors in the weakening of crystalline rocks. The effect of this type of mineral arrangement is to place a large number of well developed crystal faces, which are usually planes of easy separation of crystals, in one comparatively thin zone thus producing a line of weakness in the rock. Mica and hornblende are two excellent and common examples of this type of weakening factor. The ratio of the greatest to the mean dimension of mica is 10:1.[21] The ratio of the greatest to the mean dimension of hornblende is 4:1.[22]

The presence of (c) fibrous or soft minerals has an obvious effect on the strength of rocks, which, so far as the strength of a rock is concerned, may as well be replaced by cavities. Most of these minerals are incoherent fibers or fine scaly aggregates. Examples of minerals of this type are serpentine, chlorite, and kaolin. They are usually formed by alteration processes from other minerals.[23]

(2) Alteration of any of the mineral constituents of a rock produces a weakening effect in the rock. Minerals such as the feldspars frequently are subject to alteration to sericite, kaolin, and other products[24] which are fibrous or scaly and ~~and~~ which separate easily. This alteration takes place along cleavage planes and along fractures in a crystal.[25] It is obvious that when

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21. Ibid.
22. Ibid.
23. Van Hise, C. R.: "A Treatise on Metamorphism," U. S. Geol. Survey Monograph 47, 1904, pp. 369-371.
24. Ibid., p. 374.

portions of a mineral are replaced by such products, the crystal will become less resistant to stresses imposed upon it.

Practical applications

The factors discussed in the preceding paragraphs naturally fall into two main groups:(I)Those which make for strength in rocks and(II)those which weaken rocks. The well known mechanical principle which states that "a chain is no stronger than its weakest link" likewise applies to rocks. No matter how strong and favorably arranged its minerals may be, if a sufficient quantity of those minerals which weaken a rock be concentrated in a particular plane or zone, these weakening minerals will be the controlling factor in the crushing strength or stress resistance of the rock.

Theoretically, according to the aforementioned considerations,[25] the strongest rock would be a single crystal of some hard crystalline substance with practically no cleavage planes, or a rock composed entirely of equidimensional crystals of this sort oriented at random so as to minimize the weakening effects produced by the tendency of the minerals to separate from the surrounding mass along their crystal faces; and so as to obtain the strengthening effect afforded by the interlocking

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25. See pages 15 and 16.

of crystals of this arrangement.

The strongest rock reported from the Central Mineral Region is the so-called opaline granite which has a compressive strength of 25,400 pounds per square inch.[26] This rock is granitic and is described as a "feldspar porphyry, in which is bedded hard, lustrous, bluish quartz."[27] As shown by chemical analysis[28] this so-called opaline granite is an acid rock. The presence of sodium, the extremely small quantity of calcium-- 0.20 per cent-- and the absence of potassium are conclusive evidence that the plagioclase feldspar albite is the only feldspar present in appreciable quantities.[29] Considering the factors laid down heretofore as controlling elements in the strength of rocks, this opaline granite approaches the ideal in mineral content and arrangement for a strong rock.[30] Actually it is one of the strongest granites.[31]

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26. Nash, J. P.:"Texas Granites", Univ. of Texas Bull. 1725, 1917, p. 6.
27. Ibid.
28. Ibid., p. 7.
29. For composition of feldspars see Clarke, F. W.: "The Data of Geochemistry", Fifth Edition, U. S. Geol. Survey Bull. 770, 1924, pp. 366-371.
30. See pages 15-19.
31. Although granites have been reported with a crushing strength as high as 43,000 pounds per square inch, the usual range of stress resistance as given by Leith in "Structural Geology" page 289, for granites is 15,000 to 25,000 pounds per square inch.

The rocks taken from the Hamilton Dam Site are mica schists and amphibolites.[32] Amphibolites are schists containing a large quantity of amphiboles--hornblende in this case. They usually contain some mica and grade into mica schists.[33] The proportions of mica and hornblende are extremely variable in these rocks.[34] Some are composed almost entirely of feldspar and quartz with a small percentage of mica and some contain feldspar and quartz with little or no hornblende. These two types grade into mica-rich schists, hornblende-rich schists, and amphibolites containing as high as 65 per cent total mica and hornblende.[35]

The Hamilton Dam Site specimens range in crushing strength from 2,000 pounds per square inch to 20,000 pounds per square inch.[36] The majority of the specimens from this locality range in crushing strength from 6,000 to 14,000 pounds per square inch.[37] Examination of

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32. This statement is not contradictory to Paige's map on which this area is mapped as gneiss of Valley Spring age. Paige states that the Valley Spring gneiss also contains schists, amphibolites, and other rocks. See Paige, Sidney: U. S. Geol. Survey Geol. Atlas, Llano-Burnet Folio (No. 183), 1912, p. 3 and geologic map.

33. Pirsson, L. V.: Rocks and Minerals, Revised Edition by Knopf, Adolph, New York, 1926, pp. 393-394.

34. Descriptions of minerals, Appendix B.

35. Appendix A, Table 1.

36. Ibid.

37. Ibid.

these specimens and determination of their quantitative mineralogical content indicate that as these rocks depart from the ideal mineralogical arrangement for a strong rock, their stress resistance decreases.[38] A study of the accompanying graphs convinces one that mica, a tabular mineral with perfect cleavage, is the greatest cause of decrease in stress resistance in the rocks studied. A mica schist--the first test core from Station A-1, depth 43 feet--broke in the press without obtaining the load.[39] Next to mica in its weakening effects on the rocks investigated is hornblende.[40] A favorable orientation of hornblende, however, (when interlocked with other minerals) does not weaken a rock to a great extent. One of the strongest rocks in the Hamilton Dam Site collection contains 72 per cent hornblende.[41]

Graph 1 is an excellent illustration of the weakening effects of the presence of the elongated, tabular mineral, mica, in varying amounts. Although these bands are character-

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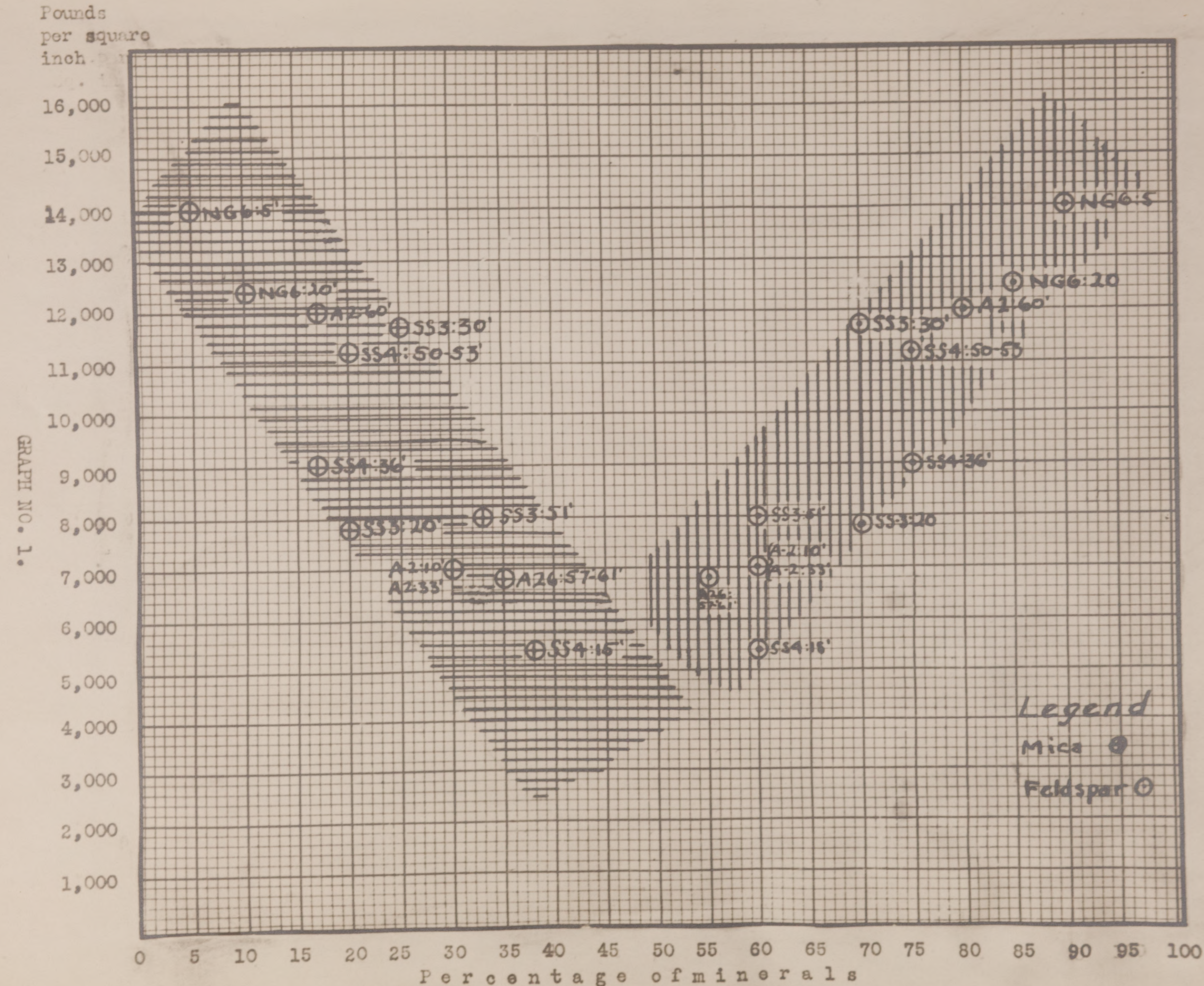
38. Ibid. and Graphs 1, 2, 3, 4, and 5.
39. Report of Mr. R.F. Dawson on crushing strength of cores from Hamilton Dam Site.
40. Appendix A, Table 1; Graphs 1, 2, 3, and 4.
41. Compressive strength 14,900 pounds per square inch. See Appendix A, Table 1 and Graph 2.

GRAPH 1

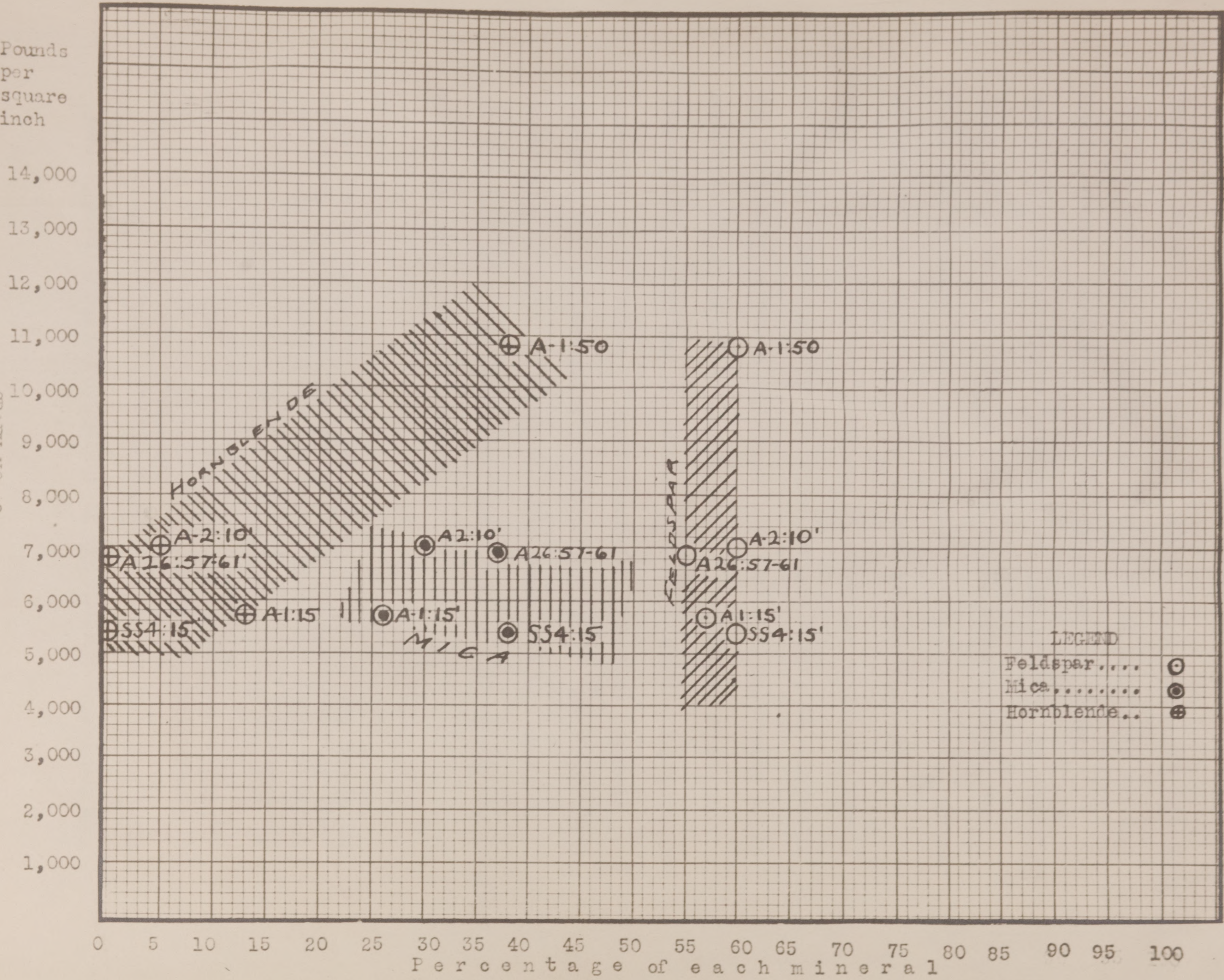
This shows graphically the relation in a general way, of the crushing strength of rocks to their mineral content. Only rocks with mica and feldspar as the chief minerals are included in this graph. Although specimens vary within wide limits, a definite tendency for the crushing strength of a rock to decrease as the mica content increases and to increase as the feldspar content increases at the expense of mica, is shown. The larger the number of specimens plotted, the more definite will be the trend.


Pounds per square inch
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percentage of minerals
NG6:5'
NG6:20'
A2:60'
SS3:30'
SS4:50-53'
SS4:36'
SS3:20'
SS3:51'
A2:10'
A2:33'
A26:57-61'
SS4:16'
NG6:5
NG6:20
A2:60'
SS3:30'
SS4:50-53
SS4:36'
SS3:20
SS3:61'
A-2:10'
A-2:33'
SS4:16'
Legend
Mica
Feldspar

GRAPH NO. 1.

GRAPH 2.

Rocks with about the same content of feldspar but with varying proportions of mica and hornblende are plotted to show the weakening effects of these two minerals. When feldspar is constant, the crushing strength of a rock increases as the hornblende content increases and decreases as the mica content increases.



Pounds per square inch
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Percentage of each mineral
HORNBLENDE
MICA
FELDSPAR
A-1:50
A-2:10'
A26:57-61'
A1:15
SS4:15
A2:10'
A26:57-61
A-1:15'
SS4:15
A-1:50
A-2:10'
A26:57-61
A1:15'
SS4:15'
LEGEND
Feldspar....
Mica........
Hornblende..

GRAPH NO. 2.

ized by rather wide limits,[42] there is a distinct tendency for the crushing strength of the rock to decrease as the mica content increases and the feldspar and other strengthening minerals decrease in proportion. In plotting this graph only specimens whose major constituents are mica and feldspar were used. A specimen (SS-3;20'), which is moderately high in feldspar and low in mica and which falls below the average in crushing strength for rocks of approximately the same composition, is composed of partially altered feldspar and has an abnormally high concentration of mica in one zone.[43] Another specimen (NG-6;20') which had an abnormally high stress resistance compared with rocks of approximately the same mineral content, is an irregularly banded schist[44] so that the weakening effects of mica in this rock are not marked on account of mica concentrations giving way to strengthening minerals in a short distance.

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42. Factors making for the great width of the bands in addition to the natural variability in character of the rocks are: 1. Inaccuracy in determination of the mineral content as explained under "Sources of error" (page 11); (2) the presence of modifying factors such as partial alteration of the minerals and the presence of other weakening minerals in addition to mica and hornblende; and (3) disregard for position of lines of schistosity in preparing rocks for crushing.

43. Graph 1, and Appendix B, Descriptions of specimens, Specimen 14.

44. Appendix B, Description of specimens, Specimen 21.

Graph 2 shows the effect of varying quantities of mica and hornblende in a rock when the feldspar content is approximately constant.[45] It is seen that as hornblende increases the crushing strength of the rock increases up to the limits for which determinations were made. As mica increases--with or without hornblende--the crushing strength decreases. It will be noticed that the weakest specimens for a given percentage of hornblende are those which contain mica.[46]

That hornblende weakens a rock to a certain extent but not so much as mica is shown on Graphs 1, 3, and 4. In Graph 3 the percentages of hornblende and feldspar are plotted in rocks in which they are the principal constituents. It will be noted that as hornblende increases and feldspar decreases, the crushing strength of the rock decreases. But this effect of feldspar does not decrease the strength of the rocks below about 7,000 pounds per square inch while approximately the same percentage of mica decreases the strength of the rock to slightly over 5,000 pounds per square inch.[47]

On Graph 4 are plotted rocks quite variable in mineral content. These rocks include hornblende schist,

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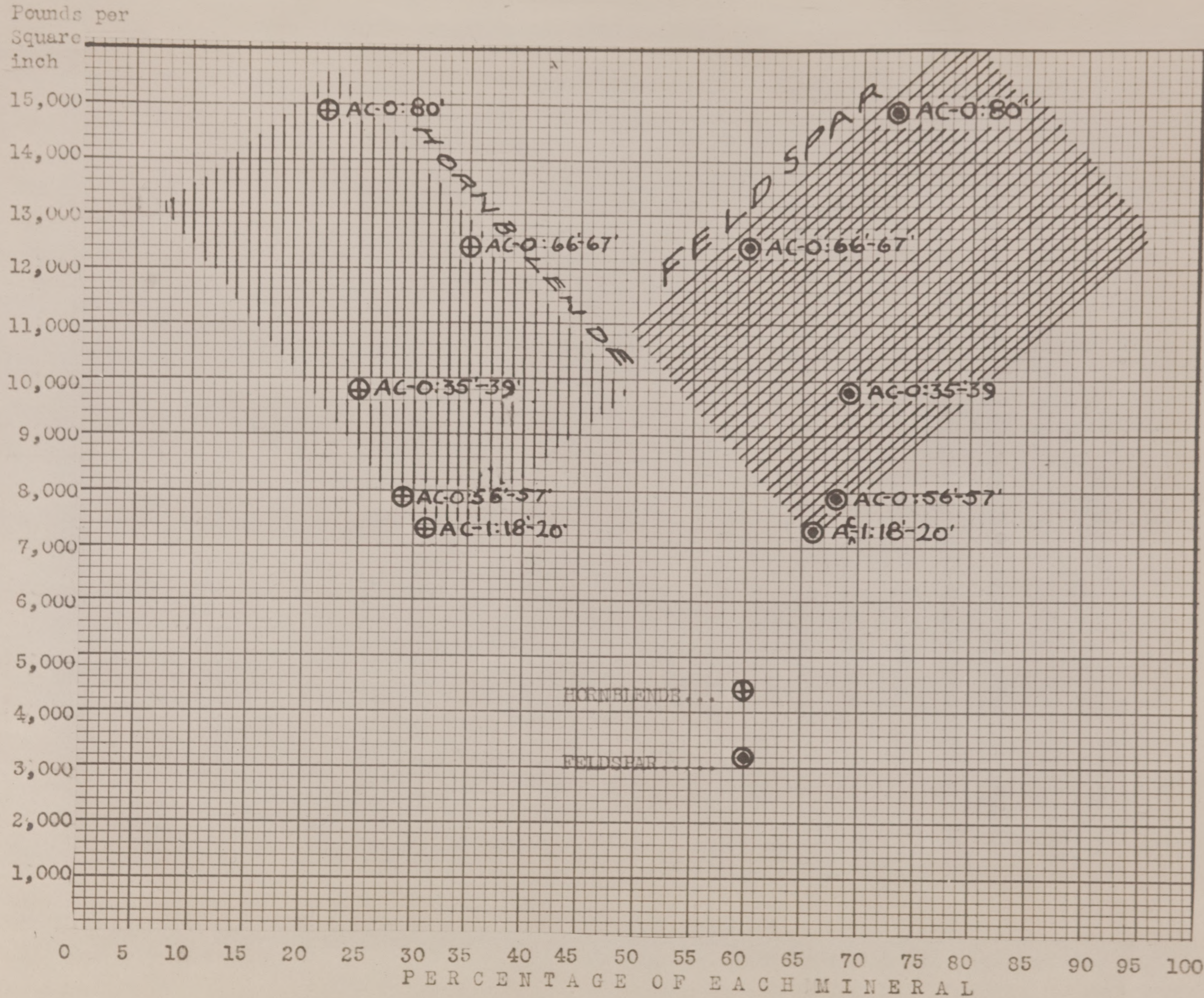
45. Fifty-seven to 60 per cent is considered constant as this variation is well within the limits of error of the determinations as explained on page 10.

46. See also Graphs 4 and 5, Specimens A-1;15', SS-4;15', and A-1;43'.

47. Appendix A, Table 1, and Graph 4.

GRAPH 3

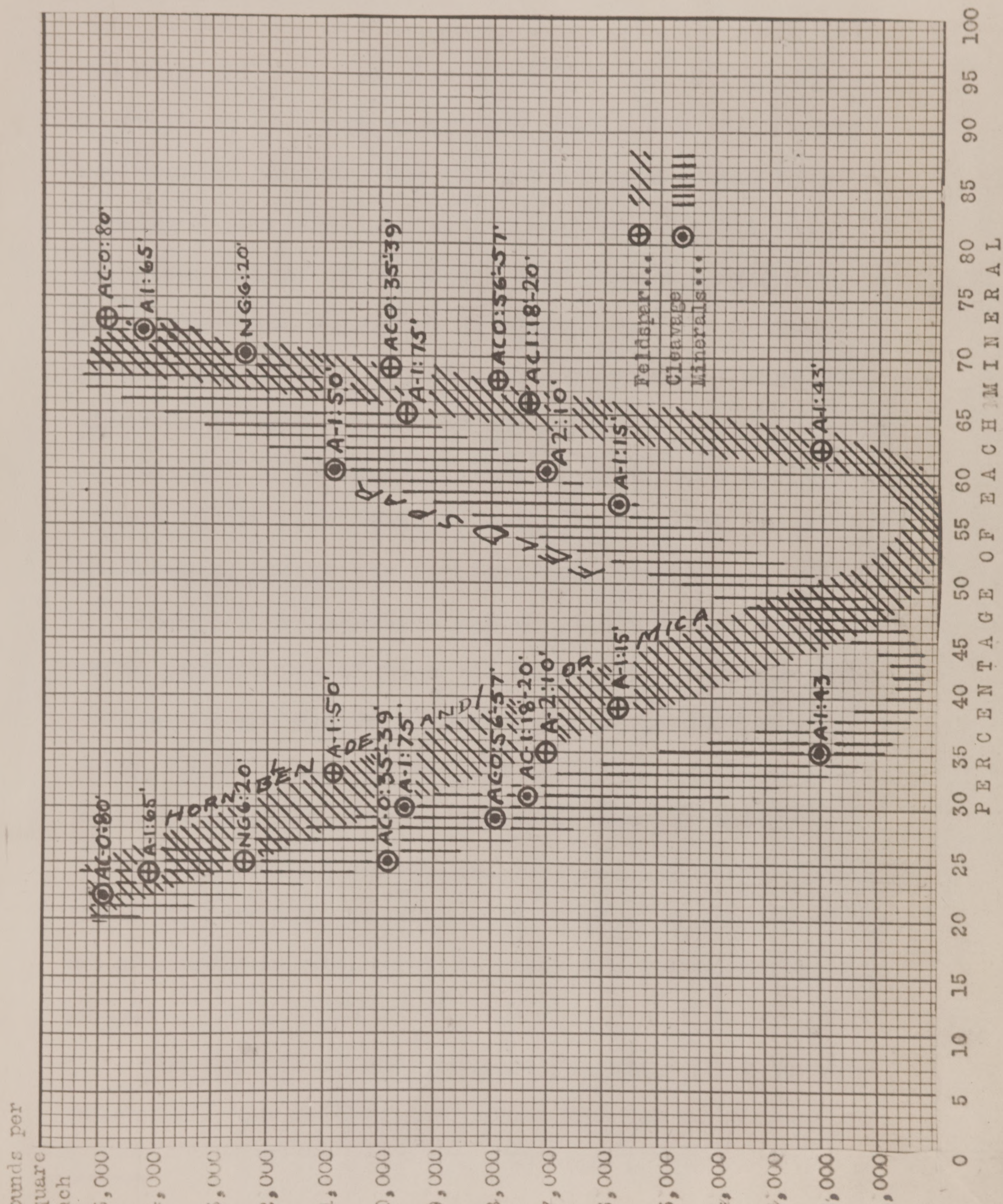
Hornblende compared with feldspar. Note that equal amounts of hornblende and feldspar does not make as weak a rock as do equal amounts of mica and feldspar. The least resistant rock represented in this graph has a compressive strength of 7,300 pounds per square inch. Compare with Graph 1.


Pounds per Square inch
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
PERCENTAGE OF EACH MINERAL
HORNBLENDE
FELDSPAR
AC-0:80'
AC-0:66'-67'
AC-0:35'-39'
AC-0:56'-57'
AC-1:18'-20'
AC-0:80'
AC-0:66'-67'
AC-0:35'-39
AC-0:56'-57'
AC-1:18'-20'
HORNBLENDE...
FELDSPAR.....

Graph 3.

GRAPH 4

Cleavage minerals (mica and/or hornblende) compared with feldspar. The curves are parabolas because as the percentage minerals reach more than 50 per cent of the volume of the rock, mica decreases at the expense of hornblende, thus making for a rise in crushing strength.



Pounds per Square inch
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PERCENTAGE OF EACH MINERAL
Feldspar...
Cleavage Minerals...
HORNBLENDE
OR MICA
AC-0:80'
A-1:65'
NGG:20'
A-1:50'
ACO:35-39'
A-1:75'
ACO:56-57'
ACI:18-20'
A2:10'
A-1:15'
A1:43'

Graph 4.

mica schist, and hornblende-mica schist. The hornblende and mica which may be present in the rock are plotted together as cleavage minerals[48] while the other curve represents feldspar. The two curves turn upward after showing a decrease in crushing strength for a limit of approximately 45 to 50 per cent cleavage minerals. The explanation suggested to account for the increase in strength with an increase in percentage of cleavable minerals is that hornblende has increased at the expense of mica and is so arranged that it provides a reenforcing effect in the rock. This is actually observed in all these rocks except the specimen from Station A-1; 75'.[49]

Graph 5 represents a series of rocks with approximately equal percentages of mica and hornblende. The mica and hornblende are plotted together for comparison with the curve for feldspar. It will be noted that in this case there is no increase in strength as the per cent of cleavable minerals increases, but that the curves continue straight downward crossing each other when the percentages of cleavable minerals and feldspar are approximately equal.

The effects of the presence of cementing materials which fill the interstitial areas and act as cements on

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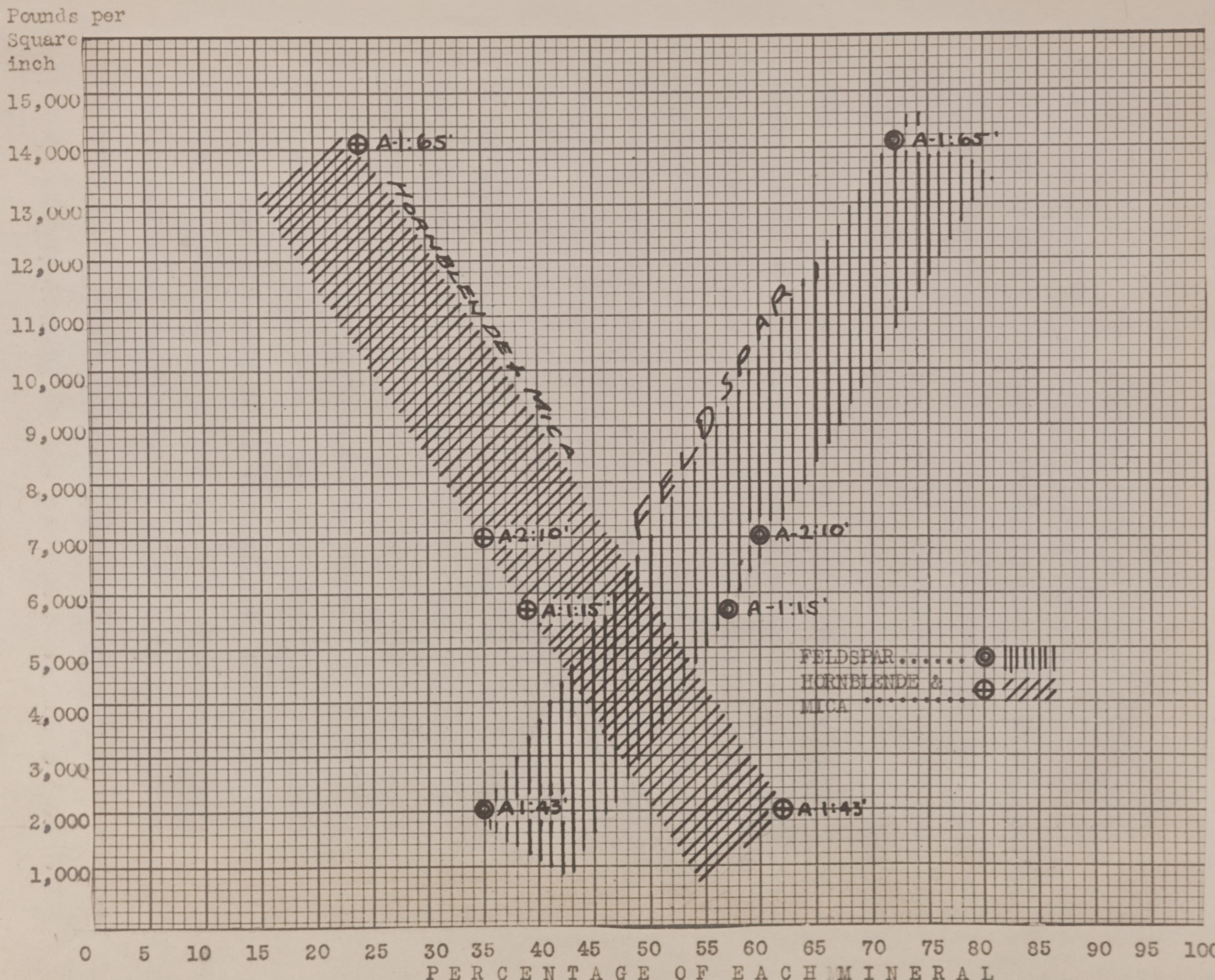
48. Appendix A, Table 1, Footnote No. 4.
49. Graph 4 and Appendix A, Table 1.

GRAPH 5

Hornblende plus mica compared with feldspar. In rocks containing both feldspar and mica in more nearly equal proportions than in those plotted in Graph 4, an increase in cleavage minerals induces a decrease in crushing strength which does not rise as the cleavage minerals reach greater proportions than feldspars, but keep on decreasing as the mica and hornblende increase.


Pounds per Square inch
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
PERCENTAGE OF EACH MINERAL
HORNBLENDE & MICA
FELDSPAR
A-1:65'
A-1:65'
A-2:10'
A-2:10'
A-1:15'
A-1:15'
A-1:43'
A-1:43'
FELDSPAR......
HORNBLENDE & MICA ....

Graph 5.

the mineral particles are known to make for a strong rock[50] but no quantitative data on these agents could be obtained from the specimens investigated.

No quantitative data could be obtained on the effects of fibrous, soft, or alteration minerals for the reasons that (1) no satisfactory method is at hand for determining and expressing quantitatively the presence of these minerals, and (2) a sufficient number of specimens containing these minerals is not at hand to permit working out methods for quantitative determinations of minerals of this character. It is thought,however, some correlation between areal extent of these minerals in a thin section and crushing strength might be secured if the right kind of material be selected. This material would be preferably rocks high in feldspar content with varying proportions of the feldspar altered and replaced by these minerals.

Orientation of specimens

One factor which was not discussed under mineral content and arrangement is that of orientation of cores in the crushing machine. The exact importance of this factor could not be determined as no data on cores was recorded which would indicate the inclinations of their planes of schistosity in the crushing machine. A core

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50. Howe, J. A.: The Geology of Building Stones, London, 1910. See discussion page 199 et seq. and tables page 362 et seq. giving tests for toughness of sandstones.

Fig.1.

Fig. 2

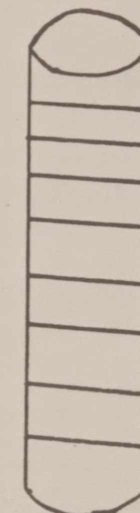

Fig. 3.

PLATE I. Orientation of specimens in crushing machine. Three possible angles at which planes of schistosity may be cut in taking cores.

oriented with its planes of schistosity at an angle of approximately 45 degrees to the direction of pressure as illustrated in Plate I, figure 1, will crush under lower pressure than will cores of the same rock oriented with its planes of schistosity parallel or perpendicular to the direction of stress a shown in Plate I, figures 2 and 3. In the case illustrated in Plate I, figure 1, the only resistance to breaking is the resistance to gliding along planes of schistosity which is very little. In the cases illustrated in Plate I, figures 2 and 3, the specimen is not so much subject to the weakening effects of schistosity, and for the core to break, it is necessary for the crystals in the stronger zones to break. One specimen (No. 16) with high mica content--35 per cent--broke at 8,000 pounds per square inch which is above the average, according to Graph 1, for a rockof this mica content. Examination showed that this specimen was oriented in the press with its cleavage planes almost parallel to the line of stress as illustrated in Plate I, figure 2, thus placing the feldspar zones in a position to resist the pressing force.

CHAPTER IV

CONCLUSIONS

The following conclusions have been reached in the present investigation of the relation of crushing strength to mineral content in certain rocks taken from the foundation of the Hamilton Dam Site, Burnet County:

1. There is a relation between the crushing strength and the qualitative and quantitative mineral content of crystalline rocks which can be expressed graphically.

2. Mica and hornblende when present in rocks weaken them in a degree comparable to the quantitative presence of these minerals.

3. The presence of a certain percentage of mica weakens a rock more than does the same percentage of hornblende.

4. An investigation of these relations on more homogeneous rocks would show more definitely the effects of the presence of various minerals in varying quantities in these rocks.

5. Investigations of the relations of crushing strength to mineral content on larger and larger numbers of specimens would result in an average result which when plotted would approach the accuracy of a mathemetical function.

PLATE II

Figure 1. Photomicrograph of Slide No. 90 showing occurrence of enstatite in zone in amphibolite. The shaded mineral showing cleavage cracks is enstatite; the dark mineral is hornblende; and the colorless mineral is feldspar. Magnified 26 diameters.

Figure 2. Photomicrograph of Slide No. 80 under crossed nicols showing large crystal of microcline. The dark mineral is biotite and the colorless mineral is feldspar. The microcline in this section is partially altered to sericite. Magnified 26 diameters.

Figure 1.

Figure 2.

PLATE II

PLATE III

Figure 1. Photomicrograph of Slide No. 48 showing concentration and orientation of hornblende. The black minerals are pyrite and magnetite; the colorless mineral is feldspar; and the dark gray and light gray mineral is hornblende. The light gray minerals showing perfect cleavage are basal sections of hornblende. Note that feldspar forms a light band through the section. Magnified 26 diameters.

Figure 2. Photomicrograph of Slide No. 64 showing elongation of biotite in direction of cleavage. The black areas are biotite; the light minerals are feldspar and quartz; and the few gray minerals are hornblende. Magnified 26 diameters.

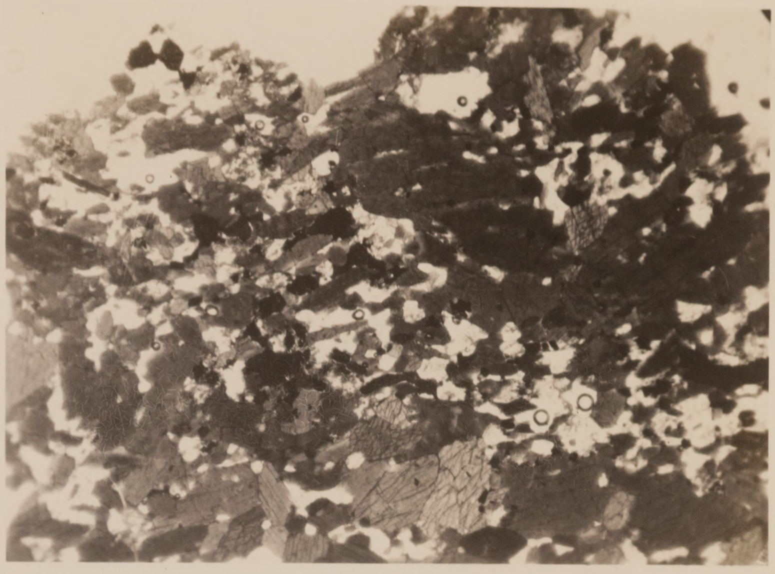

Figure 1.

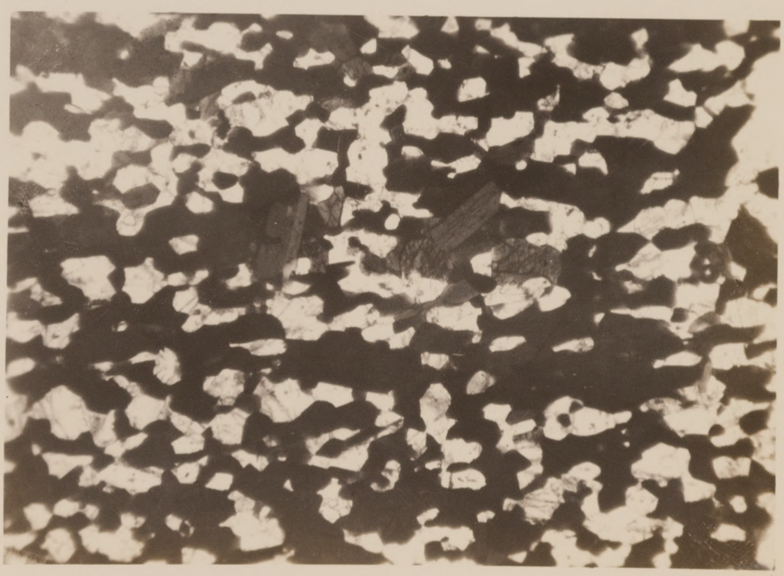

Figure 2.

PLATE III

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APPENDIX A

SUMMARY OF QUANTITATIVE DATA

APPENDIX A.

TABLE NO. 1.

SUMMARY OF QUANTITATIVE DATA

SPECIMEN NO.	STATION	DEPTH	CRUSHING STRENGTH[1]	FELDSPAR[2] %[3]	HORNBLENDE %	MICA %	CLEAVAGE MINERALS[4]	ACCESSORY MINERALS
1.	AC-0	35'-39'	9,800[5]	25	69	0[6]	69	3 to 5
2.	AC-0	56'-57'	7,900	29	65	0	65	5
3.	AC-0	80'	14,900	22	73	0	73	4 to 5
4.	AC-1	18'-20'	7,300	31	66	0	66	5
5.	AC-0	66'-67'	7,800	35	61	0	61	2
6.	A-1	15'	5,700	57	13	26	39	2 to 5
7.	A-1	43'	2,000	35	30	32	62	2 to 5
8.	A-1	50'	10,800	60	38	0	38	1
9.	A-1	65'	14,100	72	6	18	24	1 to 3
10.	A-1	75'	9,500	30	19	46	65	2
11.	A-2	10'	7,000	60	5	30	35	1 to 4
12.	A-2	33'	7,000	65	0	30	30	5
13.	A-2	60'	12,000	80	0	17	17	2
14.	SS-3	20'	7,800	70	0	21	21	5
15.	SS-3	30'	11,700	70	0	25	25	2
16.	SS-3	51'	8,000	60	0	33	33	1 to 5
17.	SS-4	15'	5,400	60	0	38	38	1
18.	SS-4	36'	9,900	75	0	17	17	5
19.	SS-4	50'-53'	11,200	75	0	20	20	5
20.	NG-6	5'	14,000	90	0	5	5	5
21.	NG-6	20'	12,400	85	0	10	10	3
22.	A-26	57'-61'	8,300	55	0	37	37	4

1. Crushing strength determined by Mr. Raymond F. Dawson, Testing Engineer, Bureau of Engineering Research, University of Texas.
2. With feldspar is included quartz as it was impracticable to separate the two in the quantitative determinations.
3. Percentage by volume as determined by Rosiwal Method of micrometric analysis.
4. The figures in this column represent total mica and hornblende. Although hornblende possesses no better cleavage than feldspar, the crystal habit--tabular--and arrangement--in bands--is thought to contribute more to the weakness of the rock than equidimensional crystals whose long axes are oriented in no particular direction as crystals of feldspar are.
5. Figures represent average pounds per square inch for all specimens tested.
6. Zero in a column under a mineral should not be taken to mean entire absence in a specimen of a particular mineral, but it may mean that the quantity of that mineral present is so small--usually below 5 per cent--as to be of no consequence as a factor in determining the strength of a rock. For list of minerals present in specimens see descriptions, Appendix B.

APPENDIX B

DESCRIPTIONS OF SPECIMENS

SPECIMEN NO. 1.

AMPHIBOLITE.

STATION: AC-0; DEPTH: 35 to 39 feet.

CRUSHING STRENGTH: 9,800 pounds per square inch.

SLIDES: 107, 108, 109, 110, 111, 112.

MACROSCOPIC CHARACTER: Dark gray to greenish black hornblende schist containing phenocrysts of quartz and feldspar.

MICROSCOPIC CHARACTER: The chief constituents are hornblende, in tabular crystals elongated sub-parallel to planes of schistosity, feldspar, and quartz in smaller quantities. Orthoclase is the most abundant feldspar while both microcline and plagioclase are present. Accessory minerals are pyrite, magnetite, ilmenite, leucoxene, sericite after feldspars, and biotite.

QUANTITATIVE DETERMINATIONS:

Hornblende	69.0 per cent.
Feldspar	25.0 " " .
Accessories	3 to 5 " " .

SPECIMEN NO. 2.

AMPHIBOLITE. Plate III, figure 1.

STATION: AC-O; DEPTH: 56 to 57 feet.

CRUSHING STRENGTH: 7,900 pounds per square inch.

SLIDES: 6, 7, 8, 46, 47, 48.

MACROSCOPIC CHARACTER: Greenish-black, fine-, even-grained, laminated hornblende schist.

MICROSCOPIC CHARACTER: This rock is chiefly a mass of tabular crystals of hornblende elongated in the direction of the planes of schistosity, in a groundmass of smaller grained feldspar, chiefly orhtoclase, some plagioclase with extinction angle approaching that of oligoclase, and smaller amounts of quartz. Much of the feldspar is badly altered to sericite. This alteration seems to be most abundant in the feldspar-rich zones. Accessory minerals are pyrite, magnetite, ilmenite, and biotite with numerous pleochroic halos surrounding minute crystalsof zircon.

QUANTITATIVE DETERMINATIONS:

Hornblende	65 per cent.
Feldspar	29 " ".
Accessories	5 " ".

SPECIMEN NO.3.

AMPHIBOLITE. Plate II, figure 1.

STATION: AC-O; DEPTH: 80 feet.

CRUSHING STRENGTH: 14,900 pounds per square inch.

SLIDES: 77, 78, 89, 90.

MACROSCOPIC CHARACTER: Greenish-black, fine-,even-grained, poorly laminated hornblende schist.

MICROSCOPIC CHARACTER: A mass of tabular hornblende crystals elengated subparallel to lines of shcistosity which are somewhat discontinuous, in a matrix of orthoclase and plagioclase feldspar. Accessory minerals are biotite, sericite after feldspar, ilmenite, quartz, pyrite, apatite, zircon, and enstatite. In one slide an enstatite-rich zone corresponding to a light colored band in the rock showed a concentration of enstatite running as high as 35 per cent by volume. In this zone hornblende showed a marked defficiency, while orthoclase feldspar partially altered to sericite composed the matrix.

REMARKS: Specimens from this core showed a marked variation in crushing strength. One core broke at 20,100 pounds per square inch while the other broke at only 8,850 pounds per square inch. The other specimen is a poorly cleaved rock with discontinuous bands of amphibole probably representing the high stress specimen.

QUANTITATIVE DETERMINATIONS:

Hornblende	73 per cent.
Feldspar	22 " " .
Accessory Minerals	4 - 5 Per cent.

SOECIMEN NO 4.

AMPHIBOLITE.

STATION: AC-1; DEPTH: 18 to 20 feet.

CRUSHING STRENGTH: 7,300 pounds per square inch.

SLIDES: 62, 63, 64.

MACROSCOPIC CHARACTER: Greenish-black, slightly friable, well banded, hornblende schist.

MICROSCOPIC CHARACTER: A mass of hornblende crystals of tabular development elongated in planes of banding in a matrix of orthoclase and plagioclase (oligoclase) feldspar and quartz. Accessory minerals are magnetite, pyrite, biotite, containing zircon surrounded by pleochroic halos, rutile microlites as inclusions in orthoclase crystals, and an undetermined anisotropic, optically anomalous mineral.

QUANTITATIVE DETERMINATIONS:

Hornblende	66 per cent.
Biotite	1 " " .
Feldspar	31 " " .
Accessories	3 " " .

SPECIMEN NO. 5.

AMPHIBOLITE.

STATION: AC-O; DEPTH: 66 to 67 feet.

CRUSHING STRENGTH: 7,800 pounds per square inch.

SLIDES: 12, 13, 14, 15, 16, 17, 18.

MACROSCOPIC CHARACTER: Dark green to black fine-, even-grained, schist cut by light colored bands.

MICROSCOPIC CHARACTER: Elongated green to brown pleochroic hornblende oriented subparallel to, and concentrated in, planes of schistosity. The matrix is orthoclase with some plagioclase and quartz. Accessory minerals are biotite, sericite as an alteration product after feldspars, secondary pyrite in veinlets and fractures, and probably titanite.

QUANTITATIVE DETERMINATIONS:

Hornblende	61 per cent.
Feldspar	35 " " .
Accessories	2 " " .

SPECIMEN NO. 6.

HORNBLENDE-MICA SCHIST.

STATION: A-1; DEPTH: 15 feet.

CRUSHING STRENGTH: 5,700 pounds per square inch.

SLIDES: 93, 94, 95.

MACROSCOPIC CHARACTER: Pinkish gray, coarse textured, crystalline, well banded schist.

MICROSCOPIC CHARACTER: Tabular crystals of green hornblende and large flakes of biotite with many pleochroic halos in a groundmass of orthoclase, plagioclase, and quartz. some of the plagioclase, at least, is oligoclase. Accessory minerals are apatite in laths and hexagonal sections, pyrite, and minute zircon crystals as inclusions in the biotite surrounded by pleochroic halos.

QUANTITATIVE DETERMINATIONS:

Mica	26 per cent.
Hornblende	13 " " .
Feldspar	57 " " .
Accessories	3 " " .

SPECIMEN NO. 7.

HORNBLENDE-MICA SCHIST.

STATION: A-1; DEPTH: 43 feet.

CRUSHING STRENGTH: 2,000 pounds per square inch.

SLIDES: 101, 102, 103, 104.

MACROSCOPIC CHARACTER: Green to black hornblende-mica schist with phenocrysts of pink feldspar. This rock is very friable and contains an abundance of mica and hornblende throughout.

MICROSCOPIC CHARACTER: Tabular crystals green hornblende and large flakes of biotite containing numerous inclusions of zircon within pleochroic halos, embedded in a ground-mass composed chiefly of orthoclase with a small amount of quartz. Other minerals in this section are plagioclase partially altered along twinning planes to sericite, laths of apatite, magnetite, and a few small grains of an undetermined mineral.

QUANTITATIVE DETERMINATIONS:

Feldspar	35 per cent.
Mica	32 " " .
Hornblende	30 " " .
Accessories	3 " " .

SPECIMEN NO. 8.

HORNBLENDE SCHIST.

STATION: A-1; DEPTH: 50 feet.

CRUSHING STRENGTH: 10,800 pounds per square inch.

SLIDES: 68, 69, 70.

MACROSCOPIC CHARACTER: Dark green to black,banded, fairly hard schist; lustrous black of fresh fracture.

MICROSCOPIC CHARACTER: A mass of tabular crystals of green hornblende elongated in one direction, embedded in a groundmass of orthoclase and plagioclase. Accessory minerals in this specimen are biotite, apatite, and zircon inclusions within pleochroic halos in biotite. No quartz was seen in the three slides of this specimen examined.

QUANTITATIVE DETERMINATIONS:

Hornblende	38 per cent.
Feldspar	60 " ".
Mica	1 " ".
Accessories	1 " ".

SPECIMEN NO. 9.

MICA SCHIST.

STATION: A-1; DEPTH: 65 feet.

CRUSHING STRENGTH: 14,100 pounds per square inch.

SLIDES: 71, 72, 73.

MACROSCOPIC CHARACTER: Dark gray hornblende-mica schist. Fragments in some cases very friable due to local concentrations of large mica plates in planes of schistosity. This concentration and variability accounts for the wide range in crushing strength which varies from 11,230 to 16,920 pounds per square inch.

MICROSCOPIC CHARACTER: Tabular crystals of green hornblende and brown flakes of biotite, carrying many inclusions of zircon surrounded by pleochroic halos elongated subparallel to planes of schistosity, in a groundmass of microcline, orthoclase, and quartz. Accessory minerals are apatite, plagioclase, anorthoclase, and secondary sericite in alteration zones within the feldspar crystals partially replacing the crystals themselves.

QUANTITATIVE DETERMINATIONS:

Hornblende	6 per cent.
Feldspar	72 " " .
Biotite	18 " " .
Accessories	3 " " .

SPECIMEN NO. 10.

HORNBLENDE-MICA SCHIST.

STATION: A-1; DEPTH: 75 feet.

CRUSHING STRENGTH: 9,500 pounds per square inch.

SLIDES: 113, 114, 115, 116, 117.

MACROSCOPIC CHARACTER: Dark pinkish gray banded micaceous hornblende schist.

MICROSCOPIC CHARACTER: Elongated large and small crystals of green hornblende and large flakes and laths of mica arranged subparallel to planes of cleavage, in a groundmass of orthoclase, microcline, and quartz. The feldspars have been subjected to sericitization and many of the crystals have their centers and borders replaced by sericite. Accessory minerals are apatite, zircon within pleochroic halos in crystals of biotite, and an isotropic mineral of low index of refraction.

QUANTITATIVE DETERMINATIONS:

Biotite	46 per cent.
Hornblende	19 " " .
Feldspar	30 " " .
Accessories	2 " " .

SPECIMEN NO. 11.

HORNBLENDE-MICA SCHIST.

STATION: A-2; DEPTH: 10 feet.

CRUSHING STRENGTH: 7,000 pounds per square inch.

SLIDES: 33, 34, 35, 36, 37, 65, 66, 67.

MACROSCOPIC CHARACTER: Dark gray to black micaceous schist, with alternate bands of lighter colored minerals.

MICROSCOPIC CHARACTER: Large dark brown laths and flakes of biotite arranged parallel to planes of cleavage in a groundmass of feldspar and quartz. The biotite is characterized by an abundance of pleochroic halos surrounding minute crystals of zircon. Orthoclase is the most abundant feldspar while several good crystals of microcline and plagioclase (oligoclase-andesine) are present. Accessory minerals are apatite, ilmenite, and very small amounts of secondary sericite around borders of feldspars.

QUANTITATIVE DETERMINATIONS:

Feldspar	60 per cent.
Biotite	30 " " .
Hornblende	5 " " .
Accessories	4 " " .

SPECIMEN NO. 12.

MICA SCHIST

STATIONS: A-2; DEPTH: 33 feet.

CRUSHING STRENGTH: 7,000 pounds per square inch.

SLIDES: 105, 106.

MACROSCOPIC CHARACTER: Dark gray to black micaceous schist with bands of lighter colored minerals.

MICROSCOPIC CHARACTER: Matrix of feldspar--orthoclase and plagioclase--partially altered to sericite around borders and in cleavage cracks within the crystal, containing elongated medium size laths and flakes of biotite and muscovite in lesser quantities. It is estimated that 50 to 60 per cent of the feldspars are althered to sericite, whole crystals being replaced by this product in some cases. Accessory minerals are apatite, magnetite, hematite, associated with, and probably secondary after magnetite, zircon in pleochroic halos, and an undetermined mineral of high index of refraction.

QUANTITATIVE DETERMINATIONS:

Feldspar	65 per cent.
Mica	30 " " .
Accessories	5 " " .

SPECIMEN NO. 13.

MICA SCHIST.

STATION: A-2; DEPTH: 60 feet.

CRUSHING STRENGTH: 12,000 pounds per square inch.

SLIDES: 87, 88.

MACROSCOPIC CHARACTER: Black to light gray, fine-, even-grained, fairly well consolidated schist with irregular banding.

MICROSCOPIC CHARACTER: Orthoclase and smaller amounts of plagioclase and microcline and elongated laths and small flakes of biotite make up most of the rock. All feldspars are altered and replaced partially around borders and in cleavage cracks and fractures by sericite. Some of the feldspar is probably altered to kaolinite although a positive determination of this mineral was not undertaken. Accessory minerals are hornblende in elongated green crystals showing green to brown pleochroism, pyrite, zircon in pleochroic halos in biotite, magnetite, laths of apatite,and quartz.

QUANTITATIVE DETERMINATIONS:

Mica	17 per cent.
Feldspar	80 " " .
Accessories	2 " " .

SPECIMEN NO. 14.

MICA SCHIST.

STATION: SS-3; DEPTH: 20 feet.

CRUSHING STRENGTH: 7,800 pounds per square inch.

SLIDES: 22, 23, 24, 25.

MACROSCOPIC CHARACTER: Light gray schist with light bands of feldspar alternating with dark bands of mica. Freshly fractured surfaces along planes of schistosity are lustrous black.

MICROSCOPIC CHARACTER: Plates of biotite are arranged in subparallel planes in a matrix of microcline, orthoclase, plagioclase, and quartz. Orthoclase crystals carry inclusions of quartz. Each of the feldspars is partially altered in fractures and cleavage planes to sericite. The biotite contains minute inclusions of zircon surrounded by pleochroic halos. Accessory minerals in addition to zircon are pyrite in elongated masses and in veinlets developed in association with mica plates.

QUANTITATIVE DETERMINATIONS:

Feldspar	70 per cent.
Mica	21 " " .

REMARKS: A biotite-rich zone of cleavage showed a concentration of mica amounting to 50 per cent.

SPECIMEN NO. 15.

MICA SCHIST.

STATION: SS-3; DEPTH: 30 feet.

CRUSHING STRENGTH: 11,700 pounds per square inch.

SLIDES: 96, 97, 98, 99, 100.

MACROSCOPIC CHARACTER: Dark gray, light-banded, fine-,even-grained mica schist.

MICROSCOPIC CHARACTER: Brown elongated laths and flakes of biotite and muscovite distributed in discontinuous planes of schistosity in a groundmass of equidimensional crystals of orthoclase, microcline, and plagioclase (oligoclase). Small amounts of quartz are present in small small grains in the groundmass. The biotite contains many pleochroic halos surrounding minute crystals of zircon. Accessory minerals in addition to zircon are magnetite, ilmenite, leucoxene, rutile in well developed prisms terminated by hexagonal bipyramids, and tourmaline. Chlorite slightly altered to serpentine and sericite as alteration products of feldspars are abundant in places.

QUANTITATIVE DETERMINATIONS:

Mica	25 per cent.
Feldspar	70 " " .
Accessories	2 " " .

SPECIMEN NO. 16.

MICA SCHIST.

STATION: SS-3; DEPTH: 51 feet.

CRUSHING STRENGTH: 8,000 pounds per square inch.

SLIDES: 79, 82, 83, 84.

MACROSCOPIC CHARACTER: Dark gray to black, banded micaceous schist.

MICROSCOPIC CHARACTER: Elongated plates and laths of biotite arranged in parallel bands in a groundmass of microcline, orthoclase, plagioclase, and quartz. Feldspars are altered on the borders and along cleavage planes to sericite while quite a few crystals are entirely replaced by sericite. Biotite contains many inclusions of zircon surrounded by pleochroic halos. Other minerals present are ilmenite, magnetite, and chlorite altering to serpentine on a small scale. Part, at least, of the plagioclase feldspar is oligoclase. Much of the quartz is in small grains.

QUANTITATIVE DETERMINATIONS:

Feldspar	60 per cent.
Mica	33 " " .
Accessories	4 " " .

SPECIMEN NO. 17.

MICA SCHIST.

STATION: SS-4; DEPTH: 15 feet.

CRUSHING STRENGTH: 5, 400 pounds per square inch.

SLIDES: 91, 92.

MACROSCOPIC CHARACTER: Pinkish-gray coarsely crystalline structure characterized by concentration of mica in planes of schistosity which are well developed and contimuous. Phenocrysts of pink feldspar are present.

MICROSCOPIC CHARACTER: Elongated laths and plates of brown mica, spotted by numerous pleochroic halos, arranged in parallel planes of cleavage in a matrix of microcline, orthoclase, and plagioclase feldspar with a small amount of free quartz. The feldspars are badly altered to sericite and probably chlorite. Other minerals present in smaller quantities are zircon in biotite and muscovite.

QUANTITATIVE DETERMINATIONS:

Feldspar	60 per cent.
Mica	38 " " .
Accessories	1 " " .

SPECIMEN NO. 18.

MICA SCHIST.

STATION: SS-4; DEPTH: 36 feet.

CRUSHING STRENGTH: 9,900 pounds per square inch.

SLIDES: 56, 57, 58, 124, 125, 126, 127, 128, 129.

MACROSCOPIC CHARACTER: Greenish-gray, fine-, even-grained micaceous schist.

MICROSCOPIC CHARACTER: Elongated laths and plates of biotite and muscovite in a groundmass of orthoclase and plagioclase (oligoclase) with some free quartz. Biotite contains many inclusions of zircon, surrounded by pleochroic halos. Other minerals identified are ilmenite partially altered to leucoxene, magnetite, pyrite, phlogopite, sericite as an alteration product after both feldspars, shlorite, and serpentine. Chlorite occurs in broad flakes while serpentine replaces part of its borders and is gradually replacing the chlorite along fractures within the crystals.

QUANTITATIVE DETERMINATIONS:

Feldspar	75 per cent.
Mica	17 " " .
Accessories	5 " " .

SPECIMEN NO. 19.

MICA SCHIST.

STATION: SS-4; DEPTH: 50 to 53 feet.

CRUSHING STRENGTH: 11,200 pounds per square inch.

SLIDES: 52, 53, 54, 55, 74, 75, 76.

MACROSCOPIC CHARACTER: Gray banded, fine-, even-grained mica schist. Concentrations of mica are not great and continuous; therefore lines of cleavage do not greatly wealen this specimen.

MICROSCOPIC CHARACTER: Laths and flakes of mica arranged in planes of schistosity in a matrix of microcline, plagioclase (oligoclase), orthoclase, and quartz. Much of the feldspar is subject to slight alteration to sericite. Other minerals identified are magnetite, zircon in pleochroic halos within crystals of biotite, pyrite, ilmenite, leucoxene, apatite, and several particles of chlorite partially altered to serpentine.

QUANTITATIVE DETERMINATIONS:

Mica	20 per cent.
Feldspar	75 " " .
Accessories	5 " " .

SPECIMEN NO. 20.

MICA SCHIST. Plate II, figure 2.

STATION: NG-6; DEPTH: 5 feet.

CRUSHING STRENGTH: 14,000 pounds per square inch.

SLIDES: 26, 27, 28, 80, 81.

MACROSCOPIC CHARACTER: Pink even-grained micaceous schist with discontinuous black bands.

MICROSCOPIC CHARACTER: Flakes and laths of biotite in a matrix of orthoclase, microcline, and plagioclase (oligoclase). Ninety per cent of the feldspar is partially altered to sericite in places. Other minerals identified are apatite, ilmenite partially replaced by leucoxene, calcite, and zircon.

QUANTITATIVE DETERMINATIONS:

Feldspar	90 per cent.
Mica	5 " " .
Accessory minerals	5 " " .

SPECIMEN NO. 21.

MICA SCHIST.

STATION: NG-6; DEPTH: 20 feet.

CRUSHING STRENGTH: 12, 400 pounds per square inch.

SLIDES: 38, 39, 41, 42, 43.

MACROSCOPIC CHARACTER: Pink laminated mica schist. The planes of schistosity contain a high content of mica but are irregular and non-continuous. Total mica will not run over 10 per cent.

MICROSCOPIC CHARACTER: Elongated, tabular crystals of biotite in a matrix of feldspar and quartz. The feldspars are microcline, plagioclase, and orthoclase. Accessory minerals are pyrite, hornblende, ilmenite, garnet, zircon within pleochroic halos in laths of biotite, and an undetermined colorless, isotropic mineral.

QUANTITATIVE DETERMINATIONS:

Feldspar	85 per cent.
Mica	10 " " .
Accessories	5 " " .

SPECIMEN NO. 22.

MICA SCHIST.

STATION: A-26; DEPTH: 57 to 61 feet.

CRUSHING STRENGTH: 8,300 pounds per square inch.

SLIDES: 4, 5, 9, 10, 11, 49, 50, 51.

MACROSCOPIC CHARACTER: Gray to pink banded crystalline schist with phenocrysts of free quartz and feldspar.

MICROSCOPIC CHARACTER: Elongated laths and flakes of biotite containing pleochroic halos in a groundmass of feldspar and quartz some of which shows undulatory extinction. Feldspars include microcline, orthoclase, and plagioclase all three of which are partially altered to and replaced by sericite. The mica flakes are arranged in bands of cleavage. Accessory minerals are zircon within pleochroic halos in biotite, limonite, apatite, magnetite, and ilmenite.

QUANTITATIVE DETERMINATIONS:

Feldspar	55 per cent.
Mica	37 " " .
Accessories	4 " " .

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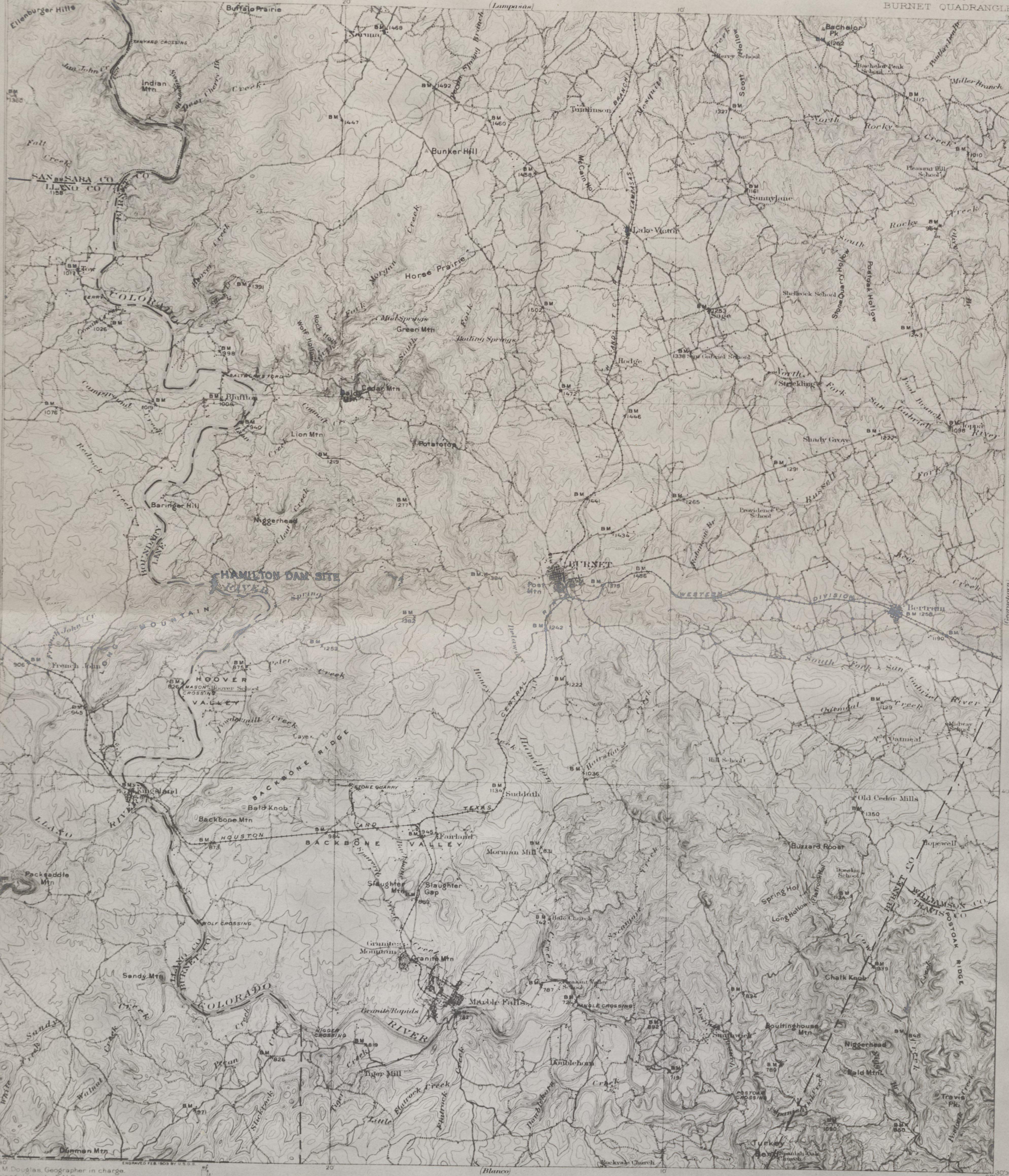
GEORGE OTIS SMITH, DIRECTOR

TOPOGRAPHY

TEXAS
BURNET QUADRANGLE



E.M. Douglas, Geographer in charge.
Triangulation by E.M. Douglas.
Topography by W.M. Beaman and H.H. Hodgeson.
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Scale 1/125000
Contour interval 25 feet.
Datum is mean sea level.

Edition of Dec. 1909.