1968

Mineralization of the Boss Bixby anomaly, Iron and Dent Counties, Missouri

Frederick Joseph Smith

Follow this and additional works at: http://scholarsmine.mst.edu/masters_theses

Part of the Geology Commons

Recommended Citation

MINERALIZATION OF THE BOSS
BIXBY ANOMALY, IRON AND
DENT COUNTIES, MISSOURI

by

Frederick J. Smith, M.S.

A

THESIS

submitted to the faculty of

THE UNIVERSITY OF MISSOURI AT ROLLA

in fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE IN GEOLOGY
Rolla, Missouri
1968

approved by
(Advisor)

A. Legedín
ABSTRACT

The Ross-Sixby deposit is located on the line dividing Iron and Dent Counties and belongs to the Southeast Missouri Precambrian Iron Metallogenic Province. The sequence of events leading to the formation of the deposit is reviewed. The mineralization occurred after intrusion of intermediate magma, but prior to the intrusion of granite. The ore minerals present are the following in the order of deposition: magnetite, ilmenite, giddiclite, hematite, rutile, pyrite, polybasite, cobaltite, chalcopyrite, bornite, sphalerite, galena, limonite, chalcocite, and cuprite. Four different methods of zoning are presented. Partial pressures of oxygen and sulphur, as well as temperature controlled sequential deposition of ore. This deposit is classified as a pyrometasomatic body.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td></td>
<td>LIST OF PLATES</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>I</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>Location and Accessibility</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>Previous Work</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>Purpose and Scope</td>
<td>3</td>
</tr>
<tr>
<td>D</td>
<td>Acknowledgments</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>Regional Geologic Setting</td>
<td>5</td>
</tr>
<tr>
<td>II</td>
<td>METHOD OF INVESTIGATION</td>
<td>11</td>
</tr>
<tr>
<td>A</td>
<td>Sampling Procedure</td>
<td>11</td>
</tr>
<tr>
<td>B</td>
<td>Polished Section Preparation</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td>Mineral Determination Methods</td>
<td>15</td>
</tr>
<tr>
<td>III</td>
<td>IGNEOUS AND METAMORPHIC PETROLOGY</td>
<td>17</td>
</tr>
<tr>
<td>A</td>
<td>General Statement</td>
<td>17</td>
</tr>
<tr>
<td>B</td>
<td>Volcanic Rocks</td>
<td>18</td>
</tr>
<tr>
<td>C</td>
<td>Intrusive Rocks</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>Syenites</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Diorites</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>Andesites</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>Granites</td>
<td>26</td>
</tr>
<tr>
<td>D</td>
<td>Metamorphic Rocks</td>
<td>26</td>
</tr>
<tr>
<td>E</td>
<td>Petrogenesis</td>
<td>30</td>
</tr>
<tr>
<td>IV</td>
<td>ORE MINERALIZATION</td>
<td>35</td>
</tr>
<tr>
<td>A</td>
<td>General Statement</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>General Structure Types</td>
<td>35</td>
</tr>
<tr>
<td>C</td>
<td>Mineralogy</td>
<td>35</td>
</tr>
<tr>
<td>1</td>
<td>Oxides</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>Sulphides</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>Hydrous Oxides</td>
<td>41</td>
</tr>
<tr>
<td>D</td>
<td>Mineralogic Relationships</td>
<td>42</td>
</tr>
<tr>
<td>V</td>
<td>PARAGENESIS AND ZONING</td>
<td>61</td>
</tr>
<tr>
<td>A</td>
<td>General Statement</td>
<td>61</td>
</tr>
<tr>
<td>B</td>
<td>Paragenesis</td>
<td>61</td>
</tr>
<tr>
<td>C</td>
<td>Zoning</td>
<td>63</td>
</tr>
<tr>
<td>D</td>
<td>Causes of Sequential Deposition</td>
<td>69</td>
</tr>
</tbody>
</table>
Chapter VI. ORE GENESIS AND CLASSIFICATION .............. 70

A. General Statement ...................................... 70
B. Composition ............................................... 70
C. Manner of Transportation ................................. 70
D. Deposition .................................................. 71
E. Classification ............................................... 72
F. Source ....................................................... 73

Chapter VIII. CONCLUSIONS .................................. 74

BIBLIOGRAPHY ..................................................... 75

VITA ................................................................. 76
**LIST OF PLATES**

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-A</td>
<td>Photomicrograph of rhyolite porphyry</td>
<td>19</td>
</tr>
<tr>
<td>1-B</td>
<td>Photomicrograph of a hornblende rhyolite</td>
<td>19</td>
</tr>
<tr>
<td>2-A</td>
<td>Photomicrograph of a quartz-K-feldspar-magnetite veinlet in a syenite porphyry</td>
<td>23</td>
</tr>
<tr>
<td>2-B</td>
<td>Photomicrograph of microsyanite</td>
<td>23</td>
</tr>
<tr>
<td>3-A</td>
<td>Photomicrograph of a diorite porphyry</td>
<td>25</td>
</tr>
<tr>
<td>3-B</td>
<td>Photomicrograph of a microdiorite</td>
<td>25</td>
</tr>
<tr>
<td>4-A</td>
<td>Photomicrograph of a fine-grain biotite granite</td>
<td>27</td>
</tr>
<tr>
<td>4-B</td>
<td>Photomicrograph of a magnetite-bearing andesite</td>
<td>27</td>
</tr>
<tr>
<td>5-A</td>
<td>Photomicrograph of a contact metamorphosed rhyolite</td>
<td>29</td>
</tr>
<tr>
<td>5-B</td>
<td>Photomicrograph of a biotite schist</td>
<td>29</td>
</tr>
<tr>
<td>6-A</td>
<td>Photomicrograph of magnetite and chalcopyrite</td>
<td>43</td>
</tr>
<tr>
<td>6-B</td>
<td>Photomicrograph of martite</td>
<td>43</td>
</tr>
<tr>
<td>7-A</td>
<td>Photomicrograph of magnetite and chalcopyrite and ilmenite</td>
<td>46</td>
</tr>
<tr>
<td>7-B</td>
<td>Photomicrograph of magnetite, chalcopyrite, and ilmenite</td>
<td>46</td>
</tr>
<tr>
<td>8-A</td>
<td>Photomicrograph of magnetite, bornite, and chalcopyrite</td>
<td>47</td>
</tr>
<tr>
<td>8-B</td>
<td>Photomicrograph of magnetite and chalcopyrite</td>
<td>47</td>
</tr>
<tr>
<td>9-A</td>
<td>Photomicrograph of magnetite, chalcopyrite, and ilmenite</td>
<td>48</td>
</tr>
<tr>
<td>9-B</td>
<td>Photomicrograph of magnetite, hematite, and pyrite</td>
<td>48</td>
</tr>
<tr>
<td>10-A</td>
<td>Photomicrograph of magnetite and hematite</td>
<td>49</td>
</tr>
<tr>
<td>10-B</td>
<td>Photomicrograph of magnetite, chalcopyrite, and bornite</td>
<td>49</td>
</tr>
<tr>
<td>Plate</td>
<td>Photomicrograph of mineral(s)</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11-A</td>
<td>Photomicrograph of magnetite, hematite, and ilmenite</td>
<td>50</td>
</tr>
<tr>
<td>11-B</td>
<td>Photomicrograph of magnetite, hematite, and chalcopyrite</td>
<td>50</td>
</tr>
<tr>
<td>12-A</td>
<td>Photomicrograph of magnetite and hematite</td>
<td>51</td>
</tr>
<tr>
<td>12-B</td>
<td>Photomicrograph of magnetite and hematite</td>
<td>51</td>
</tr>
<tr>
<td>13-A</td>
<td>Photomicrograph of pyrite, sphalerite, and chalcopyrite</td>
<td>54</td>
</tr>
<tr>
<td>13-B</td>
<td>Photomicrograph of pyrite and magnetite</td>
<td>54</td>
</tr>
<tr>
<td>14-A</td>
<td>Photomicrograph of pyrite, magnetite and galena</td>
<td>55</td>
</tr>
<tr>
<td>14-B</td>
<td>Photomicrograph of pyrite and magnetite</td>
<td>55</td>
</tr>
<tr>
<td>15-A</td>
<td>Photomicrograph of bornite, chalcopyrite, and magnetite</td>
<td>57</td>
</tr>
<tr>
<td>15-B</td>
<td>Photomicrograph of magnetite, pyrite, bornite and chalcopyrite</td>
<td>57</td>
</tr>
<tr>
<td>16-A</td>
<td>Photomicrograph of magnetite, chalcopyrite, and sphalerite</td>
<td>58</td>
</tr>
<tr>
<td>16-B</td>
<td>Photomicrograph of pyrite, chalcopyrite, and magnetite</td>
<td>58</td>
</tr>
<tr>
<td>17-A</td>
<td>Photomicrograph of cobaltite, hematite, and magnetite</td>
<td>59</td>
</tr>
<tr>
<td>17-B</td>
<td>Photomicrograph of hematite, chalcopyrite, and bornite</td>
<td>59</td>
</tr>
<tr>
<td>18-A</td>
<td>Photomicrograph of sphalerite, chalcopyrite, and pyrite</td>
<td>60</td>
</tr>
<tr>
<td>18-B</td>
<td>Photomicrograph of sphalerite, chalcopyrite and pyrite</td>
<td>60</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geologic Map</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Ore Mineral Paragenesis of the Boss-Bixby Anomaly</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>Distribution of Ti Content of the Purified Magnetites - Boss-Bixby Deposit</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>Distributions of Brown and Blue Magnetites - Boss-Bixby Deposit</td>
<td>66</td>
</tr>
<tr>
<td>5</td>
<td>Distribution of Magnetite/Ilmenite Ratio - Boss-Bixby Deposit</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Distribution of Oxide/Sulfide Ratio - Boss-Bixby Deposit</td>
<td>68</td>
</tr>
</tbody>
</table>

LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Characteristic Features of the Proterozoic Iron Deposits of Missouri</td>
<td>9</td>
</tr>
<tr>
<td>II</td>
<td>Selected Spectrochemical Analyses of Magnetite of Boss-Bixby</td>
<td>44</td>
</tr>
</tbody>
</table>
Chapter I
INTRODUCTION

A. Location and Accessibility

The Boss-Bixby Anomaly, named by American Zinc Company is located in portions of Sections 8, 9, 16 and 17 of T. 34 N., R. 2 W., in southeastern Missouri between the towns of Boss and Bixby. The anomaly, which is the surface magnetic expression of a Precambrian iron and copper deposit, straddles the line dividing Iron and Dent Counties. Stainbrook (1954) and other authors refer to it as the Boss Anomaly.

The area can be reached by Missouri Highway 32 east of Salem, Missouri, or by Missouri Highways 19 and 49 southeast of Cuba, Missouri. In addition to highway accessibility, the area is serviced by a recently completed railroad spur from Keysville, Missouri to Buck, Missouri. Private air strips are also found in the area.

B. Previous Work

The magnetic anomaly was discovered in 1943 by the Missouri Geological Survey in the process of preparing the first magnetic map of Missouri. The station interval used in that ground survey was so wide that the true extent and intensity of the anomaly was not expressed. Later aeromagnetic maps published by the Missouri Geological Survey of the area revealed that the Boss-Bixby Anomaly
was not a single magnetic high, but a double-coned one.

The American Zinc Company, formerly known as the American Zinc, Lead and Smelting Company, of St. Louis, Missouri, acquired rights to explore the anomalous zone. The first exploratory holes were drilled in 1956, and the discovery of a large copper-iron mineral deposit was announced in 1954. The anomaly is still under active exploration, and no details of the grade, tonnage, and geology of the deposit have been published.

The deposit was the site for studies by two graduate students of the University of Missouri at Rolla. The significance of their findings will be reviewed in this section of the thesis.

Kisvarsanyi (1956, 1957) sampled the drill core of the deposit for his study of geochemical and petrological character of Precambrian Iron Metallogenic Province of Southeast Missouri. His study revealed that trace element content of magnetite tends to decrease from the center of ore bodies towards the margins, and that pairs of high and low electronegativity such as V/Zn, V/Cu, and Mg/Co show the same pattern. Kisvarsanyi suggested that this is strong evidence of temperature control of trace element concentration. Furthermore, he compared the trace element content of purified magnetites from Boss-Bixby with that of other Missouri iron deposits. He felt that there are significant differences which could be explained by mineralogic, geologic, and genetic
difference of the deposits.

Stainbrook (1966) measured the temperature of the water in the diamond drill holes and collected rock samples from the cores to measure the thermal conductivity of the rock. His major purpose was to calculate the heat flow in the deeply buried Precambrian. He found, that at depths 300 to 400 meters below the top of the Precambrian surface, the regional heat flow is 1.3 microcalories/cm²/sec. Furthermore, he was able to distinguish a high and a low thermal conductivity zone. The calculated attitude of these zones led to an interpretation of geologic structure.

Several unpublished reports by consultants for the American Zinc Company point out the petrologic complexities of this deposit and the dissimilarities with other Precambrian apatitic iron deposits in the region.

C. Purpose and Scope

The purpose for study of the deposit is as follows:
1) To determine metallic minerals present,
2) To establish the relationships of metallic minerals in time (paragenesis),
3) To determine relationships of metallic minerals in space (zoning),
4) To classify the deposit by constructing a model of genesis.
With the determination of mineral components and their sequence in time and space, the processes leading to the formation of the deposit will be better understood. This will help the project geologist in directing further exploratory drilling. The textures and structures of solid phases seen under the microscope will aid the metallurgist in his selection of concentration techniques if the ore of Boss-Bixby will be developed for mining.

The analyses and synthesis of geologic data is based primarily on seventy polished sections. Those samples were selected after a review of all the drill core and other geological data related to the core. During the past three years the author has carefully studied the drill core and reviewed the entire core material at least twice.

The American Zinc Company supplied 110 thin sections of the various rock types. Descriptions of those thin sections were available to the author. The sections and their descriptions were reviewed for the purpose of describing the igneous environment of the deposition and establishing a possible petrogenesis.

The polished sections were studied under reflected-light microscope. Other non-destructive methods such as x-ray analysis were also used for mineral identification.
D. Acknowledgements

Thanks are expressed to Dr. Geza Kisversanyi who supplied some of the samples and guided the author through the investigation. The author appreciates the efforts of Dr. Paul D. Proctor in attracting the interest of all parties involved in this thesis.

Appreciation is also extended to the management of American Zinc Company and to Project Geologist George Bussell for allowing the author's use of the drill core and unpublished reports on various aspects of the Boss-Bixby exploration program for thesis purposes.

Special thanks is expressed to the V. H. McConnell Foundation for financial assistance during a phase of this research. Gratitude is extended to the author's parents whose consideration and confidence helped immeasurably during the research leading to this thesis.

The suggestions of faculty of the Department of Geology and friends on subject matter is also appreciated. The author is indebted to Mehdi H. Mirbaba for his help in preparing the photomicrographs included in this thesis.

E. Regional Geologic Setting

The Boss-Bixby deposit is a member of the Southeast Missouri Iron Metallogenic Province as defined by Kisversanyi (1966). This area includes Crawford, Washington, St. Francois, Madison, Iron, and Dent
INDEX MAP of
PRECAMBRIAN IRON DEPOSITS
counties. Figure 1 is a location map of Precambrian iron deposits and a surface geological map of the region.

Rocks of Precambrian and Paleozoic age are found at the surface. The area of outcrops of the Precambrian rocks is less than that of Paleozoic rocks. The outcrop pattern shows some of Precambrian igneous rocks rimed by Paleozoic rocks, with the Paleozoics decreasing in age as the distance from the exposed Precambrian surface increases. This regional structure is the Ozark Dome.

The Precambrian rocks can be divided into two major groups: 1) a volcanic sequence at least 4,000 feet thick, and 2) intrusive types of varied shape and composition. Metamorphic rocks are known in the area, but their extent is very limited.

The volcanic rocks are mostly rhyolitic flows, pyroclastics, and ignimbrites, yet some subvolcanic intrusives occur locally. A reddish, alkali rhyolite is the predominant rock type of the volcanic group. Latites, dacites, andesites, and trachytes are also known. The sequence of flows in the area is uncertain because of the lack of extensive outcrops in critical locations.

The intrusive masses of the Province cut the volcanic rocks. The intrusive bodies range from batholithic size to small dikes. Granitic rocks predominate, yet gabbroic and dioritic rocks occur as discordant bodies within the granitic and rhyolitic masses. The chemical composition of granites is similar to that of the rhyolites. On the
basis of chemical similarity one can visualize a mantle of extrusives intruded by the same magma forming granitic batholiths.

The major events in the geologic history of Precambrian of southeastern Missouri has been outlined by Snyder and Wagner (1961). Starting in Precambrian time and continuing upward through early Paleozoic time includes:

- Extrusion of volcanics
- Folding and faulting
- Intrusion of granites
- Iron mineralization (?)
- Intrusion of basic rocks
- Hypothermal vein-type mineralization
- Faulting tilting erosion
- Deposition of Upper Cambrian Lomotte Formation

Whether this sequence is valid for the Boss-Bixby area is not known.

The major characteristics of the Precambrian iron deposits are found in Table I, taken from Kisvarsanyi (1964). From Table I it is evident that the overall characteristics of the Boss-Bixby deposit are different from other iron deposits.

A distinct nonconformity exists in the St. Francois Mountain area where prominent knobs and ridges of Precambrian rocks are in contact with Cambrian strata.
# TABLE I

Characteristic Features of the Procamelrian
Iron Deposits of Missouri

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Replacement</th>
<th>Structural</th>
<th>Main Ore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot Knob</td>
<td>Replacement in volcanic tuff,</td>
<td>Stratiform tabular</td>
<td>Hematite</td>
</tr>
<tr>
<td></td>
<td>agglomerate &amp; flows</td>
<td></td>
<td>Magnetite</td>
</tr>
<tr>
<td>Cedar Hill</td>
<td>Replacement &amp; filling in volcanic</td>
<td>Irregular and</td>
<td>Hematite</td>
</tr>
<tr>
<td></td>
<td>agglomerate</td>
<td>veins</td>
<td></td>
</tr>
<tr>
<td>Shepard Mtn.</td>
<td>Fissure fillings in volcanic flows</td>
<td>Vein</td>
<td>Magnetite</td>
</tr>
<tr>
<td>Iron Mtn.</td>
<td>Fissure fillings &amp; dissemination &amp;</td>
<td>Cone dike</td>
<td>Hematite</td>
</tr>
<tr>
<td></td>
<td>replacement in volcanic flows and</td>
<td>Irregular veins</td>
<td>Magnetite</td>
</tr>
<tr>
<td></td>
<td>breccias</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pea Ridge</td>
<td>Massive fissure &amp; breccia fillings</td>
<td>Dike-like</td>
<td>Magnetite</td>
</tr>
<tr>
<td></td>
<td>and replacement in volcanic flows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bourton</td>
<td>Replacement and fracture filling in</td>
<td>Hat-shaped to</td>
<td>Magnetite</td>
</tr>
<tr>
<td></td>
<td>volcanic flows</td>
<td>tabular</td>
<td></td>
</tr>
<tr>
<td>Ross-Bixby</td>
<td>Fracture-broccia filling and</td>
<td>Irregular</td>
<td>Magnetite</td>
</tr>
<tr>
<td></td>
<td>replacement in intrusive and</td>
<td></td>
<td>Chalcocpyrite</td>
</tr>
<tr>
<td></td>
<td>volcanics</td>
<td></td>
<td>Bornite</td>
</tr>
</tbody>
</table>

The Upper Cambrian Series directly overlying a basal conglomerate consists of quartzose sandstone, dolomite and chert. The Ordovician strata unconformably overlie the Upper Cambrian and Precambrian rocks. The rocks of Lower
Ordovician age are principally sandstones and cherty dolomites.

The Boss-Bixby area lies within the now famous "Viburnum Trend". The trend is the site for one of the biggest lead-zinc-copper districts of the Mississippi Valley type in the United States. The mineralized zone extends from the southern portions of Washington and Crawford counties and south to southeasterly through Iron and Reynolds counties into Shannon county. These deposits however are found in the Upper Cambrian marine sediments.
Chapter II

METHOD OF INVESTIGATION

A. Sampling Procedure

The success or validity of any study is based primarily on sampling. The type of samples, number of samples, and size of samples are critical factors in any geological investigation. In sampling the drill core of the Boss-Dixby Anomaly the variant character of copper-iron mineralization is the basic consideration. This meant that an extensive rather than intensive sampling program had to be employed. It would have been an easy task to sample a few drill holes at some systematic interval, then project the data in three dimensions, and finally draw some conclusions. The mineralization of Boss-Dixby is heterogeneous in both a horizontal and vertical direction, so sampling of few drill holes would not have shown the true character of the deposits.

The drill core of all exploratory holes was set out in the American Zinc Company Core Laboratory. The description of each individual drill core was reviewed as well as the assay data for that hole. The rock types, structures, and alteration minerals seen by the author were recorded. A sample approximately 1 inch by 0.5 inch by 1.25 inches, was taken in the mineralized zones and recorded. The number of samples per hole varied from
3 to 15. The number of samples per hole depended on the length of mineralized core, type of mineralization, and number of ore minerals recognized in hand sample.

Because the overall fine grain nature of the oxides and sulphides present, the chips of core taken from a drill hole were studied under a binocular microscope. Those observations were recorded along the previously mentioned data. This step was important because it aided in orientation of the samples for preparation of polished sections. The results of this phase will be taken up in a portion of a later chapter.

Considering the dimension of the Boss-Bixby deposit a minimum of 50 samples would yield sufficient data to draw valid conclusions. The author took 73 samples in order to insure adequate coverage and gain some repetition of data. This meant that correlation of mineralization types from drill hole to drill hole could be done with confidence.

B. Polished Section Preparation

Each of the samples were cut in a manner determined from the observations under the binocular microscope, such as right angles to veinlets. With a flat surface attained, the excess material was trimmed in order for sample to fit a 1.5 inch bakelite mold.
A trimmed sample was placed flat side down on the pedestal of the mold and the retaining ring placed down on the pedestal. The mold was then filled with a transoptic powder (Buehler No. 20-3400) twice the thickness of the sample. A label indicating the location was placed on the top of the powder and the label in turn was covered with powder. The piston was then placed into the mold and pressed down. The mold was heated to 200°F and kept under a constant 1500 psi until the temperature of 220°F was attained. The mold was taken from the heating unit and was allowed to cool to 90°F at a constant pressure of 1000 psi. At 90°F the mold was cool enough to allow the removal of the mounted sample. Time required to produce a mounted specimen was about 30 minutes.

In the grinding and polishing stages the techniques were slightly different from those generally used. The conditions for polished surfaces are as follows:

1) Absence of pits and scratches.
2) Constancy of angle of reflection, i.e., the surface must be essentially free from undulation.
3) Freedom from undue relief between hard and soft materials.

To accomplish those conditions care was taken to keep the surfaces flat and free from contamination through all the steps of preparation.
The mounted samples were first ground on a glass plate using a slurry of -600 mesh silicon carbide abrasive and mineral oil. The time involved for fine grinding varied from 10 to 30 minutes per section. Then a "matte" surface with little or no relief was attained the section was then ready for coarse polishing.

The coarse polishing phase was accomplished in two phases. The samples rich in magnetite tended to pit during fine grinding, it was necessary to correct this defect. A mixture of -500 mesh chromium oxide and liquid soap was used. The slurry was applied to a flat surface covered with billiard cloth. Using slight pressure and circular motion, the pitting in magnetite was reduced to a level where it would not interfere with microscopic study. The chromium oxide step led to some relief between the hard and soft minerals. This relief was reduced by -400 mesh aluminum oxide abrasive. The time involved for the coarse polish step was about 45 minutes per section.

At this point the samples were thoroughly cleaned with an ultrasonic cleaner with a hydrocarbon solution. This was found to be extremely effective for removing any remnant abrasive materials and oily substances.

The fine polish stage was accomplished in three steps. The samples were first polished on a rotating lap using a 5-micron diamond abrasive. Processing was continued until all evidence of the matte surface had disappeared and grain boundaries were well defined.
Processing time was short, 3 to 10 minutes per section. After the samples were cleaned again a secondary polishing step began. The samples were mounted in holders and then placed on a vibromat containing 1-micron diamond abrasive. The sections remained on the vibromat for approximately 3 hours. Most sections were ready for study at this stage, although they contained some scratches. The scratches were removed with a fine grade of aluminum oxide.

C. Mineral Determination Techniques

The principal instrument used in this investigation was the "ore" or reflected light microscope. The polished sections were studied under low to very high power in order to determine the opaque minerals present and the textures and structures shown by them. Quantitative identification techniques, such as reflectivity and Vicker's hardness, were employed.

Qualitative methods of x-ray diffraction were also used to determine unknown minerals if they were present in sufficient quantity. Qualitative chemical methods to identify cations present in some samples were used to a limited extent.

All the samples were examined under ultra-violet light to check for any fluorescent minerals such as scheelite, willemite, or fluorite. No fluorescent minerals
were found in the samples collected. The samples were checked for any anomalous radioactivity by means of a Geiger counter; none of the samples showed any radioactivity.
Chapter III
IGNEOUS AND METAMORPHIC PETROLOGY

A. General Statement

The rocks of Boss-Bixby are all of Precambrian age. This age can be assigned to rocks on the basis of similar composition and similar igneous and tectonic position to those of the St. Francois Mountains, whose ages have been established by radioactive age determinations. Goldich (1961) reports ages of 1,200 to 1,350 million years for the igneous rocks of the St. Francois Mountains.

A detailed description of the complex petrologic assemblages is not the purpose of this study. The author will attempt only a general description of the rocks and a basic interpretation of the petrogenesis. Much of the data pertaining to this problem has been collected by consultants for American Zinc Company. Some of the ideas on the processes that formed the deposit were produced by other authors. This study of collected samples resulted in new mineralogical data. Those and other personal observations of the author are added to the understanding of the ore formation.

In the following presentation, the rocks of the Boss-Bixby area will be described in the order of decreasing age. The Company designation of the rock types is used as a classification. The rock types can be subdivided into the following groups: 1) volcanics, 2) intrusives, and 3) metamorphics.
3. Volcanic Rocks

The volcanic rocks are of rhyolitic composition. On the basis of color, texture, groundmass, phenocrysts, and structure, nine different rhyolites have been recognized in and near the deposit. The colors of the rhyolites vary from pink to reddish brown and from light grey to black. The textures are generally hypocrystalline or hypocrystalline-porphyritic. The phenocrysts are generally quartz, pink orthoclase and occasionally plagioclase. The groundmass in general is an aphanitic quartzo-feldspathic material. Some of it is undoubtedly a recrystallized glass. Flow lines, which are characteristic of surface lava flows in the St. Francois Mountains, are present in most of the units. Locally flow breccias are also recognized. Brecciation of volcanic rocks and deposition of ore are frequently associated.

Plate 1-A is a photomicrograph of a rhyolite porphyry. The large phenocrysts (about 1 mm in length) are quartz, and albite-microcline, with quartz being the most abundant. The albite-microcline phenocrysts show very distinct poly-synthetic albite and pericline twinning. The matrix is mainly quartzo-feldspathic material containing a small amount of opaque minerals and muscovite. The texture is allotrimorphic-porphyritic. The mineralogy and the textures of the rock is typical of many of the Missouri rhyolites.

Plate 1-B is a photomicrograph of an amphibole-bearing rhyolite. Albite occurs as phenocrysts of approximately
Plate 1-A. Photomicrograph of a rhyolite porphyry. Phenocrysts of quartz (upper right-hand area), and albite-microcline (lower central area) set in a quartz-feldspar matrix. Crossed nicols (40X).

2 mm in length. The groundmass consists of albite, quartz, potash feldspars and greenish needle-like materials. At close inspection, the needle-like material was found to be composed of hornblende, chlorite and muscovite. This material was probably aegirine, now altered.

From the two mineralogical descriptions, it appears that both potassic (Plate 1-A) and sodic (Plate 1-B) types of rhyolite are present.

C. Intrusive Rocks

The intrusive rocks of the Boss-Bixby Anomaly can be subdivided into four groups on the basis of composition and age of intrusion: 1) syenites, 2) diorites, 3) andesites and 4) granites.

1. Syenites

The syenites are the host rock for much of the ore mineralization. They are a variable sequence of rocks. Xenoliths of rhyolite are found in the sequence. The size of xenoliths range from a few inches to tens of feet in length. Some of the xenoliths are completely recrystallized, while the others show little or no recrystallization. The contacts between the syenites and rhyolites may be sharp but are in most places gradational, hence the exact dimensions of the syenite body cannot be defined. At many places signs of mixing, and complete assimilation of rhyolites are displayed.
Consequently the question arises: are the syenites products of normal mafic differentiation or products of the assimilation of rhyolitic rocks possibly by a dioritic magma? This problem has been recognized by others working on these rocks but the author has collected some new data pertinent to the question. It is important to note that chemical analyses are not available to solve this problem satisfactorily at this stage. A possible petrogenesis of syenites will be presented later.

Macroscopically, the syenites are medium to dark gray in color, yet medium brown varieties are known. In these rocks which contain the major proportion of potential ore, the color appears to be a function of ore mineralization. Mineralogy and texture of the rocks are the most useful guides in distinguishing the syenite varieties. On the basis of these two parameters, three varieties of syenites have been recognized. The field relations of the three are gradational to each other and to the surrounding phylolites.

One phase named a syenite porphyry consists of highly altered phenocrysts of plagioclase, which are called "ghost" phenocrysts by the American Zinc staff, set in a fine to medium grain groundmass. The texture of this rock can be best described as porphyritic-holocrystalline. In the study of the thin sections of this rock type the "ghost" phenocrysts were found to be plagioclase being replaced by microcline, fine-grained micas, and chlorite.
The groundmass is composed of microcline, plagioclase, euhedral hornblende, and traces of quartz. Small opaque minerals were found in the rims of "ghost" phenocrysts and in the groundmass of the rock. In one thin section, a patchy area of quartz was found to contain needles of actinolite mixed with opaque minerals.

Another phase known as the porphyritic syenite was studied from three thin sections. They are similar to the previously described syenite porphyry. The difference between the two rock types is percentage of phenocrysts. The phenocrysts of the porphyritic syenite form less than 10 percent of the total volume, while the volume occupied by phenocrysts of the syenite porphyry is much greater.

Despite the overall similarity of the two rock types, subtle differences exist. For example, the biotite and microcline content is higher in the porphyritic syenite than the other rock.

An allotriomorphic-microporphyritic textured rock is known as the micro-syenite. This phase is similar to other syenites in its overall mineralogy, yet the small grain size and the presence of certain trace minerals make this rock unique. The "ghost" phenocrysts are not present, but only occasional faint outlines of them remain.

Microcline occurs as microphenocrysts, and sometimes plagioclase is found in cores of these microphenocrysts. The biotite of the microsyenite tends to produce lineation
Plate 2-A. Photomicrograph of a quartz-K-feldspar-magnetite veinlet in a syenite porphyry. Note the fine-grain (whitish) needles of actinolite in the central portion of the photomicrograph. Biotite is seen as the medium grey aggregates associated with quartz-K-feldspar. Crossed nicols (80X).

Plate 2-B. Photomicrograph of microsyenite. Hornblende (medium grey image in central area) being replaced by quartz-feldspar-biotite. Note the magnetite grains (black) disperse through the rock. Crossed nicols (80X).
effects, and is found in great abundance along with iron oxides. Muscovite tends to occur as a replacement of both microcline and plagioclase. Garnet, epidote, and chlorite are developed in many portions of this rock type. These same minerals were observed occasionally in the other syenites, but the frequency of occurrence in the microsyenite is greater. Plate 2 shows some relationships seen in thin sections.

2. Diorites

The diorites of the Boss-Bixby can be subdivided into two types on the basis of grain size. The field relationships of these two rocks suggest that one type is coarser grained holocrystalline equigranular rock, while the other type is a holocrystalline-porphyritic rock. In the latter, cubic and subhedral altered phenoocrysts of plagioclase and, locally, pink orthoclase make up about 50 percent of rock by volume. In the equigranular, medium to coarse grained phase the main mafic mineral, hornblende, occurs uniformly throughout and makes up approximately 30 to 50 percent of the rock by volume.

A thin section of a finer grained variety of the main dioritic intrusive is shown in Plate 3-B. Laths of plagioclase of andesine-labradorite composition are being replaced by a mixture of hornblende, biotite and chlorite. The groundmass of the rock consists of hornblende, biotite, muscovite, and traces of leucoxene, calcite, and actinolite.
Plate 3-A. Photomicrograph of a diorite porphyry. Lath-like phenocrysts of altered oligoclase (central area) surrounded by a fine-grained matrix of biotite-epidote-iron oxides. Crossed nicols (80X).

Plate 3-B. Photomicrograph of a microdiorite. Phenocryst of plagioclase is largely replaced by a mixture of fine-grained muscovite-chlorite, note smaller phenocryst of albite (lower right-hand area) partially replaced. Crossed nicols (80X).
Plate 3-A shows the porphyritic phase of the diorite intrusive. The large phenocrysts of calcic plagioclase are completely altered to fine-grain muscovite and epidote. Fresh, fine-grained laths of oligoclase are found in the groundmass with biotite, hornblende, garnet, and iron oxides. Veinlets of quartz-feldspar cut the rock.

The change in composition of the plagioclase, from calcic-rich toward sodic-rich, indicates that alkali metamorphism could have taken place probably before the complete crystallization of the intrusive body.

3. Andesites

Andesites occur as dikes. They are generally medium to dark greenish grey and have a holocrystalline to porphyritic texture. Locally, the andesites show slight to intensive metamorphism along shear planes paralleling the attitude of the unit itself.

A thin section of a porphyritic andesite is shown in Plate 4-B. The phenocrysts are altered albite; the alteration minerals are chlorite and biotite. The groundmass consists of albite, biotite, chlorite, hornblende, sphene, calcite and iron oxides. The type of alteration shown in best described as porphyritization.

4. Granites

The granites appear as dikes. They are generally pink in color and show an hypidiomorphic granular texture. The bodies generally show no internal structure. The
Plate 4-A. Photomicrograph of a fine-grain biotite granite. Biotite and magnetite are black, but magnetite is much finer grained than biotite. Anhedral phenocrysts of orthoclase are rimmed by quartz-feldspar. Ordinary light (20X).

Plate 4-B. Photomicrograph of a magnetite-bearing andesite. Black image of magnetite of variable size is distributed in a fine-grained matrix of biotite-chlorite-albite. Crossed nicols (40X).
Typical granite of Boss-Bixby is usually medium-grained (5 mm to 2 cm), but granites with aplitic and pegmatitic grain sizes occur locally.

Plate 5-A shows a fine-grained sample of the pink granites. Some phenocrysts of quartz are present in a quartz-feldspathic groundmass. Biotite, the major mafic mineral, has been altered to chlorite and iron oxides.

D. Metamorphic Rocks

There are three types of metamorphic rocks present: 1) contact metamorphosed rhyolite, 2) biotite schist, and 3) possible "migmatites". Of these three, the most important and widespread is the contact metamorphosed rhyolite. The other two are limited in extent and relatively unimportant in ore mineralization processes.

The contact metamorphosed rhyolite is known as the variegated epidote rhyolite. This rock is color banded, alternating reddish brown and green bands predominately. In thin sections, the rocks retain some of their primary characteristics. The local but conspicuous development of garnet, actinolite, epidote, chlorite, fluorite, calcite, and gypsum is strong evidence for contact metasomatism. This rock apparently acted as a barrier to the ore solutions because rich mineralization is found between it and the syenites. Plate 5-A is a photomicrograph of the contact metamorphosed rhyolite.
Plate 5-A. Photomicrograph of a contact metamorphosed rhyolite. A lath of plagioclase (central area) is cut by epidote, and rimmed by biotite-magnetite. The groundmass is mainly quartz-albite. Crossed nicols (40X).

Plate 5-B. Photomicrograph of a biotite schist. Some magnetite present but not in line with foliation. Crossed nicols (40X).
Plate 5-A. Photomicrograph of a contact metamorphosed rhyolite. A lath of plagioclase (central area) is cut by epidote, and rimmed by biotite-magnetite. The groundmass is microcrystalline quartz-albite. Crossed nicols (40X).

Plate 5-B. Photomicrograph of a biotite schist. Some magnetite present but not aligned with foliation. Crossed nicols (40X).
The schists are generally related to the andesite dike rocks. Foliation is generally parallel to attitude of the dike. The rock is generally black due to the high biotite content. Texturally, the rock is highly schistose. In thin sections, the biotite plates show strong alignment with some chlorite replacing biotite. Porphyroblasts of quartz are present in a minute quantity, and some blast-ropaths of untwinned plagioclase are present in a similar quantity. The biotite schist is very similar to the andesite on the basis of mineralogy and structural position. Plate 5-B is a photomicrograph of the schist.

The "migmatites" are rocks that are partly granite and partly rhyolite or microdiorite. The granite occurs as closely spaced veinlets or lenses within the microdiorite or rhyolite. Thin section analysis of these rocks generally show weakly-developed alignment of platy biotite and muscovite associated with quartz-orthoclase-muscovite veinlets cutting the enclosing rhyolite or microdiorites.

E. Petrogenesis

The purpose of this section is to describe the general conditions that existed during the development of the intermediate intrusive complex and the related assimilation and contact metasomatic phenomena.
The major events leading to the formation of the present structure and igneous bodies and their associated mineralization can be summarized in the following:

1) Extrusion of volcanic flows and pyroclastics,
2) Intrusion of an intermediate magma (dioritic in composition?).
3) Large scale assimilation of the volcanics.
4) Contact metamorphism and metasomatism of the volcanics, the partially assimilated rock and, the intrusive body.
5) Oxide and sulphide mineralization.
6) Intrusion of diorite and andesite dikes.
7) Dislocation metamorphism of the diorite and andesite dikes.
8) Intrusion of granite dikes.

The series of rhyolite flows and pyroclastics that covered the area was invaded by an intermediate magma which appears today as the intrusive body around which the ore was deposited. The composition of this body is monzonitic to syenitic, but the presence of rhyolite xenoliths and partially assimilated rhyolite blocks suggests the possibility of a strong change of composition of the invading magma. This might indicate that the magma was initially dioritic in composition.

The body itself is a typical discordant epizonal intrusive which was emplaced by a stoping mechanism in a zone of weakness. The contacts, are mostly gradational
because of the above described processes. Since chemical analyses of the rocks have not been made, the actual chemical changes from syenite to rhyolite cannot be documented. Megascopic appearance of the drill core and microscopic work seems to validate these inferences.

The exact nature of these igneous rocks is additionally complicated by thermal metamorphism and metasomatic transfer of materials in wide zones of the contact, emplacement of the oxide-sulphide mineralization.

The strong changes in these rocks are manifested by the formation of garnet-bearing, skarn-like rocks in and near the ore body, extensive development of epidote in the contact rhyolites, and widespread reaction rims of microcline around plagioclase within the intrusive body. The appearance or small nests of actinolite, muscovite, and biotite may be due to this metamorphic-metasomatic alteration. It appears that the invaded rocks were enriched in calcium, while the intrusive was enriched in potassium and sodium. Widespread albitionization points to widespread mobility of alkalies during crystallization of the intrusive body. Because of the gradational overlapping and intertonguing relationships, the altered zones appear to be contemporaneous. Careful mapping of these zones in future underground openings could modify the present interpretations.

Ore deposition followed the consolidation of the intermediate rocks. In rapid succession, the diorite
and andesite dikes were emplaced, cutting all the older rocks and ore mineralization. It is possible that these dikes represent a magma composition similar to the first magma that invaded the rhyolites. This hypothesis could not directly substantiate, however, because of the lack of gradual transitions between syenites and the diorite dikes.

These events have been followed by local development of schistosity in some dikes and by intrusion of granitic bodies. The granite dikes are transsecting all other rocks. Some chloritization, silicification, and slight mobilization of sulphides and oxides can be attributed to the emplacement of granites.

The original floor of rhyolites cannot be recognized. These older rocks must have been eliminated or been present at great depth.

It would be an interesting study to investigate in detail the shallow depth assimilation process of the rhyolite flows by the invading intermediate magma.

Yoder and Tilley (1962) found that basaltic liquid exists at around 1000°C and 1 Kb water pressure. With increasing water pressure the basalt magma exists at lower temperatures. Melting or granite takes place at temperatures much lower than 1000°C and 1 Kb water pressure. If the temperature and water pressure of intermediate magma was above, 800°C and 2 Kb, assimilation
of the stoped rhyolite blocks could occur. There rhyolitic xenoliths within these xenoliths represent a late thermal and chemical equilibrium condition between xenoliths and contaminated magma.
Chapter IV
ORE MINERALIZATION

A. General Statement

The nature of mineral concentration and distribution will be briefly described. Attention will be focused on the mineralogy and texture of the mineralization. The genetic and paragenetic significance of these data will be discussed later in the genesis and paragenesis sections.

B. General Structure Types

The ore mineralization can be subdivided on a geometrical basis into the following: 1) breccia-fillings, 2) disseminations, and 3) fracture-fillings. The three types grade into another and at many places occur together.

The breccia-fillings are widespread and contain most of the potential ore of the deposit. Breccia is developed in both syenites and rhyolites. Light, moderate, and heavy brecciated zones have been recognized, but they show no systematic relationship to the intrusive. Iron and copper minerals are most commonly found as breccia fillings. Magnetite is the most persistent mineral in these structures. The copper mineralization does not show any apparent relationship to the heavy, moderate or light brecciation.

Disseminated ore zones, like the breccias, are zones in the sense that higher and lower grade areas can be
They make up much of the marginal grade at the present time. The iron minerals predominate here as they do in the breccia ores.

The fracture-filling type is associated with high-angle fractures rather than the low-angle fractures found in syenites and rhyolites. In places, fracturing is so closely-spaced that it is a problem to distinguish light brecciation from strong fracturing.

C. Mineralogy

The ore minerals of Ross-Bixby are generally fine-grained (less 5 mm in length or diameter). Numerous zones are present where the ore minerals are medium-grained (5 mm to 3 cm), yet on the basis of volume, fine-grained ore is more abundant than medium-grained ore. Due to that characteristic, only the major ore minerals could be identified megascopically. Kisvarsanyi (1966) in his treatment of the entire Metallogenic Province reported the presence of magnetite, hematite, chalcopyrite, bornite, pyrite, sphalerite, traces of cubanite, molybdenite, chalcocite, and galena.

In the more detailed investigation of the deposit several new minerals have been discovered which are not known to occur in other deposits of the Metallogenic Province.
The mineralization will be described as follows:
1) oxides, 2) sulphides, and 3) hydroxides.

1. Oxides

The following oxide minerals have been found in the deposit: 1) magnetite, 2) hematite, 3) ilmenite, 4) rutile, and 5) goekielite.

Magnetite is, by far, the most abundant ore mineral in the deposit. It ranges in size from less than 0.04 mm to more than 0.6 mm. The mineral exhibits a variety of shapes with equidimensional grains prevailing.

In the reflecting microscope the dominant variety of magnetites has a gray color with weak bluish tint, while a minor variety has a gray color with a weak to strong brownish tint. The bluish variety of magnetite commonly contains inclusions of pyrite, chalcopyrite, bornite, and ilmenite. The brownish variety is generally free of inclusions, yet a few grains contain bornite and ilmenite. In general, the inclusions show no preferred orientation within an individual grain; but they tend to be more concentrated near the margins rather than at the cores of magnetite grains. The two magnetites could not be separated on the basis of Vicker's hardness since both the hardnesses ranged from 535 to 570; these values are within the range of magnetite given by Cameron (1961). Upon making the Vicker's hardness tests, it was found that the brownish variety is more brittle than the bluish variety. Reflectivities were the same for the two types.
They were around 20, which is similar to the values given by Cameron (1961). Contact relationship of the two varieties will be described in the texture section of this chapter.

Hematite is the second most abundant iron-bearing mineral of the deposit. Its amount is significantly less than that of magnetite. The size of the hematite crystals is variable and similar to that of magnetite. The shapes exhibited by hematite vary from cubic to anhedral. This mineral is generally associated with magnetite, especially with the brownish variety. It is easily identified by its whitish gray color, birefringence, anisotropy and relatively high hardness.

Ilmenite, rutile, and geikielite are listed in the order of decreasing abundance. Ilmenite is found as exsolution laths within magnetite, distinct spindle-shaped grains in hematite and magnetite, and anhedral grains bordering magnetite. Rutile occurs as needle-like crystals arranged in network pattern in hematite. Geikielite, occurring in magnetite as elongated grains, can be distinguished from ilmenite by a lower reflectivity and very strong brownish red internal reflections. It was found in only one polished section.

2. Sulphides

Pyrite, molybdenite, cobaltite, chalcopyrite, bornite, sphalerite, galena, and chalcocite are the sulphide minerals found in the deposit.
Pyrite is easily identified by its yellow color, high hardness, and usual euhedral form from other similar sulphides. The mineral is very widespread and probably the most abundant sulphide in the deposit. It is found as inclusions in magnetite, chalcopyrite, and bornite. Pyrite appears to be associated frequently with bornite, occurring as inclusions. It also forms veinlets in magnetite.

Molybdenite was identified only megascopically. The author sampled a fracture that was coated with the mineral, and the sample was tested chemically in the laboratory. Finely divided flakes of mineral were placed on a plaster block in the oxidizing blowpipe flame. A white sublimate deposited, which formed a deep blue coating in the reducing flame, proving the presence of molybdenum.

Cobaltite occurs as euhedral grains in hematite rich zones of the deposit. This mineral can be easily mistaken for pyrite, because cobaltite possesses similar physical properties. The Vicker's hardness was measured and found to be around 1,300; measured reflectivity was found to be around 50 to 53. Several minerals including pyrite and cobaltite have a similar hardness and reflectivity.

Because of the difficulties in the determination, few mineral grains were analyzed in situ by x-ray fluorescence. Characteristic Ka radiation peaks for cobalt and arsenic were obtained. The ratio of peak radiation to background
radiation was measured and it was found that the ratio of cobalt was similar to that for arsenic. Since the ratios for the elements were similar the relative concentration of those elements would approximately be similar. Thus, the CO:AS ratio which is 1:1, fits the formula of cobaltite COAS S₂.

Chalcopyrite is the most abundant copper-bearing mineral present in the deposit. The mineral occurs as independent grains and ovoid to elongated inclusions in magnetite, hematite, and rarely ilmenite. Some of these inclusions (minus 0.02 mm) possess an identifiable anisotropy like that of pyrrhotite. Vicker's hardness tests could not be made on these small grains. The exact identification of these inclusions was difficult; nevertheless, they appear to be chalcopyrite. The bulk of the chalcopyrite occurs as anhedral aggregations with associated magnetite and pyrite. The larger mineral grains are easily identified under the microscope by their bright yellow color and moderate hardness.

Bornite is very widespread in smaller amounts but can be locally concentrated in the deposit. It is closely associated with pyrite and chalcopyrite. It can be recognized on the basis of its brown to orange color when polished and the violet blue after oxidation.

The sphalerite found in the deposit is a dark-colored variety, which can be easily overlooked. The mineral is usually anhedral shaped. It can be distinguished from
bluish magnetite by a lower polish hardness shown by sphalerite. In general, sphalerite is found with pyrite, especially in pyritic veinlets. Sphalerite contains exsolution laths of chalcopyrite and is found as inclusions in chalcopyrite.

Galena, like sphalerite, is present in disseminated grains and in pyrite veinlets. Galena is easily identified on the basis of its color, low hardness as compared to pyrite, and presence of triangular pits denoting the cleavage.

Chalcocite is present in the zone of oxidation as a coating on bornite, chalcopyrite, pyrite, and hematite. The low hardness, bluish gray color, and associated minerals prove the identity of chalcocite. Cuprite and covellite are present in very small amounts with chalcocite. The deep blue color, strong bireflectance and anisotropism are characteristic of covellite. Cuprite has greenish gray color in oil and has distinct red internal reflections.

3. Hydroxides

In the thin oxidized zone at the top of the deposit the minerals lepidocrocite and goethite are present. Both minerals have a medium to high hardness, low reflectivity, and a bluish gray color. In oil immersion, the two can be distinguished on the differences of internal reflections. Lepidocrocite shows blood-red internal reflection, while those of goethite are yellowish brown. The two minerals are generally associated with hematite
and oxidized copper minerals. They are the least abundant of the iron-bearing minerals.

D. Mineralogic Relationships

It is difficult to draw clear distinctions between the terms structure and texture. In general, structure refers to large-scale features recognizable macroscopically, such as mineralogical banding and lineation. On the other hand, texture refers to the degree of crystallinity, grain size, and the geometrical arrangement of the mineral components of the ore. The term mineralogic relationship, as used here, is a combination of the texture and structure as seen in the microscope.

The accompanying photomicrographs will serve as an aid for the reader to visualize the ore mineral relationships seen in polished sections. The discussion will follow the sequence of the mineralogy.

The observable relations between bluish and brownish magnetite are rare, generally only one variety is present in a polished section, and of the samples studied only three sections contained both varieties. In all three sections, brown magnetite is present as a discontinuous rim around the bluish variety. The contact is smooth but somewhat undulated. Plate 6-A is a photomicrograph of the relationship of the bluish to brownish magnetite. The author interprets the relationship as the brownish being derived by slight oxidation from the bluish magnetite.
Plate 6-A. Photomicrograph of magnetite and chalcopyrite. Magnetite (gray) containing irregular-shaped inclusions of chalcopyrite and being replaced by chalcopyrite (light gray). Brownish and bluish magnetites present (upper left-hand area). Ordinary light (200X).

Plate 6-B. Photomicrograph of martite. Remnants of unreplaced magnetite (medium gray) in hematite (light gray). Ordinary light (60X).
<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Ts</th>
<th>Tp</th>
<th>Tn</th>
<th>Tq</th>
<th>Tm</th>
<th>Tp</th>
<th>Tn</th>
<th>Tq</th>
<th>Tm</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-1-5</td>
<td>.044</td>
<td>.370</td>
<td>.0013</td>
<td>.023</td>
<td>.039</td>
<td>.013</td>
<td>1.01</td>
<td>.022</td>
<td>.0001</td>
<td>.043</td>
</tr>
<tr>
<td>J-15-3</td>
<td>.083</td>
<td>.840</td>
<td>.0007</td>
<td>.21</td>
<td>.031</td>
<td>.0049</td>
<td>.36</td>
<td>.01</td>
<td>.0019</td>
<td>.014</td>
</tr>
<tr>
<td>J-15-2</td>
<td>.058</td>
<td>.072</td>
<td>.0004</td>
<td>.086</td>
<td>.048</td>
<td>.0018</td>
<td>.0094</td>
<td>.01</td>
<td>.0001</td>
<td>.013</td>
</tr>
<tr>
<td>J-17-1</td>
<td>.178</td>
<td>.059</td>
<td>.0013</td>
<td>.108</td>
<td>.052</td>
<td>.0072</td>
<td>.050</td>
<td>.01</td>
<td>.0013</td>
<td>.036</td>
</tr>
<tr>
<td>J-17-3</td>
<td>.25</td>
<td>.075</td>
<td>.0001</td>
<td>.45</td>
<td>.047</td>
<td>.0075</td>
<td>.032</td>
<td>.029</td>
<td>.0013</td>
<td>.021</td>
</tr>
<tr>
<td>J-18a-8</td>
<td>.20</td>
<td>.057</td>
<td>.001</td>
<td>.84</td>
<td>.0082</td>
<td>.0012</td>
<td>1.0</td>
<td>.018</td>
<td>.0001</td>
<td>.125</td>
</tr>
<tr>
<td>J-18a-4</td>
<td>.186</td>
<td>.165</td>
<td>.0018</td>
<td>.27</td>
<td>.068</td>
<td>.0083</td>
<td>.170</td>
<td>.023</td>
<td>.0001</td>
<td>.058</td>
</tr>
</tbody>
</table>

After Kisvarsanyi (1966)
It will be shown later on a cross-section of the deposit that brownish-colored is generally located above the bluish variety of magnetite. Table II is a listing of selected spectrochemical analyses of purified magnetites from Kisvarsanyi (1966). The odd numbered analyses are of bluish magnetite, while even numbered are analyses of brownish variety. It can be seen that the overall trace element differences between any two pair, such as 1-2, 3-4, 5-6, 7-8, are slight. Yet Mn, Cu, and Al tend to be more concentrated in the bluish rather than the brownish magnetite. The author believes that the brownish variety is derived from the bluish magnetite because of the following: 1) bluish variety is found mainly in lower portions of the ore zones, while the brownish is located in the upper portions of the ore zones; 2) the observed contact relations indicate such a relationship; 3) the trace element analysis indicates that the bluish variety has a trace element content slightly higher than the brownish magnetite. The brownish variety is probably a slightly oxidized product of the bluish magnetite. The former probably contains more \( \text{Fe}^{3+} \) than the latter variety.

The magnetite of the deposit contains inclusions of several minerals. Plates 6-A, 7-A & B, 8-A & B, 9-A, 10-B, 11-B, 12-A, and 15-B show the various minerals and their shapes and distribution within magnetite. It is evident that the ore mineralization is heterogeneous.
Plate 7-A. Photomicrograph of magnetite and chalcopyrite. Euhedral magnetite (medium gray) being engulfed by chalcopyrite (light gray). (Pits and scratches are black). Ordinary light (200X).

Plate 7-B. Photomicrograph of magnetite, chalcopyrite, and ilmenite. Magnetite (medium gray) containing oval like inclusions of chalcopyrite (light gray) and ilmenite (medium gray: lower central area) replacing gangue (dark gray). Chalcopyrite (light gray) partly replacing gangue and magnetite. Ordinary light (200X).
Plate 8-A. Photomicrograph of magnetite, bornite, and chalcopyrite. Magnetite (white) containing oviform inclusions of bornite and chalcopyrite (medium gray). Ordinary light (200X), oil immersion.

Plate 8-B. Photomicrograph of magnetite and chalcopyrite. Magnetite (medium gray) being replaced by chalcopyrite. Note the concave surfaces into the magnetite by chalcopyrite in addition to "caries" of chalcopyrite in magnetite. Ilmenite as present in the magnetite as granules and as islands in the chalcopyrite. Ordinary light (200X).

Plate 9-B. Photomicrograph of magnetite, hematite, and pyrite. Magnetite (medium gray) being rimmed by hematite (light gray). Pyrite (white showing idiomorphic boundaries against hematite-magnetite). Ordinary light (150X).
Plate 10-A. Photomicrograph of magnetite and hematite. Magnetite (medium gray) being rimmed and veined by hematite (light gray). Ordinary light (80X).

Plate 10-B. Photomicrograph of magnetite, chalcopyrite, and bornite. Magnetite (light gray) containing ovoid chalcopyrite and bornite inclusions. Ilmenite present as irregular-shaped inclusions within magnetite. Chalcopyrite (white) follows the outlines of magnetite. Ordinary light (20X).
Plate 11-A. Photomicrograph of magnetite, hematite, and ilmenite. Magnetite (dark gray) with exsolution laths of ilmenite (light gray). Magnetite is being replaced by twinned hematite (light and medium gray bands). Crossed nicols, oil immersion (600X).

Plate 11-B. Photomicrograph of magnetite, hematite, and chalcopyrite. Magnetite (medium gray) being rimmed and veined by hematite (light gray) and chalcopyrite (white). Chalcopyrite is present in oviform inclusions in magnetite. Ordinary light (400X).
Plate 12-A. Photomicrograph of magnetite and hematite. Magnetite being rimmed by hematite, then by gangue (dark gray). Ordinary light (200X).

Plate 12-B. Photomicrograph of magnetite and hematite. Brownish magnetite showing mutual boundary relations with hematite. Ordinary light (300X).
The ovoid chalcopyrite, bornite, and pyrite inclusions within magnetite (Plates 7-B, 8-A, 9-A, and 10-B) are interpreted as being sulphide droplets trapped within the magnetite at the time of crystallization. Bastin (1950) records a similar interpretation for ovoid inclusions within the host mineral.

Irregular-shaped inclusions of chalcopyrite within magnetite are interpreted as "caries". Thus, replacement of magnetite by chalcopyrite is now established. Plate 8-B shows some chalcopyrite replacing magnetite along crystallographic directions.

Ilmenite is present as laths or spindles (Plates 7-B, 9-A, 11-A) and as granules (Plates 8-B and 9-A) with magnetite. Intensive investigation of these inclusions showed that they are for the most part free inclusions themselves, yet some grains were observed containing exsolved spindles of hematite. The presence of ilmenite spindles and granules within magnetite is interpreted as a produce of oxidation-exsolution of titanomagnetite as presented by Buddington and Lindsey (1964). Geikielite is present as granules within magnetite. Since the mineral is chemically and crystallographically similar to ilmenite, its relationship with the host mineral is interpreted similarly.

Hematite was found as rims and veins in magnetite. Thus hematite appears to replace magnetite. Plate 6-B shows un replaced magnetite "islands" in a "sea" of hematite, while Plates 9-B, 10-A, 11-B, and 12-A show
initial stages of the process. Plate 12-B shows an unusual relationship of brownish magnetite showing mutual boundaries with hematite. In the oxidized zone hematite plates are present yet magnetite is found as cones in the plates. Some of the hematite is observed as exsolution lamellae within ilmenite. In turn, ilmenite is found as exsolved laths in hematite; these relationships, though rarely found, indicate unmixing Ti-rich and Ti-poor phases during ore deposition. Excessive unmixing of these phases in rare cases resulted in exsolved needles of rutile arranged in a network pattern within hematite. The hematite-ilmenite and hematite-rutile associations tend to be restricted to iron-rich disseminated ore.

Pyrite (Plates 13 and 14) is found as continuous to discontinuous fissure filling-replacement veinlets in magnetite and the wall rock. In some cases borders of fractures match in detail, while in most cases mismatching borders exist. These, in turn, are commonly rimmed and veined with chalcopyrite. Some pyrites are disseminated. The interpretation of the inclusions of galena and sphalerite (Plate 14-A) indicates that pyrite has been replaced. If pyrite would replace those minerals the inclusions would have a very ragged outline such as the magnetite remnants present; but galena and sphalerite inclusions show sharp and angular contacts with pyrite. Plate 13-B is a photomicrograph of a pyrite pseudomorph after magnetite. Two lineations that meet at right angles are
Plate 13-A. Photomicrograph of pyrite, sphalerite, and chalcopyrite. Pyrite (white) being veined by chalcopyrite. Inclusion of sphalerite (medium gray) present in the middle left edge of the photomicrograph. Ordinary light (300X).

Plate 13-B. Photomicrograph of pyrite and magnetite. Pyrite showing two directions of fracture at right angles. Note the rectilinear shapes of the magnetite and gangue inclusions. Ordinary light (100X).

Plate 14-B. Photomicrograph of pyrite and magnetite. Pyrite veinlet cutting magnetite. Chalcopyrite is present as inclusions in magnetite. Ordinary light (200X).
present within the pyrite, some of the outlines of the
magnetite inclusions match the directions of lines. Thus,
presence of angular inclusions of magnetite and
their alignment with lineations indicate pyrite is pre-
morphous after a mineral with parting or twinning lines or
planes at right angles. If the mineral was magnetite
these lineations would correspond to its parting planes.

The boundary relationships of chalcopyrite within
(Plates 15-A & B and 16-A) indicate nearly contemporaneous
deposition. Both minerals are found rimming magnetite,
hematite and pyrite.

Cobaltite as seen in Plate 17-A shows idiomorphic
outlines against hematite. This mineral appears to have
been formed prior to deposition of hematite.

Plate 18 shows the exsolution of chalcopyrite within
sphalerite. In places, as seen in Plate 18-A, exsolution
lamellae grade into large blobs, perhaps even replacing
a little of sphalerite. Pyrite is seen as nearly extrusive
grains within sphalerite. Thus pyrite was deposited
before the sphalerite.
Plate 15-A. Photomicrograph of bornite, chalcopyrite, and magnetite. Mutual boundary relationship between bornite (medium gray) and chalcopyrite (light gray). Magnetite is present. Ordinary light (150X).

Plate 15-B. Photomicrograph of magnetite, pyrite, bornite and chalcopyrite. Magnetite being rimmed by chalcopyrite. Concave surfaces into magnetite by gangue. Chalcopyrite showing mutual boundaries with bornite. Pyrite being replaced by chalcopyrite. Ordinary light (100X).
Plate 16-A. Photomicrograph of magnetite, chalcopyrite, and sphalerite. Magnetite (medium gray) being replaced by chalcopyrite. The exsolution textured mineral grain near center of photomicrograph is chalcopyrite blebs in sphalerite. Ordinary light (100X).

Plate 16-B. Photomicrograph of pyrite, chalcopyrite and magnetite. Pyrite (white) showing sharp boundaries against chalcopyrite (gray) which contains euhedral grains of magnetite (medium gray). Ordinary light (100X).
Plate 17-A. Photomicrograph of cobaltite, hematite, and magnetite. Cobaltite (light gray) showing euhedral boundary against hematite (medium gray) containing cores of magnetite (dark gray). Ordinary light (300X).

Plate 17-B. Photomicrograph of hematite, chalcopyrite, and bornite. Chalcopyrite (medium gray) containing inclusions of bornite (medium gray) is being replaced by hematite (light gray). Ordinary light (100X).
Plate 18-A. Photomicrograph of sphalerite, chalcopyrite and pyrite. Sphalerite (dark gray) with exsolved chalcopyrite (light gray), some pyrite crystals present (light gray). Ordinary light (100X).

Plate 18-B. Photomicrograph of sphalerite, chalcopyrite and pyrite. Similar to Plate 18-A. Ordinary light (300X).
Chapter V
PARAGENESIS AND ZONING

A. General Statement

The paragenesis, or chronologic order of minerals, was determined by the studies of mineral relationships both macroscopically and microscopically. For this reason, the emphasis was placed on the microtextures and microstructures because of the fine-grained nature of the mineralization.

The zoning, or spatial distribution of minerals, was determined in the same manner as paragenesis. Zones can be defined by differences in mineral composition, differences in types of metal, changes in trace element content of particular minerals, or even subtle changes in ratios between certain minerals.

B. Paragenesis

The ore mineral paragenesis of the Post-Bixby | deposit is presented on Figure 2. According to the investigation, the majority of contact minerals were deposited before the metallic minerals. However, during the metalization, they still replaced the earlier formed oxides. The metallic minerals are listed in the order of deposition, the earliest formed minerals being first. Relative time is indicated from left to right. The amount of overlap is proportional to the frequency observed between mineral pairs, thus contemporaneous deposition of rutile-hematite...
Figure 2  ORE MINERAL PARAGENESIS OF THE BOSS BIXBY ANOMALY

Magnetite  --- blue --- ? --- brown ---
Limonite
Geikiliite
Rutile
Hematite
Molybdenite  ? --- ?
Cobaltite  ? --- ?
Pyrite
Chalcopyrite
Bornite
Sphalerite
Galena
Limonite
Chalcostite
Cuprite

primary mineralization

secondary mineralization
is more frequent than ilmenite-hematite.

The paragenetic model expresses the basic facts of observations about the time of deposition of the ore minerals. The following generalizations may be made about the sequence of ore deposition:

1) Oxides of iron and titanium were deposited early.
2) Sulphides of iron, copper, cobalt, and molybdenum were deposited in part contemporaneously with the oxides in part later.
3) Sulphides of zinc and lead were deposited later than oxides and Cu-Fe sulphides.
4) Secondary oxides, sulphides, and hydroxides of iron and copper were formed much later by the weathering of the deposit.

The textural relationship and the genetic significance between bluish and brownish magnetite was not established because of their rare occurrence together. The position of molybdenite in the paragenetic sequence was determined microscopically in the drill core where it was being replaced by pyrite, thus its extent through time is uncertain.

C. Zoning

The zoning within the deposit is shown in four different ways. Figure 3 taken from Kisvarsanyi (1961) shows the distribution of Ti content of purified magnetite. He concluded that the pattern developed was a function of the variations in the temperature at the time of
Fig. 3 Distribution of Ti content of the purified magnetites — Boss ladies deposit. After Kisvarsanyi (1966)
crystallization since crystal chemical factors were the same throughout the ore body. Thus, in areas near the center of the deposit high Ti content with magnetite crystallized at a higher temperature than in areas of lower Ti content.

Figure 4 shows the distribution of brown and blue magnetite. Here, we can see that brown magnetite is overlying the blue magnetite, with areas of blue occurring within the area of the brown. No doubt the blue variety was the original form and by some processes, such as oxidation, the brown was derived from the blue.

Figure 5 shows the distribution of the magnetite to hematite ratio. In any given drill hole, hematite decreases with increasing depth. The line dividing the areas of magnetite equals hematite (mt=hm) from magnetite greater than hematite (mt>hm) if superimposed on Figure 4 would show that the area with brown magnetite would occupy more area of mt=hm and mt<hm than mt>hm. From this we can infer a close relationship between brown magnetite and hematite.

Figure 6 shows the distribution of oxide to sulphide ratio. All the metal-bearing minerals were considered and the relative proportions were visually estimated. Two fields were determined, with more oxide than sulphide (O>S) and with less oxide than sulphide (O<S). It can be seen that sulphide rich areas tend to be restricted to margins while the central areas are oxide rich. This
Fig. 4  Distributions of brown and blue magnetites — Boss Dixby deposit.
shows some relation to Figure 3. This relationship can be interpreted as additional evidence that the variation in temperature at the time of deposition was sufficiently great to cause differences within the deposit and to lead to the development of the internal pattern of the deposit.

D. Causes of Sequential Deposition

The establishment of the time and space arrangement of minerals is one of the most controversial subjects in the field of economic geology. Park and McDaniels (1971) have reviewed attempts that have been made to correlate zoning and paragenesis. Among these, sequential deposition has been correlated with densities of fluids, atomic weights of the metals, mineral hardmesses, free energies of mineral formation, volatilities, metal-sulphur ratios, electrode potentials, and fugacities of sulphur and oxygen.

The trace element content of magnetites that were determined by Kisvarsanyi (1956) were interpreted by him as evidence for temperature control of sequential deposition. The distributions of the various ratios, such as oxide to sulphide, indicate that the partial pressure of oxygen and sulphur influenced paragenesis and zoning.
Chapter VI
ORE GENESIS AND CLASSIFICATION

A. General Statement

The ore genesis of this deposit will be explained on the basis of mineralogy, paragenesis and outlined zoning. The composition, manner of transportation, properties of ore fluid, and the possible source will be discussed. Finally, the deposit will be classified according to the Modified Lindgren Classification.

The geologic history of the deposit is complex. Much of the events that lead to its formation are not well understood nor are the lithologies well defined. Thus we can only broadly point out the general aspects of the genesis of this deposit.

3. Composition

The close relationship of ore mineralization to Fe, Na, and K metasomatism would indicate that the ore fluid was alkaline in composition. The ore fluids have been fluids highly concentrated in O, Fe, Cu, H, and S. Because of the deposition of early oxides the amount of S gradually increased along with Cu.

4. Manner of Transportation

At the high temperatures and pressures that probably existed at the time of ore deposition the ore fluid probably flowed through fissures and breccia zones within
the intrusive, and at the contact zone. The intragranular porosity of the rock was probably greater at that site, thus intragranular flow may also have been contributing to the transport. The metals were probably transported as complex ions. Holgeson (1964) shows from experimental data and theoretical assumptions that most hydrothermal ore deposited from metal complexes which controlled the concentration of metals in ore fluid and influenced their mode of deposition.

D. Deposition

The causes of ore deposition are generally attributed to a decrease in temperature, pressure or velocity of transportation medium or chemical reaction with the wall rock.

The depth of intrusion was less than 6 Km, thus the load pressure was not great (less than 2 Kb). The initial temperature of the intrusive was probably near 800-900°C. With the decrease in temperature in the crystallized body, which caused shrinkage fracturing the introduction of contact metasomatic fluids, the stage was set for ore deposition. The mechanism of ore was partly fracture and possibly filling and partly replacement of the host rocks.

At the time of formation of magnetite, Ti, Cu and S, were present in ore solution. If the Ti replaced some of the iron in magnetite, an magnetite-ulvospinel solid solution could exist. Buddington and Lindsey (1964)
present good evidence for this solid solution series. They found from laboratory investigations and polished sections studies that increasing oxidation of the magnetite-ulvospinel solid solution would lead to the formation of magnetite-ilmenite, magnetite-hematite, and hematite-rutile. This is similar to the sequence at Boss-Bixby. The temperature given for the magnetite and ilmenite exsolution is greater than 550°C with other associations taking place at lower temperatures (yet unknown). This oxidation process takes place under high oxygen partial pressures created by the expulsion of water from a cooling magma. With high oxygen fugacity the chemical activity of sulphur would be reduced. Thus the formation of iron-copper sulphides and pyrite would occur rather than phases rich in sulphur such as pyrrhotite. The value of 500°C given by Burchett (1924) for exsolution of chalcopyrite-bornite fits with temperature and oxygen fugacity conditions indicated by Buddington and Lindsley (1964).

According to these mineralogical data the oxide minerals of Boss-Bixby formed above 550°C, possibly as high as 600-700°C, and some of the sulphide formed at 500°C or below.

E. Classification

According to the Modified Lindgren Classification, Boss-Bixby belongs to the pyrometasomatic class because,
1) the deposit is chemically concentrated, and 2) it is in a rock formed by igneous activity.

II. Source

On the basis of mineralogy and structural location of the deposit the probably source for ore solutions was an intermediate magma. The place of origin of the magma must have been at much greater depth. The accumulations of Ti, Co, Cu are genetically significant. They too point toward the probability of an intermediate magma as being the source rather than granitic or ultrabasic magma.
Chapter VIII
CONCLUSIONS

The primary objectives of this study were to determine the ore mineralogy and its textures. On the basis of this data the following conclusions are made:

1) The sequence of events and processes of formation of the deposit are complex.

2) Ore mineralization, as a whole, shows a close relationship to metasomatism of the enclosing rocks.

3) The presence of ilmenite, rutile, silicilite, cobaltite, and molybdenite was established. These minerals are unknown to the other Missouri Proterozoic iron deposits.

4) The paragenesis of the deposit indicates that oxides, in general, were deposited slightly before and contemporaneous with Cu-Fe sulphides.

5) Four different types of zoning indicate that the temperature and partial pressure of oxygen and sulfur controlled ore deposition.

6) The deposit on the basis of mineralogy and structure is classified as a pyrometasomatic deposit.

7) On the basis of petrology, mineralogy, and trace element chemistry the source mineralization was an intermediate magma.
BIBLIOGRAPHY


VITA

Frederick Joseph Smith was born April 9, 1943 in Arlington, Virginia to Mr. and Mrs. Frank L. Smith. The author received his primary education in Illinois, Texas and Kentucky. On May 30, 1961 he graduated from Trinity High School in Louisville, Kentucky.

The author entered the University of Missouri atRolla in September of 1961. He received a Bachelor of Science in Geology in May, 1965. As an undergraduate he was a member of many organizations and held offices in some of them. The author entered graduate school in the Department of Geological Engineering and Geology in September of 1965. During the past three years he has been a Graduate Teaching Assistant in the department.

The author has worked for the American Zinc Company and the Texas Gulf Sulphur Company during summers in mineral exploration. He will join the Atlantic Richfield Company's uranium exploration unit after he receives his M.S.