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A petrofabric study of the iron ore of Benson Mines, Star Lake, New York

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A PETROFABRIC STUDY OF THE IRON ORE
OF BENSON MINES, STAR LAKE, NEW YORK

BY

REMO ANTONIO MASIELLO - 1948

A

THESIS

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ABSTRACT

The petrofabrics of the host gneiss silicates and ovate ore grains were studied in thin sections of oriented specimens collected from widely scattered positions in the iron ore deposit at Benson Mines, New York.

Ten oriented specimens selected for petrofabrics study were comprised primarily of feldspar, quartz, garnet and orres, with lesser quantities of biotite and sillimanite. Petrofabric diagrams were prepared for the orientation fabrics of magnetite and biotite in eight of the ten specimens, but sillimanite and quartz were sufficiently abundant for fabric determination in only three specimens. Duplicate thin section and perpendicular sections were utilized to check the resultant orientation patterns. A total of 28 petrofabric diagrams were prepared.

The petrofabric diagrams for the basal cleavage of biotite grains reveals foliation which is much more distinct than that observed megascopically. The c-axes of sillimanite are distinctly aligned in a direction of lineation which lies within the biotite foliation plane. The petrofabric diagrams for the long axes of ovate ore grains exhibit more scatter than those of biotite and sillimanite, but those axes exhibit a tendency to lie within the biotite foliation plane and to be relatively concentrated in the direction of sillimanite lineation. This tendency is strongest in the more strongly foliated and lineated specimens respectively.

The correspondence between host gneiss silicate petrofabrics and orientation of ovate ore grains suggests that the iron oxide
grains have developed preferred orientation during the metamorphism which developed the foliation in the host rock gneiss and that the iron was introduced or simply present in the rock prior to the last stages of metamorphism.
# TABLE OF CONTENTS

## ABSRACCT

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ii</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

<table>
<thead>
<tr>
<th>vi</th>
</tr>
</thead>
</table>

## LIST OF TABLES

<table>
<thead>
<tr>
<th>viii</th>
</tr>
</thead>
</table>

## Chapter I. INTRODUCTION

| A. Purpose of Investigation | 1 |
| B. Physiography | 1 |
| C. Culture | 4 |
| D. Climate | 4 |
| E. Field Procedure | 5 |
| F. Laboratory Procedure | 6 |
| G. Acknowledgements | 20 |
| H. Economic Mineral Deposits | 20 |

## Chapter II. GENERAL GEOLOGY

| A. Core | 27 |
| B. Intermediate Zone | 28 |
| C. Outer Zone | 34 |
| D. General Structure | 36 |

## Chapter III. THE BENSON MINES

| A. History and Production | 39 |
| B. Iron Ore | 40 |
| C. Lithology | 41 |
| D. Structure | 43 |
| E. Genesis of the Benson | 44 |

## Chapter IV. PETROFABRICS OF THE BENSON IRON ORE

<p>| A. Previous Investigations | 54 |
| B. Petrofabrics | 55 |
| 1. Specimen A-7 | 56 |
| 2. Specimen A-3 | 62 |
| 3. Specimen H-36 | 71 |
| 4. Specimen N-5 | 74 |
| 5. Specimen S-1 | 78 |
| 6. Specimen N-22 | 84 |
| 7. Specimen H-32 | 86 |
| 8. Specimen A-1 | 92 |
| 9. Specimen B-18 | 97 |
| 10. Specimen N-25 | 97 |
| 11. Summary of Petrofabrics | 100 |</p>
<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter V. SUMMARY AND CONCLUSIONS</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
</tr>
<tr>
<td>VITA</td>
</tr>
<tr>
<td>APPENDIX</td>
</tr>
<tr>
<td>Figure</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3a</td>
</tr>
<tr>
<td>3b</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
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<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>13</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>Figure</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>17</td>
</tr>
<tr>
<td>18</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>21</td>
</tr>
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<td>22</td>
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<td>24</td>
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<tr>
<td>25</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>27</td>
</tr>
<tr>
<td>28</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>30</td>
</tr>
</tbody>
</table>
Figure | Page
--- | ---
31 | Orientation diagram for poles of (001) of biotite in the horizontal thin section of specimen S-1..... 82
32 | Orientation diagram for long axes of magnetite grains in the horizontal thin section of specimen S-1..... 83
33 | Orientation diagrams for poles of (001) of biotite in the horizontal thin section of specimen N-22..... 85
34 | Orientation diagram for long axes of magnetite grains in the vertical thin section of specimen N-22 87
35 | Orientation diagram for poles of (001) of biotite of specimen H-32.................. 89
36 | Orientation diagram for long axes of sillimanite of specimen H-32.......................... 90
37 | Orientation diagram for long axes of magnetite of specimen H-32.......................... 91
38 | Orientation diagram for poles of (001) of biotite in the vertical thin section of specimen A-1........ 93
39 | Orientation diagram for long axes of sillimanite grains in the horizontal thin section of specimen A-1.......................... 95
40 | Orientation diagram for long axes of magnetite grains in the vertical section of specimen A-1........ 96
41 | Orientation diagram for quartz (0001) in the horizontal thin section of specimen B-18............. 98
42 | Orientation diagram for quartz (0001) in the horizontal thin section of specimen N-25............. 99

LIST OF TABLES

Table
1 | Summary of Petrofabric Data..................101
Chapter I
INTRODUCTION

A. Purpose of Investigation

The ovate nature of many of the ore grains of the Benson magnetite-hematite ores suggested to Dr. Richard D. Hagni that a petrofabric study of the ore and gneissic host rock might contribute to a better understanding of the genesis of this and similar iron deposits in the Adirondack region. The writer was interested by Dr. Hagni to establish and carry out a laboratory study of oriented samples from the Benson pits and the surrounding area.

The principal purpose of this petrofabric study was to determine whether or not these ovate ore grains had a preferred orientation, and then to examine the relationships between the orientation of the ore grains and the petrofabrics of the metamorphic host rocks. Such information can be useful in better understanding the genesis of the iron deposits.

B. Physiography

The Adirondack region (Fig. 1) can be broadly subdivided into two topographic sections: a central area known as the Adirondack Highlands, and a low-lying surrounding area known as the St. Lawrence-Champlain lowlands.

The Highlands contain the highest mountains in New York State, especially in the High Peaks area of the east-central Adirondack Mountains. Many peaks in the area have elevations above 4,000 feet with Mount Marcy and Mount Algonquin having elevations of 5,344 and
Figure 1. Index map showing location of Adirondack Mountains and approximate area of the Benson Mines. (After Buddington, 1939).
5,114 feet respectively. The average relief in the area is 2,000 feet. To the north, west and south of the High Peaks area the average elevation gradually decreases to 3,000 feet with an approximate relief of 1,000 feet. Eastward from the High Peaks, the elevation drops abruptly in a series of step faults to the level of Lake Champlain which is 95 feet above sea level. Northeast-southwest trending fault valleys transect the Adirondacks and locally control the drainage and land forms. Many lakes are formed along geologic contacts or are confined by fault valleys. Glacial deposits have clogged the normal radial drainage and lower areas are scattered with lakes, ponds and swamps.

The St. Lawrence-Champlain Lowlands or the Grenville Lowlands, lying southeast of the St. Lawrence River, form a belt approximately 100 miles long and 30 miles wide. The junction between the Lowlands and the Adirondack Highlands is marked by a fall line. Relief in this area is approximately 100 feet.

The Benson Mines are located east of the fall line in Township 12, town of Finna, St. Lawrence County, New York, approximately two miles east of Star Lake, New York. The area is one of low rounded hills with many small lakes and streams, typical of glacially eroded terrain. It is thickly wooded with pine, spruce, birch, maple and poplar trees. Many areas have been cut and are overgrown with underbrush and secondary growth. Altitudes in the area range from 900 to 1,900 feet.

New York State Route 3, a two lane blacktop highway, is the main road traversing the area in an east-west direction; it passes near the south end of the Benson Mines.
The Carthage and Adirondack branch of the New York Central Railroad serves the area.

C. Culture

The Adirondack Highlands have been a tourist attraction for many years. Many cabins and resorts have been built along the shores of the lakes. The abundance of timberland in this region also gives rise to some of the income of the area.

The Star Lake and Benson Mines area also receives some income from tourist trade, but the larger part of its income comes from the Benson Mines and the Newton Falls paper mill, where most of the residents in this area are employed.

The junction between the Adirondack Highlands and the Grenville Lowlands is marked by a fall line. Waterfalls have developed where large rivers cross the junction and have been partially responsible for the location of towns such as Carthage, Natural Bridge, Harrisville, South Edwards, Russell and Colton.

The Grenville Lowlands are cleared and give rise to dairy farming and minor crop growing.

D. Climate

The climate in the Benson Mines area is variable according to seasons. The summers are mild with considerable rainfall in early spring and late fall. The winters are severe with heavy snow falls and temperatures as low as minus 45 degrees.
E. Field Procedure

Specimens were collected from the Benson Mines along four general cross sections, and lettered according to the pit from which they were taken: B for the Benson pit, A the Anticline pit and N the Newton Falls pit (see Appendix I). The specimens from each pit were numbered consecutively. They were collected along a horizontal line at intervals of about 10 feet, but the sample elevation and interval were modified according to factors such as access to the mine wall and suitability of the rock for petrofabric study. Those specimens in which the disseminated magnetite was present primarily as unclustered, individual grains were most suitable for this study. Two specimens, from drill hole 1191, were obtained from Dr. Richard D. Hagni for this study and were given the letter designation H.

In order to orient each specimen, a sun compass was standardized by setting up and sighting over a previously established north line and recording correction factors every five minutes throughout one entire day. These correction factors were checked, using the above procedure, every two weeks and the necessary adjustments were made.

A north line was marked on the top of each specimen. In cases where the top of the specimen was inaccessible, the north line was placed on the bottom and the word "top" was written on the top of the specimen. A horizontal line was marked on two faces using a Brunton compass as a level to complete the orientation. Where possible the specimens were marked before removal; others were removed first, returned to their original position, and then marked.
Specimens were collected from unmineralized granite gneiss in the vicinity of the mines in order to compare the petrofabrics of their accessory iron oxides with those of the Benson ores. These specimens were marked in the same manner as the specimens from the mine. A Brunton compass was used for all markings instead of the sun compass. A specimen from Sevey, New York was designated with the letter S.

Most of the specimens exhibit weak foliation, but some of the sillimanite-rich samples may show strong foliation and lineation. Foliation and lineation data were measured and recorded at each sample site.

F. Laboratory Procedure

The laboratory procedure consisted of five basic steps:
1) preparation of oriented thin sections, 2) orientation of the different minerals, 3) plotting of data on the transparent overlays of the equal-area net, 4) contouring the petrofabric data, and 5) checking the results of contour patterns.

1. Preparation of Oriented Thin Sections

Those specimens showing stronger foliation and abundant disseminated magnetite grains were selected for petrofabric study. They were oriented and sawed into horizontal slabs and vertical, north-south slabs for thin section preparation. Thin sections prepared from the slabs were mounted on a glass plate with the north direction coincident with the long dimension of the glass.

*The term foliation is used in this thesis to refer to the preferred orientation of platy minerals in a plane. Lineation is restricted to the alignment of linear elements in one direction.
plate and the north direction was marked on each plate for orientation. Thin sections prepared from the vertical slabs were mounted so that the top of the specimen was toward the right side of the glass plate as shown in Figure 2b.

![Diagram](image)

(a) (b)

Figure 2. Sketch showing the orientation of thin sections: (a) horizontal thin section; (b) vertical thin section.

Completed thin sections were first studied with the conventional petrographic microscope to determine both the mineralogy and the nature of individual iron oxide grains in each slide. The thin section was then placed on a five-axis universal stage with a Schmidt sliding bar, so that the north direction faced away from the observer. The glass hemispheres of the universal stage and the immersion oil had an index of refraction of 1.554. The universal stage was mounted and centered on a Leitz Pamphot microscope.

Transparent minerals in the host rock granite gneiss utilized for petrofabric study were quartz, biotite and sillimanite. The opaque mineral studied generally was magnetite; some hematite grains
were oriented, but no distinction between the two was made for this investigation. The thin sections were left slightly thicker than the normal 0.03 mm to aid in determining of orientation of the opaque grains. An external light source was used while orienting the magnetite grains. This light source facilitated the orientation of the opaque grains by illuminating their inclined edges. The sections were etched with hydrofluoric acid fumes for three minutes to facilitate distinguishing quartz grains from untwinned feldspars. The quartz remained unaltered and clear making it easily distinguishable from the etched and darker feldspars.

2. Methods of Orientation

Optical directions were determined for quartz grains, while physical directions were oriented for biotite, sillimanite and magnetite. The methods utilized for each mineral are described below.

a. Quartz

The optic axis of quartz was oriented in the following manner (Emmons, 1943):

1) Find and center a quartz grain under the cross hairs.

2) Rotate on the inner-vertical axis to a position of extinction. This rotation places the optic axis in the north-south or east-west vertical plane.

3) Determine in which plane the optic axis lies by rotating about the outer east-west axis. If the optic axis is in the north-south plane, the grain will remain extinct. If it is
east-west, the grain will leave extinction and should be rotated 90 degrees on the inner vertical axis to place the optic axis in the north-south position. Return outer east-west to the zero position.

4) Rotate 45 degrees clockwise on the axis of the microscope to place the plane containing the optic axis in the northeast 45 degree position. In this position the outer east-west axis is perpendicular to that plane.

5) Rotate on the outer east-west axis to extinction. This rotation brings the c-axis to the vertical position. The grain remains extinct during rotation on the axis of the microscope.

An alternate procedure can be used if extinction cannot be reached by rotation on the outer east-west axis, indicating that the optic axis lies in or nearly in the plane of the thin section. This procedure consists of the following steps:

1) Rotate the centered quartz grain on the inner vertical axis to the extinction position at which it will remain extinct during a rotation about the north-south axis. In this position the optic axis is oriented in the east-west vertical plane.

2) By trial and error rotate on the north-south axis to various positions until one is found at which the crystal remains extinct during rotation on the outer east-west axis. This brings the optic axis of the crystal to the horizontal east-west position.

b. Biotite

Poles normal to the (001) basal cleavage in biotite were determined by the method given by Turner and Weiss (1963, p. 202) as follows:
1) Find and center a biotite crystal under the cross hairs.

2) Rotate on the inner vertical axis until the cleavage cracks are aligned east-west.

3) Rotate on the outer east-west axis until the cleavage cracks are at their sharpest possible definition. The biotite basal cleavage is oriented vertically and the pole normal to the cleavage is horizontal and north-south.

c. Sillimanite

The long, c-crystallographic axes of fibrous to prismatic sillimanite crystals were oriented in the following manner:

1) Select and center a sillimanite crystal under the cross hairs.

2) Rotate on the inner vertical axis until the prismatic cleavage of the crystal is parallel to the east-west cross hair.

3) Two possibilities now arise:
   a) The prismatic cleavage and thus the c-crystallographic axis is oriented closer to the vertical than to the horizontal. In this case the crystal may be rotated about the north-south axis until the prismatic cleavage is sharp and vertically oriented.

   b) The prismatic cleavage may have an orientation closer to the plane of the horizontal thin section. In this case rotate on the north-south axis until the c-axis of the grain is horizontal and parallel to the east-west cross hair. The ends of the
prismatic sillimanite crystals remains stationary upon rotation on the outer east-west axis when the crystal is in the horizontal position.

d. Magnetite

The magnetite grains were oriented by a method developed by the writer. The opaque nature and general lack of cleavage eliminate the orientation methods normally applied to transparent minerals, but the common tendency of the opaque minerals in the Benson ore to occur in ovate shapes (Fig. 3a) made it possible to orient the long axis of the ovate grains in the following manner:

1) Select and center an individual magnetite grain under the cross hairs.

2) Rotate on the inner-vertical axis until the longest dimension of the grain is parallel to the east-west cross hair.

3) Two possibilities now arise:

a) The longest axis of the ovate shaped grains may be oriented closer to the vertical than the horizontal. In this case rotation about the north-south axis will cause the grain to have a circular outline (Fig. 3b) when the long axis of the spheroid is vertical.

b) The longest axis of the ovate grain may be oriented closer to the horizontal than to the vertical. In this case the grain is carefully examined during rotation on the north-south axis until its long axis is discerned. The long axis is oriented horizontal and east-west by rotation on the north-south axis.
Figure 3a. Ovate magnetite grain before orientation.

Figure 3b. Ovate magnetite grain after orientation.
Tilting on the outer east-west axis helps to check the accuracy of the orientation.

Careful study of magnetite grains to be oriented is necessary for successful orientation. The long axis for some grains may be obscured and misinterpreted due to their irregular shapes or to the manner in which they were cut for the thin section. If an ovate magnetite grain is cut at an angle and near either end, so that the major portion of the grain is lost (Fig. 4a) and the smaller end portion remains in the thin section, the long axis of the elliptical surface produced can be misinterpreted to be the long axis of the ovate grain (Figs. 4b and 4c). Examination of the grains during rotation about the outer east-west axis eliminates such an error. Those grains which lie entirely within the thin section or are only partly ground away give the most reliable orientations.

The degree to which the magnetite may depart from that of ovate-shaped grains toward that of an ellipsoid with three unequal axes, is a factor which tends to complicate the interpretation of the
diagrams for magnetite. This factor probably is responsible for the relatively greater scatter shown by the magnetite diagrams as compared to those of biotite and sillimanite.

Some grains are tabular shaped and could not be utilized. However, these grains were not abundant in the specimens studied.


Two types of projection nets are commonly utilized to record orientations of structural and mineralogical elements: the stereographic net and the equal-area net. The stereographic net is the most commonly used net because it preserves the angular relationships between linear and planar elements. Because centrally situated areas on the net are diminished relative to peripheral areas of equivalent size on the reference sphere, the stereographic net cannot be used for petrofabric studies. For such studies an equal-area net, known as a Lambert (the inventor) projection or a Schmidt projection (after W. Schmidt who first used it in structural geology) was developed. Equal areas are maintained on this net and the density of points on the projection fully represent the density of those positions in the fabric projected from the reference hemisphere.

The equal-area net is an orthogonal projection of a hemisphere upon a plane. The parallels of latitude and meridians of longitude, inscribed at two degree intervals on the reference hemisphere, project upon the plane of the net principally as elliptically arcs, except where they lie in or normal to the plane of projection (the boundary circle and the diameters of the projection respectively)
(Fig. 5). The equatorial plane appears as the peripheral circle of the projection and it is referred to as the primitive circle. The meridians of the net represent the traces on the reference hemisphere of planes passing through the center and the north and south poles of the hemisphere. The meridians are termed great circles of the net. The parallels represent traces of the planes normal to the plane of projection but not passing through the center of the hemisphere. The parallels are termed small circles of the net. The two diameters of the net are great circles normal to the plane of projection.

The net was mounted on a fixed base over which a transparent overlay could be rotated 360 degrees.

Two methods were used to plot universal stage data on the equal-area net. The first method, given by Turner and Weiss (1963), was used to plot the poles normal to the (001) cleavage of biotite. It consists of two steps:

a. Mark the north and south directions on the overlay with index arrows and rotate the transparent overlay in the same direction and magnitude (degrees) as was rotated on the inner-vertical axis.

b. Plot the point (or pole) on the north-south axis of the net by measuring the number of degrees rotated on the outer east-west axis, measuring from the primitive circle toward the center in a direction opposite to that of the rotation on the outer east-west axis. For example, if the outer east-west axis was turned away from the observer, the measurement would be made from the south end of the north-south diameter.

A second method was used to plot the optic axis of quartz, the
Figure 5. Equal area net
c-axis of sillimanite and the longest axis of magnetite. The axes of these minerals were oriented vertically in some cases and horizontally in others. Vertically oriented axes were plotted on the equal-area net in the following manner:

a. Rotate the transparent overlay in the same direction and number of degrees as turned on the inner vertical axis.

b. Measure from the center and along the east-west diameter of the net, the same number of degrees rotated on the north-south axis. The direction of measurement is determined by the direction of stage rotation. For example, if the north-south axis is moved down from the left, the point will be plotted along the left portion of the east-west diameter.

Axes which were brought to the horizontal position were plotted by the following steps:

a. Rotate the transparent overlay in the same direction and number or degrees as turned on the inner vertical axis.

b. Measure on the east-west diameter of the net, from the periphery toward the center, the same number of degrees rotated on the north-south axis of the stage. For example, if the north-south axis was tilted down 20° on the left, measure 20° from the right periphery of the net. If the tilt was in the opposite direction, measure from the left periphery.

4. Contouring the Point Densities

Points plotted on a transparent overlay of the equal-area net may be contoured to outline the character of their distribution density. Three contouring methods are commonly used: 1) the Schmidt
or grid method, 2) the free-counter method, and 3) the Mellis or circle method (Turner and Weiss, 1963, pp. 61-67).

The Schmidt grid method is used for those petrofabric diagrams which have a large number of points, generally in excess of 400, or for those which have unusually high concentrations of points. The transparent point diagram is superimposed on a grid consisting of squares 1 cm. on a side. The center of the circle of the counting bar or point counter shown in Figure 6, is placed successively at each intersection and the number of points are counted and marked on the overlay. The numbers marked at the intersections are contoured using the appropriate intervals.

![Figure 6. Point counter](image)

The free-counter method generally is used for diagrams which have between 200 and 400 points and where concentrations are less than 12 points. Appropriate contour intervals are selected by preliminary counting with the point counter. The highest contour is drawn first by marking the overlay at the center of the counting circle whenever it contains the number of points selected as that contour. The marks are connected to form the contour.
Additional contours are determined in the same manner.

The Mellis or circle method is most suitable for petrofabric diagrams containing less than 150 points. The circle of the point counter is centered over each plotted point, and a circle is drawn. The resulting series of overlapping circles are marked with appropriate symbols to distinguish, for example, an area of three overlapping circles from an area of two overlapping circles. Since the radius of the circle of the point counter is such that its circular area represents 1 percent of the area of the net, three overlapping circles indicate an area of 3 percent point density. Near the periphery of the net, for points whose circles extend beyond the net, the completion of the circle must be drawn at the opposite edge of the net using the second circle of the point counter. The Mellis method is the least subjective of the three methods. For this reason and because of the number of points plotted, the Mellis method was used in this investigation.

5. Pattern Checks

The patterns produced by this petrofabric study were confirmed by two types of controls. The first of these types consisted of replotting certain minerals in selected or additional thin sections. The pattern produced in both plates should be the same.

The second method was accomplished by preparing perpendicular thin sections from one rock specimen. The petrofabric pattern for a mineral in one thin section will appear in the point diagram for that mineral in the other thin section, but one pattern will be
rotated 90° from the other. Thus, an axial pattern toward the periphery of the net for one thin section will appear at the center of the net for the other thin section. Similarly, a cleft girdle pattern in the horizontal thin section will appear as a girdle pattern in the vertical thin section. Seven checks of this type are included in this thesis.

G. Acknowledgements

The author is grateful to Dr. Richard D. Hagni, University of Missouri at Rolla, for suggesting the problem and for guidance and suggestions during the course of this investigation.

The writer expresses his sincere thanks to the Jones and Laughlin Steel Corporation staff at the Benson Mines who provided access to the mine area and for extending many courtesies during his study at the mine. A north line which was utilized to standardize the sun compass was surveyed by members of the Engineering Department at the Benson Mines.

Thanks are due Mr. James Gilstrap for his aid in reproducing the orientation diagrams.

H. Economic Mineral Deposits

New York State has a wide variety of economic mineral deposits which placed it in the upper third of the states in value of mineral production. These economic minerals may be conveniently divided into metals, nonmetals and mineral fuels.

1. Metals

The mining of metals is located principally in the Adirondack
region where iron, lead, zinc, silver, and titanium currently are produced (Fig. 7). Copper has been an important product in the past, but is not produced today.

a. Iron

Iron is one of the State's most valuable mineral resources. The largest open-pit magnetite mine in the world is the Benson Mines near Star Lake, St. Lawrence County. Two underground mines (Fisher Hill, and Bed-Harmony) near Mineville, Essex County, and a combined open-pit and underground mine (Lyon Mountain) near Chateaugay, Clinton County, are now mined for magnetite.

b. Titanium

Titanium is mined from ilmenite-magnetite ore bodies at Tahawus, New York; it is among the world's largest titanium producers. The ore bodies occur in an orthosite and gabbro. In addition to magnetite and ilmenite, the associated minerals are plagioclase, pyroxene, hornblende, biotite, olivine, garnet, apatite, spinel and quartz. The titanium is used primarily as a white pigment in high quality paints.

c. Zinc, Lead and Silver

Zinc, lead and silver are produced from the Balmat-Edwards district in St. Lawrence County. Sphalerite, galena and pyrite occur as veins or replacements along the bedding and banding of silicated Greenville marbles. Silver occurs in solid solution in the galena and is recovered as a by-product. Balmat is the forth largest zinc mine in the United States and the district ranks as the fifth largest zinc-lead producing district in the country.
2. Nonmetals

a. Carbonates

Among the most widely distributed industrial minerals in New York are the carbonate rocks, including limestone, dolomite and marble. These rocks account for over 90 percent of the stone sold in the State. They are used for many purposes, such as highway foundation material, agricultural limestone, railroad ballast, flux in steel manufacturing, and the production of portland, masonry and natural cements.

b. Emery

New York has the only mines which continue to produce emery in the United States. These mines are located near Peekskill, Westchester County, New York. Two types of emery are mined: a black emery which occurs in norite, and a gray emery in corderite-sillimanite-rich norite. Variable amounts of magnetite, sapphire and andalusite occur with the emery. Emery is used as an abrasive and as a nonslip aggregate in stair treads and floors of buildings such as creameries.

c. Garnet

New York is the leading state in garnet production with the major portion coming from Gore Mountain. The deposits lie along the contact between a body of gabbro on the north and a body of syenite on the south, and along the periphery of an outlier of anorthosite and gabbro. The ore occurs both as very large, hornblende-sheated garnets set in a coarse, dark matrix of hornblende and plagioclase, and as smaller garnets in a feldspathic matrix. The principal use of this garnet is as an abrasive agent, but some
of the garnet is of gem quality.

d. Talc

Talc is produced in St. Lawrence and Lewis Counties. Talc is a hydrated magnesium silicate which occurs in this area in two forms: a primary deposit which has scaly, foliated habit, and a secondary deposit of a granular, fibrous or massive nature due to local alteration of the anhydrous magnesium silicates such as tremolite and enstatite. Much of the material locally referred to as talc comprises silicates, such as tremolite, as well as true talc. The productive talc area is defined by a belt of Grenville limestone where it occurs as beds or sheetlike and lenticular bodies within the limestone. Its uses are found as a paint extender, a filler in roofing materials, putty, linoleum and as a carrier for insecticide dusts.

e. Salt

The State of New York ranks third in the production of salt. More than 10,000 square miles of western and central New York State is underlain by rock salt of Silurian age. Fourteen workable beds up to 1,300 feet thick underlie the Watkins Glen area. Rock salt is used in the chemical and food processing industries. During recent years, the salt deposits have been used as a storage area for liquid hydrocarbons and for chemical and radioactive wastes.

f. Gypsum

Present gypsum production in New York is limited to mines in Erie, Genesee and Monroe Counties. Gypsum is associated with the Salina Formation of Silurian age, where it occurs with the salt deposits. The gypsum as it is found in New York is a gray
or drab color and contains varying amounts of impurities in the form of lime and magnesium carbonates, clay, silica and a small amount of organic matter. Its most important use is in the manufacturing of wall board and plaster. It is also an important constituent of portland cement.

g. Wollastonite

Wollastonite was first discovered in 1810 in the vicinity of Willsboro, Essex County. However, it was not developed until soon after World War II when an open-pit mine was developed near Willsboro. The deposits consist of bands of wollastonite (a calcium silicate) associated with diopside and garnet infolded with anorthosite. It is used principally in ceramic wall tile and porcelain and as paint extender.

Other nonmetallic minerals mined in New York State include clay, peat, sand and gravel, sandstone and slate.

3. Mineral Fuels

The mineral fuels of petroleum and natural gas make up only about 4 percent of the state's total mineral production. Although there are more than 15,000 producing oil wells in New York, their individual production is small and the total production decreases every year. Nearly three-quarters of the oil produced comes from Allegany County.

The production of natural gas has had a short history in New York. Chautauqua County formerly was the leading producer of natural gas. Exploration in the 1930's located gas reserves in Schuyler, Allegany and Steuben Counties and gave rise to 39 billion
cubic feet of natural gas. Due to wasteful production, this supply was quickly decreased, and by the late 1940's production was below 3 billion cubic feet. In the past few years, exploration for new gas pools and storage areas have brought annual production to the 5 billion cubic foot level.
FIGURE 7. DISTRIBUTION OF ECONOMIC MINERALS IN NEW YORK. (AFTER GEOLOGIC MAP OF NEW YORK, 1961).
Chapter II
GENERAL GEOLOGY

For the purpose of this thesis, the Adirondack region may be conveniently divided into three main areas: 1) a core occupying an area of approximately 46 miles across, 2) an intermediate zone, approximately 38 miles wide, lying between the core and the outer zone, and 3) an outer zone about 25 miles wide and 100 miles long (Fig. 8).

A. Core

The core of the Adirondacks consists predominantly of anorthosite which has been subdivided into two types: 1) the Marcy, named for its exposure on Mount Marcy, and 2) the Whiteface, which outcrops on Mount Whiteface (Miller, 1929).

The Marcy anorthosite is described by Miller (1919, pp. 17-20) as a coarse-grained, light to dark bluish-gray rock consisting of 90 to 98 percent plagioclase feldspar. The plagioclase crystals vary from one-quarter of an inch to several inches long, but some crystals may be as long as six inches. Accessory minerals may include magnetite, monoclinic pyroxene, biotite, hornblende and garnet. Marcy anorthosite is characterized by a lack of foliation, but locally the feldspars show some degree of parallelism.

Miller (1929) believes the Marcy anorthosite displays laccolithic structure for the following reasons:

1) an upper and outer gabbroid, chilled border (Whiteface) facies resting on and against the Marcy anorthosite; 2) lack of Grenville country rock further
within the anorthosite than just below the inner and under the margin of the chilled border, thus strongly suggesting a lifting rather than a penetrating or engulfing power of the anorthosite; and 3) a general failure of the syenite granite to penetrate the main portion of the southwestern half of the great body of anorthosite, and considerable intrusion of its northeastern half, thusly suggesting a laccolith very thick on its southwestern portion and relatively thin in its northern portion.

The Whiteface anorthosite, first described by Kemp (1898, pp. 57-58) is a medium-grained, light gray moderately gneissoid rock consisting of white, or nearly white, plagioclase (labradorite), and containing 5 to 15 percent dark minerals such as hornblende and monoclinic pyroxene. Much of the rock is a gabbroic anorthosite or an anorthositic gabbro, but both types are mapped and termed Whiteface anorthosite (Buddington, 1939).

Miller (1929) believes that the Whiteface anorthosite is an upper and outer chilled zone of the Marcy anorthosite because it occurs in a zone around the Marcy anorthosite.

Along the margins of the core, but partly within the core, are small areas of gabbros and shonkinites. The gabbros range from medium to coarse-grained gabbroic anorthosites and anorthositic or feldspathic gabbro. Local bands range in composition from gabbroic or noritic anorthosite to mafic gabbro or mafic norite, and are composed of anorthite, diopside, hypersthene, ilmenite, orthoclase and magnetite.

B. Intermediate Zone

Surrounding the core, especially to the west and south, is a complex of igneous and metasedimentary rocks. Approximately one-sixth of this area, termed the intermediate zone in this thesis,
is covered by glacial drift, and consequently the geology of the underlying rocks is less well known.

There are three major types of granitic rocks within the intermediate zone: 1) a hornblende granite and its equivalent gneiss, 2) an alaskite variety and 3) a potassium-rich microcline-granite gneiss.

The hornblende granite and its equivalent gneiss, termed the younger granite by Buddington and Leonard (1962, p. 64), is the most abundant rock in the intermediate zone. This younger granite or granite gneiss is varied ranging from gneissoid hornblende-microperthitic granite to a strongly deformed wholly granoblastic gneiss in which the microperthitic feldspar is recrystallized to microcline and plagioclase with some local development of sphene. Generally the rock is a medium-grained pink granite with well developed foliation and consists mainly of hornblende, quartz feldspar (microperthite) and some plagioclase. These rock types are believed by Buddington and Leonard (1962, p. 61) to constitute a batholithic complex which underlies about one-half of the area.

The alaskite variety occurs predominantly as sheets within the metasedimentary rocks, and as an upper border of the younger hornblende granite and granite gneiss where these younger granites adjoin belts of metasedimentary rocks. Locally it occurs as lenses within areas of hornblende granite and granite gneiss, and may grade into hornblende granite. The alaskite displays no foliation but its microstructure is characteristically gneissic. It is composed mainly of quartz (about 40 percent) and feldspar.
The feldspar in the alaskite is microperthite, but it has been recrystallized to potassic feldspar and plagioclase in the alaskite gneiss. Minor amounts of partially chloritized biotite, iron oxides and intergranular fluorite occur in the rock.

The potassium-rich microcline-granite gneiss occurs as thin lens-shaped sheets, a few feet thick, isolated within the metasedimentary rocks, and as sheets hundreds of feet thick within synclinal structures. The granite gneiss consists of microcline, quartz, biotite, sillimanite or sillimanite-quartz nodules, almandite, hornblende, pyroxene and andradite. Microcline granite gneiss is the host rock for the ore deposits at the Benson Mines.

Westward from the core and within the intermediate zone, there are three tabular complexes, Tupper, Stark and Diana, which are thought by Buddington (1939, pp. 116 and 122) and Buddington and Leonard (1962) to be differentiated igneous bodies which were subsequently metamorphosed. All three of these complexes include syenite, quartz syenite and granite facies. They have exposed lengths of 35 to 45 miles and widths of a few miles.

1. Tupper Complex

The Tupper complex consists of three parts. The eastern portion forms a narrow belt 20 miles in length along the northwest flank of the anorthosite core and it is considered to be lowest part of the complex (Buddington and Leonard, 1962, p. 54). It is a mafic syenite gneiss and grades upward to a normal quartz-bearing pyroxene-syenite gneiss.

An anticlinal prong, known as the Arab Mountain sheet, extends
15 miles westward. It consists predominantly of a medium-grained, green pyroxene syenite gneiss which is referred to by some writers as a shonkinite or shonkinite gneiss. The syenite gneiss exhibits well-foliated structure and contains some small porphyroblasts of feldspar.

A belt of pyroxene and quartz syenites, known as the Inlet sheet, forms an outlier of the Tupper complex. It extends about 13 miles to the west beyond the Arab Mountain sheet and 20 miles south of the Benson Mines. Much of the Inlet sheet is covered by glacial drift and its geology is not well known. This area consists predominantly of a uniform, massive syenite to syenite gneiss which consists of the unusual mineral assemblage, fayalite, ferrohedenbergite and ferrohypersthene.

2. Stark Complex

The Stark complex is a narrow northeast trending belt located along the northwest outer margin of the intermediate zone. It is 4 to 5 miles wide and extends a distance of 45 miles from an area near the town of Santa Clara, southwestward to Round Lake near the northern border of the Oswegatchie quadrangle. The major rock type in the complex is a pink phacoidal hornblende-granite gneiss which locally grades into a pink pyroxene-hornblende-granite gneiss. To the east of Colton the rock type is a green pyroxene-quartz-syenite gneiss interlayered with pink hornblende-quartz-syenite gneiss. The core of the complex in the Stark quadrangle consists of mortar augen gneisses.
3. Diana Complex

The Diana complex, which lies southwest of the Stark complex, is named for the township of Diana, Lake Boneparte quadrangle. The complex forms the northwest border of the intermediate zone from the towns of Carthage west to South Edwards. It is 35 miles long extending from the town of Lowville north to Russell. The complex has been studied by Buddington (1939) and the lithologic varieties have been enumerated by Buddington and Leonard (1962). The southwestern part of the Diana complex consists of the following rock types:

a. Pyroxene-quartz-syenite gneiss: A gneiss which consists of feldspar, quartz, ferroaugite, hornblende, combined magnetite-ilmenite and accessory minerals which include sphene, zircon, and apatite.

b. Pyroxene-syenite gneiss: A gneiss which has a larger grain size than the quartz syenite gneiss and which ranges from a mortar gneiss to an augen gneiss.

c. Shonkinitic and feldspathic ultramafic gneiss: A gneiss with layers of normal pyroxene gneiss interlayered with shonkinitic syenite gneiss, shonkinite gneiss and feldspathic ultramafic gneiss.

d. Hornblende-quartz-syenite gneiss: A gneiss of medium-grained, roughly equigranular texture, and consisting of microcline and oligoclase feldspar, 7 to 18 percent quartz, hornblende, magnetite-ilmenite, pyroxene and the accessory minerals, apatite, zircon and sphene.
e. Phacoidal hornblende-granite gneiss: A gneiss characterized by a coarse phacoidal structure much like the granite gneiss series and which grades into a granite gneiss with an evenly foliated, coarse, equigranular structure. The feldspar usually is microcline and oligoclase varying in size from 1 to 4 mm. Magnetite, apatite and zircon are accessory minerals.

The northern part of the Diana complex, near the town of Russell, is different from the southern part, and consists of the following lithologies:

a. Biotite syenite gneiss: A gneiss which contains inclusions of metamorphosed, silicated limestone, pyroxene granulite and quartz-feldspar granulite. It is a fine-grained, evenly foliated gneiss with granoblastic texture, and it consists of microcline, oligoclase, biotite, quartz, magnetite, apatite, zircon and sphene.

b. Outlying syenite gneisses: These gneisses occur in the Oswegatchie quadrangle and partly in the Russell quadrangle. They are granite gneisses and quartz-bearing syenite gneisses generally consisting of microcline, oligoclase, augite, hypersthene, hornblende, iron oxides and accessory apatite and zircon.

An area of intermediate zone gneisses with outliers of anorthosite, anorthositic gabbro and norites located about 40 miles south-southwest of the margins of the Adirondack core has been intensely studied by Romey and de Waard (1964) and Walton and de Waard (1964). They believe that the anorthosite, anorthositic gabbro and norites in that area and elsewhere are metamorphic rocks with metamorphic
textures and assemblages. They feel that the anorthosites are actually meta-anorthosites with a granulite facies mineral assemblage in which large relic andesine plagioclase makes up a large part of the rock, and that the gabbros and norites are actually meta-gabbros and meta-norites which commonly display a relic ophitic texture and contain cores of relic pyroxene, olivine and plagioclase. "The origin of the great majority of rocks...is not certain; they may have been plutonic, volcanic or sedimentary" (de Waard, 1964, p. 3). These interpretations are in contrast to those of Buddington and Leonard.

C. Outer Zone

The term "outer zone" is used in this thesis to apply to the Grenville Lowlands. The line between the outer and the intermediate zones passes through the towns of Russell, Edwards and Natural Bridge. The western border of the outer zone generally is the St. Lawrence River, but Grenville-type rocks also extend into Canada. The outer zone in New York is approximately 25 miles wide and 100 miles long. The rocks of this area comprise a Precambrian complex consisting approximately of two-thirds metasedimentary rocks of the Grenville series and one-third intrusive igneous and meta-igneous rocks (Buddington, 1939).

The northeast-striking metasedimentary rock types include marbles, granite gneisses, migmatites and amphibolites (Engle and Engle, 1953). The most abundant and characteristic of the metasediments are the marbles. They range from calcic-marbles, through dolomitic marbles, to highly siliceous types varying in color and
magnesia content. Some marble beds are as thick as 8,000 feet, and together the marble beds comprise about one-third of the areal map exposure of the outer zone.

The gneisses are the next most abundant rock types in the outer zone. They may occur in thick zones interlayered with amphibolite, quartzite and marble, or they may be thin and interlayered with associated metasediments. Their mineralogical composition is similar to that of a granite, but the nature of their occurrence and the chemical composition of some, suggests that most of these gneisses were sedimentary rocks.

Amphibolites are widely distributed but less abundant than the marbles and gneisses in the outer zone. They are nearly bimineralic rocks consisting of hornblende and andesine. Some amphibolites originally may have been sediments, others were basic igneous rocks.

Granites, of Precambrian age, are common in the outer zone where they comprise about one-third of the map exposures. They have been subdivided into two types, the Alexandria and the Herman types. The former type is thought to be of igneous origin by Buddington (1939, p. 161), and the latter type is thought to be partially of magmatic and partially of replacement origin by Buddington (1939, p. 160) and Engle and Engle (1953, p. 1076).

All of the rocks in the outer zone have been highly metamorphosed and compressed into very tight folds in which the limbs have a nearly vertical dip. Engle and Engle (1953, p. 1054) have outlined a regional anticlinorium in which the Gouverneur marble belt constitutes the core and the Grenville rocks to the southeast.
comprise the overturned east flank.

D. General Structure

The trends and general dips of the foliation in the Adirondack region, together with the areal arrangement of zones, has lead to the belief that the general structure of the Adirondacks is that of a broad dome. For instance, in the northwest part of the Adirondacks the foliation dips steeply to the northwest, while in the southern portion it dips steeply to the south. Buddington (1939, pp. 237-246) have discussed in detail the relationship between the foliation in the Grenville rocks and that of the intermediate zone and core of the Adirondack region.

In the western portion of the intermediate zone of the Adirondack region Buddington (1962) has emphasized two different structural trends. One trends east-northeast in a southern area and the other trends northeast in a northwest area. The two structural complexes also are distinguished by the nature of their folds which are overturned to the northwest in the southern portion and to the southeast in the northwest area adjacent to the massif. The St. Lawrence County magnetite district lies in the vicinity of the intersection of the two trends, in a node of extremely complex structure. This node was conditioned by rigid anticlinal masses of older quartz syenite rocks, between which metasedimentary gneisses and younger granites have been squeezed into folds of diverse orientation, and of sizes ranging from several miles long to mere crenulations. Many of the magnetite deposits of the St. Lawrence district exhibit conformable or nearly conformable
relations with these folds. The Benson deposit occurs along the overturned limb and nose of a northerly trending syncline.
Chapter III
THE BENSON MINES

A. History and Production

The Benson Mines consisted of three open-pits which are now connected to form one huge open-pit mine which is approximately 3 miles long and varies in width from 200 to 1,600 feet. The mine, operated by the Jones and Laughlin Steel Corporation, is one of the nation's leading producers of "non-titaniferous" iron ore. Its crude ore production has at times ranked fifth, sixth and seventh among the largest producers of iron ore in the United States. It is said to be the largest open-pit magnetite mine in the world (Buddington, 1962).

The Benson Mines have been operated intermittently since 1918. In 1941, the Jones and Laughlin Steel Corporation leased the Benson mineral deposit and they have produced ore from it continuously since that time. The Benson ore is subdivided, according to the relative percentage of magnetite and hematite, into two types, magnetite and hematite ores. The magnetite ores are concentrated magnetically, the hematite ore, or as it is called locally, martite ore is concentrated by gravity means with spirals. Much of the concentrate is sintered before shipping from the mine site. In 1961, the Benson Mines produced 352,798 gross tons of concentrates and 1,062,830 gross tons of sintered concentrates. The magnetite concentrates contain 63 to 65 percent iron with approximately two-thirds of a percent titania; the martite concentrates contain 62 to 63 percent iron with approximately
2 percent titania.

B. Iron Ore

The known ore reserve within the open-pit is about 65 million tons of magnetite ore and 38 million tons of hematite ore, equivalent respectively to 22 and 12 million tons of magnetite and hematite concentrates, but the bottom of the deposit is not known.

The Benson iron ore consists of magnetite and hematite grains in metamorphic gneisses. The opaque iron oxide grains are disseminated to partly clustered in layers which alternate with iron oxide-poor, silicate-rich layers. The bands average about one-eighth of an inch wide and are more pronounced in the hematite-rich ore. The crude ore contains approximately 24 percent soluble iron and 0.8 percent titania. The magnetite and martite ores are mined separately, the gradational contact between them are assay contacts based on economic factors. Ore which has more than 17 percent of the soluble iron present as magnetite is termed magnetite ore.

The individual grains of magnetite and hematite are identical in mode of occurrence. Crystalline hematite grains were termed primary by Leonard and Buddington (1964), but these grains generally have been called martite at the Benson Mine. True martite and earthy hematite are scarce in the deposit, but are common locally.

Sporadic grains, small clusters and veinlets of sulfides especially pyrite, pyrrhotite and chalcopyrite occur in small amounts in the magnetite ore and are even more scarce in the hematite
ore. Molybdenite and bornite are rare.

Chemically the ore averages 24 percent soluble iron. Large amounts of silica, potassium and aluminum are contributed by the silicates. Small amounts of Mn, Ti, Ba, S and P have been detected. Titanium is present as sparse exsolution blades of ilmenite in the iron oxides, as anatase and as a solid solution constituent in the primary hematite and magnetite (Hagni, 1967). Manganese is present as spessartite, and barium is present in the potash feldspar and as sporadic grains of barite (Leonard and Buddington, 1964).

C. Lithology

The host rock for the Benson iron ore consists of three types: disseminated garnet gneiss, microcline granite gneiss and ferro-magnesian gneiss. The disseminated garnet gneiss is the host for most of the footwall magnetite ore body. It is a fine to medium-grained rock consisting of disseminated small garnets and is composed microcline, quartz, plagioclase and biotite. The microcline granite gneiss is composed mainly of microcline and accessory minerals of biotite, sillimanite, hornblende and pyroxene. Biotite and sillimanite facies of this gneiss are the host for most of the hematite ore. The ferro-magnesian gneiss is the host for most of the hanging wall ore body. It is a fine to medium-grain, melanitic gneiss composed of orthoclase, quartz, hypersthene, magnetite, ilmenite and apatite.

The host rocks for the magnetite ore bodies are believed
to be metasedimentary, but the microcline granite gneiss, which
cours as heterogeneous sheets conformable with these metasedimentary
rocks, was believed by Buddington (1939) to be a meta-igneous
rock. Crump (1965) believed that the chemical composition and a
quartzitic-like facies indicated the rock to be a metasediment.
Subsequently, Buddington (Buddington and Leonard, 1962, p. 70)
has modified his interpretation to that in which the microcline
granite gneiss either is the product of mass material transfer
effected by volatile rich microcline granite magma, or that the
rock is simply a reconstituted member of the Grenville series.
He believes metasomatism is indicated by the gradational contact
between biotite-quartz-plagioclase gneiss and sillimanite-
microcline-granite gneiss, by the restricted occurrence of the
microcline granite gneiss to the igneous complex, and by the
fact that the quartz content is much lower than that expected
from a thick sedimentary bed. The occurrence of hematite with
exsolution laths of ilmenite and rutile in the gneiss is
interpreted by Buddington to have resulted from the high-temperature
oxidizing fluids.

In addition to disseminated garnet gneiss, microcline
granite gneiss and ferromagnesian gneiss host rocks, two rock
types are exposed at the margins of the mine, stratigraphically
below and above the ore bodies. Plagioclase gneiss occurs
stratigraphically below the ore bodies. Due to the overturned
nature of the east limb, it constitutes the hanging wall gneiss.
It consists of albite or oligoclase, quartz, subordinate micro-
perthite or microcline, biotite, hornblende and augite. Blotchy
garnet gneiss occurs stratigraphically above the ore, and forms
the footwall gneiss which may be locally mineralized. It is a fine
to medium-grained rock which contains coarse garnet crystals
and is composed of microcline, quartz and plagioclase.

D. Structure

The structure of the Benson Mines area is complex due to
intense deformation during metamorphism. The general structure
has been determined by Dr. R. M. Crump and other Jones and
Laughlin staff geologists to be that of a syncline whose axis
trends and plunges slightly east of north. The west limb of the
syncline dips about 30 degrees to the east; the east limb is
overturned throughout most of the mine and generally dips very
steeply, about 85 degrees, to the east. The Benson Mines are
situated along the overturned east limb (Fig. 9a) and they
extend along the nose of the fold.

In the central portion of the Benson Mines the overturned
east limb of the syncline was further deformed and compressed
to form a recumbent syncline and anticline (Fig. 9b). These
subsidiary folds extend approximately 3,000 feet along the
strike of the ore and they plunge south in a direction opposite
to that of the major syncline.

To the west of the Benson pit, a small fold which has been
interpreted by some geologists to be another recumbent fold,
contained sufficient iron ore to have been formerly mined. That
open pit is called the Amoeba mine.

A series of east-west cross sections (Figs. 10-14), partly
sketched by the writer in the mine and partly taken from selections prepared by Dr. R. M. Crump and other Jones and Laughlin geologists, illustrate the structural relations in more detail. The locations of the sections are shown in Appendix I. Locations at which specimens were taken for this investigation are indicated on the sections.

Figure 9. (a) East-west cross section showing syncline and location of the ore; (b) section showing minor folds in major syncline.

E. Genesis of the Benson

There are two basic ideas regarding the genesis of the Benson ore and similar iron ores in the Adirondack region. One idea is that of a sedimentary origin; the other is that of hydrothermal origin.

Kemp (1898) studied the deposits at Port Henry, Barton Hill and Mineville. He believed that the magnetite was formed by solutions of igneous origin and that it was the result of contact
Figure 10. Geology along section A-A. Scale approximately 400 feet across and 200 feet high.
Figure 11. Geology along sections 4 and 5 showing the location of sample B-18. Scale approximately 500 feet across and 200 feet high.
Figure 12. Geology of section 16 showing the location of sample A-7. Scale approximately 400 feet across and 200 feet high.
Figure 13. Geology of sections 22 and 23 showing the location of sample A-3. Scale approximately 600 feet across and 200 feet high.
Figure 14. Geology of section 31 showing the locations of samples N-22 and N-25. Scale approximately 1,000 feet across and 200 feet high.
replacement because of their close association to the gabbros, the relatively thin beds and "Their similarity to neighboring titaniferous ores that occur in the gabbro and that are unquestionably of igneous origin" (Kemp, 1898, p. 192). In a paper on Elizabethtown and Port Henry in 1910, he changed his opinion to interpret the ore to be a basic segregation in syenite.

Newland (1908) like Kemp believed the magnetite of the Adirondack region, especially Benson, Clifton and Jayville were of an igneous origin. He believed that iron was derived from an acid magma deficient in lime and magnesia, the excess iron being concentrated by hot vapors and waters. Features supporting that interpretation are: 1) the ore deposits occur near intrusive bodies, 2) pegmatites and vein quartz occur with the deposits, 3) the wall rock shows evidence of the segregation of iron minerals to form fluorite, apatite and hornblende which occur with the deposits, and 4) some titanium is present in the ores.

Miller (1919) studied the Lyon Mountain deposits and interpreted that ore to be formed from an end-stage, gas charged, pegmatic fluid derived from the Lyon Mountain granite gneiss. The solution became enriched in iron on contact with the metagabbro and hornblende gneiss of the area. Miller cites the following facts in support of his beliefs: 1) The constant association of magnetic iron ores with Lyon Mountain granite, pegmatite and gabbro or hornblende gneiss, 2) strike and dip of the ore zones is very close to being parallel to the strike and dip of the adjacent granite and is interpreted as due to magmatic flowage under pressure, 3) the bands, strips or lenses of nearly
pure magnetite in the ore zones are probably the result of magmatic segregation, and 4) the granite, in contact with the magnetite, contains much magnetite which was absorbed by or forced into the granite while the granite was still in some degree of magmatic condition.

Nason (1922) advocated a sedimentary origin for the ores of Benson, Barton Hill, Fisher Hill and Harmony. He emphasized that the ores were conformable with the surrounding metasediments, the composition of some bands in the wall rock is sedimentary, the wall rock structure is sedimentary and that the ore bodies could be traced for long distances along the strike of these rocks.

Colony (1923) studied the ore deposits of southeastern New York, mainly in Westchester, Putnam, and Rockland Counties, but felt that these deposits were similar to the deposits of the Adirondacks. He believed that the ore was derived by differentiation of a basic magma to produce a mobile end-phase of "aqueo-igneous" solutions rich in magnetite, quartz and gases. This end-phase then subdivided into a pegmatitic fraction and a magnetitic fraction. The magnetic fraction replaced the calcareous facies of the gneiss during a period of stress to form the ore deposits.

Alling (1939) studied the magnetite ore deposits of most of the Adirondack Mountains including Mineville, Cheever Mine and Hammondville. After a lengthy study of thin sections and polished sections, he concluded that the ore bodies were mainly due to high-temperature metasomatic replacement with some hydrothermal activity. His evidence included 1) the pyroxene is early and commonly corroded suggesting that it was derived from early
crystallization of a basic magma, 2) albite and oligoclase replace "exsolutionized" perthite, and 3) quartz and magnetite were introduced contemporaneously and are seen replacing pyroxene, perthite, and granitic quartz.

In a recent comprehensive report on the iron deposits of St. Lawrence County, Leonard and Buddington (1964) interpreted them to be high-temperature replacement deposits produced by hydrothermal emissions from younger granites. They believe that these deposits represent a process that under slightly different conditions yielded the neighboring Balmat-Edwards sphalerite-galena-pyrite deposits, the "rusty gneiss" pyrite-pyrrhotite deposits and perhaps the Gouverneur talc-tremolite deposits. The following features are believed to support a high-temperature hydrothermal origin:

1. All magnetite deposits are close to at least one and generally more than one facies of the younger granites. Assuming that the biotite and sillimanite granite gneiss are facies of the younger granite, the magnetite deposits are within 500 feet of at least one facies of the younger granite. Usually the granite gneiss ores are within 200 to 300 feet of the younger granite.

2. All ore deposits, with a few exceptions, are within 0.5 mile of the hornblende-microperthite-granite or its equivalent gneiss.

3. Some deposits are farther away from the microcline granite gneiss, but are still in very close association with the alaskite or its equivalent gneiss. The distance of ore deposits to the microcline granite gneiss varies from 0 to 7.5 miles.
4. Many sulfides such as pyrite, chalcopyrite, bornite, pyrrhotite, sphalerite and galena are found within the ore deposits.

5. The ore deposits were formed at high-temperature (approximately 500 degrees C.) as is evidenced by the exsolution blades of ilmanite within the magnetite.

6. The iron-rich primary sphalerite of the Edwards-Balmat zinc deposits suggest that the sulfide deposits are of the hypothermal or mesothermal range.
Chapter IV
PETROFABRICS OF THE BENSON IRON ORE

A. Previous Investigations

The universal stage has been applied to precisely determine the optical properties and thus the chemical composition of many minerals. Among those optical properties best determined with the universal stage are: the optic angle, the pleochroic and absorption formulas, and the angular relationships of polysynthetic twinning in the plagioclase feldspars. Coupled with a heating stage and a monochromater, the universal stage forms a superior instrument with which to determine the indices of refraction of minerals (Emmons, 1943).

The universal stage also has been used to determine the preferred orientations of minerals in igneous and metamorphic rocks. Various oriented optical and physical properties of minerals may be determined such as the optic axis of quartz, the basal cleavage of the micas and the c-axis of the carbonates. The orientations determined for many grains, together with field observations, provide valuable information for fabric analysis. The mechanics and directions of movements involved in the emplacement of igneous rock bodies are more easily understood by means of petrofabric diagrams of these rocks. Petrofabric diagrams of metamorphic rocks yield information on the stress and strain conditions and time relations between constituent minerals.

Several studies have dealt with deformation of transparent grains in sedimentary and metasedimentary rocks. Cloos (1947)
studied the deformation of oolites to obtain information on the
dating of deformation, crystallization, consolidation and generally
the relationship between diagenesis and deformation. Using a
petrographic microscope, he observed that the oolites had been
elongated during metamorphism, but petrofabric diagrams were
not prepared.

The universal stage has been used by Gilbert and Turner
(1949) and Clover (1964) to aid in the examination of the nature
of the interfaces between constituent grains and the cementing
matrix of some sedimentary rocks. These interfaces, when studied
at different angles, tend to reveal features related to the
depositional or diagenetic processes which have affected the
sedimentary rock.

Megascopic studies of deformed pebbles by Goldschmidt (1916)
and Strand (1945), and of deformed fossils by Greely (1919)
revealed stress conditions. These studies did not require the
universal stage.

Thorough literature review has revealed no previous investi-
gations dealing with universal stage orientation of ore minerals
nor opaque minerals. The writer believes this investigation is
the first of its type.

B. Petrofabrics

Ten specimens were selected for this petrofabric study.
Selections were primarily based upon the uniformly disseminated
nature of the opaque ore grains. The abundance of quartz, biotite
and sillimanite present in the specimens was a secondary consideration.
These features were determined by preliminary petrographic study.

Petrofabric diagrams were prepared for the orientation fabrics of magnetite in eight of the ten specimens selected. Biotite was sufficiently abundant to provide representative diagrams for eight of the specimens, quartz and sillimanite were abundant in only three specimens. These diagrams, together with diagrams prepared for thin sections cut perpendicular to the first set of thin sections, involve a total of 28 diagrams. Eleven petrofabric diagrams were prepared for magnetite, eleven for biotite, four for quartz, and three for sillimanite.

1. Specimen A-7
   a. Field Notes
      Specimen A-7 was collected from the Anticline pit in an area in which the foliation was nearly horizontal.
   b. Megascopic Description
      Specimen A-7 is a fine-grained, pink, biotite-microcline-granite gneiss. It is strongly foliated with dark biotite-rich bands and light bands of pinkish feldspar and other silicates. Magnetite is sparsely disseminated throughout the entire rock.
   c. Biotite
      Two mutually perpendicular thin sections were cut in a north-south direction from specimen A-7, one in a horizontal plane, the other in a vertical plane. Face poles perpendicular to the basal pinacoid of 60 biotite grains were oriented in the horizontal section to produce the diagram shown in Figure 15. Although the points are slightly dispersed, their concentration
Figure 15. Orientation diagram for poles of (001) in biotite in a horizontal thin section of specimen A-7. Microcline granite gneiss. Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
toward the center of the diagram indicates that specimen A-7 has a foliation in which biotite cleavage flakes are essentially oriented in a horizontal plane. It must be remembered that in all biotite diagrams there is a "blind area" which complicates the diagram.

Ninety biotite grains were oriented in the vertical thin section and they produced the well developed axial pattern with concentrations on the left and right sides of the equal-area net shown in Figure 16. This pattern complements the fabric determined for the horizontal section (Fig. 14) and again indicates that specimen A-7 has a foliation in which biotite is essentially horizontal.

d. Magnetite

The same thin sections of sample A-7 utilized for the orientations of the biotite flakes were used in orienting the ovoid shaped magnetite grains. The long axes of 40 magnetite grains were oriented in the horizontal thin section to produce the diagram shown in Figure 17. The concentration of points at the margins of the equal-area net indicates that the long axes of the magnetite grains are essentially horizontal and coincident with the foliation plane of biotite in specimen A-8.

The orientation of the longest axes for 71 magnetite grains were determined in the vertical thin section of specimen A-7. The orientation diagram (Fig. 18) exhibits some scattered points, but the concentration along a north-south girdle indicates that the longest axes of magnetite tend to lie within the foliation plane of the biotite, but they exhibit no strong tendency toward a direction of lineation.
Figure 16. Orientation diagram for poles (001) for biotite in the vertical north-south thin section of specimen A-7. Top of the specimen is at the right periphery. Microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 17. Orientation diagram for the long axes of magnetite grains in the horizontal thin section of specimen A-7. Microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 18. Orientation diagram for the long axes of magnetite grains in the vertical thin section of specimen A-7. Top of the specimen is toward the right. Microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
e. Quartz

The same two thin sections from sample A-7 were used for orienting the quartz grains. The optic axes of 87 quartz grains in the horizontal section were oriented and plotted as shown in Figure 19. The diagram exhibits no distinct pattern and one is led to conclude that the optic axes of quartz have random orientation.

Seventy-five quartz grains were oriented in the vertical thin section of specimen A-7. Four maxima appear in a somewhat symmetrical pattern about the center of the diagram (Fig. 20). The writer is uncertain as to the significance of this pattern, but believes that most quartz is randomly oriented in this specimen.

f. Summary

Specimen A-7 displays a plane of foliation which is essentially horizontal and is revealed by the biotite petrofabrics. The long axes of magnetite are preferentially oriented within the foliation plane of the biotite, but show no strong tendency toward any lineation. The patterns produced by the quartz grains are essentially random.

2. Specimen A-3

a. Field Notes

Specimen A-3 was collected from an area of microcline granite gneiss of in the Anticline pit near the transition to the hanging wall magnetite ore body. The gneiss exhibits pronounced foliation which strikes northerly and dips 80 degrees east.
Figure 19. Orientation diagram for quartz (0001) in the vertical thin section of specimen A-7. Top of the specimen is toward the right. Microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2%, and 1% per 1% area.
Figure 20. Orientation diagram for quartz (0001) in the vertical thin section of specimen A-7. Top of the specimen is toward the right. Microcline granite gneiss, Anticline pit. Areas of 3% or greater; 2% and 1% per 1% area.
b. Megascopic Description

Specimen A-3 is a medium- to coarse-grained granite gneiss. Parallel bands of feldspars are present with the dark constituents forming alternate parallel bands. This specimen is darker than the usual microcline granite gneiss due to its transition to disseminated garnet gneiss. Small grains of iron sulfide and chalcopyrite can be seen megascopically.

c. Biotite

Two mutually perpendicular thin sections were cut from specimen A-3: one in the horizontal plane and the other in the vertical plane. The 100-point orientation diagram of the horizontal thin section for biotite shows a strong axial pattern (Fig. 21). This pattern indicates that the biotite cleavage is strongly aligned in a plane of foliation which is nearly vertical and north-south. That the plane is not exactly vertical is shown by a greater concentration of points at the left side than at the right side. Thus, the plane of foliation shown by biotite has a steep dip to the east like that foliation which was measured in the field.

Ninety biotite grains were oriented in the vertical thin section and plotted on the overlay shown in Figure 22. The pattern excellently complements that determined for the horizontal section. The axial pattern, which is modified by the central biotite "blind area", is slightly to one side of the center, indicating that biotite is oriented in a plane of foliation which strikes nearly north-south and dips at a very high angle to the east. The biotite plane of foliation is coincident with foliation...
Figure 21. Orientation diagrams for poles of (001) for biotite in the horizontal thin section of specimen A-3. Microcline granite gneiss ore, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 22. Orientation diagram for poles of (001) in the vertical thin section of specimen A-3. Top of specimen is toward the right. Microcline granite gneiss ore, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
measured in the field.

d. Magnetite

One vertical and two horizontal thin sections were utilized for magnetite orientation for specimen A-3. Since the magnetite orientations were similar in the two horizontal thin sections, those data were combined to produce the 64 point orientation diagram given in Figure 23. The pattern is one of considerable scatter, but a weak girdle pattern, trending slightly east of north, indicates that the longest axes of magnetite tend to lie in the plane of foliation discerned by biotite orientation and by field measurements. A slight tendency toward lineation is suggested by the local concentrations of points. One of these is nearly vertical, another is almost horizontal.

In the vertical section of specimen A-3 the orientation of the longest axes of 45 magnetite grains were determined. The orientation diagram (Fig. 24) exhibits a weak girdle pattern around the periphery of the net, a pattern which is the complement of that shown by the horizontal sections. The longest axes of the magnetite grains tend to lie in the plane of foliation, but local concentrations of points may indicate a tendency toward lineation.

e. Summary

Specimen A-3 has foliation which strikes nearly north and dips 80° east. The foliation is sufficiently pronounced to measure in the field and it is shown by the biotite whose basal cleavages are strikingly oriented in the plane of foliation. The orientations of the long axes of magnetite grains in one vertical and two horizontal thin sections exhibit some scatter,
Figure 23. Orientation diagram for the long axes of magnetite grains in the horizontal thin section for specimen A-3. Microcline granite gneiss ore, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 24. Orientation diagram for the long axes of magnetite in the vertical thin section for specimen A-3. Top of the specimen is toward the right. Microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
but a weak girdle pattern in all these diagrams indicates that the magnetite tends to be aligned within the plane of foliation. Local concentration of points suggests a slight tendency toward preferred directions of lineation.

3. Specimen H-36
   a. Field Notes
      Specimen H-36 was collected by Dr. Magni from drill hole 1191 at the 290 foot level. One thin section prepared from the specimen is of unknown orientation, but the section was included in this study because of its abundant sillimanite.
   b. Sillimanite
      Forty-six sillimanite grains were oriented in the single thin section and plotted as shown in Figure 25. The orientation diagram exhibits a well developed axial pattern, which indicates that the c-axes of sillimanite are strongly oriented in a preferred direction of lineation which lies in the plane of the thin section and strikes about 75° east of an assumed north position.
   c. Magnetite
      The orientation diagram for the long axes of 68 magnetite grains in the same section used for sillimanite orientation, is shown in Figure 26. The fact that nearly all of the points lie at the periphery of the equal-area net indicates that the longest axes of magnetite are oriented in a preferred plane which is about that of the thin section. The distinct concentration of these points in the west-southwest and east-northeast direction indicates a rather strong lineation. The
Figure 25. Orientation diagram for the long axes of sillimanite grains of specimen H-36. Taken from Dr. Hagni's collection, drill hole number 1191 at the 290 foot level. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 26. Orientation diagram for the long axes of magnetite grains for specimen H-36. Taken from Dr. Hagni's collection, drill hole number 1191 at the 290 foot level. Areas of 3% or greater, 2% and 1% per 1% area.
direction of magnetite lineation is the same as that of sillimanite, but the former exhibits more scatter within the plane of the thin section, presumably the plane of foliation.

d. Summary

Specimen H-36 contains relatively abundant sillimanite whose c-axes are strongly aligned in a horizontal direction of lineation which strikes about 75° east of an assumed north position and lies nearly within the plane of the thin section. The long axes of magnetite in this specimen are strongly aligned in a horizontal plane of foliation, but most importantly, they exhibit a strong tendency toward a direction of lineation within that plane, which is the same direction of lineation shown by sillimanite.

4. Specimen N-5

a. Field Notes

Specimen N-5 was collected from the Newton Falls pit in an area in which the gneiss exhibits very weak foliation which appears to have a northerly strike and a vertical dip. The specimen is from the magnetite ore zone in the Newton Falls pit.

b. Megascopic Description

Specimen N-5 is a ferromagnesian garnet gneiss which is exceptionally magnetite-rich. Some degree of parallelism exists between the magnetite bands. The specimen is black in color due primarily to the abundant magnetite and to the dark ferromagnesian silicate minerals.
c. Biotite

Two mutually perpendicular thin sections were prepared from specimen N-5; one in a horizontal plane, the other in a vertical plane. In the horizontal thin section 57 biotite grains were oriented and plotted as shown in Figure 27. The orientation diagram exhibits a well developed axial pattern, which indicates that the basal cleavage of biotite is aligned in a preferred plane of foliation which is nearly vertical and strikes northwesterly. The writer believes that the northwest strike of the biotite plane more nearly represents the foliation of specimen N-5, than does that measured in the field due to the very weak nature of that foliation. The greater concentration of poles at the northeast periphery indicates the plane is not exactly vertical but dips very steeply to the southwest, about 85°.

In the vertical thin section 56 biotite grains were oriented as shown in Figure 28. The pattern is very much complicated by the central biotite "blind area" and by apparent scatter of the biotite poles. The pattern confirms only in a very general manner that shown by the horizontal thin section. The differences between the two patterns seem accounted for by the fact that nearly vertical biotite flakes are much more easily oriented with the universal stage in a horizontal thin section than in a vertical section.

d. Magnetite

Both the horizontal and vertical thin sections were utilized for magnetite orientation, but only a few magnetite grains were sufficiently separated from contiguous magnetite to
Figure 27. Orientation diagram for poles of (001) for biotite in the horizontal thin sections of specimen N-5. Ferromagnesian garnet gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
N

Figure 28. Orientation diagram for poles of (001) for biotite in the vertical thin section of specimen N-5. Top of the specimen is toward the right. Ferromagnesian garnet gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
determine their shape and orient them. The 40 magnetite grains oriented in the horizontal thin section are shown in Figure 29. Those points may be somewhat concentrated in the northwest vertical biotite plane of foliation, but the small number of points and their rather high degree of scatter makes such an interpretation unclear. Similarly, the orientation diagram (Fig. 30) for the longest axes of magnetite grains in the vertical thin section exhibits no clear pattern due to the small number of scattered points.

e. Summary

Specimen N-5 contains biotite grains with basal cleavage which is strongly oriented in a plane of foliation striking northwest and dipping nearly vertically. The longest axes of magnetite grains may be preferentially oriented in the plane of foliation, but the scarce number of magnetite grains oriented and the scatter of those points preclude a definite conclusion on that point for this specimen.

5. Specimen S-1

a. Field Notes

Specimen S-1 was collected 3 miles east of Sevey at a locality listed by Buddington and Lindsley (1964, p. 340) as the product of partial metasomatism and modification of biotite-quartz-plagioclase paragneiss. In this rock "The disseminated oxide minerals could have been formed by increasing oxidation and destruction of the primary biotite...in the original gneiss without appreciable loss or addition of iron and titanium". Well developed foliation at the specimen site strikes N. 35° W. and
Figure 29. Orientation diagram for the long axes of magnetite grains in the horizontal thin section of specimen N-5. Ferromagnesian garnet gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 30. Orientation diagrams for the long axes of magnetite grains in the vertical thin section of specimen N-5. Top of the specimen is toward the right. Ferromagnesian garnet gneiss. Areas of 3% or greater, 2% and 1% per 1% area.
dips 65° NE.

b. Megascopic Description

Specimen S-1 is a moderately foliated plagioclase-microcline granite gneiss. The foliation is shown best by abundant biotite clustered together in some bands. It is a light pink, fine- to medium-grained rock with parallel bands of feldspar alternately with biotite-rich bands. Magnetite is not apparent megascopically.

c. Biotite

One horizontal thin section was prepared from specimen S-1. The orientations of the basal cleavages of 110 grains of biotite were determined and plotted to produce the orientation diagram shown in Figure 31. The diagram exhibits a strong axial pattern indicating that biotite is preferentially oriented in a nearly vertical foliation plane striking northwest. The orientation of the biotite plane is that of the foliation plane measured in the field.

d. Magnetite

Magnetite grains are not abundant in the horizontal section of the unmineralized specimen S-1 and only twenty-two grains could be oriented. The few points plotted are shown in Figure 32. The points are much too sparse to allow any important conclusions to be drawn, but more points are located generally close to the northwest biotite foliation plane than far from it.

e. Summary

Specimen S-1 contains abundant biotite with basal cleavages which are strongly aligned in the nearly vertical
Figure 31. Orientation diagram for poles of (001) of biotite in the horizontal thin section of specimen S-1. Plagioclase gneiss, Sevey, New York. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 32. Orientation diagram for long axes of magnetite grains in the horizontal thin section of specimen S-1. Plagioclase gneiss, Sevey, New York. Areas of 3% or greater, 2% and 1% per 1% area.
northwest striking foliation measured in the field. The longest axes of the magnetite probably are preferentially oriented within the foliation plane as shown so well by the specimens previously discussed, but magnetite is not abundant enough in this specimen to determine the orientation point with certainty.

6. Specimen N-22
   a. Field Notes
      Specimen N-22 was obtained from the Newton Falls pit. Weak foliation in the vicinity of this specimen is difficult to measure. The strike is about N. 15° W. and its dip is approximately 75° east.
   b. Megascopic Description
      Specimen N-22 is a weakly foliated blotchy garnet gneiss. It has a fine to medium-grained texture and displays a dark color with a greenish hue. The specimen is weakly mineralized with magnetite present as disseminated grains or in small clusters. Some garnet is present as small crystals.
   c. Biotite
      Two thin sections were prepared from specimen N-22. Biotite was oriented in the horizontal thin section in which it was the most abundant, and magnetite was oriented in the vertical section in which it was most abundant. The basal cleavages of 50 biotite grains were oriented in the horizontal thin section prepared from specimen N-22. The pattern displayed by these grains is given in Figure 33. Although the diagram reveals some scatter, the axial concentration near the northeast periphery
Figure 33. Orientation diagrams for poles of (001) of biotite in the horizontal thin section of specimen N-22. Microcline granite gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
indicates that the biotite flakes are aligned in a foliation which
strikes northwesterly. The plane is nearly vertical but has a
very steep dip to the southwest. The plane of foliation
determined for biotite has nearly the same orientation as the
foliation measured in the field.

d. Magnetite

The longest axes of 54 grains of magnetite were
oriented in the vertical thin section. These poles are shown in
Figure 34. The pattern is one of considerable scatter, but there
may be a slight tendency for the poles to occur more in the north-
west vertical foliation plane (horizontal in this diagram) than
elsewhere.

e. Summary

Specimen N-22 contains biotite with basal
cleavages which tend to be aligned parallel to foliation measured
in the field. The writer believes that the longest axes of magnetite
may be somewhat preferentially oriented in the plane of foliation
as shown by the specimens previously discussed, but the rather high
degree of scatter shown by the magnetite orientation diagram
precludes a definite conclusion in this regard.

7. Specimen H-32

a. Field Notes

Specimen H-32 was obtained from drill hole 1191 at
the 449 foot level by Dr. Hagni. The specimen was used because it
contained relatively abundant sillimanite along with sufficient
amounts of biotite and magnetite to compare the orientation
Figure 34. Orientation diagram for long axes of magnetite grains in the vertical thin section of specimen N-22. Microcline granite gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
patterns of all three of these minerals in a single thin section. The orientation is unknown.

b. Biotite

The basal cleavages of 51 biotite grains were oriented in a single thin section and their orientations are shown in Figure 35. The diagram displays a strong axial pattern and indicates that the biotite flakes are oriented in a nearly vertical, northwest trending plane of foliation (assuming a north position and a horizontal orientation for the thin section).

c. Sillimanite

The c-axes of forty sillimanite grains were oriented from the same thin section and plotted on the orientation diagram shown in Figure 36. The diagram exhibits a well developed axial pattern in which the c-axes of sillimanite are oriented in a horizontal northwest direction of lineation. The sillimanite lineation lies within the plane of foliation shown by biotite.

d. Magnetite

In the same thin section, the longest axes of 47 magnetite grains were oriented. The resulting pattern is shown in Figure 37. The pattern indicates only a general correspondence between the longest axes of magnetite and the biotite plane of foliation. The pattern is insufficiently axial to compare with that of sillimanite.

e. Summary

Specimen H-36 exhibits a distinct preference for the biotite flakes to be aligned in a nearly vertical northwesterly striking plane. The c-axes of sillimanite occur in a well exhibited
Figure 35. Orientation diagram for poles of (001) of biotite of specimen H-32. Taken from Dr. Magni's collection, drill hole number 1191 at the 449 foot level. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 36. Orientation diagram for long axes of sillimanite of specimen H-32. Taken from Dr. Hagni's collection, drill hole number 1191 at the 449 foot level. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 37. Orientation diagram for long axes of magnetite of specimen H-32. Taken from Dr. Hagni's collection, drill hole number 1191 at the 449 foot level. Areas of 3% or greater, 2% and 1% per 1% area.
horizontal direction of lineation which lies within the plane of foliation determined by biotite orientation. The longest axes of magnetite grains exhibit a broad correspondence to the biotite plane of foliation.

8. Specimen A-1

a. Field Notes

Specimen A-1 was collected from an area in the Anticline pit where the foliation is weak and indistinct but appears to strike about N. 55° E.

b. Megascopic Description

Specimen A-1 is a dark colored, disseminated garnet gneiss in which the foliation is weak and indistinct. Sillimanite is a common constituent in this specimen because it was located near the transition into microcline granite gneiss. Generally the specimen is fine-grained and contains rare grains of chalcopyrite. The specimen is only weakly mineralized with magnetite.

c. Biotite

Two mutually perpendicular thin sections were cut from specimen A-1. The vertical section was utilized for biotite and magnetite, but sillimanite was best oriented in the horizontal section. The orientations of the basal cleavages of 52 biotite grains are shown in Figure 38. The resulting pattern is a moderately well defined axial pattern in which the biotite flakes are nearly horizontal.

d. Sillimanite

The c-axes of 58 sillimanite grains were oriented in the horizontal section of specimen A-1. The orientation diagram for
Figure 38. Orientation diagram for poles of (001) of biotite in the vertical thin section of specimen A-1. Top of the specimen is toward the right. Biotite-sillimanite-microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
these axes is given in Figure 39. The well developed axial pattern shows that the c-axes of sillimanite are aligned in a horizontal northwest direction of lineation. The lineation direction of sillimanite is within the horizontal plane of foliation determined for biotite.

e. Magnetite

The longest axes of 43 magnetite grains were oriented in the vertical section of specimen A-1. These orientations are given in Figure 40. The orientation diagram exhibits a moderately well developed axial pattern which indicates that the long magnetite axes are mostly horizontal and moderately concentrated in a north-northwest direction of lineation. Thus, the magnetite axes are preferentially aligned in the biotite plane of foliation; they have tendency toward a direction of lineation which is less pronounced than that of sillimanite, but is roughly in the same direction.

f. Summary

Specimen A-1 contains moderately abundant biotite with basal cleavages which reveal a well defined, nearly horizontal plane of foliation. Both sillimanite and magnetite exhibit axial patterns which indicate that their directions of lineation lie within the horizontal biotite plane of foliation. The magnetite lineation pattern exhibits more scatter, but trends north-northwesterly, roughly coincident with that of the sillimanite lineation.
Figure 39. Orientation diagram for long axes of sillimanite grains in the horizontal thin section of specimen A-1. Biotite-sillimanite-microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 40. Orientation diagram for long axes of magnetite grains in the vertical section of specimen A-1. Top of the specimen is toward the right. Biotite-sillimanite-microcline granite gneiss, Anticline pit. Areas of 3% or greater, 2% and 1% per 1% area.
9. Specimen B-18
   a. Field Notes
      Specimen B-18 was collected from the Benson pit in an area where the foliation strikes N, 30° E, and dips 83° SE.
   b. Megascopic Description
      Specimen B-18 is a light grey to pink, medium-grained hanging wall plagioclase gneiss which displays weak foliation. Light colored bands of feldspar show some parallelism. Quartz and feldspar are the principal constituents of this specimen with biotite, magnetite and iron sulfides present in minor amounts.
   c. Quartz
      The final two specimens are included here only to show the random orientation of quartz in the microcline granite gneisses. The optic axes of 60 quartz grains were oriented in the horizontal thin section prepared from specimen B-18. The resulting plots are shown in Figure 41. The pattern is one of random orientation. The several local maxima appear to be of no significance.

10. Specimen N-25
   a. Field Notes
      Specimen N-25 was collected from the Newton Falls pit from an area where the foliation strikes N, 50° W, and has a variable southwest dip of 30 to 80 degrees. Local swirling of the foliation accounts for its variable dip.
   b. Megascopic Description
      Specimen N-25 is a coarse-grained, pink, microcline
Figure 41. Orientation diagram for quartz (0001) in the horizontal thin section of specimen B-18. Microcline granite gneiss, Benson pit. Areas of 3% or greater, 2% and 1% per 1% area.
Figure 42. Orientation diagram for quartz (0001) in the horizontal thin section of specimen N-25. Microcline granite gneiss, Newton Falls pit. Areas of 3% or greater, 2% and 1% per 1% area.
granite gneiss. It consists of pinkish feldspar, quartz, iron oxide and biotite.

c. Quartz

Specimen N-25 is included only to demonstrate the random orientation of quartz. The optic axes of 64 quartz grains were oriented in a single horizontal thin section, and the resulting pattern is shown in Figure 42. The essential feature of the pattern is that of random orientation of the quartz axes. Small, local maxima appear to be of little significance.

11. Summary of Petrofabrics

The results of the petrofabric study are summarized in Table I. The correspondance between iron ore petrofabrics and that of the host silicates is most marked for those specimens exhibiting stronger foliation and less pronounced for those with weaker foliation. Those specimens containing smaller numbers of magnetite grains suitable for orientation display a less distinct correlation.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Rock Type</th>
<th>Foliation</th>
<th>Biotite</th>
<th>Sillimanite</th>
<th>Magnetite</th>
<th>No. or Orient. Mag. Grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-7</td>
<td>Microcline Granite Gneiss</td>
<td>Strong</td>
<td>Horizontal</td>
<td>---</td>
<td>Concentrated in biotite foliation, Tendency toward lineation.</td>
<td>110</td>
</tr>
<tr>
<td>A-3</td>
<td>Garnet Gneiss Transitional to disseminated garnet gneiss.</td>
<td>Strong</td>
<td>Vertical N-S</td>
<td>---</td>
<td>Concentrated in biotite foliation, Tendency toward lineation.</td>
<td>64</td>
</tr>
<tr>
<td>H-36</td>
<td>Microcline Granite Gneiss</td>
<td>Strong</td>
<td>Vertical N-W</td>
<td>Horizontal N-W</td>
<td>Horizontal N-W, Parallel to sillimanite lineation.</td>
<td>68</td>
</tr>
<tr>
<td>N-5</td>
<td>Ferro-Magnesian Gneiss</td>
<td>Weak</td>
<td>Vertical N-W</td>
<td>---</td>
<td>Scattered</td>
<td>40</td>
</tr>
<tr>
<td>N-21</td>
<td>Plagioclase Granite Gneiss</td>
<td>Moderate</td>
<td>Vertical N-W</td>
<td>---</td>
<td>Roughly in biotite foliation.</td>
<td>22</td>
</tr>
<tr>
<td>N-22</td>
<td>Blotchy Garnet Gneiss</td>
<td>Weak</td>
<td>Vertical N-W</td>
<td>---</td>
<td>Roughly in biotite foliation.</td>
<td>54</td>
</tr>
<tr>
<td>H-32</td>
<td>Microcline Granite Gneiss</td>
<td>Strong</td>
<td>Horizontal</td>
<td>Horizontal N-W</td>
<td>Roughly in biotite foliation. Tendency to be parallel to sillimanite lineation.</td>
<td>47</td>
</tr>
<tr>
<td>A-1</td>
<td>Disseminated Garnet Gneiss</td>
<td>Weak</td>
<td>---</td>
<td>Horizontal N-W</td>
<td>In biotite foliation. Fair lineation nearly parallel to sillimanite lineation.</td>
<td>43</td>
</tr>
<tr>
<td>B-18</td>
<td>Hanging Wall Plagioclase Granite Gneiss</td>
<td>Weak to Moderate</td>
<td>Quartz is essentially random</td>
<td>---</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>N-25</td>
<td>Microcline Granite Gneiss</td>
<td>Weak</td>
<td>Quartz is essentially random</td>
<td>---</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>
Chapter V
SUMMARY AND CONCLUSIONS

The iron ore deposit at Benson Mines, New York is characterized by disseminations of magnetite and hematite in metamorphic gneisses. The gneisses are medium- to coarse-grained rocks which have developed under conditions of high-grade regional metamorphism. Feldspars, quartz, garnet and iron oxide ores are the principal constituents in the gneisses, but biotite, sillimanite and other silicates are abundant in some facies. Foliation generally is only weakly developed, but some facies, especially the microcline granite gneiss, may exhibit moderately well developed foliation.

Petrographic study of the gneisses shows no alteration which can be correlated with the introduction of the iron ores and reveals that the individual ore grains are similar in size and shape to the major silicate grains in the gneiss. Those magnetite or hematite grains which are surrounded by silicates tend to exhibit rounded shapes similar to that of the silicate grains, and many have an ovate or egg shape. The tendency for the longest axes of ovate ore grains to lie approximately in the same direction and parallel to that of some associated silicate grains suggested this petrofabric investigation.

Universal stage determination of the orientations of biotite basal cleavages, sillimanite c-axes, magnetite (and hematite) long axes and quartz optic axes shows that these features of the first three minerals often exhibit a close correspondence. The
basal cleavages of biotite grains are clearly aligned in a plane of foliation which is much more distinct than that which can be observed megascopically. The c-axes of sillimanite are distinctly aligned in a direction of lineation which lies within the plane of biotite foliation. The petrofabrics for the long axes of ovate ore grains exhibits more scatter than those for biotite and sillimanite. In the more strongly foliated gneiss specimens, the long axes of magnetite generally lie within the plane of biotite foliation. In weakly foliated gneisses and in those specimens for which few ore grains were available for orientation, only a rough correspondence between magnetite long axes and biotite foliation could be determined. The petrofabric diagrams also reveal a tendency for the long axes of the ore grains to be concentrated in a direction of lineation. This tendency is greatest in those specimens containing abundant sillimanite and in those specimens the two minerals are aligned essentially in the same direction of lineation. In those specimens of gneiss which contain sufficient quartz, their c-axes appear to be randomly oriented. To summarize, in those specimens which show the relationships best, the long axes of the ore grains are oriented within the biotite plane of foliation and concentrated in a direction of sillimanite lineation.

The correspondence of orientation of ore grains with that of the host silicates may have developed in one of two manners. The iron ore minerals may have replaced the host rock gneiss due to hydrothermal introduction in a manner prescribed by Buddington (1966). In this case, the high degree of orientation placed upon
the introduced ore grains by the foliated host rock would be remarkable. This feature, together with the lack of alteration, general metamorphic texture of the ore, the conformable relation of the ore with the host rock and the general restriction of ore types to corresponding host rock types suggests that the Benson ores may not have formed from post-metamorphic hydrothermal introduction. Instead, these features, and especially the petrofabric results from this study suggest that the iron was present in the host rocks at the time at which it was subjected to the metamorphism which produced the host rock petrofabrics. The ultimate origin of the iron may have been pre- or synmetamorphic hydrothermal introduction or simply that of an originally iron-rich sediment.
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APPENDIX I
MAP VIEW OF BENSON MINES
SHOWING SAMPLE LOCATIONS

SCHEDULE 0-260
SCALE 0 FEET

MINING FACE
LINES NUMBERED 1 TO 33 ARE DRILL HOLE COORDINATES
AFTER JONES AND LAURIE; STEEL CORPORATION
NEW YORK ORE DIVISION, STAR LAKE, NEW YORK