



Some geochemical aspects of the cedar tree laccolith, Gallatin Canyon, Southwestern Montana
by Daniel B Hawkins

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree
of Master of Science in Chemistry
Montana State University
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Abstract:

An attempt has been made to determine how the silts in connection with a particular laccolith gained space for themselves. The study was restricted to a small area where the andesite porphyry in the form of sills and elliptically shaped bodies referred to by the author as "eyes", of the neighboring laccolith has intruded the Meagher limestone.

Chemical and petrographic analyses, as well as specific gravity and structural measurements were utilized in an effort to find a solution. Chemical analyses for calcium, magnesium, and carbonate were used as a measure of possible assimilation of the limestone by the intrusive.

The specific gravity and structural measurements were used to estimate the amount of space gained through brecciation and Mechanical displacement. The analyses for calcium and magnesium were carried out by means of a Beckman Model DU spectrophotometer with an oxy-hydrogen flame attachment. The carbonate content of the samples was determined by titration.

The results of the chemical analyses and the specific gravity measurements were expressed graphically so as to observe the variation of the samples in relation to their position within the sills.

Assuming that the sample showing the lowest amount of calcium represents most closely the original uncontaminated magma, and that the original magma was homogenous throughout the amount of limestone assimilated was calculated. On the basis of the calculation it appeared that from 0.3 to 2.5% of the volume of the sill had been gained by assimilation. The remaining space had been gained by purely mechanical means.

Many problems remain before a more exact Solution can be arrived upon.

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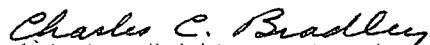
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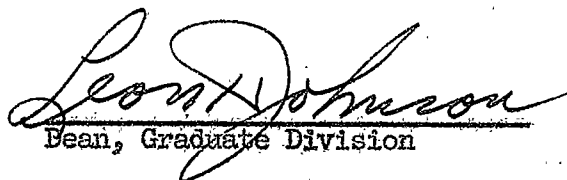
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Bozeman, Montana
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ABSTRACT

An attempt has been made to determine how the sills in connection with a particular laccolith gained space for themselves. The study was restricted to a small area where the andesite porphyry in the form of sills and elliptically shaped bodies, referred to by the author as "eyes", of the neighboring laccolith has intruded the Meagher limestone.

Chemical and petrographic analyses, as well as specific gravity and structural measurements were utilized in an effort to find a solution. Chemical analyses for calcium, magnesium, and carbonate were used as a measure of possible assimilation of the limestone by the intrusive. The specific gravity and structural measurements were used to estimate the amount of space gained through brecciation and mechanical displacement. The analyses for calcium and magnesium were carried out by means of a Beckman Model DU spectrophotometer with an oxy-hydrogen flame attachment. The carbonate content of the samples was determined by titration.

The results of the chemical analyses and the specific gravity measurements were expressed graphically so as to observe the variation of the samples in relation to their position within the sills.

Assuming that the sample showing the lowest amount of calcium represents most closely the original uncontaminated magma, and that the original magma was homogenous throughout; the amount of limestone assimilated was calculated. On the basis of the calculation it appeared that from 0.3 to 2.5% of the volume of the sill had been gained by assimilation. The remaining space had been gained by purely mechanical means.

Many problems remain before a more exact solution can be arrived upon.

INTRODUCTION

One of the major problems in geology today is in regard to the emplacement of large bodies of igneous rock. This problem reaches the height of its complexity in regard to batholiths, yet remains on a smaller but more accessible scale in regard to laccoliths and associated intrusive bodies. The problem is essentially this: How did the igneous bodies gain space for themselves? Did the material, which we refer to as igneous rock, form from some molten magma originating beneath the crust of the earth, well up and thrust aside the overlying sediments? Or did the magma stope out blocks of these sediments which settled into the magma reservoir and presumably became incorporated, or sank to the bottom? Or did solutions emanate from some small body of magma, and move through the overlying sediments and convert them to a material similar to igneous rock? This problem is especially "knotty" because of the size of the bodies involved, and of the complex relationships both physical and chemical which exist within them. The fact that man has been unable to observe the emplacement of any of these bodies is a further complicating factor.

Thus we have a problem which is extremely complex, and which probably defies exact solution, yet remains intriguingly interesting.

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A. C. Peale, 1896, was responsible for the only other study made of the Squaw Creek sills. In his work, he simply indicated the presence of these sills at the junction of Squaw Creek and the West Gallatin River, and identified the rock composing the sills as an andesite porphyry. It was assumed from his work that these sills are part of the Lone Mountain laccolith system, because of the similar rock type, and fairly close proximity. The laccolith of which these sills are a part has been referred to by the author as a cedar tree laccolith, because of its similarity in appearance with a cedar tree laccolith by the Vlatava River in central Czechoslovakia which was described by R. Kettner, (Hunt, 1953).

DESCRIPTION OF AREA

The area where this work was done is about 23 miles southwest of Bozeman, in Gallatin Canyon, at the junction of Squaw Creek and the West Gallatin River.

The Gallatin River in the process of cutting the canyon, has exposed about 2500 feet of sediments. The bulk of these sediments are limestone, ranging from the Meagher limestone (Cambrian) to the Mission Canyon formation of the Madison limestone (Mississippian). There are many andesite porphyry sills present in these sediments, and the biggest sills are associated with the various shale beds, either directly within them or on the contact between the shale and the limestone.

In the accompanying photograph (Plate I) only the lower-most cliffs formed from the Meagher limestone are shown. These cliffs rise vertically for some 250 to 350 feet. There are several sills and three large eyes of andesite porphyry present in the faces of these cliffs. It was upon

Plate I



(5a)

these sills and eyes that this work was done.

SAMPLING AND PREPARATION OF SAMPLES

In order to estimate the part played by chemical assimilation as a means of gaining space, it was necessary to obtain suites of samples from each sill. These samples were taken from the limestone above the sill, the sill itself, and from the limestone below the sill. The problem of obtaining such suites of samples from the face of a large cliff proved to be somewhat difficult.

The first method used in sampling these cliffs was rappeling. In this method the rope is passed around ones' body in a particular way, and the friction thus created is used to control the rate of descent. This method was discarded, as it was not satisfactory.

The method which met with the most success involved the use of a "Bosun's" chair and a block and tackle. Figure 1 is a sketch of the "chair" and the rigging. The materials used in rigging the chair were 600 feet of $3/8$ inch manila rope, 50 feet of $1/8$ inch steel airplane cable, cable clamps, two blocks with a pulley diameter of 3 inches, and one Lineman's Safety Belt and Harness, style number 1306, manufactured by the Buckingham Manufacturing Company, Binghamton, N. Y.

The sampling chair was assembled as follows: the airplane cable was fastened to a small tree at the top of the cliff by passing one end of the cable completely around the tree and clamping this end to the rest of the cable by means of two cable clamps. The other end of this cable was fastened to one of the eyes on the block in the same manner. One end of the rope was now tied to the other eye on this

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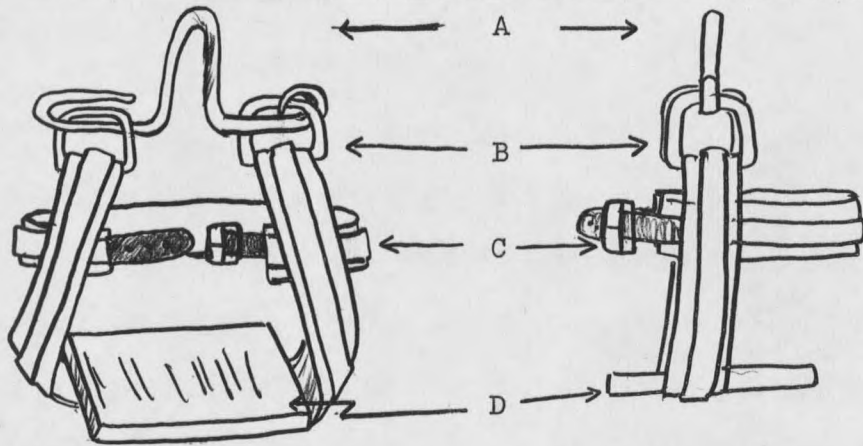
same block and was taped with friction tape for several feet to help prevent wear of the rope against the cliff. The rope was then passed down through the lower block around the pulley and up through the pulley on the upper block and this free end was allowed to dangle. By attaching the seat to the eye in the lower block by means of a carabiner or snap link, and pulling on the free end of the rope, it was possible to lift oneself up the face of the cliff and sample with comparative ease.

This method overcame the difficulties incurred by the method of rappelling. That is, it was much more comfortable and to a certain extent, sampling under overhangs was possible. To sample under the overhangs pitons were driven into cracks on the rock face and by tying a rope to these pitons and then to the chair, the chair was anchored to the cliff. This method of sampling under overhangs by use of pitons was not too successful, since in driving in the pitons they had a tendency to stoop out a large block of rock directly above ones' head. If the work were to continue this was to be avoided.

Another difficulty in using the chair was that the ropes had a tendency to tangle or wrap around one another. This made pulling oneself up the cliff a rather strenuous proposition.

In sampling the cliff the following procedure was carried out: an unweathered sample from 2 to 4 inches in diameter was obtained. This sample was then labeled with masking tape and given a number. The sample number along with its description and position in relation to the sill-limestone contact were recorded in a notebook.

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Front

(A)

Side

A- Steel Hook
C- Reinforced Webbing

B-Steel "D" Ring
D-Hardwood Seat

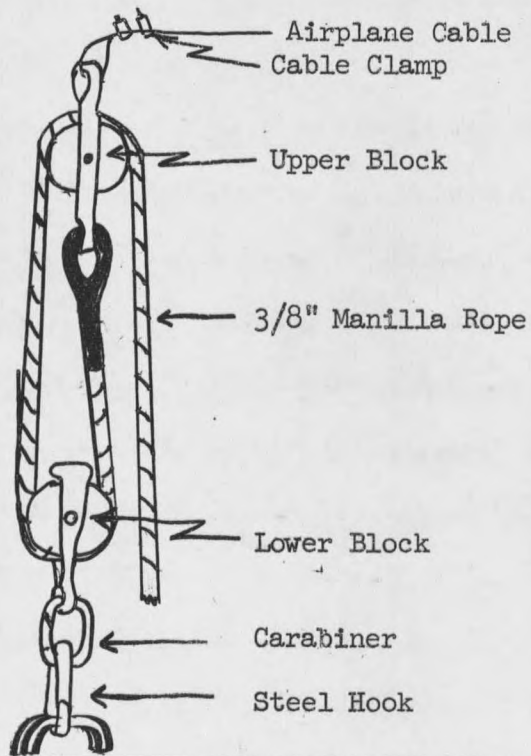


Figure 1

For labeling purposes each of the major cliffs or outcrops was designated by a Roman numeral, and since these outcrops had several sills and eyes within them, the outcrops were then divided into sections labeled A, B, C, etc. These section letters usually referred to a single eye or a section of a sill. Usually these sills or eyes were large enough so that two vertical samplings were desired. The first sampling was labeled as 1-horizontal, and the second as 2-horizontal. After this the samples were labeled 1, 2, 3, etc. starting with 1 as the topmost sample and proceeding downward. Thus, a sample might be labeled IIDIIIIIV, meaning outcrop II, section D, first horizontal sampling, the 11th vertical sample.

Specific gravities of the samples thus obtained were measured with a Jolly balance. Subsequently they were broken up with a hammer, and run through a Braun pulverizer. The powdered sample was poured out on a large sheet of paper and was mixed by folding opposite corners of the paper over one another, producing a rolling and tumbling motion of the sample. After thorough mixing, the sample was heaped in the middle of the paper and a smaller sample was taken by removing small scoops with a spatula from different points on the pile. These scoops were then placed in an agate mortar and ground as finely as possible. The resulting powder was transferred to a "pill box". It was this sample that was used in the chemical analysis.

DEVELOPMENT AND DISCUSSION OF ANALYTICAL PROCEDURE

Because of the number of analyses, it was felt that a rapid analytical

method for calcium and magnesium, on limestone and the silicates would be desirable. As flame photometric determinations on the alkali and alkaline earth metals have proven both rapid and quite accurate, an analytical method for the determination of calcium and magnesium utilizing this instrument seemed to offer the greatest possibilities of meeting the requirements of both speed and accuracy.

DISSOLUTION OF ROCK SAMPLES

The first problem met in the development of a procedure was that of dissolving the samples. The limestone presented no difficulties in this respect. The powdered sample was moistened slightly with water to avoid spattering when a mixture of concentrated nitric and perchloric acids was added. The perchloric insured solution of the samples and complete oxidation of any organic matter present. The resulting solution was then heated to moist dryness to remove excess perchloric acid and the residue was taken up in dil. HCl.

In order to bring the sill rock into solution two methods were tried. The first was the classical sodium carbonate fusion of the powdered sample. After the fusion the carbonate was destroyed by addition of HCl and the silica was dehydrated. This method was discarded for three reasons:

1. The fusion and destruction of the carbonate was lengthy.
2. The fusion involved the addition of sodium to the system, which was to be avoided because of the enhancing effect of sodium on calcium and magnesium flame emissions.
3. The fusion gave a high salt concentration which resulted

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in clogging of the burner, and erroneous results.

The second method, and the one that met with the most success, is to treat the powdered sample in a platinum crucible with 8 ml. HF , and 2 ml. HClO_4 , and take to dryness slowly on the hot plate. This method had the advantage that the time required to dissolve the sample and take it to dryness is fairly short, around 1 1/2 to 2 hours. The reason the dehydration takes this long is that care has to be taken to avoid spattering the sample when heating the open crucible on the hot plate.

One possible disadvantage of this method is that it adds fluoride ions to the system. The fluoride ion must be removed because of its depressing effect on the calcium flame emission, and because it interferes with the complete precipitation of aluminum, (Veitch), 1900. The removal of the fluoride ion presents no difficulties, since Selch¹ has pointed out that complete removal can be affected by taking perchloric-hydrofluoric acid mixture to dryness, taking up in more perchloric acid and taking again to dryness. Besides being necessary for the removal of the fluorides, the perchloric converts the remaining ions to soluble perchlorates.

The major obstacle in connection with the development of a flame photometric procedure for calcium and magnesium was the problem of interference due to other ions. The principal ions causing interference are Fe^{+3} , Al^{+3} , PO_4^{-3} , Na^{+1} , F^{-1} , ClO_4^{-1} .²

1. Hillebrand (1929)
2. See appendix pp. 53--57.

As can be seen from the graphs in the appendix, iron and aluminum have a pronounced depressing effect while sodium has an enhancing effect. Baker, 1952, has shown that PO_4^{-3} has a strong depressing action on the calcium emission and that ClO_4^- has an enhancing effect. Since iron, aluminum, sodium, and phosphate are present in appreciable quantities in most igneous rocks, it was necessary either to remove these ions or to minimize their effects. In the case of the iron, aluminum, and phosphate, the easiest solution was to simply remove them. The phosphate was removed by adding ZrOCl_2 plus some asbestos as a carrier to the acid solution containing the dissolved rock sample.¹ Subsequently the classical wet method procedure for the removal of iron and aluminum was followed. The addition of 6 N. NH_4OH precipitated the phosphate as $\text{Zr}(\text{HPO}_4)_2$ and the iron, aluminum, and excess zirconium as hydroxides.

It was then necessary to remove the ammonium salts since too high a concentration of salt clogged the burner on the flame photometer.

After the removal of the ammonium salts the residue containing mainly sodium, calcium, and magnesium was taken up in dil. HCl and transferred to a 250 ml. volumetric flask and diluted to volume. An aliquot of this solution was removed and transferred to a 100 ml. volumetric flask and diluted to volume, in order to obtain the desired concentration range.²

1. Curtman, (1938)

2. See appendix pp. 49-52

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ANALYTICAL PROCEDURE

Limestone

Weigh out a 0.500 gm. sample of finely ground limestone and transfer to a 300 ml. tall form beaker. Add 10 ml. conc. HNO_3 and 5 ml. conc. HClO_4 to the sample, and take to moist dryness on the hot plate, take this residue up in dilute HCl. To the HCl solution add a few drops Methyl Red indicator and two grams NH_4Cl and heat to boiling on the hot plate. Neutralize with 6 N NH_4OH and add 5 ml. in excess. Boil the solution for 1 to 3 minutes and then allow the precipitate to settle. Decant through a rapid (Whatman 41) filter paper and wash by decantation with several 20 ml. portions of hot 2% NH_4Cl solution, retain the filtrate and washings for the calcium and magnesium analysis. Take the precipitate and filter paper and transfer to a beaker, add 30 ml. of hot 3 N HCl and break up the filter paper with a stirring rod. When the precipitate is completely dissolved dilute to 100 ml. with distilled H_2O , add 2 gm. NH_4Cl solution. Precipitate as before, adding the filtrate and washings to the filtrate from the first precipitation, make acid with HCl and evaporate on hot plate. When the solution is almost to dryness add conc. HNO_3 and evaporate to dryness. Take up the residue in dilute HCl and transfer to a 250 ml. volumetric flask and dilute to volume with distilled H_2O . Read this solution at 554 m μ for calcium, and at 371 m μ for magnesium.

Sill Rock

Weigh out a 0.500 gm. sample of finely ground sill rock and transfer to a platinum crucible. Add 5 ml. conc. HF , and 2 ml. conc. HClO_4 , and take to dryness again. Take up this residue in HCl and transfer to a

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300 ml. beaker. Add 2 gms. NH_4Cl and 10 ml. ZrOCl_2 solution, (50 mg Zr per ml.) drop by drop with stirring. Add 2 gm. asbestos and heat to boiling, add several drops Methyl Red indicator and neutralize with 6 N. NH_4OH . Proceed from here with the procedure outlined for limestone.

CARBONATE DETERMINATION

The carbonate content of the andesite porphyry was estimated by treating a 0.500 gm. sample of the powdered rock with 10 ml. HCl, 0.4825 N. This solution was heated to boiling on the hot plate to insure destruction of the carbonate. After boiling for a few minutes the flask was removed from the heat and was diluted to a volume of 100 ml. with distilled water. After this several drops of phenolphthalein indicator were added and the solution was titrated to the phenolphthalein endpoint with standard NaOH 0.1007 N., and the amount of HCl neutralized was calculated. The difference between this calculated amount and the amount HCl added was due to neutralization by the carbonate. From the amount of HCl neutralized by the carbonate, the percentage of carbonate in the sample was calculated. Assuming that all the carbonate present was calcium carbonate¹, the amount of calcium present as a carbonate in the andesite porphyry was calculated.

SPECIFIC GRAVITY

The specific gravities of the samples were obtained by means of a Jolly balance. The following brief description of this instrument is given by Hurlbut².

1. A study of thin sections revealed that calcite was the only carbonate present.
2. Hurlbut, C. S. jr., (1953) DANA'S MANUAL OF MINERALOGY Revised, 16th Ed. 98--99. Wiley & Sons, New York.

The data necessary for making the calculations of specific gravity are obtained by measuring the stretching of a spiral spring. From the spring are suspended two small pans, one above the other. The apparatus is so arranged that the lower pan is always immersed in a beaker of water which resting upon an adjustable platform can be placed at the required height. In all types of Jolly balances it is necessary to adjust the apparatus so that index of the spring is at zero with the lower pan immersed in water. The sample is then placed in the upper pan, and the stretching of the spring W_a necessary to return the indicator to zero is determined by means of an affixed scale. The sample is then placed in the lower pan and another adjustment, and W_w reading taken. The specific gravity is then calculated by:

$$G = \frac{W_a}{W_w}$$

THIN SECTIONS

The thin sections used in this study were prepared by G. S. Rev, New York. These sections were studied by means of an Ernst Leitz, (Wetzlar) petrographic microscope.

RESULTS

The accompanying photograph (plate II) is of outcrop II section D. The dimensions of this sill or eye are 150' by 35'. The metamorphic zone extends about 8 feet into the limestone. The sill-limestone contact is sharp with no evidence of chilling. There is no distinct lineation of the hornblende phenocrysts, but a statistical study of their orientation might reveal the presence of lineation. Figure 2 is an overlay of the photograph and contains traces of limestone bedding planes about the sill. From a study of the drag of the bedding planes the direction of movement along the fault is indicated. This fault appears to terminate the sill, as no sill rock is present on the other side of it.

Figures 3 and 4 are graphs showing the results of the chemical analyses and specific gravity measurements, on two suites of samples

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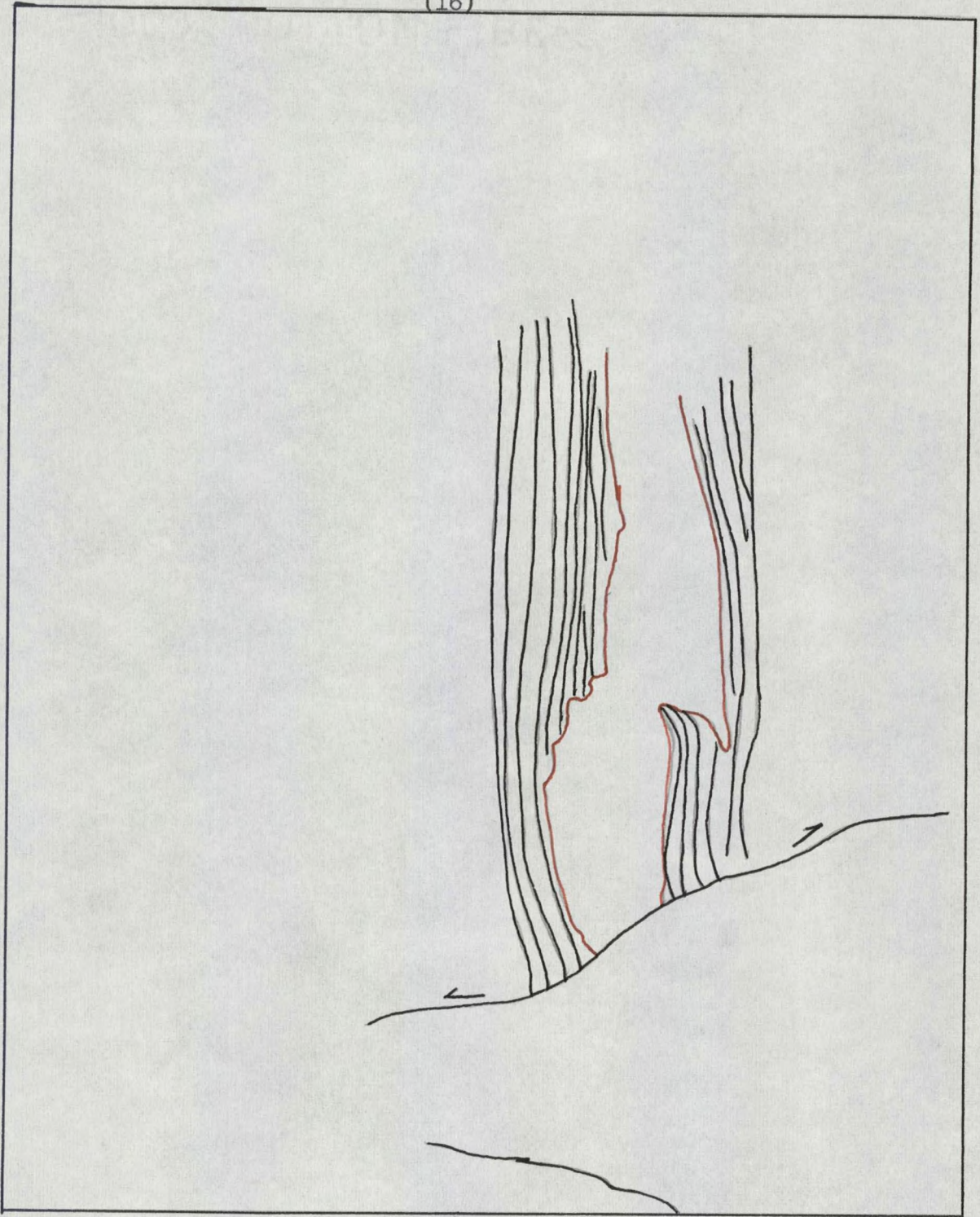
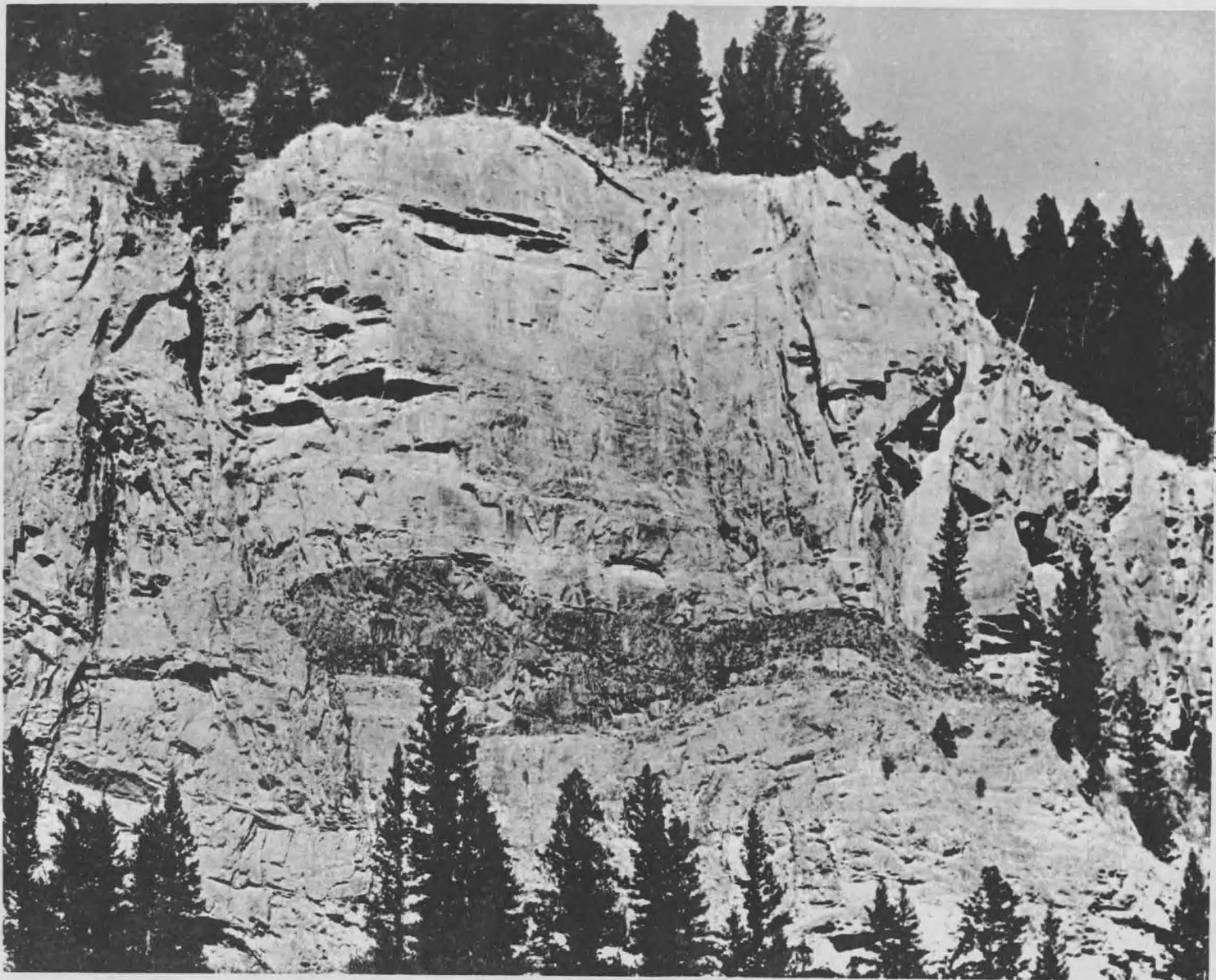


Figure 2. An Overlay Of Plate II.

Plate II. Outcrop II, Section D



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Figure 3. OUTCROP II, SECTION D, 1 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.

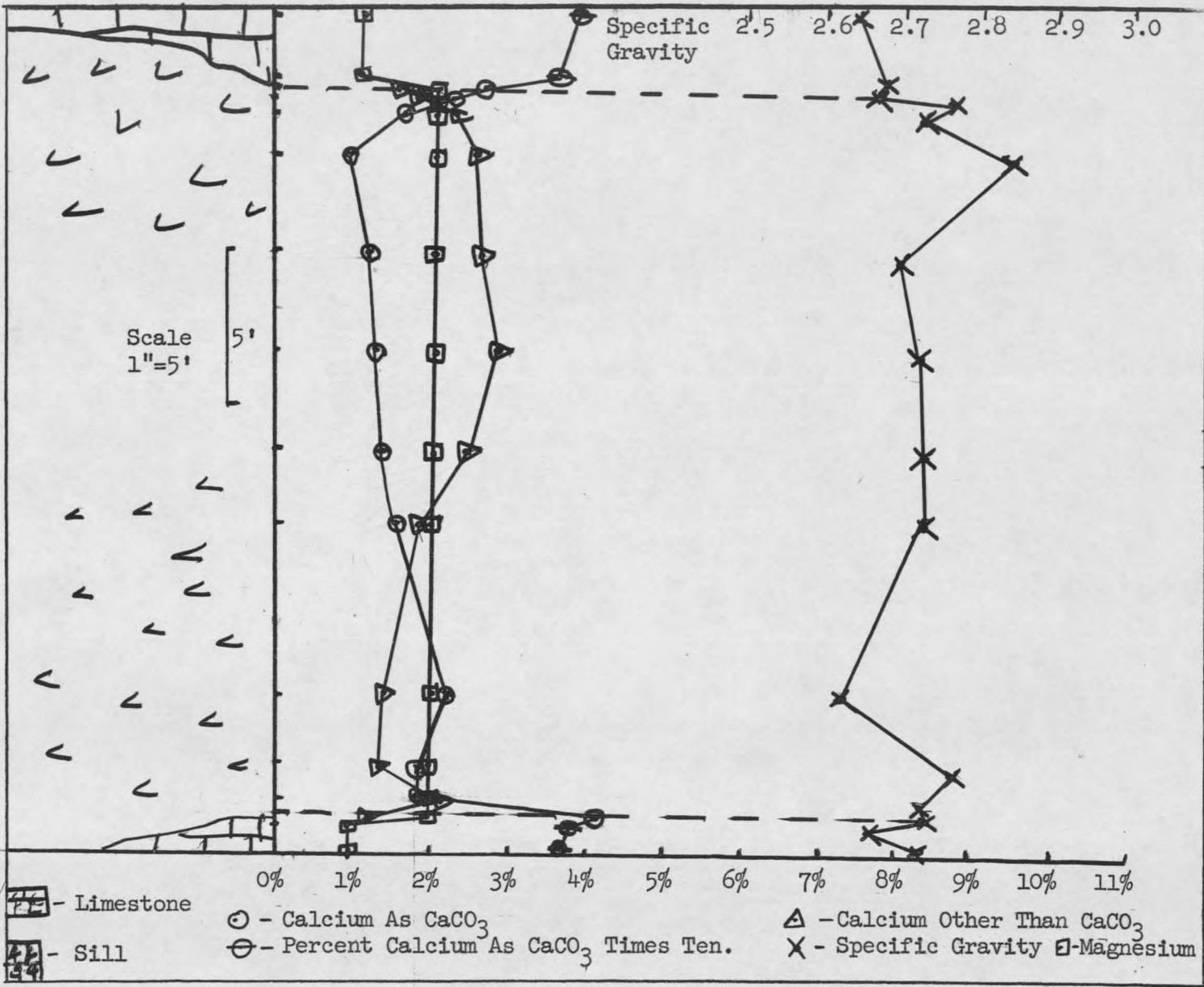
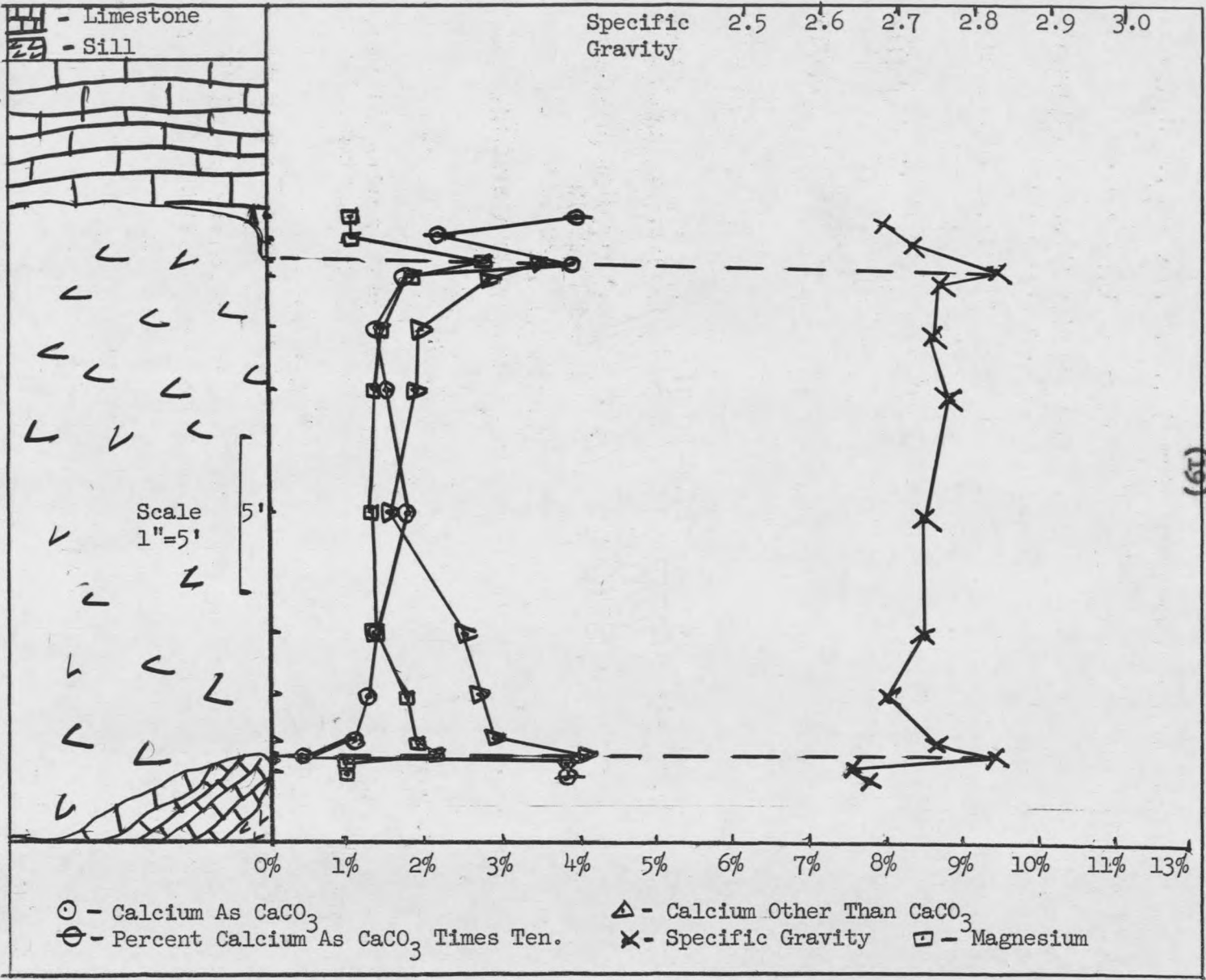


Figure 4
 OUTCROP II, SECTION D, 2 HORIZONTAL: Specific Gravity And
 Percent Calcium And Magnesium Versus Sample Position.



through the above described sill. These graphs were prepared by plotting the percent calcium and magnesium and specific gravity on the abscissa, versus sample position on the ordinate. The graphs figures 3 and 4 are very similar in most respects. They show a high in specific gravity, calcium, and magnesium on the contacts, and both show the rather intimate relationship existing between calcium present as a carbonate and calcium as a silicate.

The magnesium curve tends to be the same in both graphs. In each there is a tendency toward a high on the contacts followed by a leveling out in the interior of the sill.

The specific gravity curves are almost identical, differing only in scale. Each shows a high in specific gravity on the contact, followed by a tendency to remain constant through the interior of the sill. In each case the specific gravity curve plunges to a minimum near both contacts followed by a rapid rise to a maximum at the contact.

PETROGRAPHIC STUDY

A petrographic study of this sill was not made. This was regrettable as much useful information could probably have been gained. Since chemical assimilation as a means of gaining space was felt to be a small scale affect, a petrographic study of the small sills and eyes was carried out in hopes that assimilative effects would be more obvious. For this reason the larger sills and eyes were not included in the petrographic study.

Figure 5¹ is a graph of the analysis of a small aureole or embayment of sill in the limestone. The metamorphic zone in the limestone extends about 8 feet from the contact. The contact is again sharp but not chilled, with no discernable lineation of the hornblende phenocrysts evident.

The curves of calcium, magnesium, and specific gravity again show highs at the contact followed by a tendency to remain fairly constant down into the main body of the sill. The relationship of the calcium carbonate to the calcium silicate is again evident. No samples from the lower contact could be obtained as this was under debris.

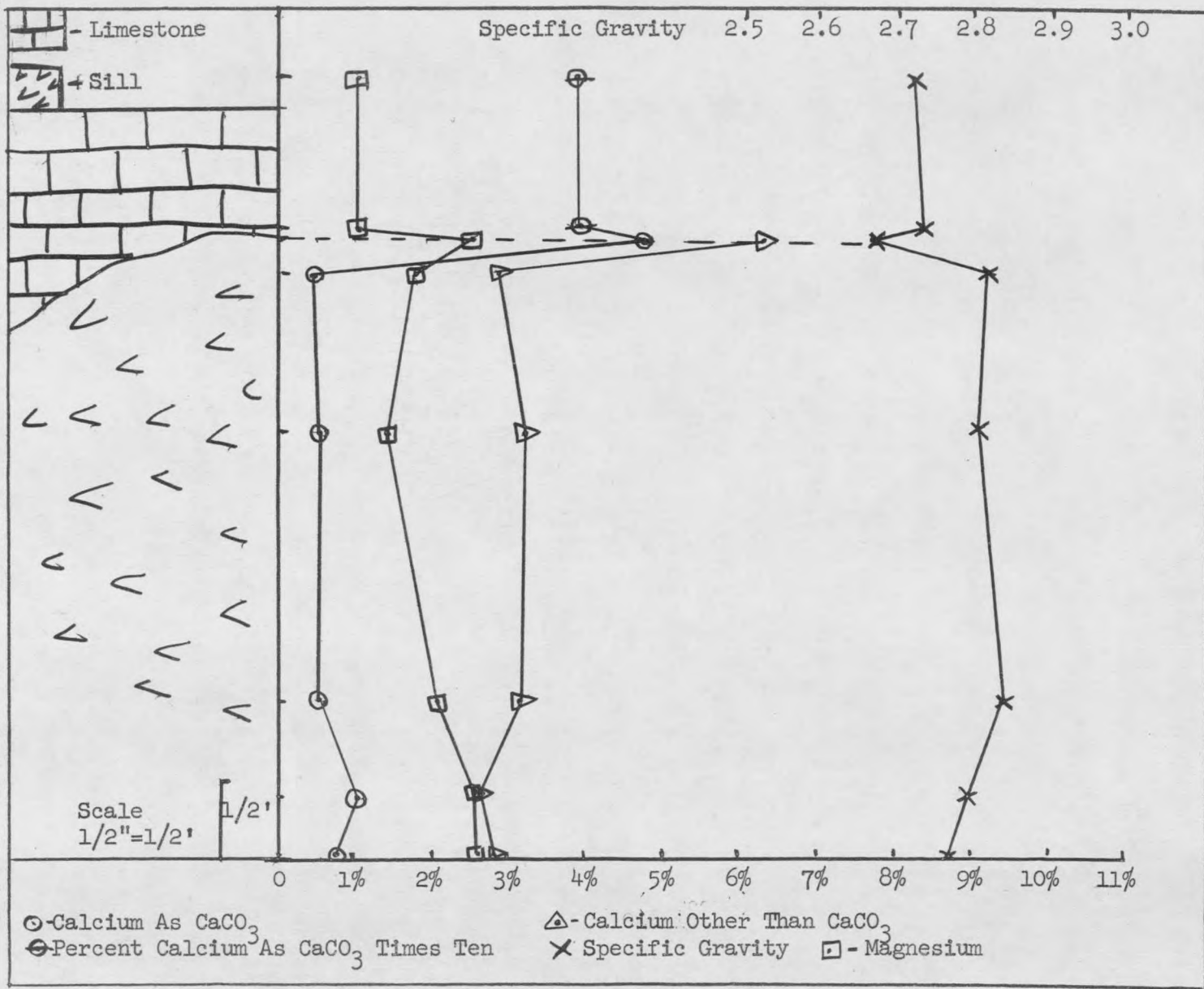
PETROGRAPHIC STUDY

A limited petrographic study was made of this little aureole utilizing only four thin sections. These include a section from the limestone contact, a section from the sill contact, and two sections from the interior of the sill.

The "limestone" contact material is a calcitic marble. This marble shows some evidence of cataclastic adjustment in that there are many large grains of calcite surrounded by much smaller grains. Along most of the cracks in this section can be found concentrations of magnetite and an unidentifiable, fine grained earthy material.

1. Graphs, figures 3, 4, and 5 were included in the body of the thesis, since they were representative of all the graphs, and showed the results most plainly. To avoid needless repetition in the body of this thesis, the remaining graphs were placed in the appendix, pp. 71--78.

Figure 5. OUTCROP II, SECTION A, 1 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.



The estimated total composition of the thin sections from the sill contact and the interior of the sill, is given in figure 6.

Of interest is the high anorthite content of the plagioclase on the contact, with a decrease in anorthite away from the contact. This gradation is not limited to this particular outcrop but is also shown in thin sections from other sills.¹

The right hand side of the graph shows the variation in calcite in relation to the other accessory minerals.² This simply shows that in the sill contact sample the calcite is no longer an accessory mineral. About 80% of this calcite is due to ground water, as it is present as vein fillings, while the remaining 20% is present as inclusions within the hornblende and plagioclase, and occupying the interstices between mineral grains. This calcite seems to be due to inclusion of the marble by the magma. The presence of calcite due to ground water deposition is more the exception than the rule. A study of the other thin sections³ reveals that very little of the calcite is due to ground water deposition.

The accessory minerals thomsonite, penninite, and opal occur chiefly in the sill contact slide, however penninite is also present in the sections from the interior of the sill.

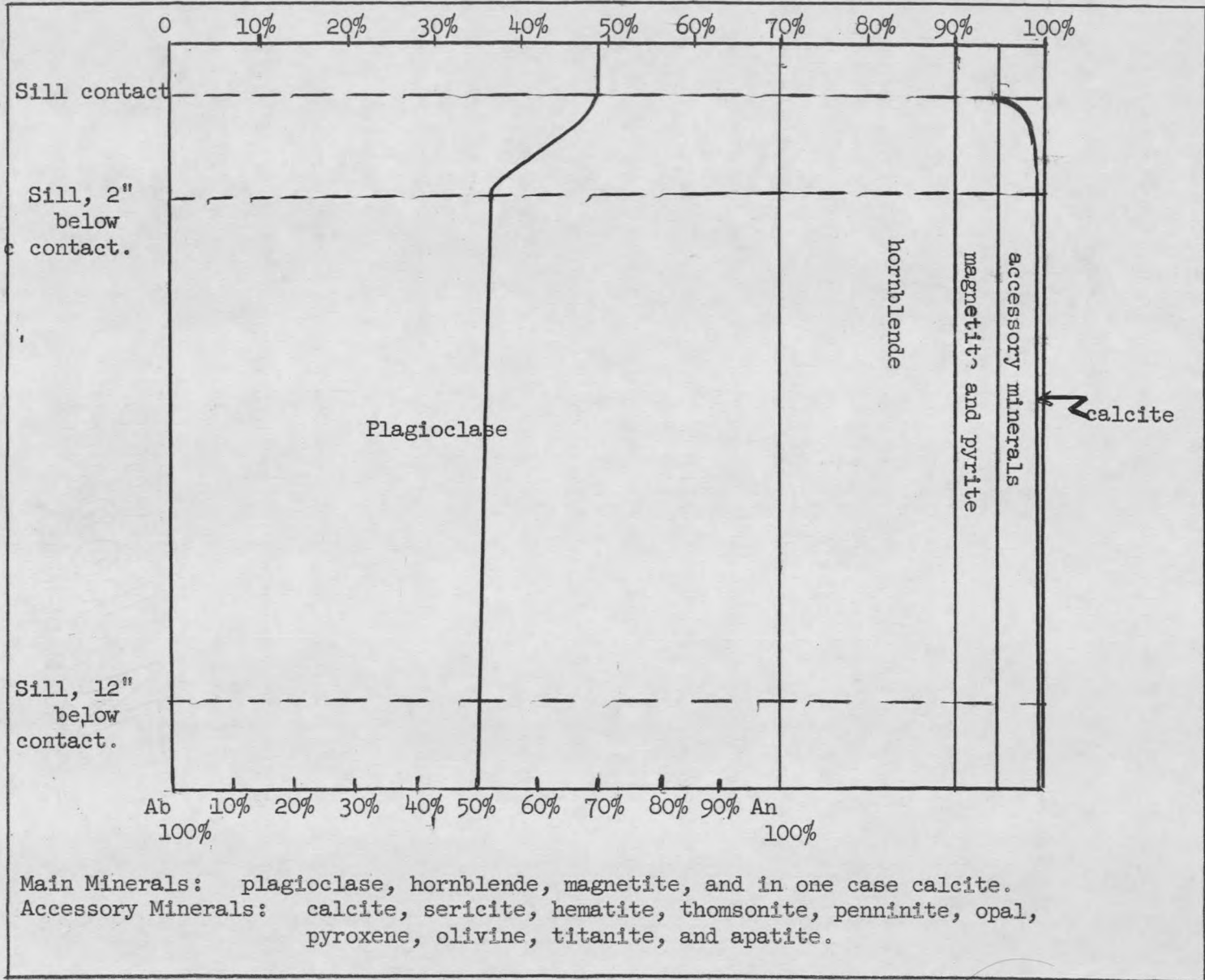
The hornblende phenocrysts are fairly large in size, some about 1/4 inch in length. These phenocrysts occur at random throughout the sill, with no tendency to concentrate near the bottom of the sill.

1. See appendix, pp. 80--81.

2. Accessory mineral is taken in this paper to mean any mineral that composes less than 5% of the total composition.

3. See appendix, pp. 79--98.

Figure 6



These phenocrysts contain inclusions notably plagioclase, calcite, and apatite. The principle source of the apatite in the andesite porphyry are these inclusions. For the most part the grain boundaries of the hornblende are sharp, but all have been sericitized.

The plagioclase forms the bulk of the matrix for the andesite porphyry. Olivine, pyroxene, and apatite are found in small quantities, and calcite in larger quantities as inclusions within the plagioclase. The calcite in some cases acts as the core around which the feldspar has grown. In all cases the plagioclase has been attacked by sericite most noticeably at or near the core.

Magnetite and pyrite occur at random throughout the slide. However, in some cases a more noticeable concentration of these two minerals is found in the vicinity of pyroxene relics.

The pyroxene, titanite, and olivine are present in such minute quantities that many times their identification is only tentative.

DISCUSSION

Nature of Magma

The exact nature of the magma that formed the sills can only be inferred, but many features of the sill and limestone give some insight as to the physical and chemical character of the magma.

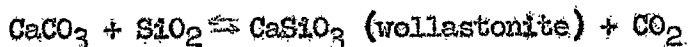
Temperature of Magma

It is felt that the magma was not extremely hot (magmatically speaking). The temperature of the magma was not greater than 750°C. This limit was obtained by the use of the stability curve of calcium carbonate and silica after V. M. Goldschmidt.¹

1. Ramberg, H. (1952)

Figure 7 is a reproduction of this curve. Quoting from Shand:¹

"An application of the "geological thermometer" principle is possible when limestone occurs in contact with an eruptive rock or among the fragments enclosed in the latter. Under moderate pressure the reaction



moves toward the right above 500°C. The effect of higher pressures upon the temperature of reaction is shown in the stability curve of calcium carbonate and silica after V. M. Goldschmidt. It will be seen that if the pressure under which a given rock crystallized, can be estimated from stratigraphic data, then the presence or absence of wollastonite in the contact zone will enable one to set either a lower or an upper limit to the temperature of the magma at the place of contact."

As wollastonite was found on the contact of several of the sills, it was only necessary to estimate the pressure in order to obtain the temperature of the magma at the contact.

Taking the time of the emplacement of the magma to be late cretaceous or early tertiary, the cambrian limestone studied in this work probably had at least 15,000 feet of overlying sedimentary rock upon it. Taking the specific gravity of the sediments as 2.72, the pressure exerted upon a square inch of rock was found to be 1200 atmospheres. From the curve this pressure corresponds to an approximate temperature of 600°C. to 675°C.

Another feature of the andesite porphyry which lends itself to the geological thermometry is the presence of common green hornblende. Kozi, Yoshiki, and Kani, Shand, (1947) have shown that green hornblende transforms to a dark brown variety of hornblende at 750°C. No lower limit of the temperature was established from a study of the sills.

1. Shand, S. J. (1947) Eruptive Rocks, 3rd Ed., Pg. 59
John Wiley & Sons., New York

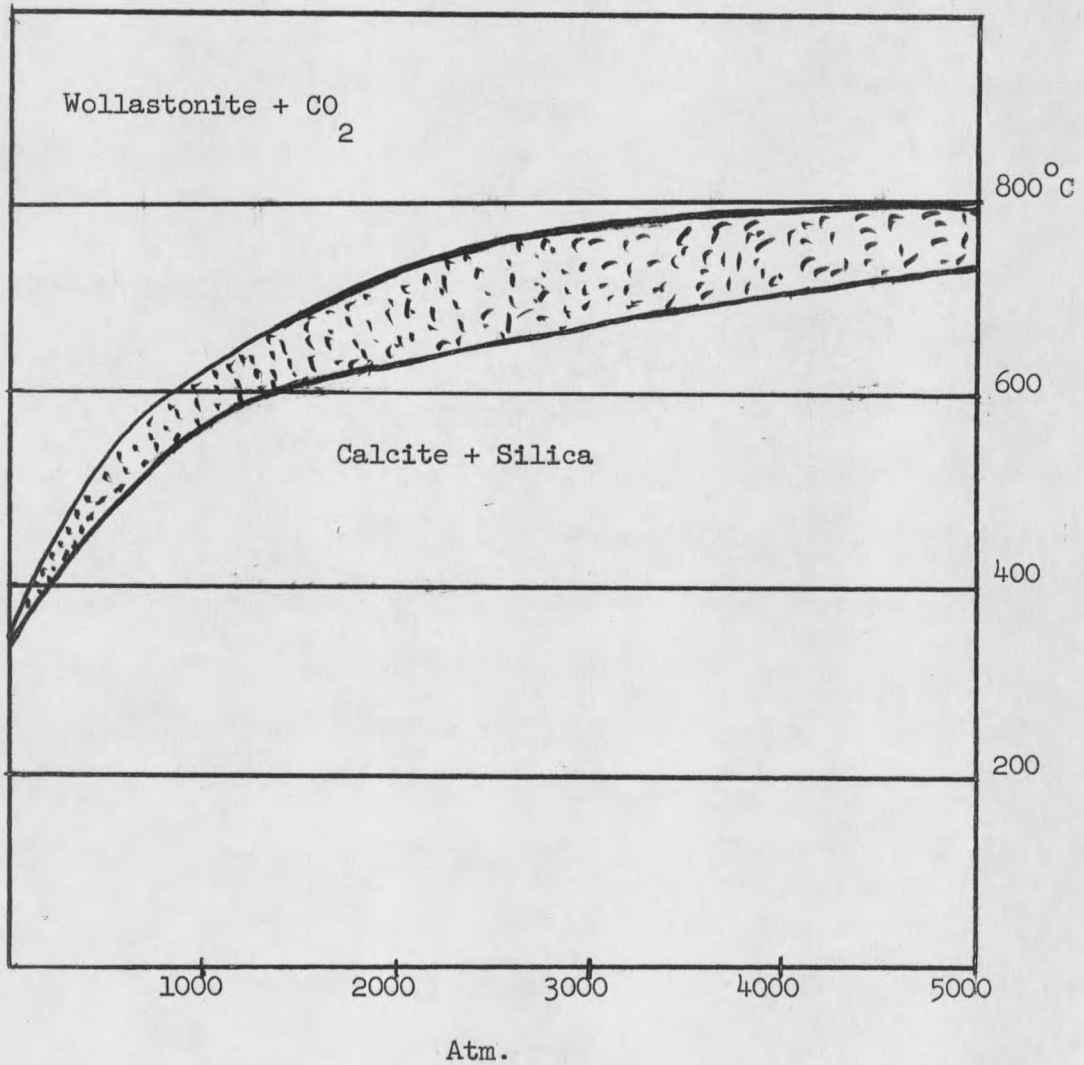


FIGURE 7. Stability Curve Of Calcium Carbonate And Silica, after Goldschmidt.

VISCOSITY

A study of the position of the hornblende phenocrysts within the sill has led the author to assume that the magma was quite viscous.

Hornblende has a specific gravity of 3 - 3.2, the average specific gravity of the andesite porphyry was 2.72. Thus, if the magma were quite fluid one would expect a settling out of the hornblende phenocrysts resulting in their concentration along the lower portion of the sill. The hornblende phenocrysts occurred at random throughout the sill with no observable increase in their concentration at the bottom of the sill. Hunt, 1953, has pointed out that failure of the hornblende phenocrysts to sink means either high viscosity of the magma or quick quenching or both. Since the intrusive bodies dealt with in this work are small they should cool quite rapidly. Thus, rapid cooling was probably an important factor in preventing the sinking of the hornblende phenocrysts.

Additional weight is added to the above argument by the presence of gneissic basement rocks as xenoliths within the sills. Some of these inclusions of gneiss are 6 to 8 inches in diameter. A very fluid magma injected rapidly would probably carry these blocks along, but a very viscous slow moving magma could achieve the effect more readily.

If the magma were quite viscous, as the evidence seems to indicate, its resistance to flow might be responsible for the dome-like shape of the eyes, shown in Plate III. Hunt, 1953, has given a very good discussion concerning the importance of viscosity in controlling the shape of an intrusive body. The interested reader would do well to consult this work.

Rate of Intrusion

As Hunt, 1953, and others have pointed out, the rate of intrusion of the magma plays an important part in controlling the shape of an intrusive body. Quoting from Hunt:¹

"An increased rate of intrusion has the effect of increasing the viscosity. A fluid magma injected rapidly can become as bulbous as a viscous magma injected slowly."

On the basis of the above discussion one is led to speculate that the sills were formed from either a less viscous magma or were injected more slowly than the "eyes". Certainly this is pure speculation and has the disadvantage of necessitating the explanation of why the magma in one part should be less viscous or injected more slowly than the magma in another.

Emplacement Mechanisms

Two means of physical emplacement of the magma have been considered.

These are:

1. A series of tiny individual injections of magma.
2. One massive injection of magma.

The first mode of emplacement was discarded for two reasons. Since the magma appears to have been quite viscous, there would be little tendency for the formation of thin sheets of magma. Also one would expect to find the contacts of each of these sheets and possibly a lineation of the phenocrysts at intervals within each of the large sills.

1. Hunt, Chas. B., (1953) Geology and Geography of the Henry Mountains Region Utah, U. S. Geological Survey Professional Paper 228

This lack of lineation of the hornblende phenocrysts could mean that the hornblende was formed after the magma had been emplaced, but the fact that much of the hornblende has calcite cores seems to dispute this.

Favoring the latter mode of emplacement i. e., a single massive injection are the viscosity of the magma, the lack of lineation of the hornblende phenocrysts, the rather uniform appearance of the calcium, magnesium, and specific gravity curves, and the presence of gouged out limestone which forms a uniform cap over one of the eyes. See Plate III.

Various means by which the invading magma could gain space for itself are outlined below.

- I Mechanical
 - A. Displacement
 - B. Brecciation
 - C. Compaction
 - D. Plastic Flow

- II Chemical
 - A. Assimilation
 - B. Replacement

It is felt that the magma achieved most of its space by purely mechanical means. Probably the biggest factor contributing space to the magma is displacement of the limestone. By displacement is meant the warping up of the limestone beds, and if carried past the breaking point, the faulting of these beds. That faulting and folding were definitely a means of obtaining space is evident from the overlays, accompanying Plates II, III, and IV. On these overlays are traces of the bedding planes of the limestone surrounding the sills and eyes. One can see that the surrounding limestone has been shoved aside and in some cases this action has been so violent that folding of the limestone could no longer compensate

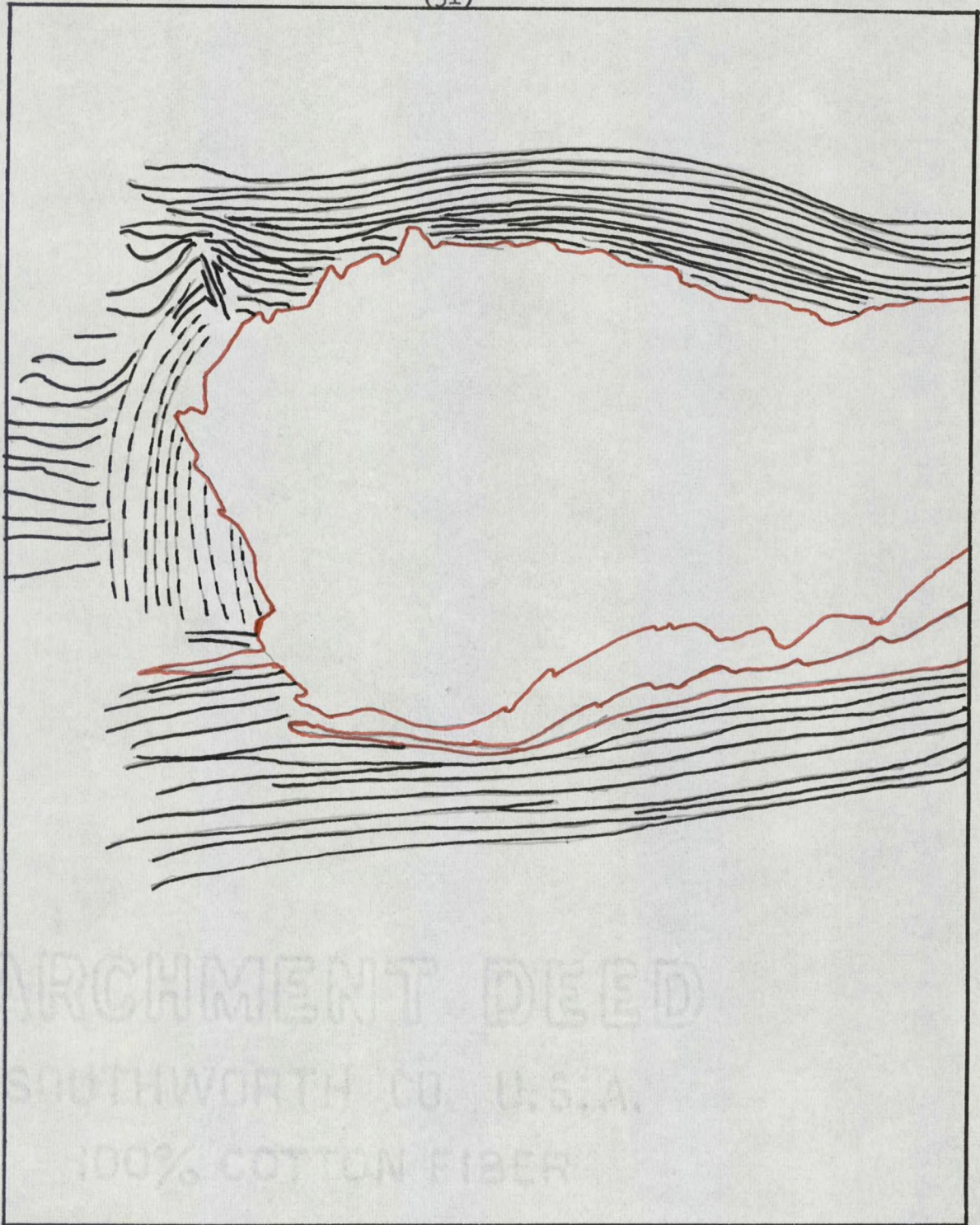


Figure 8. An Overlay Of Plate III.

(32)



Plate III. Outcrop III, Section C.

and faulting resulted. The direction of movement along the faults is indicated by the arrows.

A study revealed that brecciation of the limestone contributed some perhaps much of the space for the invading magma. Around several of the sills are small areas showing how the magma gained space by this means. These areas, usually only several feet in diameter, are composed of fractured pieces of limestone with little interfingerings of sill material around them.

Specific gravity measurements of the limestone surrounding all the sills indicate that this limestone has been fractured by the magma. The average specific gravity of the limestone is 2.72, which is the same as that of pure calcite. Thus, any value of specific gravity of the limestone lower than 2.72 can only be attributed to space between the calcite grains.¹

Because the contact is so sharp, and only a few of the sills have the little interfingerings of sill rock jutting into the limestone, the magma was probably subject to movement after it had become emplaced.

The contributions of space to the magma by compaction and plastic flow are very difficult to ascertain. While specific gravity measurements give some estimate concerning the extent of brecciation, it is doubtful that any compaction of the limestone by the magma could be measured.

The amount of space contributed by plastic flow is unknown.

1. For a further discussion of brecciation as a means of gaining space see appendix, pp. 85-86.

That plastic flow is a factor was seen in the study of the thin sections.¹ These showed large calcite grains surrounded by many smaller grains. This is usually interpreted as the result of some cataclastic movement. It seems logical that plastic flow should result in the thinning of the bedding planes of the limestone. However, chemical assimilation and direct removal by a bulldozing action of the magma would have the same effect. While the amount of limestone assimilated can be estimated, the amount of limestone gouged out is unknown.

Although unable to measure the amount of space contributed by compaction and plastic flow, the author feels that their contribution is relatively minor.

Chemical Mechanisms

There remains now only to consider the contribution of space by chemical means. It is felt that assimilation of a fairly reactive substance such as limestone, by an invading magma, contributes a small but significant amount of space. The reasons for this statement stem from a study of the graphs¹ of the chemical analyses. These graphs make evident a calcium magnesium, and specific gravity gradient through the sills.

There are several ways by which such a gradient could be established, namely: fractional crystallization, crystal settling, Soret effect, and by assimilation of a moderate amount of limestone.

1. See appendix pp. 71--78 and figures 3, 4, 5.

Fractional Crystallization

How can fractional crystallization explain the calcium, magnesium, and specific gravity gradients? To answer this let us consider what effect the lower temperature of the limestone should have on a magma. As the magma was forced into the limestone, the boundary zone of this magma should be of a lower temperature than the interior. Thus, the high temperature minerals, i.e. olivine, pyroxene, and calcic plagioclase, should crystallize out in a greater concentration (of) the contacts than in the interior of the magma. Considering only the plagioclase; the removal of calcic plagioclase should leave the magma deficient in calcium, which on further crystallization of the plagioclase, should result in a more and more sodic plagioclase in the interior. The calcic plagioclase might appear not only because of the lower temperature of the contact but because of the high lime environment of the contact. That is if the system were saturated in calcic plagioclase the addition of calcium would have a tendency to "seed" the system, and precipitate the calcic plagioclase.

From figure 6 it can be seen that a high anorthite content of the plagioclase was present at the contact, with a decrease toward the interior of the sill, thus lending weight to the above argument.

Not only can fractional crystallization account for the calcium gradient, but for the magnesium and specific gravity gradients as well, since the early forming minerals, olivine, and pyroxene are of a higher iron and magnesium content than the latter minerals and thus more dense. A study of thin sections revealed some pyroxene and olivine at the contact,

but much of this appeared to have altered to hornblende. This in no way alters the above argument since the composition and specific gravity of the hornblende is such that it can account for the observed results.

Crystal Settling

Crystal settling would produce a gradient in the sills, but this method of differentiation must be discarded for the obvious reason that the gradient would be restricted to the bottom of the sill.

Soret Effect

The Soret Effect of thermal diffusion could quite possibly account for the gradient evident from the graphs. Bowen, (1928) has argued that the Soret Effect is of little consequence in igneous differentiation. He reasoned that adjustment of the composition to temperature differences by diffusion would, in the case of a magma, take a great deal of time.

Wahl, (1946) revived the importance of the Soret Effect. His work summarizes the work done by chemists in the separation of isotopes. Wahl points out that in applying this method to magmatic differentiation, the effects depend on such factors as temperature gradient, size and shape of the body of magma, and the initial composition of the magma.

Wahl also stated that under certain conditions of temperature gradient, no diffusion will occur, or else the heavy components might migrate either to the warm or cold regions. Wahl argues that thermal diffusion may account for features in rocks that can't be explained by any other means.¹

1. For a more detailed discussion of the Soret Effect see Wahlstrom, (1952) p. 182

The author feels that the Soret Effect would be greatly hampered in producing the observed gradients, since the bodies involved are small, and should cool rapidly thus allowing little time for diffusion. While the Soret Effect remains a possibility there seems little reason to search for such an exotic explanation when assimilation and fractional crystallization offer such reasonable explanations.

Assimilation

Although fractional crystallization offers a very plausible explanation for part of the observed gradients, the author sees no way in which to explain the relationship existing between the calcium carbonate and the calcium silicate, by this method. A reasonable explanation of this relationship is that it is due to the inclusion and assimilation of a small amount of limestone.

Let us look first at the calcium carbonate gradient. As can be seen from the graphs the calcite is high at the contact, low in the interior, and high again at the lower contact. This gradient could be produced in the following manner: inclusion of marble, and failure of this marble to diffuse into the interior due to the viscosity of the magma.

Ground water deposition has been discarded for several reasons. The main reason is that the gradient should be in one direction, i.e., high at the upper contact and low at the lower contact, since the ground water should move under the influence of gravity. It is true that some of the calcite is due to ground water deposition, as some calcite is present as vein fillings, but the thin sections revealed that most of the calcite was due to other causes.

Another source for the calcite is that carbon dioxide was present originally in the magma, and that some calcite was formed by the release of calcium as a by-product of the alteration of some mineral. It is difficult to see how calcite produced in such a way would arrange itself in a gradient.

Assuming that the calcite gradient were produced by improper mixing and through assimilation of the marble let us see what effect the included calcite should have on the magma.

Bowen, (1928) has pointed out that when sedimentary minerals are included within a magma, the tendency is for the sedimentary minerals to be converted to igneous type minerals, which are in equilibrium with the melt at the temperature in question. Or else these sedimentary minerals are melted and later precipitated in the ordinary crystallization sequence of the reaction series. He has further shown that the addition of lime to a magma will among other things increase the anorthite content of the plagioclase.

Thus, it would seem that the observed gradients could have been produced in one of two ways. Fractional crystallization of the magma could produce the changes in the calcium-silicate gradient, and diffusion of the included fragments of marble could produce the calcite gradient, or the calcium-silicate curve could have been produced by assimilation of a moderate amount of included marble, and the calcite gradient again produced by diffusion of the included calcite. The first method seems doubtful for the following reasons:

1. To produce the calcium-silicate gradient by fractional

crystallization, it is necessary for the calcium ions in the interior of the magma to diffuse to the contacts. This process of diffusion, would probably require more time than was available since the magma was at a low temperature and would probably solidify quite rapidly. It would be much easier for the igneous minerals to obtain the necessary calcium by diffusion of calcium ions from the included calcite, since the distance the ions must migrate is very short, and not so dependent upon time.

2. It was seen that in the thin sections studied the composition of the plagioclase at the contact was found to be $An_{72}Ab_{28}$. Two inches below this the composition of the plagioclase was $An_{52}Ab_{48}$, and twelve inches below the contact the plagioclase contained albite and anorthite in equal proportions. One would expect a much more uniform composition gradient than was observed, if fractional crystallization were responsible.

It would seem much more likely that the high anorthite content of the plagioclase at the contact was due to assimilation of calcite. Further evidence in support of assimilation is the calcite cores within the hornblende and plagioclase.

Fractional crystallization undoubtedly plays an important role in the differentiation of the magma, mainly in the interior of the sills, but the evidence available at this time, seems to indicate that assimilation of calcite is responsible for much of the observed gradient, particularly at the contacts.

Calculation of the Amount of Limestone Assimilated

In view of the manner by which the author feels the calcium gradients

were established, the calculation of the amount of limestone assimilated can only be considered an approximation.

In the calculation it was assumed that in each suite of samples the sample showing the least amount of calcium represents most closely the composition of the original magma, which was homogeneous throughout.

The following formula gives the mass of calcium in a column 1cm^2 in cross section between two sample locations.¹

$$M_{\text{Ca}}^i = D_0 P_0 L_1 + (D_1 - D_0) P_0 + (P_1 - P_0) D_0 \frac{L_1}{2} + (D_1 - D_0)(P_1 - P_0) \frac{L_1}{3}$$

Where:

M_{Ca}^i = Mass of calcium between two adjacent samples.

P_0 = Percent calcium in first sample times 10^{-2} .

D_0 = Specific gravity of first sample.

P_1 = Percent calcium in second sample times 10^{-2} .

D_1 = Specific gravity of second sample.

L_1 = Measured distance between samples.

After the mass of calcium between each pair of samples in the suite has been calculated, the total mass of calcium in the column is obtained, by adding each of these individual masses together. Next, the mass of calcium contained in the column, if it were homogeneous throughout, and of a calcium concentration and specific gravity equal to the sample showing the lowest amount of calcium, is calculated. This mass of calcium is subtracted from the total mass of calcium and the remainder is the amount of calcium due to assimilation. This mass is converted from grams calcium to grams calcium carbonate and the grams calcium carbonate are

converted to volume calcium carbonate by dividing the mass of calcium carbonate by 2.72. This volume due to the assimilation of the calculated mass of calcium.

On the basis of these calculations it was found that from 0.3% to 2.5% of the total space had been gained by assimilation.

Discussion of Calculation

The higher values obtained from the calculations are subject to doubt, since these were made on small sills where ground water deposition probably accounts for quite a bit of the calcite. A good average value of the amount of space gained by assimilation is 1%. It should be remembered that this figure represents the volume occupied by assimilated calcite in a column of sill rock 1 cm.² in cross section and of a length equal to the thickness of the sill. It can only be assumed that this figure is representative of the volume of the sill.

Replacement

Probably some replacement of the limestone by magmatic solutions did occur. There is some evidence of this in several thin sections.¹ In these can be seen a sort of "front" consisting of an iron rich solution, that has moved into the marble and attacked it. This front is only an inch or so away from the contact and has altered or replaced only a very small amount of marble. If replacement has occurred it seems to have been a very minor means by which the magma could have gained space.

1. See appendix for a more detailed description of these thin sections.

SUMMARY

A study of the sills in connection with a particular laccolith was made in an effort to determine their means of emplacement.

From this study it was concluded that the bulk of the space needed by the magma was obtained by purely mechanical means. The magma obtained most of this space by simply shoving aside the limestone, resulting in bowed and faulted limestone beds. In the process of thrusting its way in, the magma compacted, fractured, and gouged out some of the limestone. The magma probably attacked the limestone chemically while in the process of emplacement, but the calcium, magnesium, and specific gravity gradients, were produced through fractional crystallization and an assimilative action of the magma upon fragments of limestone from the brecciated zone surrounding the magma. An attempt was made to calculate the amount of space attained by chemical assimilation, and an approximate figure of 1% of the total volume was arrived upon. Very little space seems to have resulted from replacement of the limestone.

More work must be done and several problems solved before more exact figures concerning the contribution of space from each of the various means can be calculated.¹

1. See appendix for suggestions on further work and unsolved problems.

ACKNOWLEDGEMENTS

The author would like to take this opportunity to express his thanks and appreciation to Dr. Charles C. Bradley, for his direction of the research work, and his help in writing this thesis. The author's thanks are conveyed to Dr. E. W. Anacker, for his assistance in solving some of the problems encountered, and for his help in writing this thesis. Thanks are extended to the Research Corporation, of New York City, for the financial aid which made this work possible. Others deserving thanks are Dean P. C. Gaines, Dr. E. E. Frahm, Dr. Ray Woodruff, and Mr. Graeme Baker, for their assistance in the development of the analytical procedures. Thanks are also conveyed to Mr. G. D. Robinson, of the U. S. Geological Survey for his many helpful suggestions; Mr. William Schmitt for his help in the preparation of the graphs, and to my wife, Mildred Hawkins for typing this thesis.

APPENDIX

Preparation of Standard Solutions

Aluminum: A 0.4000 gm sample of aluminum metal ribbon was weighed out and transferred to a 250 ml. beaker and dissolved in conc. HCl. This solution was transferred to a 1000 ml. volumetric flask and diluted to volume with distilled water. This gave a concentration of 400 ppm aluminum.

Calcium: A 0.4993 gm. sample of calcite was weighed out and transferred to a 300 ml. tall form beaker, where it was dissolved in dil. HCl and evaporated to dryness on the hot plate. The residue was taken up in distilled water and was transferred to a 1000 ml. volumetric flask, where it was diluted to volume with distilled water. This gave a concentration of 200 ppm calcium.

Iron: A 0.4000 gm. sample of standard iron wire was weighed out; transferred to a 250 ml. beaker and dissolved in conc. HCl. This solution was transferred to a 1000 ml. volumetric flask and diluted to volume with distilled water to give a concentration of 400 ppm iron.

Magnesium: A 0.2000 gm. sample of magnesium ribbon was weighed out and transferred to a 250 ml. beaker, and dissolved in dil. HCl. This solution was evaporated to dryness on the hot plate and the residue taken up in distilled water. This solution was transferred to a 1000 ml. volumetric flask and diluted to volume with distilled water. This gave a concentration of 200 ppm magnesium.

Sodium: A 1.0170 gm. sample of sodium chloride was weighed out and transferred to a 1000 ml. volumetric flask and diluted to volume with

distilled water. This gave a concentration of 400 ppm sodium.

Solutions for Standard Curves of Calcium and Magnesium

Limestone: Solutions ranging in concentration from 0-150 ppm calcium were prepared, by drawing different aliquots from the primary standard solution and transferring them to 100 ml. volumetric flasks. Then 25 ml. of the primary magnesium standard solution were added to each flask, and the flasks were diluted to volume with distilled water. The magnesium was added to the calcium standards since magnesium had a very slight depressing effect on the calcium flame emission.¹ Since magnesium was found in the limestone, the addition of the magnesium to the standards counteracted this depressing effect.

Solutions ranging in concentration from 0-150 ppm magnesium were prepared by drawing aliquots from the primary magnesium standard solution and transferring this to 100 ml. volumetric flasks. To each of these flasks 25 ml. of the calcium standard solution was added, and the flasks were diluted to volume with distilled water. The calcium was added to the magnesium standards to take into account the slight enhancing effect of the calcium on the magnesium flame emission.²

Standard Solutions For Sill Rock Analysis

The calcium and magnesium standard solutions for the analysis of the sill rock were prepared in the same manner as were those for the limestone analysis. The only difference was that to each of the standards, 10 ml.

1. See accompanying graphs showing the effect of calcium on the magnesium flame emission.
2. See accompanying graph showing this effect.

(46)

of the primary sodium standard solution was added. Thus, in the case of the calcium; standard solutions were prepared each containing 50 ppm magnesium, 40 ppm sodium, and from 0-150 ppm calcium. In the case of the magnesium; the standard solutions contained 50 ppm calcium, 40 ppm sodium, and magnesium ranging in concentration from 0-150 ppm.

Instrumentation

The instrument used to produce the standard curves and for the analysis of the limestone and andesite porphyry was a Beckman Model DU spectrophotometer. This instrument was equipped with the Model 9220 flame photometry attachment, utilizing the Model 4020 hydrogen atomizer. The fuel used as an excitation source was a mixture of hydrogen and oxygen. The pressure of the oxygen was 28 psi. on the tank, and 10 psi. on the instrument. The pressure of the hydrogen was 10 psi. on the tank, and 5 psi. at the instrument. The wavelength used for the calcium analysis was 554 m μ . This wavelength represents one of the principle lines in the calcium emission spectra, and was chosen because of the detection limits established for this instrument by Beckman Instruments Inc.¹

The slit width used in the calcium analysis was 0.01 mm. with the Beckman Model 4304 Photomultiplier attachment. The load resistor, Model 657, was set at position 2, giving a maximum resistance of 10,000 megohms.

To carry out the magnesium analysis, the settings were retained in their position of maximum sensitivity. All that was changed from the above described positions, were the slit width and the wavelength.

1. Harley, John H., & Wiberly, S. E., (1954)

(47)

The wavelength used was 371 m μ , chosen because of the limits of detection. The slit width was 0.06 mm, using the photomultiplier attachment.

Production of Standard Curves

Calcium Standard Curve: To produce this curve, the instrument set at the position of maximum sensitivity, with a wavelength of 554 m μ , and a slit width of 0.01 mm, using the photomultiplier attachment. The instrument was adjusted to give a transmittance¹ reading of 100.0, for a standard solution containing 150 ppm. calcium. Following the above adjustments, the transmittance readings for 10 solutions, containing 0, 4, 10, 20, 30, 40, 50, 60, 80, and 100 ppm respectively were obtained. These transmittance readings were plotted against concentration to produce the graphs, figures 9 and 10.

Magnesium Standard Curve: To produce these curves the instrument was set at the positions of maximum sensitivity, with a wavelength of 371 m μ , and a slit width of 0.06 mm, with the photomultiplier attachment. The instrument was then adjusted to give a transmittance reading of 100.0 for a solution containing 150 ppm magnesium. Next transmittance readings were obtained for 10 solutions containing, 0, 4, 10, 25, 30, 40, 60, 80, 100, and 125 ppm magnesium respectively. These transmittance readings were plotted against concentration to give the graphs, figures 11 and 12.

The graphs, figures 13 - 17 showing the effects of the various ions on the calcium and magnesium flame emissions were prepared by adding the

1. Percent transmittance is used in this paper as a convenient scale for recording the relative intensities of the calcium and magnesium flame emissions.

indicated increments of the various cations to a standard calcium or standard magnesium solution, and reading the percent transmittance. This was then plotted versus the concentration of the various ions to produce the graphs.

CHECK ANALYSES ON FLAME PROCEDURE

Sample	Volumetric Ca	Flame Ca	Gravimetric Mg	Flame Mg
IA1H8V	37.60%	39.50%		
IA2H22V	29.90%	31.20%		
IA1H14V	3.35%	4.01%	5.24%	5.50%
II08V	4.31%	4.45%	2.42%	2.96%
II0	16.30%	18.50%	4.45%	5.00%
IID1H17V	3.72%	4.00%	1.74%	2.00%
IID2H1V	38.72%	38.00%		
III1H6V	6.20%	6.50%	2.47%	2.90%
III1H4V	38.80%	40.00%		

Figure 9. CALCIUM STANDARD CURVE FOR LIMESTONE. Concentration Calcium In Parts Per Million Versus Percent Transmittance.

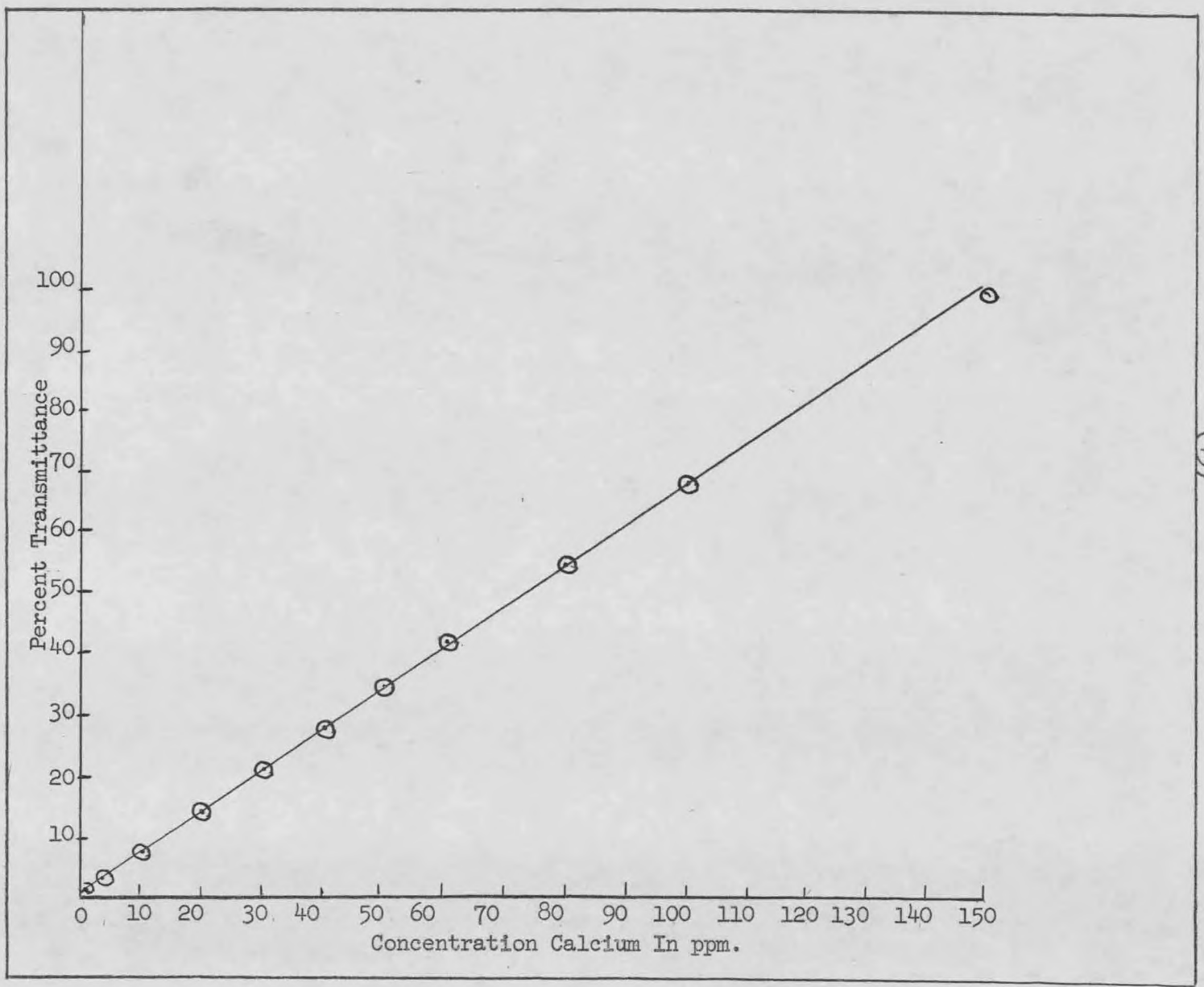


Figure 10 CALCIUM STANDARD CURVE FOR ANDESITE PORPHYRY. Concentration Calcium In Parts Per Million Versus Percent Transmittance.

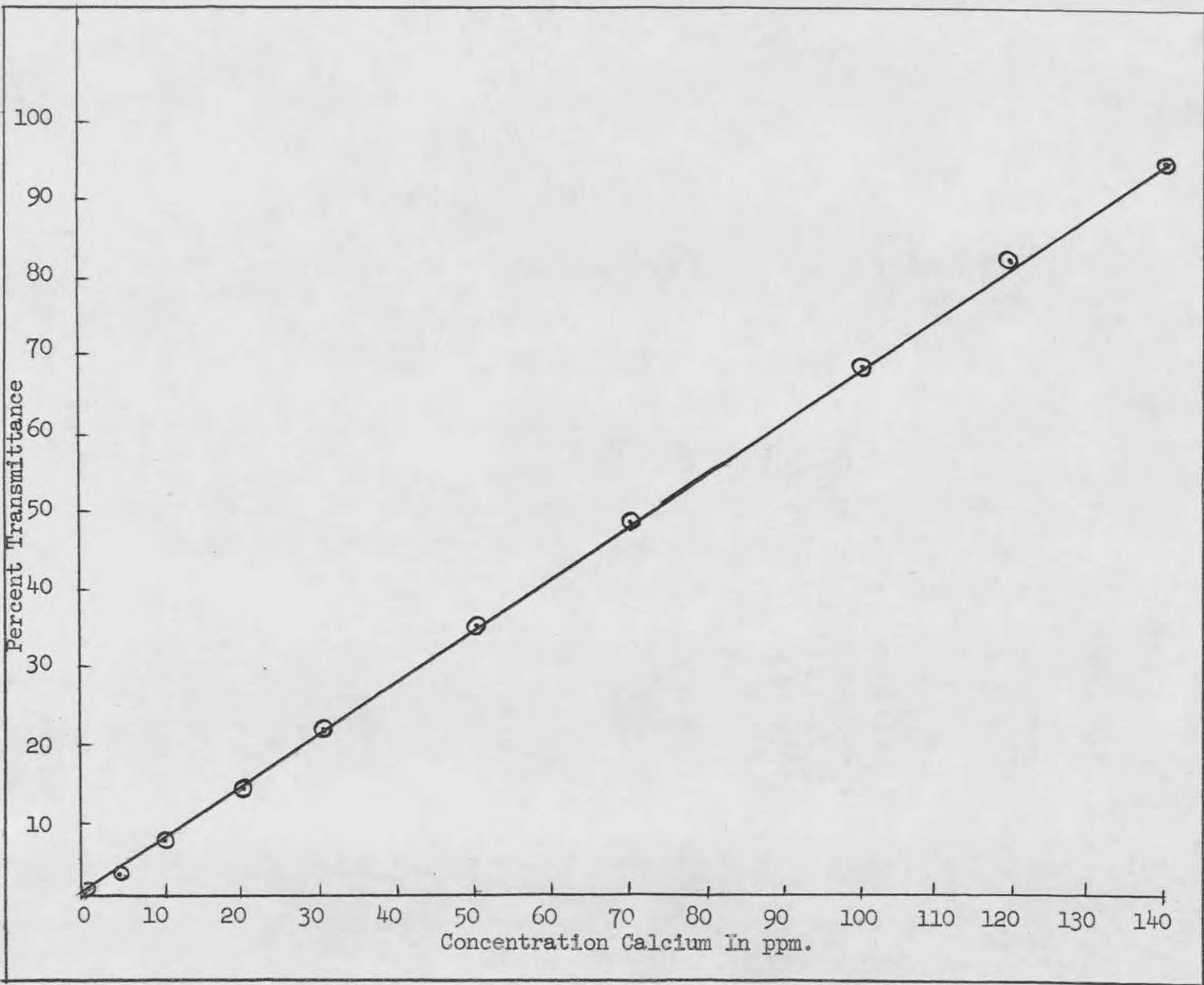
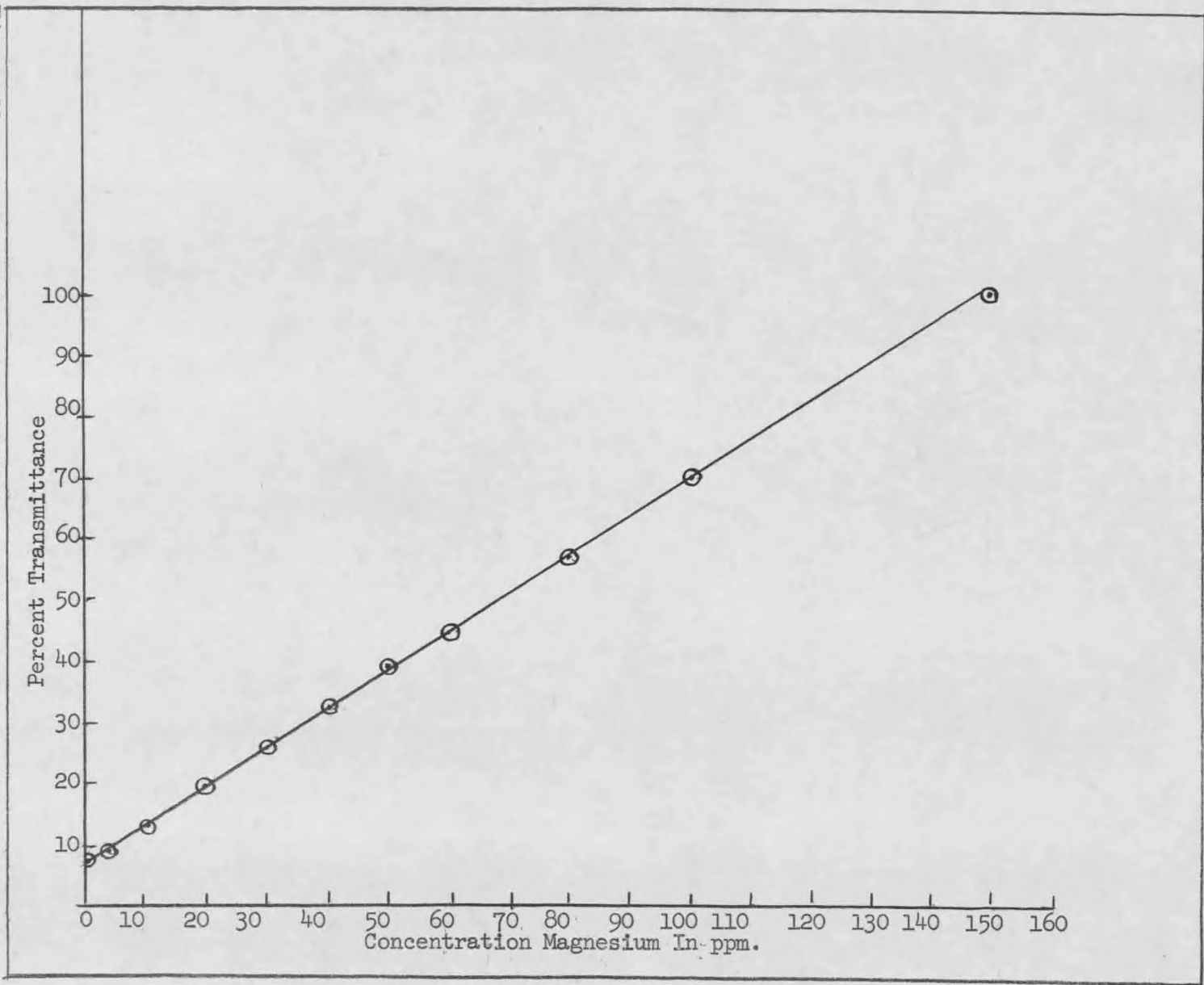


Figure 11. MAGNESTUM STANDARD CURVE FOR LIMESTONE. Concentration Magnesium In Parts Per Million Versus Percent Transmittance.



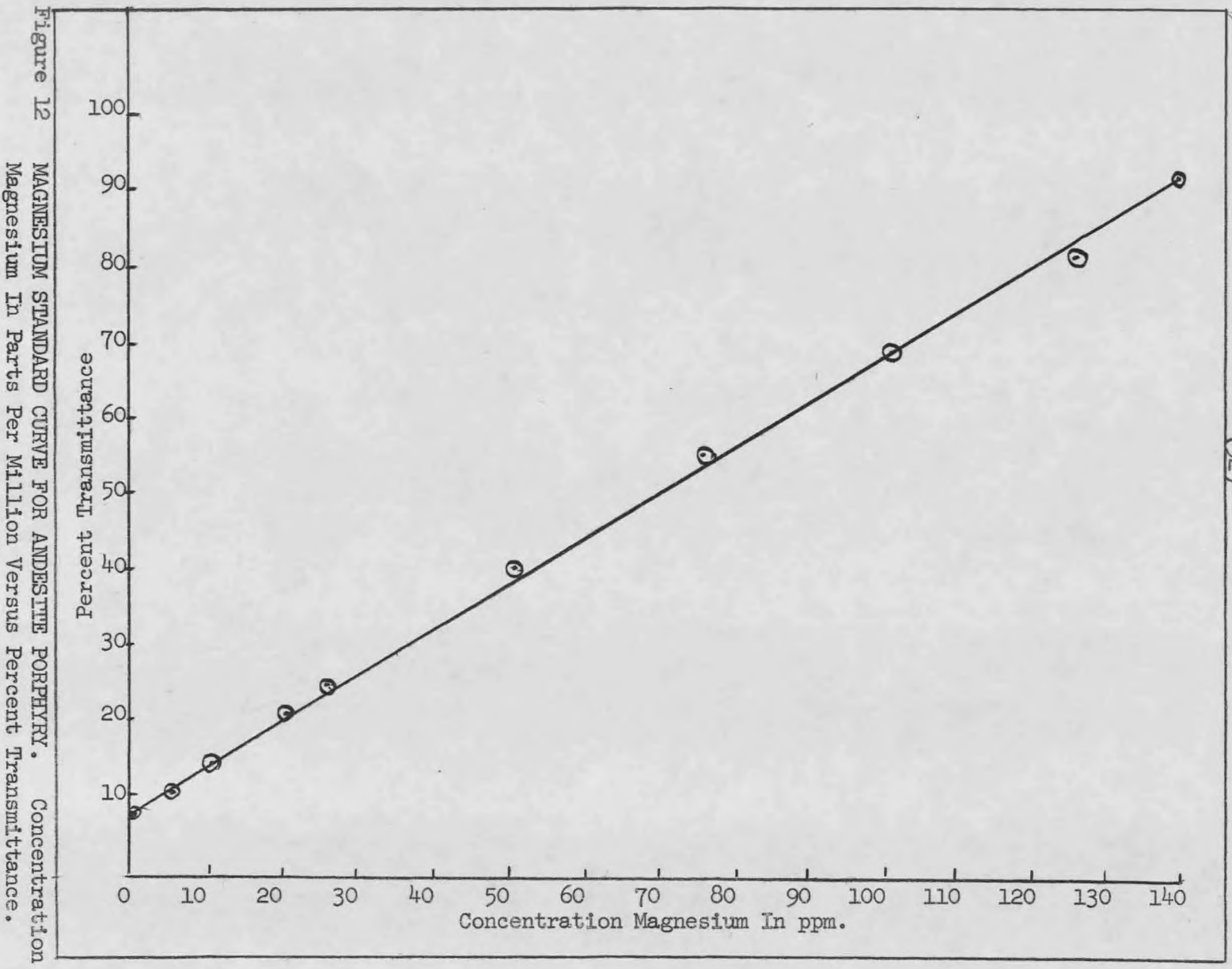


Figure 12 MAGNESIUM STANDARD CURVE FOR ANDESITTE PORPHYRY. Concentration Magnesium In Parts Per Million Versus Percent Transmittance.

Figure 13 EFFECT OF SODIUM ON CALCIUM FLAME EMISSION. Concentration Sodium In Parts Per Million Versus Percent Transmittance.

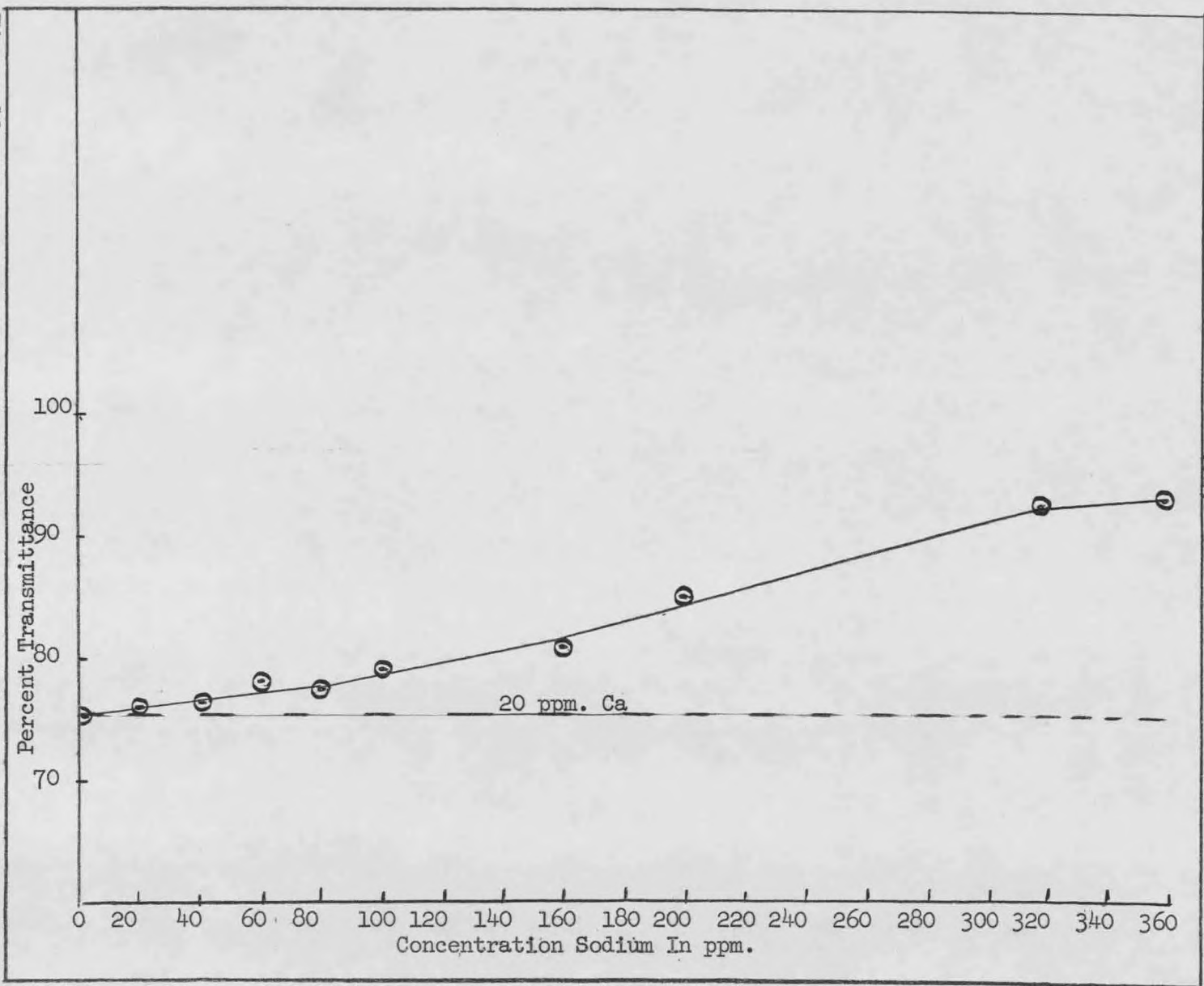


Figure 14. EFFECT OF CALCIUM ON MAGNESIUM FLAME EMISSION. Concentration Calcium In Parts Per Million Versus Percent Transmittance.

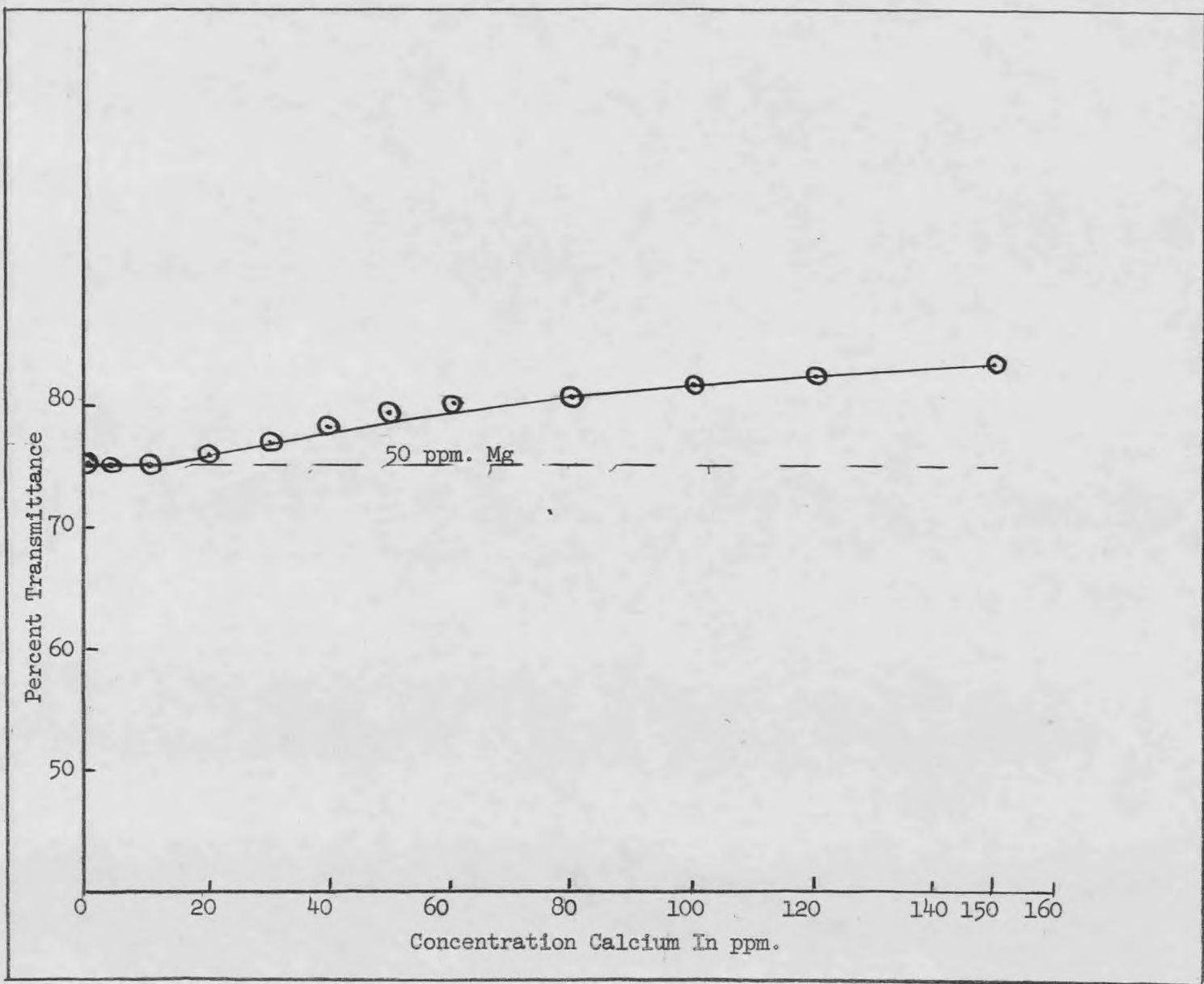


Figure 15 EFFECT OF IRON ON CALCIUM FLAME EMISSION. Concentration Iron In Parts Per Million Versus Percent Transmittance.

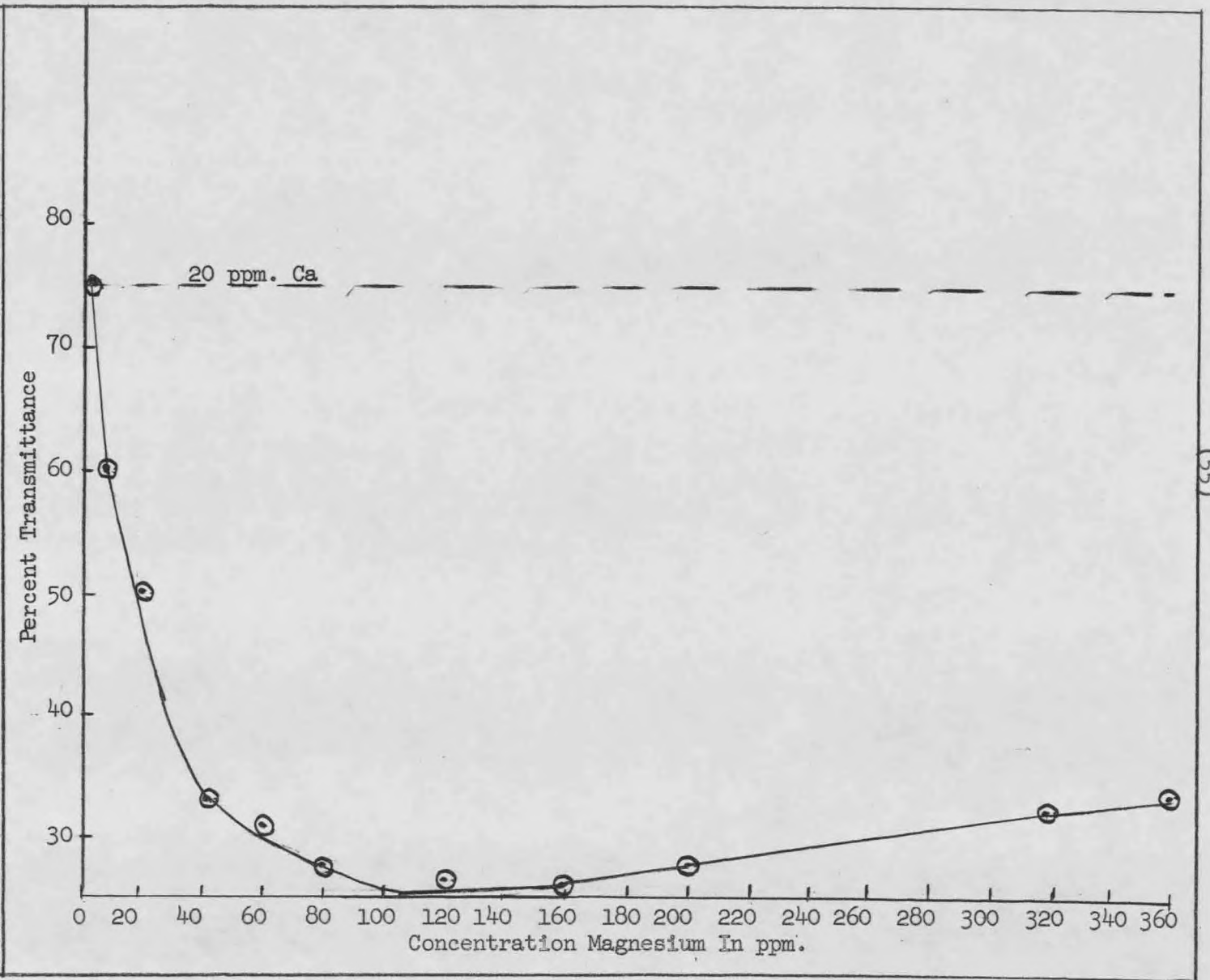


Figure 16. EFFECT OF MAGNESIUM ON CALCIUM FLAME EMISSION. Concentration Magnesium In Parts Per Million Versus Percent Transmittance.

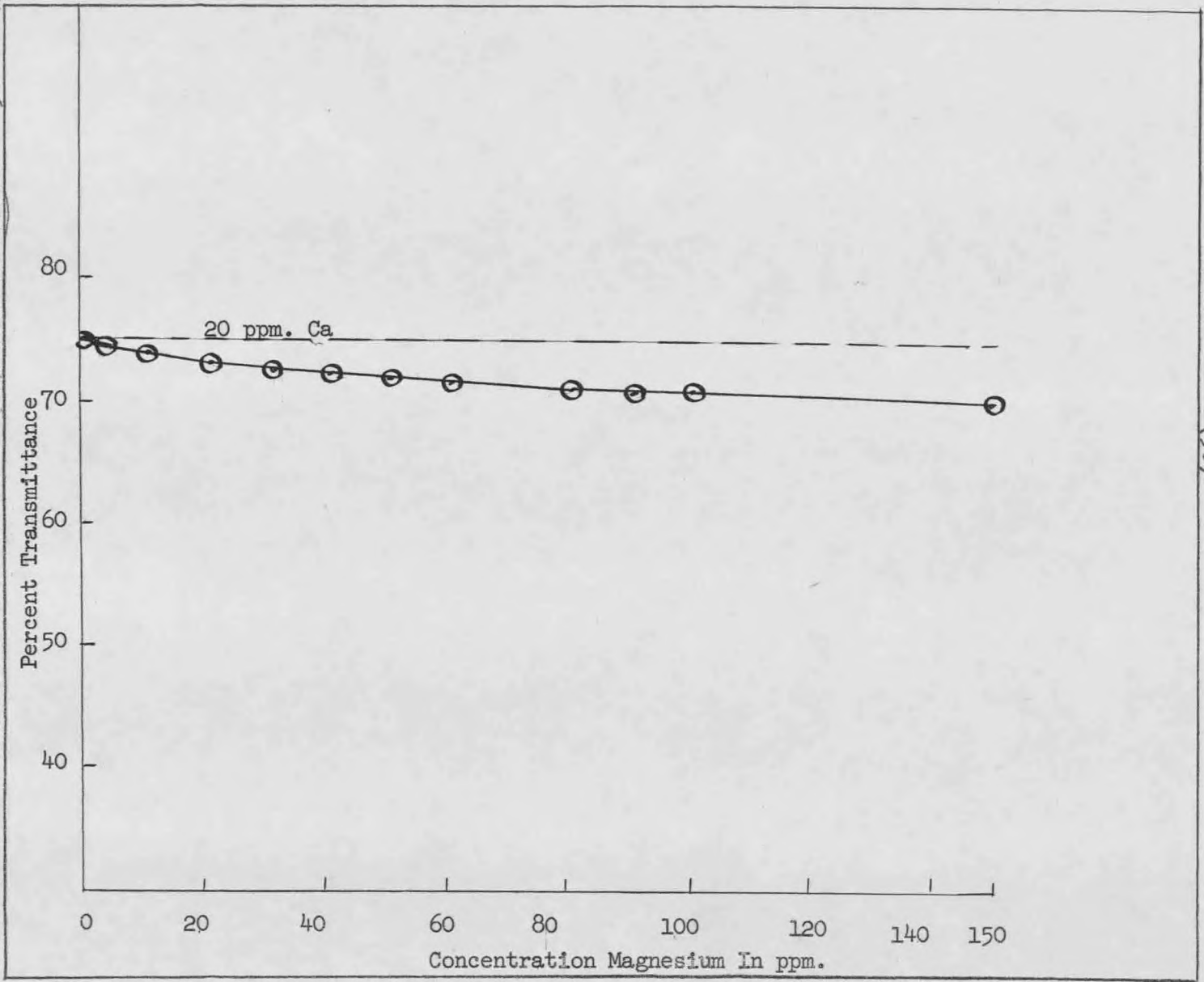
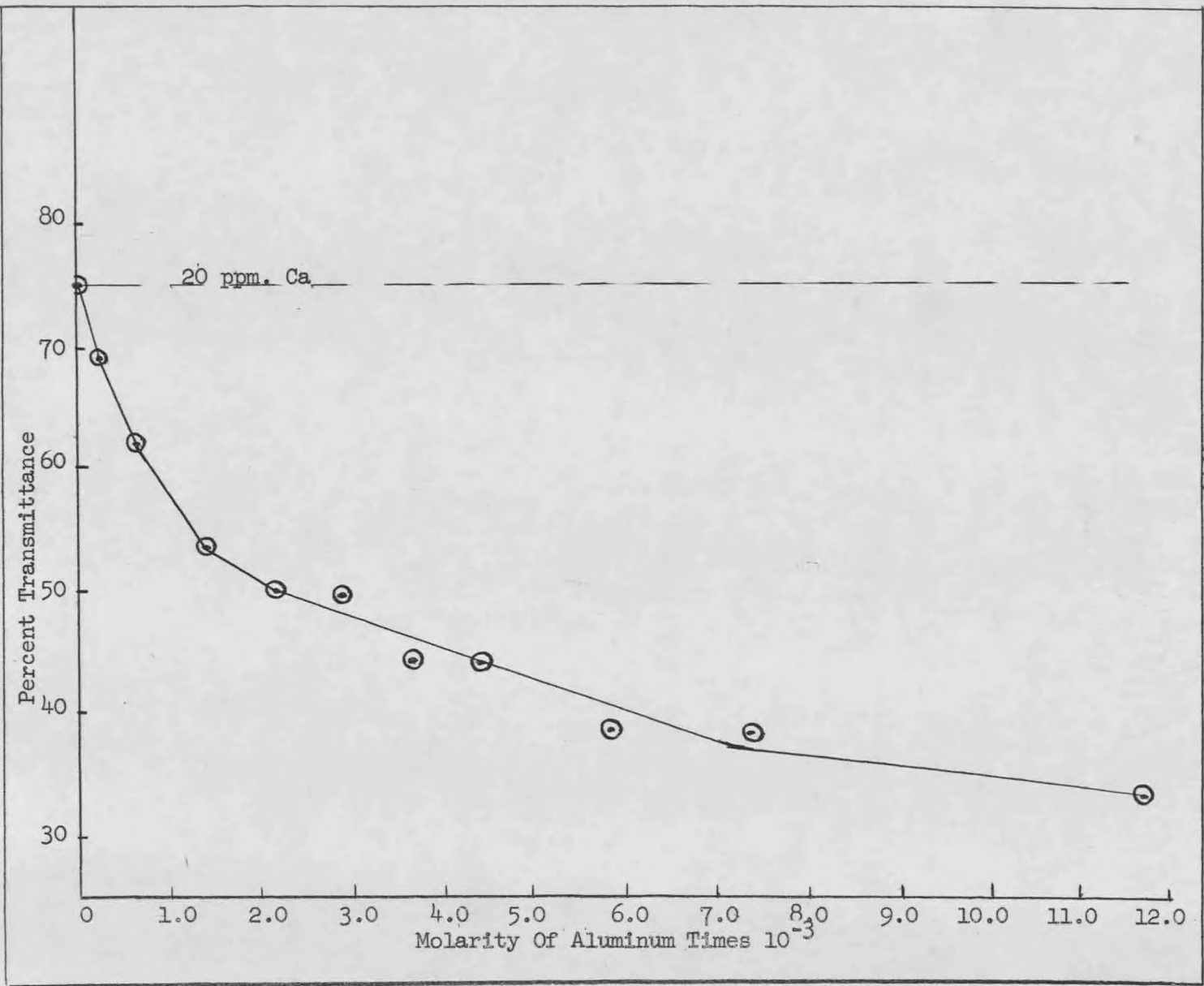


Figure 17 EFFECT OF ALUMINUM ON CALCIUM FLAME EMISSION. Moles of Aluminum Times 10^{-3}



DESCRIPTION OF SAMPLES

Outcrop I, Section A, 1 horizontal:

Sample:

1A1H1V---Thin bedded dark limestone, 3 feet above contact. Sp.G. 2.81,

%Ca, 40.46, %Mg, 2.0

" 2V---Limestone, 2 1/2' above contact. Sp.G. 2.70, %Ca, 38.16

%Mg, 2.0

" 3V---L.S. 18" above contact. Sp.G. 2.72, %Ca, 38.00, %Mg, 2.0

" 4V---L.S. 4" above contact. Sp.G. 2.74, %Ca, 38.10, %Mg, 1.50

" 5V---L.S. 3" above contact. Sp.G., 2.73, %Ca, 37.10, %Mg, 1.50

" 6V---L.S. 2" above contact. Sp.G., 2.70, %Ca, 38.50, %Mg, 1.50

" 7V---L.S. contact, part of terminated bed. Sp.G., 2.72, %Ca, 36.75

%Mg, 1.50

" 8V---Sill-L.S. contact. Sp.G. 2.77, %Ca, 39.50, %Mg, 2.00, %CO₂, 54.94

" 9V---Sill contact and 2" below. Sp.G. 2.65, %Ca, 3.18, %Mg, 4.11,

%CO₂, 3.32

" 10V---Sill, crumbly. Sp.G., 2.64, %Ca, 2.41, %Mg, 3.45, %CO₂, 2.41

" 11V---Sill, crumbly, 24" below top contact, and 8" above contact with

included block of limestone. Sp.G., 2.78, %Ca, 1.81, %Mg, 2.97,

%CO₂, 2.55

" 12V---Sill-L.S. contact. Sp.G. 2.65, %Ca, 3.14, %Mg, 3.50, %CO₂, 3.72

" 13V---L.S. 2" below contact, part of this bed is terminated by sill.

Sp.G., 2.72, %Ca, 39.50, %Mg, 1.5

" 14V---Sill contact, with terminated point. Sp.G., 2.76, %Ca, 4.01,

%Mg, 5.50, %CO₂, 3.70

IA1H15V---L.S., 2" above contact with lower fork of sill. Sp.G., 2.73,

%Ca, 38.50, %Mg, 1.50

" 16V---L.S. contact, lower fork of sill. Sp.G., 2.74, %Ca, 38.00,

%Mg, 1.50

" 17V---Sill contact. Sp.G., 2.75, %Ca, 4.31, %Mg, 4.87, %CO₂, 3.70

" 18V---Sill, 4" below contact. Sp.G., 2.74, %Ca, 3.72, %Mg, 4.50,

%CO₂, 3.53

" 19V---Sill, 6" below contact, and 8" above lower contact. Sp.G.,

2.57, %Ca, 2.58, %Mg, 4.55, %CO₂, 2.00

" 20V---Sill contact, from end of terminated bed. Sp.G., 2.92, %Ca, 5.21,

%Mg, 5.45, %CO₂, 2.11

" 21V---L.S. contact. Sp.G., 2.71, %Ca, 37.50, %Mg, 2.00

" 22V---L.S. 4" below contact. Sp.G., 2.74, %Ca, 38.00, %Mg, 2.00

" 23V---L.S. 2" below contact. Sp.G., 2.68, %Ca, 40.45, %Mg, 2.00

" 24V---L.S. 4" below contact. Sp.G., 2.78, %Ca, 37.50, %Mg, 2.00

Outcrop I, Section A, 2 horizontal:

Sample:

IA2H1V---Thin bedded dark limestone, 4" above contact. Sp.G., 2.71,

%Ca, 40.50, %Mg, 2.00

" 2V---L.S. 3" above contact. Sp.G., 2.71, %Ca, 41.50, %Mg, 2.00

" 3V---L.S. 2.1/2" above contact. Sp.G., 2.68, %Ca, 41.00, %Mg, 2.00

" 4V---L.S. 2" above contact. Sp.G., 2.56, %Ca, 40.75, %Mg, 2.00

" 5V---L.S. 4" above contact, part of this bed is terminated by sill,

4" to the right of here. Sp.G., 2.71, %Ca, 40.50, %Mg, 2.00

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IA2H6V---L.S. contact. Sp.G., 2.89, %Ca, 40.00, %Mg, 2.00

" 7V---Sill contact, Sill follows quite closely the dip of the limestone, but terminates it at a shallow angle. Sp.G., 2.72, %Ca, 3.56, %Mg, 2.70, %CO₂, 5.03

" 8V---Sill, center of upper fork, badly weathered was unable to get a solid sample. %Ca, 7.50, %Mg, 2.00, %CO₂, 10.69

" 9V---Sill-L.S. contact, block inclusion, beds in this block dip at same angle as limestone cliff. Sp.G., 2.69, %Ca, 24.00, %Mg, 2.00, %CO₂, 28.54.

"10V---L.S. 2" below contact. Sp.G., 2.73, %Ca, 39.00, %Mg, 1.00

"11V---L.S., center of block. Sp.G., 2.68, %Ca, 39.50, %Mg, 1.00

"12V---L.S., 8" above lower contact. Sp.G., 2.80, %Ca, 37.50, %Mg, 1.00

"13V---L.S., 4" above lower contact. Sp.G., 2.74, %Ca, 37.60, %Mg, 1.00

"14V---L.S. contact. Sp.G., 2.74, %Ca, 39.00, %Mg, 1.00

"15V---Sill contact with included blocks. Sp.G., 2.97, %Ca, 5.50, %Mg, 4.45, %CO₂, 4.92

"16V---Sill, 12" below contact. Sp.G., 2.74, %Ca, 3.50, %Mg, 3.12, %CO₂, 4.03

"17V---Sill, 4" above bottom contact. Sp.G., 2.83, %Ca, 4.00, %Mg, 3.70, %CO₂, 4.51

"18V---Sill contact. Sp.G., 2.78, %Ca, 3.15, %Mg, 3.05, %CO₂, 3.96

"19V---L.S. contact, not disturbed as far as warping is concerned, but beds truncated in spots by sill. Sp.G., 2.73, %Ca, 40.00, %Mg, 1.00

"20V---L.S. 4" below contact. Sp.G., 2.78, %Ca, 40.25, %Mg, 1.00

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IA2H2IV---L.S., 1' below contact, Sp.G., 2.72, %Ca, 39.75, %Mg, 1.00

"22V---L.S., 4' below contact. Sp.G., 2.74, %Ca, 31.20, %Mg, 1.00

Small eye, Outcrop II, Section A, 1 horizontal:

Note: There is no compensation of bedding for this eye, all the beds are abruptly terminated, also no interfingering sills. Metamorphic zone extends at least 8' above the eye. Beginning with this outcrop, only select samples of limestone were analyzed, since there was little variation in the amount of calcium and magnesium. The samples chosen for analysis were usually the first and last samples of limestone, and the two contact samples.

Samples:

IIA1H1V---L.S., has conglomeratic appearance, L.S. pebbles are loosely cemented with fine liney granules. Sample 2' above contact.

Sp.G., 2.71, %Ca, 38.80, %Mg, 1.00

" 2V---L.S., peculiar mottled appearance, slight sugary texture, 18" above contact. Sp.G., 2.73

" 3V---L.S., crumbly, 12" above contact. Sp.G., 2.68

" 4V---L.S. contact. Sp.G., 2.73, %Ca, 38.50, %Mg, 1.00

" 5V---Sill contact, this sample has a brownish appearance. Sp.G., 2.67, %Ca, 11.00, %Mg, 2.55, %CO₂, 7.00

" 6V---Sill, 3" below contact. Sp.G., 2.82, %Ca, 3.35, %Mg, 1.78, %CO₂, 0.67

" 7V---Sill, 12" above contact. Sp.G., 2.81, %Ca, 3.68, %Mg, 1.45, %CO₂, 0.77

" 8V---Sill, 3" below contact. Sp.G., 2.84, %Ca, 3.72, %Mg, 2.05,

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%CO₂, 0.81

IIA1H9V---Sill, 4' below contact. Sp.G., 2.89, %Ca, 3.80, %Mg, 2.60,

%CO₂, 1.53

"10V---Sill, bottom center of eye, Sp.G., 2.80, %Ca, 3.70, %Mg, 2.62,

%CO₂, 1.18

Note: No lower contact material for the above eye was available since the contact was under debris.

Outcrop II, Section B, 1 horizontal:

IIB1H1V---L.S., thin bedded, with a sort of conglomeratic appearance.

This sample from 1' above the contact, and 3' to the left of the terminated beds. Sp.G., 2.68

" 2V---L.S., 2" above contact. Sp.G., 2.75

" 3V---L.S. contact, has some limey sill material in contact with it.

This limestone has pits in it filled with iron oxide. Sp.G., 2.76

" 4V---Sill contact, this sill appears to terminate some beds, but the tendency is to spread apart beds, and come in on the

bedding planes. Sp.G., 2.75, %Ca, 3.65, %Mg, 3.45, %CO₂, 3.00

" 5V---Sill, 6" below contact. Sp.G., 2.75, %Ca, 3.65, %Mg, 2.95,

%CO₂, 2.57

" 6V---Sill contact with terminated block. Sp.G., 2.78, %Ca, 3.98,

%Mg, 2.90, %CO₂, 2.57

" 7V---L.S. contact at point of block. Sp.G., 2.80

" 8V---L.S. contact at lower point of block. Sp.G., 2.78

" 9V---Sill contact with lower part of block. Sp.G., 2.80, %Ca, 3.75

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%Mg, 3.00, %CO₃, 2.57

"10V---Sill, 1' below contact, Sp.G., 2.79, %Ca, 3.75, %Mg, 3.00
%CO₃, 2.57

IIBIHLIV---Sill 2' below contact, no sample from lower contact because
under debris. Sp.G., 2.77, %Ca, 3.72, %Mg, 3.22, %CO₃, 2.57

Outcrop II, Section C, 1 horizontal:

Samples:

IIGIV---L.S., 3' above contact. This section is a small jog caused by
the removal of a large bed of limestone. Sp.G., 2.62, %Ca, 38.00,
%Mg, 1.00

"2V---L.S., 18" above contact. Sp.G., 2.72

"3V---L.S. 3" above contact. Sp.G., 2.70

"4V---L.S. contact, 6" to right of jog. Sp.G., 2.68, %Ca, 38.50,
%Mg, 1.00

"5V---Sill contact, Sp.G., 2.78, %Ca, 3.30, %Mg, 3.16, %CO₃, 2.24

"6V---Sill, 3" below contact. Sp.G., 2.69, %Ca, 3.40, %Mg, 2.45,
%CO₃, 2.15

"7V---Sill 12" below contact. Sp.G., 2.73, %Ca, 3.40, %Mg, 2.20,
%CO₃, 1.90

"8V---Sill contact on point of jog. Sp.G., 2.78, %Ca, 4.45, %Mg, 2.96,
%CO₃, 2.20

"9V---Sill 2' below contact. Sp.G., 2.75, %Ca, 3.15, %Mg, 1.93,
%CO₃, 2.21

IIC'---4' above upper contact, there is a small sill, only 6" at its
widest point, and only 3' in length. This sill penetrates the

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limestone to a depth of 2".

IIC'---Sill, Sp.G., 2.67, %Ca, 18.50, %Mg, 5.00, %CO₂, 22.27.

Outerop II, Section D, 1 horizontal:

IID1HIV---L.S., 4' above contact. Sp.G., 2.72

" 2V---L.S., 3' above contact. Sp.G., 2.64

" 3V---L.S., 30" above contact. Sp.G., 2.71

" 4V---L.S., 1' above contact. Sp.G., 2.65

" 5V---L.S., 6" above contact. Sp.G., 2.71

" 6V---L.S. contact. Sp.G., 2.66

" 7V---Sill contact. Sp.G., 2.68, %Ca, 4.10, %Mg, 2.00, %CO₂, 3.89

" 8V---Sill, 4" below contact. Sp.G., 2.77, %Ca, 4.00, %Mg, 2.00,

%CO₂, 3.21

" 9V---Sill, 12" below contact. Sp.G., 2.73, %Ca, 3.75, %Mg, 2.00,

%CO₂, 2.26

" 10V---Sill, 4" below contact. Sp.G., 2.84, %Ca, 3.50, %Mg, 2.00,

%CO₂, 1.38

" 11V---Sill, 8" below contact. Sp.G., 2.70, %Ca, 3.75, %Mg, 2.00,

%CO₂, 1.73

" 12V---Sill, 12" below contact. Sp.G., 2.72, %Ca, 4.00, %Mg, 2.00,

%CO₂, 1.79

" 13V---Sill, 16" below contact. Sp.G., 2.73, %Ca, 3.70, %Mg, 2.00,

%CO₂, 1.82

" 14V---Sill, 19" below contact. Sp.G., 2.73, %Ca, 3.46, %Mg, 2.00,

%CO₂, 2.46

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"15V---Sill, 26' below contact, 5 1/2' above lower contact. Sp.G.,
2.63, %Ca, 3.50, %Mg, 2.00, %CO₂, 3.00

"16V---Sill, 2' above lower contact. Sp.G., 2.78, %Ca, 3.32, %Mg,
2.00, %CO₂, 2.93

"17V---Sill, 2' above lower contact. Sp.G., 2.73, %Ca, 4.00, %Mg,
2.00, %CO₂, 2.85

"18V---Sill contact. Sp.G., 2.74, %Ca, 5.60, %Mg, 2.00, %CO₂, 6.28

"19V---L.S. contact. L.S. metamorphosed, metamorphic zone from
6" to 2' thick. Sp.G., 2.67, %Ca, 38.50, %Mg, 1.00

"20V---L.S., 4" below contact. Sp.G., 2.73

"21V---L.S., 4" below contact. Sp.G., 2.73, %Ca, 38.00, %Mg, 1.00

Outcrop II, Section D, 2 horizontal:

"22V---L.S., 6" above contact. Sp.G., 2.68, %Ca, 38.00, %Mg, 1.00

"2V---L.S. contact. Sp.G., 2.72

"3V---Sill contact. Sp.G., 2.83, %Ca, 7.20, %Mg, 2.70, %CO₂, 5.64

"4V---Sill, 4" below contact. This contact is from 2" to 12" thick
and has a limey appearance. Sp.G., 2.76, %Ca, 4.60, %Mg, 1.80,
%CO₂, 2.69

"5V---Sill, 2' below contact. Sp.G., 2.75, %Ca, 3.20, %Mg, 1.40,
%CO₂, 1.94

"6V---Sill, 4' below contact. Sp.G., 2.77, %Ca, 3.20, %Mg, 1.40,
%CO₂, 2.05

"7V---Sill, 8' below contact. Sp.G., 2.74, %Ca, 3.20, %Mg, 1.30,
%CO₂, 2.57

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" 8V---Sill, 12" below contact, 6" above point of upturned block.

Sp.G., 2.74, %Ca, 3.80, %Mg, 1.40, %CO₂, 1.91

" 9V---Sill, 16" below contact, 2" above block. Sp.G., 2.70, %Ca,

4.00, %Mg, 1.80, %CO₂, 1.82

" 10V---Sill, 6" above point contact. Sp.G., 2.75, %Ca, 4.00, %Mg,

1.90, %CO₂, 1.59

" 11V---Sill contact. Sp.G., 2.83, %Ca, 4.50, %Mg, 2.25, %CO₂, 0.55

" 12V---L.S. contact. Sp.G., 2.65, %Ca, 37.00, %Mg, 1.00

" 13V---L.S., 6" below contact. Sp.G., 2.67, %Ca, 37.75, %Mg, 1.00.

No further samples of limestone could be obtained because of the position of the rope.

Note: The upper jog in the limestone is made by the termination of the beds by the sill. The sill appears to have come in on cracks in the limestone. The lower contact with the turned up block appears to have been at a lower temperature, than the upper contact, since this contact is not as strongly metamorphosed. Possibly this block was turned up after the magma had cooled slightly.

Outcrop III, Section A, 1 horizontal:

IIIAHIV---L.S., 8" above small oval eye. Sp.G., 2.71, %Ca, 36.50,

%Mg, 1.00

" 2V---L.S., 5" above eye. Sp.G., 2.71

" 3V---L.S., 2" above contact, on the left hand side. Sp.G., 2.71

Note: The area directly above the eye is shot through with many tiny sills. Some of these are only a fraction of an inch wide. These sills penetrate the limestone to a depth of 2" or 3". Some of these sills

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appear to follow the bedding, while others cut across it, and others follow solution channels.

III A1 H V --- L.S. Sill contact, of the above described material. Sp.G.,

2.81, %Ca, 34.80, %Mg, 1.00

" 5V --- Sill, described above. Sp.G., 2.86, %Ca, 15.80, %Mg, 3.10,

%CO₂, 10.68

" 6V --- Sill, 6" above contact, Sp.G., 2.82, %Ca, 6.50, %Mg, 2.90,

%CO₂, 3.12

" 7V --- L.S. contact, between upper small sill, and lower eye.

Sp.G., 2.69

" 8V --- Sill contact. This eye is 15' 6" long and 37" thick at its

widest point. This eye is roughly elliptical in shape.

The eye terminates some bedding, but most of the bedding tends

to bow around it. Sp.G., 2.88, %Ca, 3.50, %Mg, 1.40, %CO₂, 1.33

" 9V --- Sill, 3" below contact. Sp.G., 2.83, %Ca, 4.00, %Mg, 2.00,

%CO₂, 1.24

" 10V --- Sill, 2 1/2" above lower contact. Sp.G., 2.86, %Ca, 4.00,

%Mg, 1.80, %CO₂, 1.53

" 11V --- Sill, 2" above contact. Sp.G., 2.82, %Ca, 3.50, %Mg, 1.50,

%CO₂, 1.56

" 12V --- Sill contact. Sp.G., 2.90, %Ca, 6.60, %Mg, 3.20, %CO₂, 1.82

" 13V --- L.S. contact. Sp.G., 2.69, %Ca, 36.50, %Mg, 1.00

" 14V --- L.S. 8" below contact. Sp.G., 2.68

" 15V --- L.S., 2' below contact. Sp.G., 2.72, %Ca, 36.50, %Mg, 1.00

Note: The missing beds in this eye are roughly 2" wide by 15'6" long.

Outcrop III, Section A, 2 horizontal:

IIIA2HLV---L.S., 4 1/2" above jog in eye, 8" above tiny sill. Sp.G., 2.78,
%Ca, 35.00, %Mg, 1.00

" 2V---L.S., 3" above jog, from the center of the small sill area.
Sp.G., 2.76

" 3V---L.S., 18" above jog. Sp.G., 2.71

" 4V---L.S. contact on jog. This sample contains a small sill that
seems to grade into the limestone. Sp.G., 2.66, %Ca, 36.98,
%Mg, 1.00

" 5V---Sill contact at jog. Sp.G., 2.76, %Ca, 8.10, %Mg, 4.64,
%CO₃, 5.00

" 6V---Sill, left hand point of jog. Sp.G., 2.78, %Ca, 4.00, %Mg,
1.80, %CO₃, 1.56

" 7V---Sill contact with both sides of the jog. Sp.G., 2.75, %Ca,
4.86, %Mg, 2.30, %CO₃, 2.30

" 8V---L.S. contact with right hand part of jog. Sp.G., 2.74

" 9V---L.S. 18" below jog. Sp.G., 2.68, %Ca, 36.25, %Mg, 1.00

Outcrop III, Section B, 1 horizontal:

IIIBLHLV---L.S., 3" above contact on left hand side of eye. Sp.G., 2.73,
%Ca, 38.80, %Mg, 1.00

" 2V---L.S.-Sill contact, with tiny sill. This sill is from an area
similar to that described under IIIA1HLV. This sample is from
a spot 2" above eye. Sp.G., 2.70, %Ca, 26.50, %Mg, 2.75,
%CO₃, 31.46

IIIB1H3V---L.S., slightly metamorphosed, 8" above eye. Sp.G., 2.74

" 4V---L.S. contact. Evidence of some effect due to ground water;

MnO₂ dendrites present in limestone. Sp.G., 2.81

" 5V---L.S.-Sill contact. Sp.G., 2.79, %Ca, 36.50, %Mg, 1.00, %CO₂,

36.18

" 6V---Sill contact. Sp.G., 2.78, %Ca, 4.00, %Mg, 1.30, %CO₂, 1.96

" 7V---Sill, 4" below contact. Sp.G., 2.78, %Ca, 4.10, %Mg, 1.30,

%CO₂, 1.70

" 8V---Sill, 2" below contact, Sp.G., 2.81, %Ca, 3.40, %Mg, 1.10,

%CO₂, 2.14

" 9V---Sill contact. This sill appears to terminate the bedding

but only on the surface. Sp.G., 2.99, %Ca, 5.10, %Mg, 1.40,

%CO₂, 2.98

" 10V---L.S. 6" below contact. Sp.G., 2.76

Outcrop III, Section, 1 horizontal:

IIIC1H1V---Sill, 4" above jog in eye. Sp.G., 2.76, %Ca, 3.90, %Mg, 1.08,

%CO₂, 1.53

" 2V---Sill 8" above contact. Sp.G., 2.79, %Ca, 4.00, %Mg, 1.30,

%CO₂, 2.43

" 3V---Sill contact, Sp.G., 2.76, %Ca, 4.40, %Mg, 1.10, %CO₂, 1.62

" 4V---L.S. contact. Sp.G., 2.69, %Ca, 40.00, %Mg, 1.00

" 5V---L.S. 2" below contact. Sp.G., 2.70, %Ca, 37.75, %Mg, 1.00

IIIC1V---Sill contact. The sill at this point is covered by limestone.

Sp.G., 2.56, %Ca, 4.92, %Mg, 1.00, %CO₂, 2.66

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IIIC2V---Sill contact, 3' to the right of the last sample, in the center of a small sill. Sp.G., 2.77, %Ca, 5.60, %Mg, 0.60, %CO₂, 5.73

3V---L.S. contact. Sp.G., 2.67, %Ca, 38.00, %Mg, 1.00

IIIC2HIV---L.S. sample of gouge material. Sp.G., 2.68, %Ca, 37.75, %Mg, 1.00

A sill reference sample was also taken from a spot 800 yards above eye IIIIG. This was to be an example of uncontaminated sill rock, however, this sample had more calcite and more calcium than many of the supposedly contaminated samples. It was assumed that this sample of sill was also contaminated. Sp.G., 2.74, %Ca, 3.80, %Mg, 0.40, %CO₂, 1.38.

POSITION OF SAMPLE AREAS

In Plate I, can be seen all the major areas sampled. The large cliff to the left was designated as outcrop II. IID is the large eye visible on the face of the cliff, IIC is 20 feet to the right of this outcrop. IIB is directly around the corner of the cliff. IIA is 150' due east of IIB, almost in the gully between the two large cliffs. Outcrop I is the small cliff, in the lower center of the photograph. Outcrop III is the large cliff to the right of the photograph. IIIA is situated 150 feet to left of the large eye, and 100 feet below it. IIIB is 30 feet to the right of IIIA, and IIIC is 80 feet directly above IIIA and IIIB.

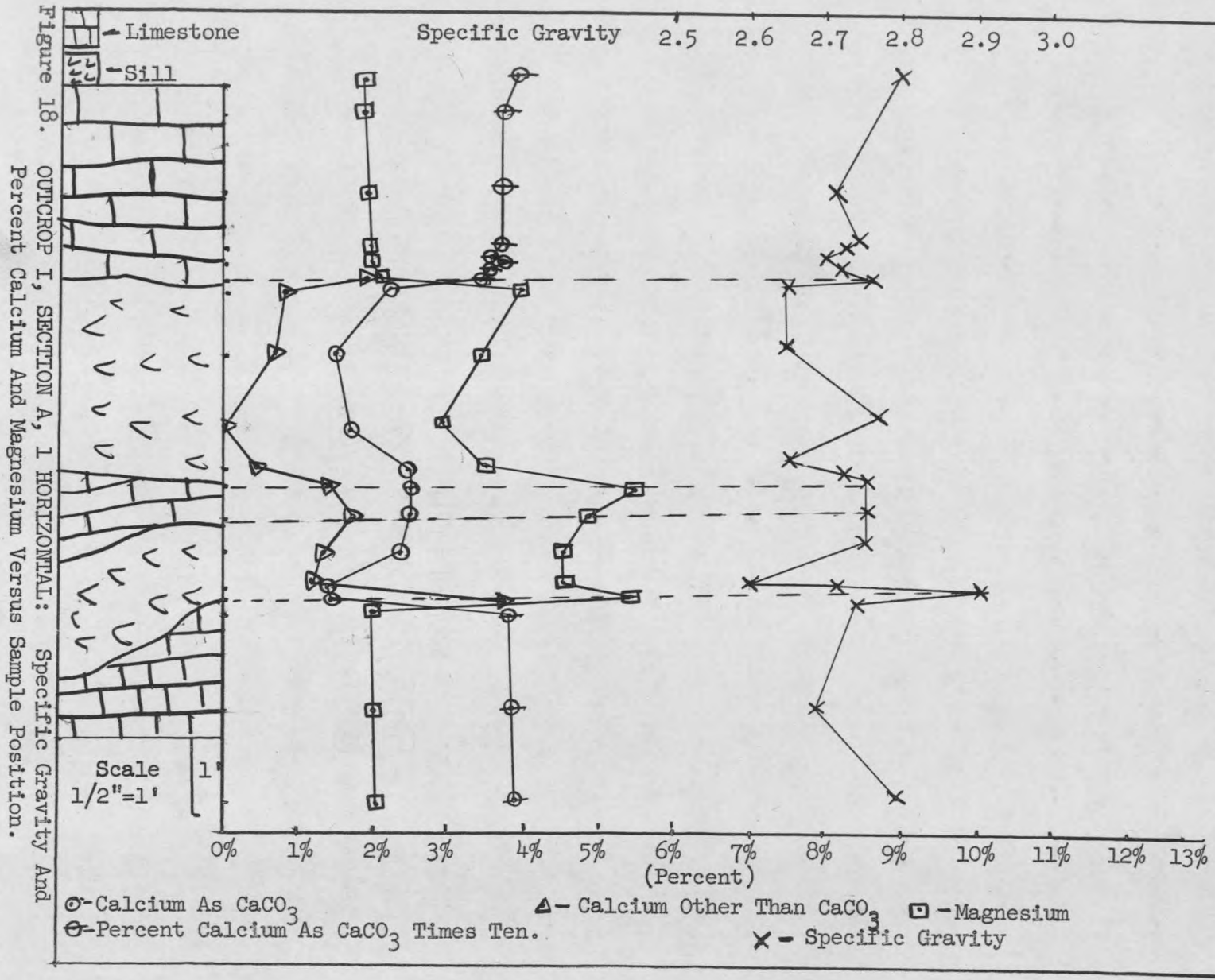


Figure 19
 OUTFCROP I, SECTION A, 2 HORIZONTALS:
 Percent Calcium And Magnesium Versus Sample Position. Specific Gravity And

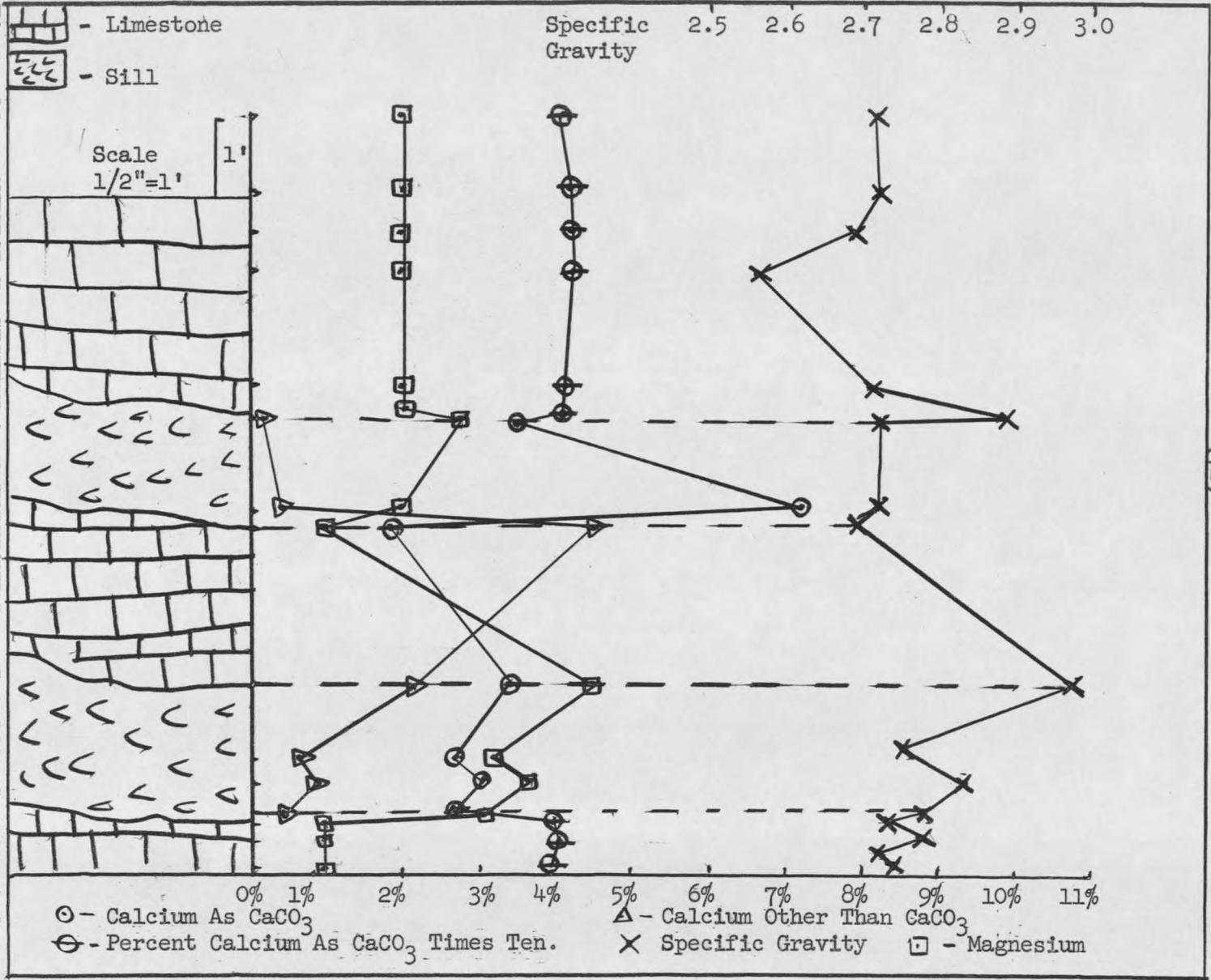


Figure 20. OUTCROP II, SECTION B, 1 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.

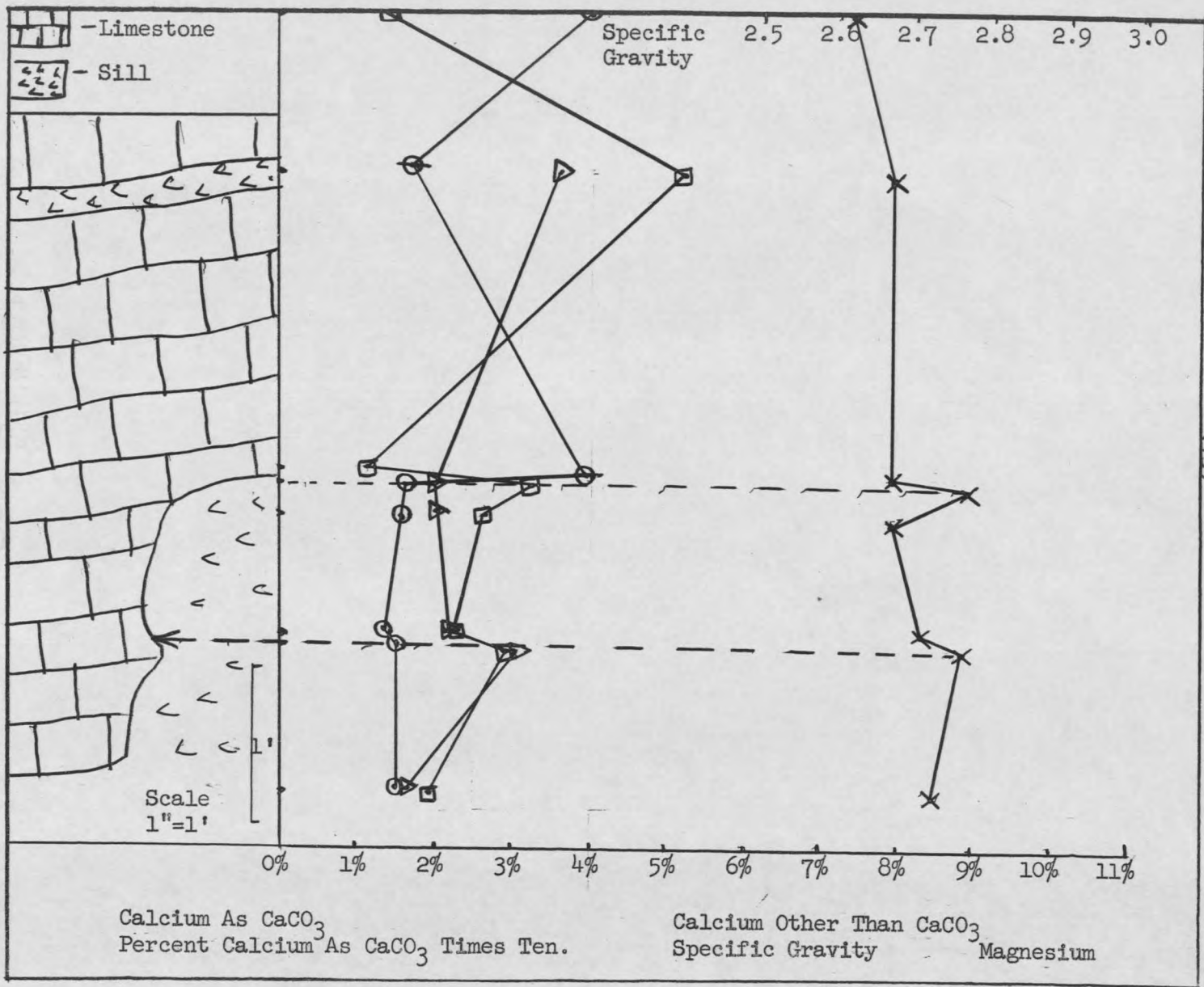
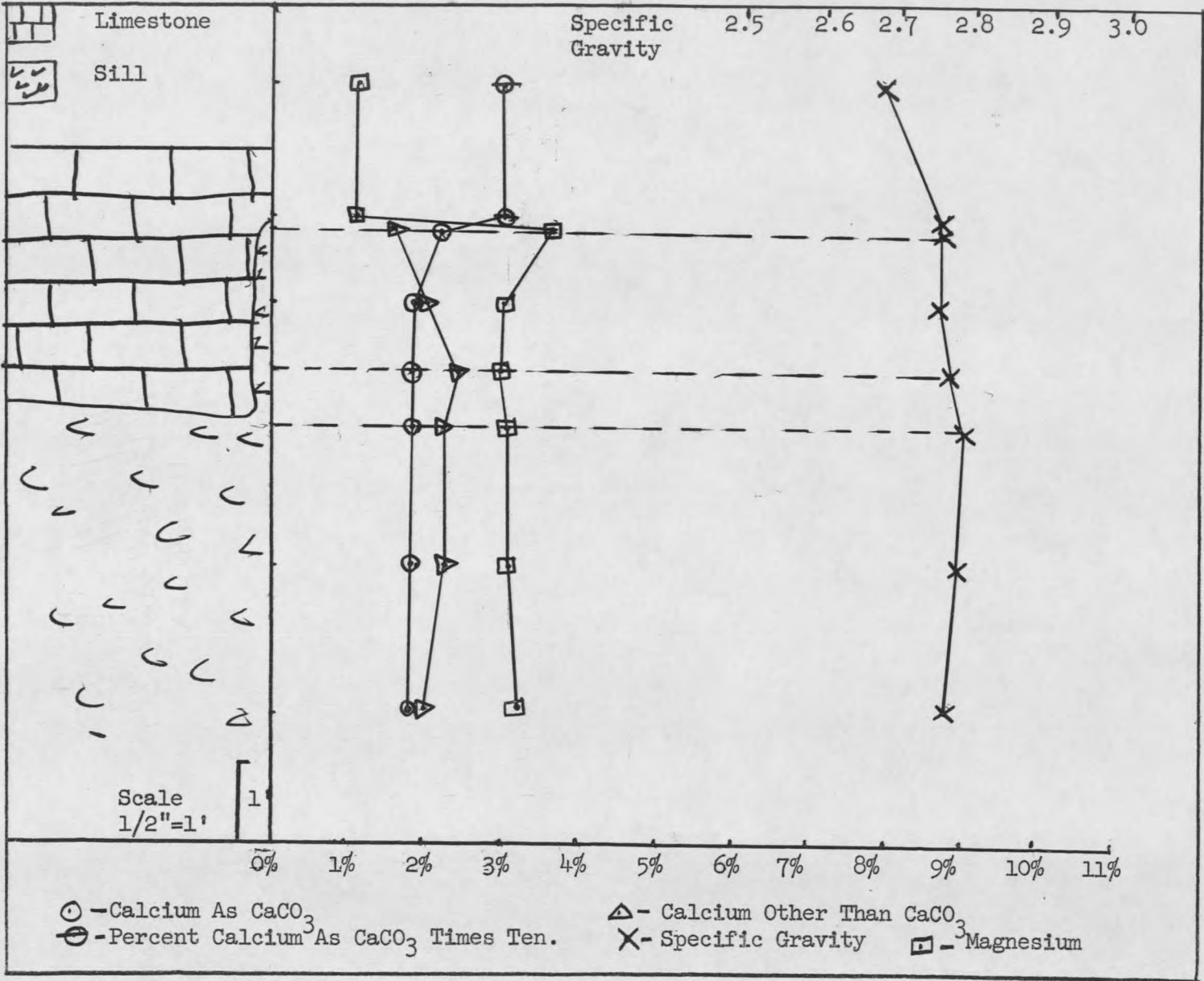
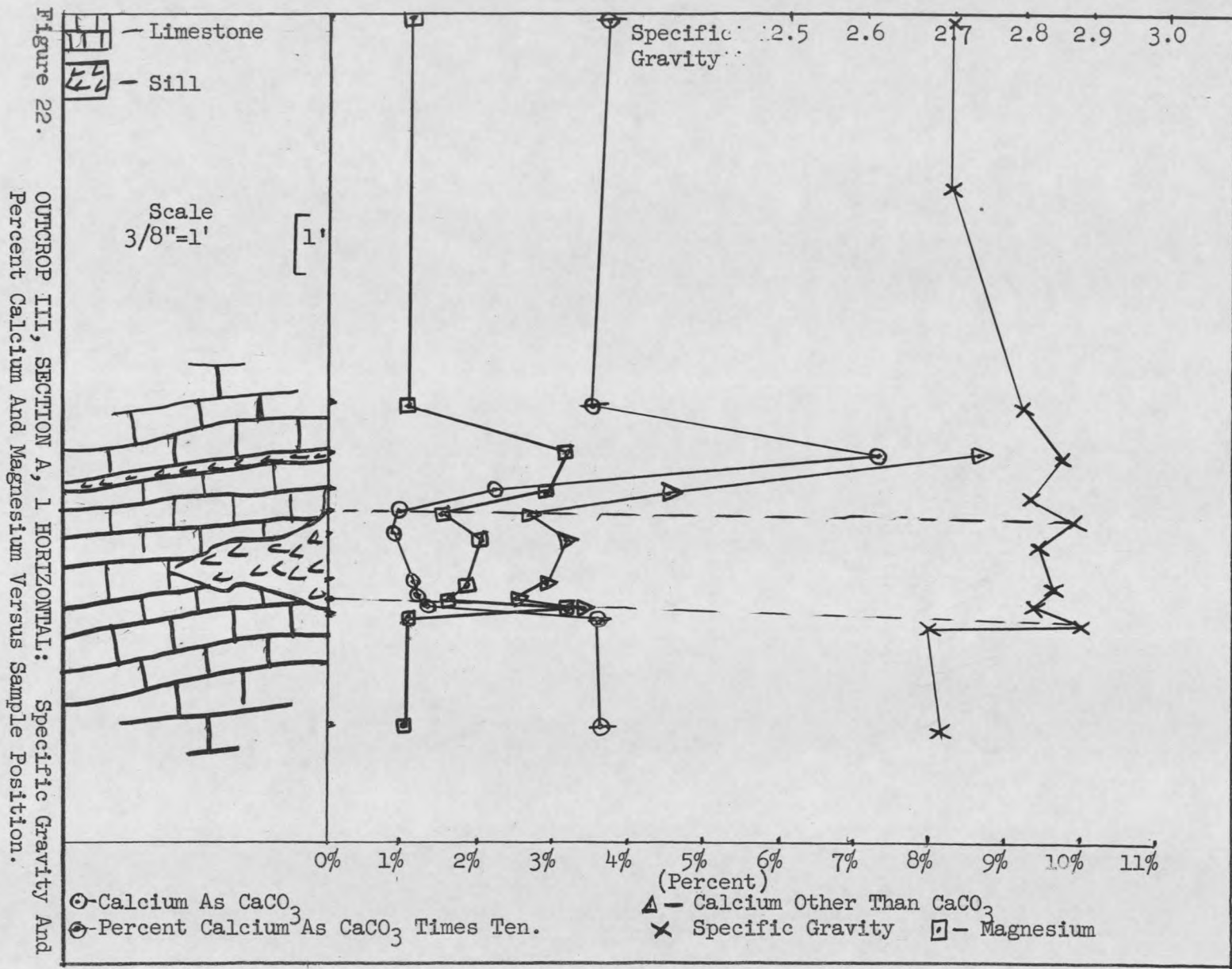


Figure 21
 OUTCROP II, SECTION C, 1 HORIZONTAL: Specific Gravity And
 Percent Calcium And Magnesium Versus Sample Position.



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Figure 23 OUTCROP III, SECTION A, 2 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.

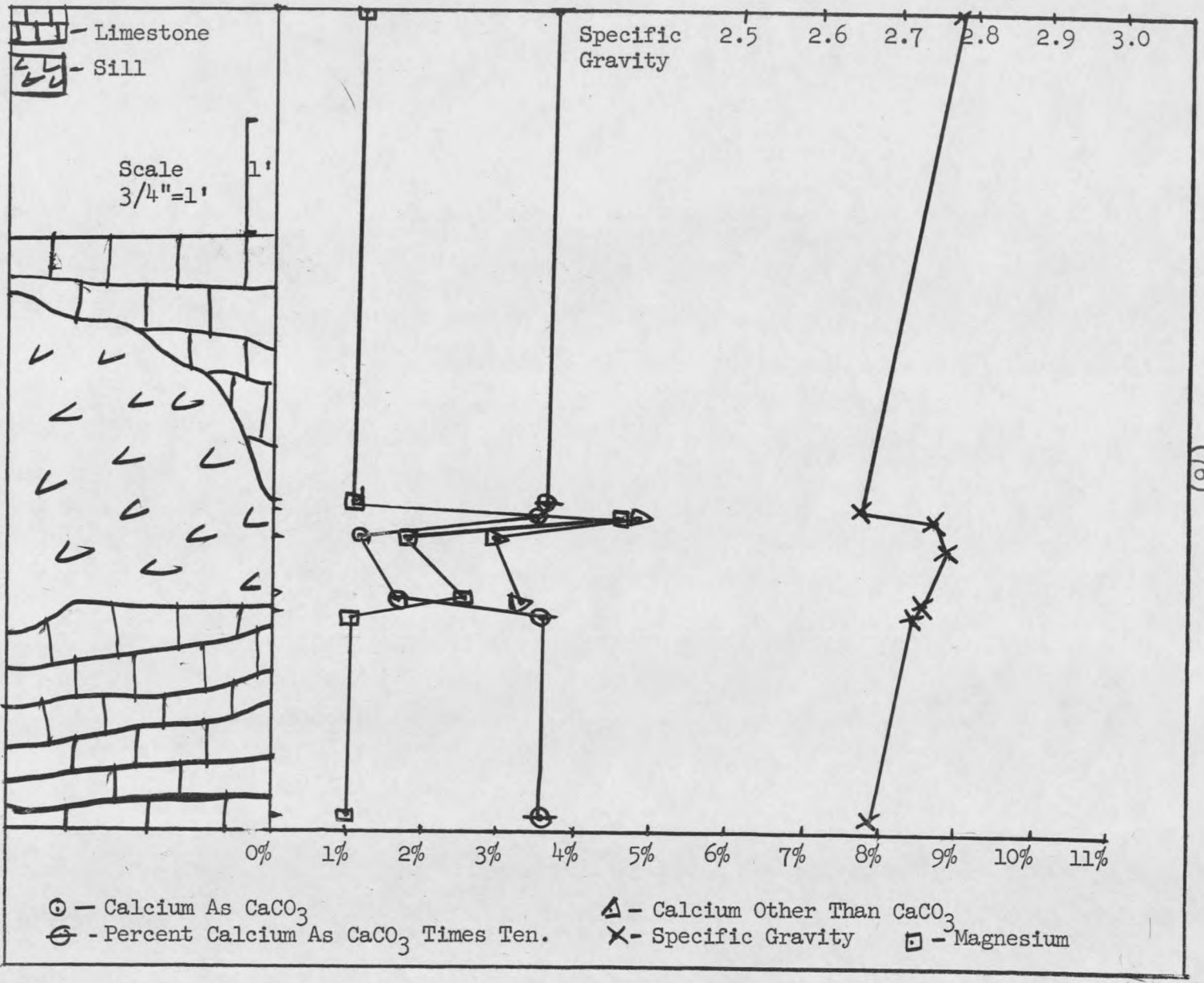
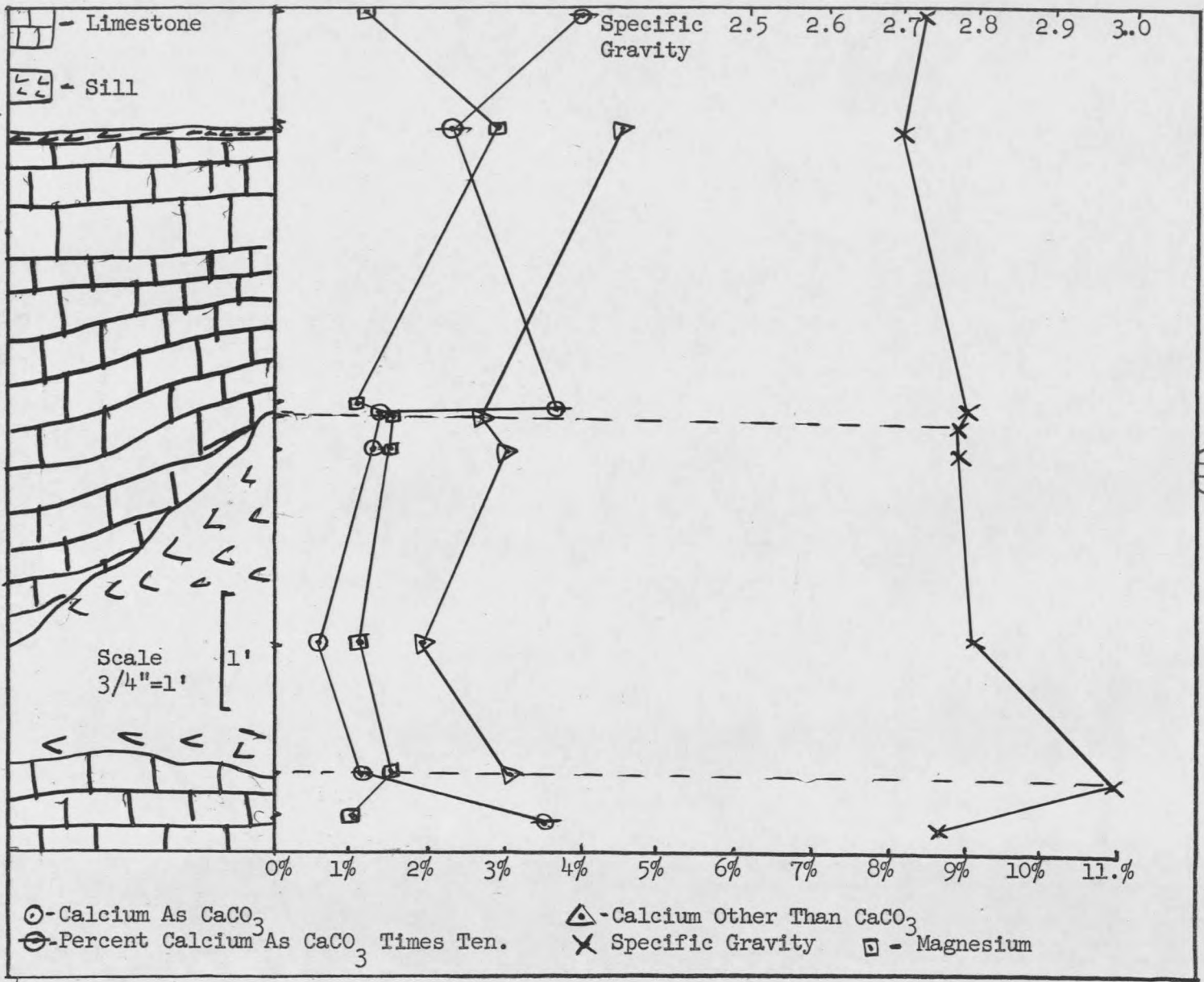
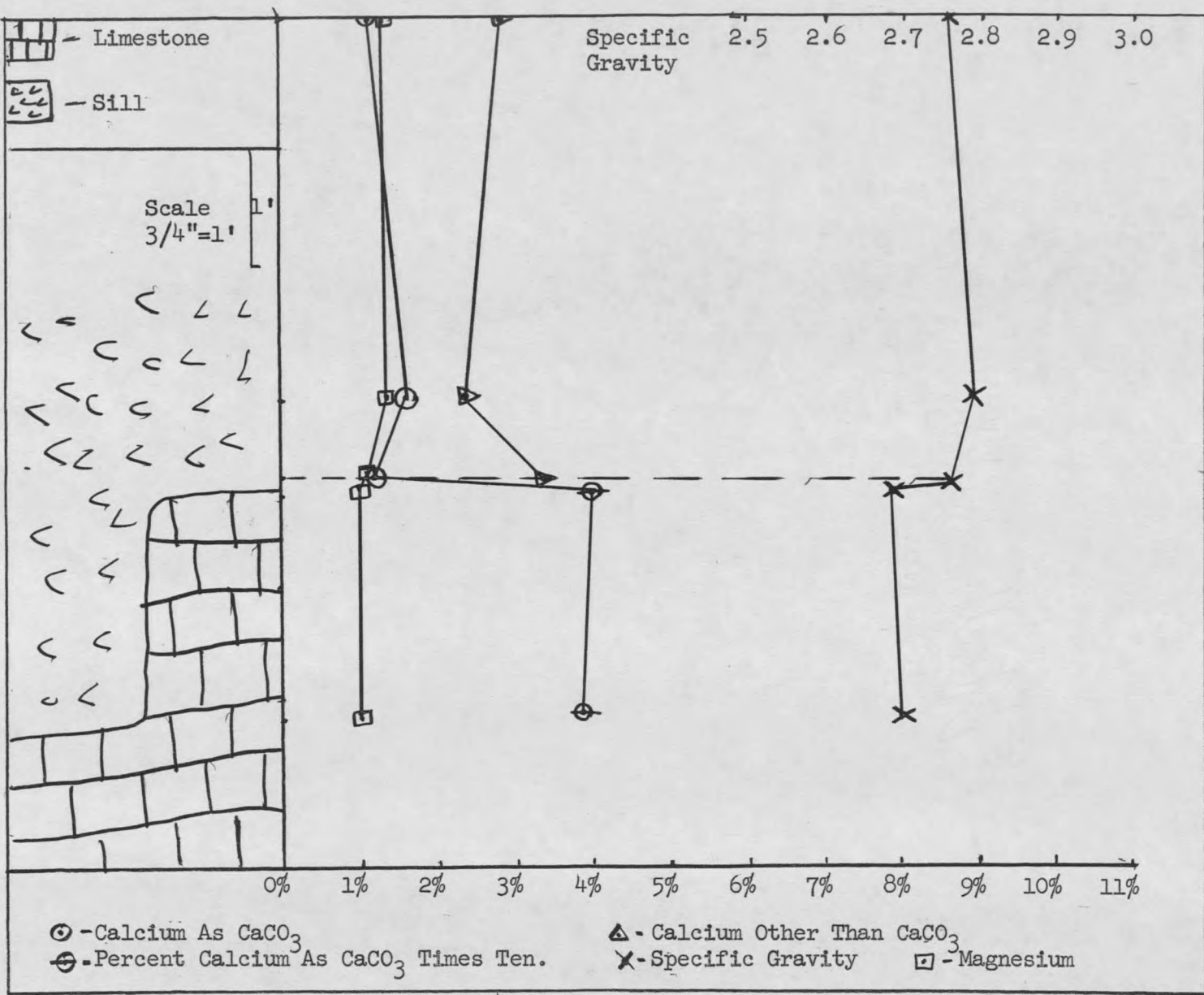


Figure 24 OUTCROP III, SECTION B, 1 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.



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Figure 25. OUTCROP III, SECTION C, 1 HORIZONTAL: Specific Gravity And Percent Calcium And Magnesium Versus Sample Position.



DISCUSSION OF GRAPHS

The preceding graphs, figures 18 to 25 were prepared in the same manner as were those in the body of the paper.¹ They express graphically the results of the chemical analyses and specific gravity measurements. In all cases the results are similar, that is, there is a pronounced high in the calcium, magnesium, and specific gravity curves at both contacts, with a tendency to remain fairly stable in the interior of the sills. In all cases there is some sort of relationship evident between the calcite, and the calcium silicate.

PETROGRAPHIC STUDY

Section II A 1H 4V.

Description: This slide is a calcitic marble, with numerous fissures and cracks. It shows evidence of some cataclastic adjustment, in that there are numerous large fragments of calcite surrounded by many finer grains of calcite.

Along most of the cracks iron has concentrated, in the form of magnetite. Associated with the iron is a brownish opaque substance that seems to be attacking the calcite. The magnetite is deposited between the grains of calcite, while the opaque material surrounds the grains of calcite.

The magnetite could have been formed by reduction of hematite during the deposition of the limestone, but, it is much more likely that the iron is the result of iron rich solutions emanating from the adjacent magma.

1. Figures 3, 4, 5.

Section IIA1H5V

Rock type: Andesite Porphyry.

Estimated % composition

Description: Main minerals:	plagioclase, An ₇₀ Ab ₃₀ -----	70%
	hornblende-----	20%
	calcite-----	7%
	accessory-----	3%

This section is heavily weathered, thus it is very difficult to obtain clear relationships.

Accessory minerals: sericite, hematite, thomsonite, penninite, pyrite, pyroxene, opal, magnetite.

Relationships: Plagioclase: Much of the plagioclase is fine grained, and much smaller than in other slides. The plagioclase is fairly free of inclusions, but in some cases calcite is included, and doesn't seem to be due to ground water. Associated with the plagioclase is much sericite and some magnetite. Hornblende: The hornblende has many inclusions, mainly apatite, calcite, and magnetite. The borders of the hornblende are much corroded by sericite, and in some cases, penninite. The hornblende phenocrysts are quite large, some are 7/16ths of an inch in length.

The magnetite occurs at random throughout the slide, and seems to be due mainly to the alteration of hornblende and pyroxene. Pyrite is closely associated with the magnetite, and around both is a halo of hematite.

The calcite present seems to be due to two causes, namely ground water deposition and inclusion of the surrounding marble by the magma.

The former seems to have supplied most of the calcite. The thomsonite and some of the penninite appear with the latter calcite and are also associated with some hornblende and plagioclase. The opal occurs along cracks and veins with the ground water deposited calcite.

History: When the magma was injected some of the calcite was torn away from the walls and became incorporated in the magma. This seems evident from the high anorthite content of the plagioclase and the inclusions of calcite in the hornblende and the plagioclase.

The early minerals formed were probably pyroxene and olivine with the hornblende occurring later. The pyroxene etc. were rather unstable and broke down to magnetite and hornblende. Most of the magnetite seems to be the result of the decomposition of the pyroxenes.

The sericite appeared in the deuteric stage of the magma and attacked the other magmatic minerals and some of the calcite.

The final stage seems to be the deposition of calcite and some opal by ground water.

Section: IIA1H6V

Rock Type: Andesite porphyry

Description: Main minerals:

plagioclase, An ₅₅ Ab ₄₅ -----	70%
hornblende-----	20%
pyrite-----	5%
accessory-----	5%

Accessory minerals: apatite, augite, calcite, penninite, sericite, titanite, magnetite, olivine, and very small amount of quartz.

Relationships: there are many hornblende phenocrysts throughout the

rock. The length of these phenocrysts is 1/4 of an inch. Included in the hornblende is apatite and in quite a number of cases, plagioclase and to a lesser extent, calcite. The boundaries of the hornblende phenocrysts are fairly sharp but all have been attacked by sericite.

The plagioclase forms most of the ground-mass. The plagioclase is noticeably lower in anorthite than was the border slide. Much sericite has attacked the plagioclase, mainly in the core. Some calcite and a sizeable amount of apatite are included in the plagioclase.

The calcite occurs as inclusions in both the hornblende and plagioclase and also as pods occupying the interstices between plagioclase grains. Little of this calcite seems to have been deposited by ground water. The augite is in fragments throughout the slide and is very much altered, mainly to hornblende and magnetite.

The olivine, titanite, and quartz are in very small amounts throughout the slide. The quartz seems to be present as an afterthought, since so little of it is present.

History: the first minerals to appear were olivine, pyroxene, titanite, and plagioclase. That the hornblende occurred later is shown by the inclusions of plagioclase in the hornblende and the association of hornblende with pyroxene relics.

The sericite seems to be one of the last minerals formed as it attacks both the hornblende and the plagioclase.

Section IIALH7V

Rock Type: andesite porphyry

Description: Main minerals: plagioclase, An₅₂, Ab₄₈-----70%

hornblende-----	20%
pyrite-----	5%
accessory-----	5%

Accessory minerals: magnetite, calcite, sericite, apatite, penninite, pyroxene, and olivine.

Relationships: The hornblende is fairly clean with boundaries not badly attacked by penninite. Included in the hornblende are plagioclase, calcite, apatite, pyrite, and magnetite. The plagioclase is for the most part rather fine grained with numerous inclusions. These inclusions are calcite, olivine, pyroxene, and apatite. Sericite attacks the plagioclase mainly at the core.

The calcite is present both as a vein filling and as isolated pods and inclusions. The first is very obviously a ground water deposition, while the latter seems more the result of an inclusive action by the magma.

The pyrite and magnetite are dispersed throughout the slide with the only noticeable concentrations occurring at pyroxene relics. Penninite also occurs at these relics.

History: the history of this slide is the same as that of the foregoing slide. The only difference is the presence of chlorite and calcite, the chlorite deposited during the deuteritic stage, and some of the calcite deposited by ground water.

Section IIC'

Rock Type: Skarn, or hornfels, and amphibolite facies.

Description: this section is of a tiny sill through the marble.

Included within this sill are grains of calcite much finer than those on the contact.

	Est.	Counted
Main minerals: calcite-----	45%	41.50%
clino-zoisite-----	40%	45.70%
magnetite-----	5%	1.98%
grossularite-----	5%	4.77%
accessory-----	5%	5.70%

Accessory minerals: pyrite, hematite, penninite, wollastonite, and pyroxene relics, penninite--2.91%, pyroxene--1.86%

Relationships: the only ferro magnesium mineral is the pyroxene. Outlining the pyroxene is penninite, while in the center and composing most of the bulk, is clino-zoisite. Also associated with these relics are calcite, wollastonite, and magnetite.

Calcite and clino-zoisite provide most of the volume of the vein. Where grossularite is present it is in the form of blobs of differing composition. The order of mineral appearance from the outside in is penninite, then penninite and grossularite, then grossularite, and finally at the core, calcite.

History: this small sill seems to be the result of the encroachment of silica and iron rich solutions upon the brecciated zone of the limestone. Due to the metamorphism of the marble the zoisite and wollastonite were formed. The pyroxene was probably present in the original intruding solutions but became unstable and was readily metamorphosed by the chlorite. It is difficult to determine the history and relationship

of the pyrite and magnetite to other minerals. All that is known for certain is that the hematite associated with these two minerals is later.

A statistical study of this thin section was made to check the estimated percentage composition and also to try and ascertain the amount of space contributed to the magma by brecciation. To do this the percentage composition of the thin section was determined through the use of zip-a-tone. Zip-a-tone is simply a transparent cellophane, parafine-backed having uniform dots printed upon the cellophane surface. To use zip-a-tone to estimate the percentage composition, it was first necessary to remove the parafine backing. Following this the zip-a-tone was fastened to the thin section with rubber bands and the section was then studied under the microscope. To estimate the percentage composition, it was only necessary to count the dots on the zip-a-tone over each mineral. Then, knowing the total number of dots, and the number of dots over a particular mineral, the percentage of this mineral in the thin section was easily calculated.

Using the percentage composition obtained in the above manner a theoretical specific gravity for a rock having this composition was calculated. The difference between this specific gravity and the measured specific gravity was attributed to space.

The volume that a rock having the calculated specific gravity and the volume of the rock having the measured specific gravity was calculated. The difference in volume gave the volume of space within the rock. The per cent of the volume occupied by space in this particular section was found to 13.4%.

No particular significance is attached to the magnitude of this figure. The reason is that more studies should be made on other small sills since it is felt that this one study might not be representative. The only significance attached to the foregoing calculation is that it seems to indicate that brecciation contributed space to the magma. That gross brecciation has been an important precursor of intrusion is seen in several of the outcrops.

Section: IIIA1HLV

Rock type: calcitic marble

Description: Main minerals: calcite-----98%
 opal-----1%
 magnetite, pyrite, &
 hematite-----1%

Description: this marble is fine grained and equa-granular with numerous fissures. Neighboring the fissures the marble is of a larger grain size. Throughout the marble is much opal, magnetite, and pyrite.

History: the finer grained marble might have been formed by brecciation, or by some method whereby more nuclei were supplied for crystallization.

The opal could have formed either from simultaneous deposition of the limestone or by ground water deposition. There is no evidence to distinguish which of these is the more probable.

The magnetite could have been formed by several processes, namely, reduction by decomposing organic matter of hematite originally deposited with the sediments, or reduction of this same hematite by the adjacent magma, or introduction of iron bearing solutions from the adjacent magma

which had a tendency to metamorphose the limestone and also to deposit iron. It is difficult to ascertain which one of these processes is correct.

Section: IIIA1H2V

Rock Type: calcitic marble

Description: Main Mineral: calcite-----99%

Accessory minerals: opal & hematite-----1%

The marble is shot through with several small fissures, having fine grained calcite along the edges. In most cases this calcite is much finer than that in the marble. One large fissure has large calcite grains, and on only one side, a band of hematite. Moving out into the marble is a sort of earthy appearing front. On the other side of the fissure, there are large grains of calcite, surrounded by many smaller grains.

History: The limestone was metamorphosed to a marble by neighboring magma. During the intrusion, the marble was subject to some cataclastic movement, as evidenced by the large grains of calcite surrounded by milonite. At the same time fissures were opened allowing the entrance of iron bearing solutions. This iron then moved into the marble in a sort of chemical front.

Section IIIA1H3V

Rock Type: calcitic marble

Description: Main mineral: calcite

Accessory minerals: hematite and opal.

This slide is much the same as the previous one. There are numerous

fissures in the marble, and some iron has moved into the marble giving it an earthy appearance. The general history is the same as that of section IIIA1H2V.

Section IIIA1H4V

Rock Type: Skarn or Hornfels

Description: This slide has a very tiny vein or sill within it.

The vein does not go completely through the slide but stops in the center.

Main minerals: calcite-----40%
 clino-zoisite-----35%
 hornblende-----20%
 accessory-----5%

Accessory minerals: magnetite, hematite, wollastonite, chlorite, and an earthy material.

Relationships: The hornblende phenocrysts appear to be growing in the vein, and excluding the other minerals. However there is some calcite in the hornblende, that looks as if it were being converted to hornblende.

The earthy material might be some unconsolidated iron and silica, that is in the process of being converted to a hornblende. Several places this earthy material seems to be growing in a hornblende like form, with a rim of clino-zoisite around this, and around the zoisite is a rim of calcite.

The bordering marble does not appear to have been shoved aside, but rather to have been incorporated within the encroaching solutions, and converted to zoisite, and wollastonite.

Further out into the marble there are numerous fissures, all of which have iron stains along them. Near the fissures are fan shaped areas, where the individual calcite grains are outlined by the earthy material. Within these fans the calcite is much finer grained than elsewhere.

History: The general sequence of events is as follows: First fissuring of the marble, then the entrance of solutions from the magms. These solutions converted the calcite to zoisite and wollastonite. Whether the earthy material represents the original material out of which the hornblende was formed, or whether it is due to the weathering, one would expect a concentration of hematite around the hornblende, and the magnetite, however no such concentration is evident, so it is assumed that this material is the source of the hornblende.

Section IIIA1H5V

Rock Type: calcite-grossularite-hornblende skarn.

Descriptions: Main minerals: calcite 40%
 grossularite 30%
 hornblende 15%
 plagioclase 10%
 accessory 5%

Accessory minerals: diopside, magnetite, hematite, chlorite, some of which is penninite, apatite, sericite, and a fine grained earthy material.

Relationships: Most of the rock is composed of calcite and grossularite. The grossularite is zoned and has sericite at the cores.

The hornblende seemed to be growing rather than weathering, as there

is a halo of fine grained earthy material around the hornblende, and at a uniform distance away. The boundaries of the hornblende are fairly sharp, and haven't been attacked by chlorite or sericite. The only inclusions in the hornblende are apatite, and a very small amount of calcite.

The diopside seems to be unstable and has broken down. Surrounding the diopside is a thick mass of grossularite, and some fine grained earthy material. Also associated with the diopside are magnetite, hematite, apatite, and chlorite.

The plagioclase is in the form of phenocrysts, and has sericite at the cores and at the rims. There is some calcite included in the plagioclase. The plagioclase is zoned, and in some cases shows oscillatory zoning.

History: Since this material is so close to the eye, there are many overlapping metamorphic facies present. These tend to confuse the issue and make it extremely difficult to reconstruct the history.

Probably quite early in the process diopside appeared, followed by plagioclase. It seems that the plagioclase is later, since none of it is included in the pyroxene relics.

The oscillatory zoning of the plagioclase might be due to fresh waves of magmatic solutions flowing past the feldspar, and causing it to crystallize in the same order as before. The hornblende was probably quite late in the scheme, since it appears to be growing with the exclusion of everything else.

The magnetite seems to be of a secondary origin, since it occurs only

in conjunction with the pyroxene relics.

The chlorite and sericite represent the last minerals.

Section IIIA1H6V

Rock type: andesite porphyry.

Description: Main minerals: plagioclase, An₃₅Ab₆₅-----70%

hornblende-----20%

magnetite-----5%

accessory-----5%

Accessory minerals: calcite, apatite, augite, chlorite, sericite, olivine. The identification of the olivine is only tentative, as the crystal was so small, that no figure was possible.

Relationships: The calcite is in pods and inclusions within the plagioclase, and doesn't seem to be due to ground water.

The pyroxene is in fragments, and seems to have broken down to hornblende, and magnetite.

The plagioclase contains numerous inclusions, notably calcite and apatite, and some magnetite. There is much sericite attacking the feldspar mainly at the borders, and in fissures in the mineral.

The hornblende is fairly large, some of the phenocrysts are 1/4" long. The inclusions in the hornblende are apatite and magnetite. Along the borders of the hornblende sericite and chlorite have attacked, giving a corroded appearance to the borders.

History: The appearance of the minerals in this rock seems to follow Bowen's reaction series. That is the olivine, and pyroxene appeared first, followed by hornblende, and the rather sodic plagioclase. The chlorite

and sericite are probably deuteric stage minerals.

Section: IIIAH7V

Rock Type: equi-granular calcitic marble.

Description: This section has a small sill running through it.

Main minerals: calcite-----60%
 clino-zoisite-----20%
 hornblende-----10%
 magnetite-----5%
 accessory-----5%

Accessory minerals: sericite, penninite, wollastonite, diopside, hematite, apatite.

Relationships: The calcite is finer grained within the vein, than on the borders. Along the borders the marble has been fragmented, and at one point the vein has been displaced, as though the vein were in a tiny fault. Much of the calcite within the vein has been altered to clino-zoisite, and to a much lesser extent to wollastonite. The wollastonite is mainly concentrated on one side of the vein and is directly on the contact.

Paralleling the vein and displaced a slight distance into the marble, is a concentration of magnetite. This magnetite is present as small "globs" or fragments.

Where magnetite appears in the vein it is associated with pyroxene relics.

The hornblende has inclusions of apatite, and in some cases, calcite. The hornblende seemed to be growing, and excluding the clino-zoisite,

and most of the calcite.

Outside the vein are tiny fissures filled with magnetite and sericite. Bordering these fissures the calcite is much finer grained than elsewhere.

History: The first minerals to appear were pyroxene and olivine. Following these came the hornblende, some of which was formed by the alteration of the pyroxene and olivine.

The magnetite bordering the vein seems to be due to a sort of chemical front. The calcite included in the vein seems to have been torn off the bordering walls, and was included in the vein material. Some of this calcite was converted to a clino-zoisite, and wollastonite.

The chlorite and sericite were the last minerals to appear.

Section: IIIA1H8V

Rock Type: Andesite porphyry.

Description: Main minerals: plagioclase, An₇₂Ab₂₈-----65%
 hornblende-----20%
 magnetite-----10%
 accessory-----5%

Accessory minerals: augite fragments, apatite, calcite, penninite, and hematite.

Relationships: The hornblende has many inclusions, mainly apatite and magnetite. The grain boundaries are sharp and show little sign of etching. In a few cases there is some plagioclase included in the hornblende, but the hornblende seems to have tried to expel it to the grain boundaries.

The plagioclase also has numerous inclusions, mainly calcite, and

apatite. Quite often the plagioclase has sericite at the cores.

The magnetite occurs at random in the rock, with the only noticeable concentrations at pyroxene relics.

History: This is a typical igneous rock, and the mineral sequence seems to be that of the Bowen series.

The high anorthite content of the plagioclase might simply be the result of early crystallization, but the calcitic inclusions seem to point toward assimilation as an explanation.

The presence of sericite at the cores of the plagioclase, simply indicated that the cores were more susceptible to corrosion.

The hematite surrounding the magnetite, seems to be the result of weathering.

Section: IIIA2HIV

Rock Type: calcite-grossularite-hornblende skarn.

Description: Main minerals:

calcite	45%
clino-zoisite	25%
hornblende	15%
grossularite	10%
accessory	5%

Accessory minerals: chlorite, thomsonite, penninite, diopside, magnetite, wollastonite.

Relationship: The hornblende seems to be jagged and broken, but since the fragments are all aligned, the hornblende must have been growing rather than being altered.

1. See, Bowen, N. L., (1928)

In contact with some of the hornblende is diopside, that seems to be in the process of being converted to hornblende. Surrounding the hornblende and diopside is a halo of earthy material. This halo keeps a uniform distance from the hornblende, but is intimately associated with the diopside. This halo in some cases seems to be composed of very fine grained clino-zoisite. The hornblende seems to have been growing to the exclusion of all the other minerals, as evidenced by the concentration of them along the borders, and the lack of many inclusions in the hornblende.

The most noticeable concentrations of grossularite appear among the fragments of hornblende.

The magnetite appears almost exclusively with the fragments of hornblende.

The clino-zoisite and calcite form the bulk of this tiny vein. The calcite is much finer grained within the vein, than that bordering the vein. The clino-zoisite appears at random throughout the vein, and seems to be the result of an alteration of the calcite.

The wollastonite appears in conjunction with the hornblende and grossularite, and seems to be due to the alteration of small amounts of calcite.

Thomsonite appears in a few isolated pods along one contact, and is associated with calcite, clino-zoisite, and grossularite.

Where penninite is present it is mainly in conjunction with the hornblende.

History: The sequence of events is as follows:

The marble was brecciated, and fissures were opened within it. Into these fissures magmatic solutions moved, and tore some of the calcite away from the walls. This calcite was converted to wollastonite, clino-zoisite, and grossularite. Probably the diopside formed at the same time as the above minerals. The diopside altered and produced some of the hornblende, and much of the magnetite. The final stage was the production of penninite, and thomsonite.

Section: IIIICLV

Rock Type: Andesite porphyry

Description: Main minerals: plagioclase, AN₈₀Ab₂₀-----70%
 hornblende-----20%
 magnetite-----5%
 accessory-----5%

Accessory minerals: sericite, chlorite, hematite, apatite, calcite, and a very small amount of clino-zoisite.

Relationships: The hornblende has inclusions of apatite, calcite, and plagioclase. The calcite seems to have reacted with the hornblende as there are many sharp fragments of the hornblende projecting into the calcite. The boundaries of the hornblende have been etched by the chlorite.

The inclusions within the plagioclase are, calcite, hornblende, and some magnetite. The calcite very often appears to be the core around which the feldspar has grown.

The magnetite occurs mainly around pyroxene relics, and is quite heavily weathered. The hematite forms a halo around the grains of magnetite.

The calcite not only appears as cores within the plagioclase but also in large irregular bodies that look like unassimilated limestone.

History: The history of the minerals in this rock seems to be quite straightforward, in that it follows the reaction series. Of particular interest is the high anorthite content of the plagioclase. This seems to be due to assimilation.

The chlorite and sericite were the last minerals to form from the magma. The hematite was formed by weathering.

Section: Sill reference

Rock Type: Quartz diorite

Description: Main minerals: plagioclase, An₅₂Ab₄₈-----70%

hornblende-----20%

magnetite & pyrite-----5%

quartz-----5%

Accessory minerals: chlorite, pyroxene, calcite, titanite, apatite.

Relationships: The plagioclase is zoned and contains calcite and in some cases hornblende as inclusions. The plagioclase has been attacked by sericite mainly at the core.

The calcite present seems to be due to an inclusive action by the magma, since there is no evidence that the calcite is due to ground water. The calcite seems to occupy the interstices between the grains of plagioclase.

The hornblende is corroded, but retains much of its shape.

The inclusions within the hornblende are plagioclase, magnetite, and apatite.

History: The general sequence seems to be that of the reaction series. The last minerals appearing were sericite, and chlorite.

While this last slide fails as a reference for the sill rock in general, it does tend to show what the appearance and composition of the sill would be if the sill rock were not a porphyry.

OUTCROP III, SECTION D

Plate IV is a photograph of outcrop III, sections C and D. Figure 26 is an overlay of this photograph showing the trace of the bedding planes around this eye. No chemical analysis could be made of this eye, since no samples could be obtained from it. The principle difficulty was the large overhang at the top of the cliff, which made it almost impossible to get into the eye. It might be possible to work ones way from outcrop III C, shown in the left hand side of the plate, by hanging onto the cliff, and more or less swinging oneself into the eye. The only difficulty with this is that if one slips one will fall away from the cliff a distance of some 80', thus, presenting a problem in getting back to the cliff, and from there, back to the ground. As this eye is 300' high, approximately 1000' of rope would be needed if one were to use the apparatus shown in figure 2, to sample this eye.

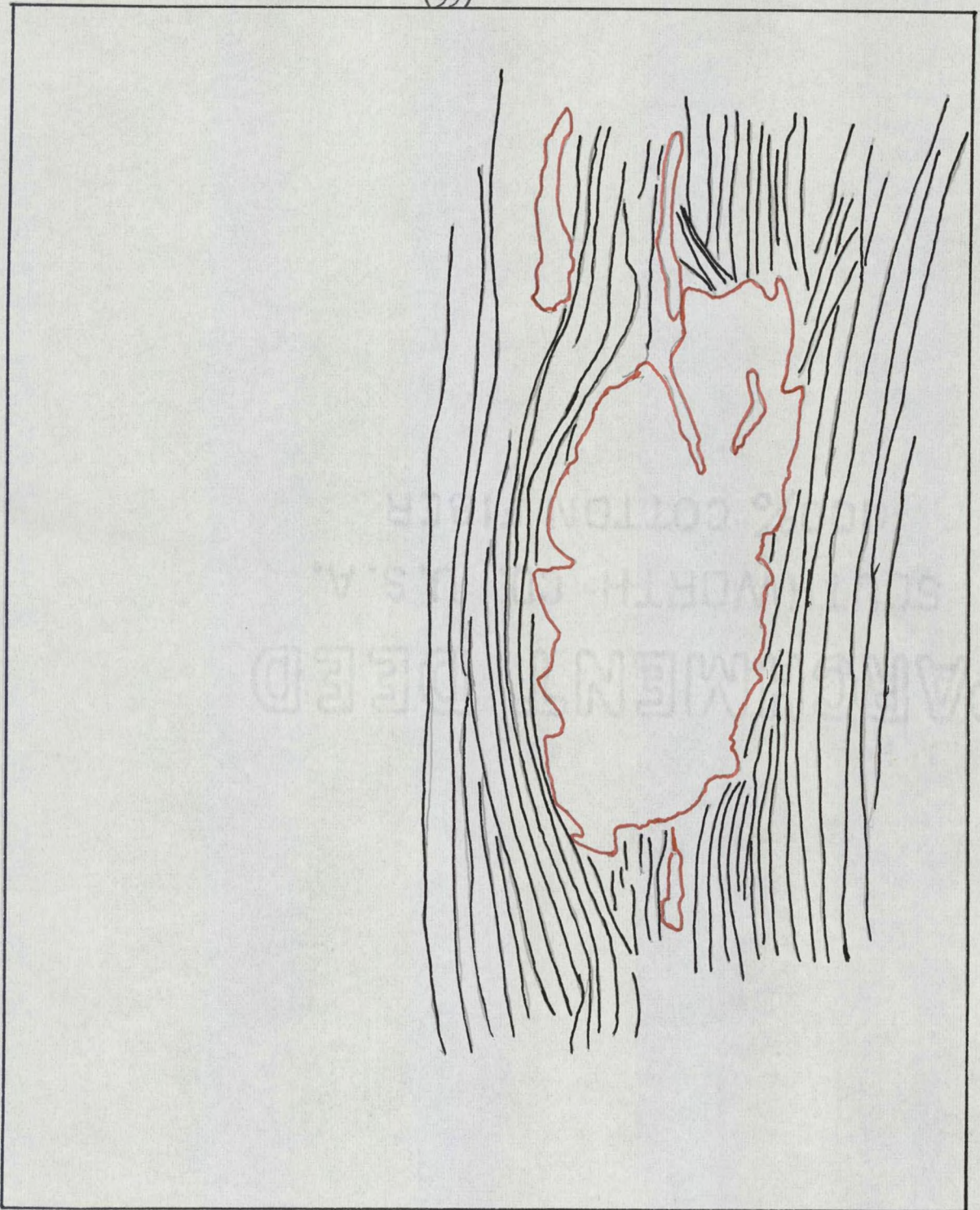
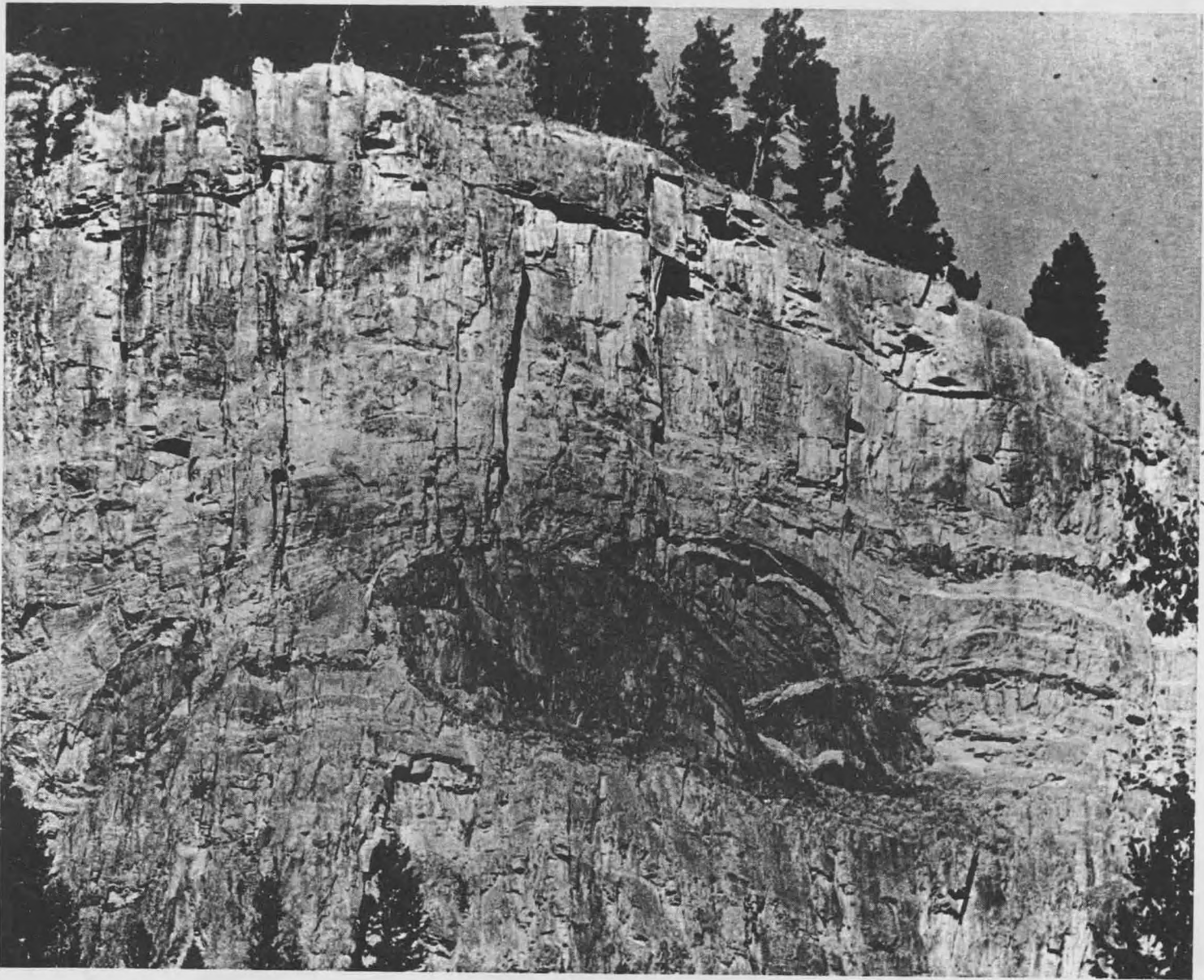


Figure 26. An Overlay Of Plate IV.



(100)

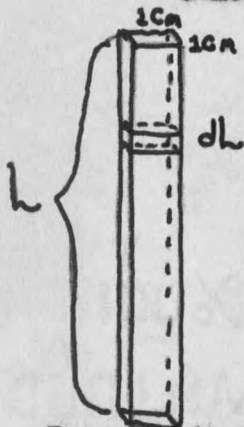
Plate IV. Outcrop III, Section D.

(101)

DERIVATION OF FORMULA

FOR

CALCULATING THE AMOUNT OF LIMESTONE ASSIMILATED



Let: $D = \text{density}$

$$P = \% \text{ Ca} \times 10^{-2}$$

$L = \text{thickness of sill.}$

$dL = \text{an infinitesimal increment of length.}$

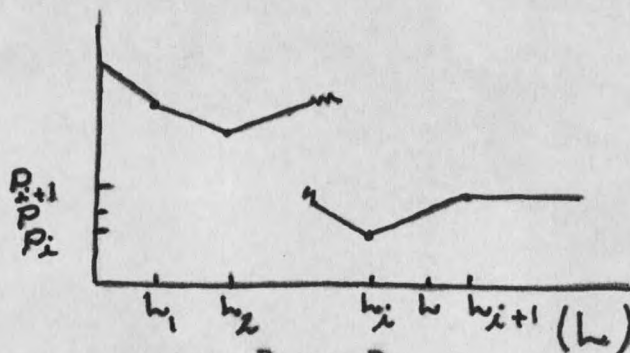
$M_a = \text{mass of calcium in column.}$

$$\text{Then: } M_a = \int_0^L DPdL$$

In order to evaluate the above integral, one must have the functional relationships between D and L and P and L . As a first approximation D and P may be supposed to vary linearly with L between sample location in a sill, i.e.,

$$P = P_i + \frac{P_{i+1} - P_i}{L_{i+1} - L_i} (L - L_i)$$

(P)



Similarly:

$$D = D_i + \frac{D_{i+1} - D_i}{L_{i+1} - L_i} (L - L_i)$$

(102)

$$\begin{aligned} \text{Thus: } M_a &= \int_0^{L_1} \left[D_0 + \frac{D_1 - D_0}{L_1 - L_0} (L - L_0) \right] \left[P_0 + \frac{P_1 - P_0}{L_1 - L_0} (L - L_0) \right] dL \\ &+ \int_0^{L_2} \left[D_1 + \frac{D_2 - D_1}{L_2 - L_1} (L - L_1) \right] \left[P_1 + \frac{P_2 - P_1}{L_2 - L_1} (L - L_1) \right] dL \\ &+ \dots + \int_{L_i}^{L_{i+1}} \left[D_i + \frac{D_{i+1} - D_i}{L_{i+1} - L_i} (L - L_i) \right] \left[P_i + \frac{P_{i+1} - P_i}{L_{i+1} - L_i} (L - L_i) \right] dL \\ &+ \dots \end{aligned}$$

Integration of the general term gives the weight of calcium in the column (1 cm² in cross section) between L_i and L_i + 1; M_a (L_i, L_{i+1})

$$\begin{aligned} M_a(L_i, L_{i+1}) &= \left(D_i - \frac{D_{i+1} - D_i}{L_{i+1} - L_i} L_i \right) \left(P_i - \frac{P_{i+1} - P_i}{L_{i+1} - L_i} L_i \right) (L_{i+1} - L_i) \\ &+ \left(\frac{L_{i+1}^2 - L_i^2}{2} \right) \left[\left(\frac{D_{i+1} - D_i}{L_{i+1} - L_i} \right) \left(P_i - \frac{P_{i+1} - P_i}{L_{i+1} - L_i} L_i \right) + \left(\frac{P_{i+1} - P_i}{L_{i+1} - L_i} \right) \left(D_i - \frac{D_{i+1} - D_i}{L_{i+1} - L_i} L_i \right) \right] \\ &+ \frac{(D_{i+1} - D_i)(P_{i+1} - P_i)}{(L_{i+1} - L_i)^2} \left(\frac{L_{i+1}^3 - L_i^3}{3} \right) \end{aligned}$$

Evaluation of each term in M_a is facilitated by moving the origin to L_i each time. Thus, L_i, L_{i+1}, P_i, P_{i+1}, D_i, D_{i+1} become respectively 0, L₁, P₀, P₁, D₀, and D₁ and the mass of calcium in the column between two sample locations is given by:

$$\begin{aligned} M_{Ca} &= D_0 P_0 L_1 + \left[(D_1 - D_0) P_0 + (P_1 - P_0) D_0 \right] \frac{L_1^2}{2} \\ &+ (D_1 - D_0)(P_1 - P_0) \frac{L_1^3}{3} \end{aligned}$$

Sample No.	%Ca. 10^{-2}	Density	Length in Cm
1 TAIH-9V	.0318	2.65	5.08
2 TAIH-10V	.0241	2.64	25.4
3 TAIH-11V	.0181	2.78	61.0
4 TAIH-12V	.0314	2.65	81.4
5 TAIH-14V	.0401	2.76	87.4
6 TAIH-17V	.0431	2.75	99.0
7 TAIH-18V	.0372	2.74	114.3
8 TAIH-19V	.0258	2.57	129.5
8 TAIH-20V	.0521	2.92	133.3

	M _{Ca}	A	B	C	D
1.	1.499	1.712	-.003	+.21	-.0005
2.	2.032	2.264	.060	-.282	-.0099
3.	1.377	1.028	-.016	.377	-.0118
4.	0.581	.500	.010	.069	.002
5.	1.329	1.284	-.0002	.048	-.0001
6.	1.800	1.815	-.003	-.012	.0003
7.	1.275	1.550	-.048	-.237	.010
8.	0.563	.252	.172	.128	.011

Total calcium in column equals 10.456 gm. The amount calcium using the lowest value equals 6.68 gm. The amount assimilated equals 3.78 gm. The volume of limestone assimilated equals 2.54 per cent of the total volume of the sill.

Outcrop I, Section A, 2 horizontal

Total calcium in column equals 5.970 gm. Mass of calcium in column calculated from the low value equals 1.890 gm. The amount assimilated equals 4.08 gm. or 17.3% of the total volume.

Outcrop II, Section A, 1 horizontal

Total mass of calcium in column equals 13.781 gm. Mass calculated from low value equals 11.890 gm. Amount of calcium assimilated equals 1.891 gm. or 1.32 per cent of the total volume of the sill.

Outcrop II, Section B, 1 horizontal

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Total mass of calcium in column 10.615 gm. Mass calcium calculated from low value equals 10.200 gm. Amount of calcium assimilated equals 0.415 gm. or 0.258 per cent of the total volume of the sill.

Outcrop II, Section C, 1 horizontal

Total mass of calcium in the column equals 5.940 gm. Mass of calcium calculated from the low value equals 5.280 gm. Amount of calcium assimilated equals 0.660 gm. or if converted to limestone represents one per cent of the total volume of the column.

Outcrop II, Section D, 1 horizontal

Total mass of calcium in the column 96.04 gm. Mass of original calcium equals 89.06 gm. The amount of calcium assimilated equals 6.98 gm. or if converted to limestone represents 0.66 per cent of the total volume of the column.

Outcrop II, Section D, 2 horizontal

Total mass of calcium in the column equals 50.264 gm. The mass of the original calcium equals 48.15 gm. The mass of calcium assimilated equals 2.149 gm. or if converted to limestone represents 0.36 per cent of the total volume of the column.

Outcrop III, Section A, 1 horizontal

Total calcium in column equals 2.407 gm. The mass of the original calcium equals 2.006 gm. The amount of calcium assimilated is equal to 0.401 gm. or represents 1.80 per cent of the total volume of the column.

Calculation of Amount of Space Gained by Compaction,
Plastic Flow, and Gouging

This calculation was carried out on outcrop III, section A. This outcrop is roughly elliptical in shape being 37 inches wide at the mid-point and tapering to 4 inches wide at the ends. The length of this eye is 15 feet 6 inches. The missing beds are approximately 2 inches wide by 15 feet 6 inches long. The amount of volume due to assimilation was found to be 1.80 per cent.

By approximating the shape of the eye with four right triangles and then finding the area of these triangles, the total area of the eye was calculated. This area was found to be 2880 square inches. The area of the missing beds was calculated to be 372 square inches. Assuming that the area is representative of the volume, the amount removed by assimilation was 52 square inches. Thus, 320 square inches were removed by compaction, plastic flow, and gouging. This represents 11 per cent of the total volume of the sill.

Unsolved Problems and Suggestions for Further Work

An accurate answer concerning the amount of space achieved by the various mechanical processes should be obtained. This could be accomplished quite easily by a structural geologist, but not so easily by a chemist.

A better estimate of the amount of calcium assimilated would be desirable. To determine how much of the observed gradient to attribute to fractional crystallization and not to assimilation, one should study the system anorthite-diopside-albite, as presented by Bowen. If the

initial calcium concentration of the uncontaminated magma could be estimated, a study of the above phase diagram would very likely give one the composition of the uncontaminated plagioclase feldspars. This knowledge, coupled with chemical analyses, should give a fairly accurate estimate.

A study should be made of the sills in contact with the gneiss, in order to observe the sort of calcium, magnesium, and specific gravity gradient present. Also, analyses of sills in contact with the Jefferson dolomite should be carried out, to determine if a magnesium gradient similar to the calcium gradients in the limestone, is present.

Complete chemical analyses of several suites of samples studied in this work would be useful in establishing chemical and mineral relationships.

To explain a specific gravity of 2.8 or above in the limestone, iron and silica analyses of this limestone should be made. This might also indicate that replacement of the calcite by iron and silica bearing solutions was of greater importance than was concluded in this work.

A study might be made concerning the emplacement of sills in shales. Aside from the shales being structurally weak, some chemical affinity might exist between the shales and the magma which might help to explain the size and prevalence of sills in shale bodies.

If further work is done upon these sills studied, the author feels that particular attention should be paid to outcrop II, section D, since this area yielded much valuable information.

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