The iron dike; a pyritized graphitic slate of the northern Black Hills

John Emery Adams

State University of Iowa

This work has been identified with a Creative Commons Public Domain Mark 1.0. Material in the public domain. No restrictions on use.

This thesis is available at Iowa Research Online: https://ir.uiowa.edu/etd/4393

Recommended Citation

https://doi.org/10.17077/etd.5k4eep94.

Follow this and additional works at: https://ir.uiowa.edu/etd
THE IRON DIKE

A PYRITIZED GRAPHITIC SLATE OF THE NORTHERN BLACK HILLS of South Dakota

BY

JOHN EMERY ADAMS

A Thesis
Submitted in partial fulfillment of the requirements for the degree of Master of Science of the Graduate College of The State University of Iowa

1923
Folds in The Pyrite Bands of The Iron Dike X30
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter I  Introduction</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nature of the problem</td>
<td>1</td>
</tr>
<tr>
<td>Geography of the region</td>
<td>2</td>
</tr>
<tr>
<td>Field work</td>
<td>4</td>
</tr>
<tr>
<td>Previous work in the region</td>
<td>4</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter II  General geology</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of beds</td>
<td>6</td>
</tr>
<tr>
<td>Lower graphitic slate</td>
<td>7</td>
</tr>
<tr>
<td>Cummingtonite series</td>
<td>8</td>
</tr>
<tr>
<td>Quartzites</td>
<td>10</td>
</tr>
<tr>
<td>Slates and schists</td>
<td>11</td>
</tr>
<tr>
<td>Pre-Cambrian structure</td>
<td>13</td>
</tr>
<tr>
<td>Pre-Cambrian history</td>
<td>14</td>
</tr>
<tr>
<td>Age of the pre-Cambrian of the Black Hills</td>
<td>17</td>
</tr>
<tr>
<td>Igneous intrusions</td>
<td>17</td>
</tr>
<tr>
<td>Erosional history</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter III  Geology of the Iron Dike</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of the formation</td>
<td>23</td>
</tr>
<tr>
<td>Areal distribution</td>
<td>25</td>
</tr>
<tr>
<td>Topographic expression and resistance to weathering</td>
<td>31</td>
</tr>
<tr>
<td>Economic features</td>
<td>33</td>
</tr>
<tr>
<td>Siliceous cap</td>
<td>36</td>
</tr>
</tbody>
</table>
Chapter IV Origin of pyritized graphitic slate

Association of pyrite and graphite ........... 42
Origin of graphitic slates .................. 44
Origin of pyrite in meta-sedimentary deposits 57

Conclusions ..................................... 71

Bibliography
THE IRON DIKE
A PYRITIZED GRAPHITIC SLATE
OF
THE NORTHERN BLACK HILLS OF SOUTH DAKOTA

CHAPTER I
INTRODUCTION

Nature of The Problem

The purpose of this study has been to investigate the geological conditions of occurrence and origin of the Iron Dike. The "Iron Dike" or "Great Iron Dike" is a miners' name given to a prominent member of the pre-Cambrian formations of the northern Black Hills. It is not, as its name might imply, an igneous intrusion, but rather, it is a highly altered and metamorphosed sediment. In the Lead-Deadwood region it strikes in a generally north-south direction and dips eastward at high angles, averaging about 70°. Because of the high angle of dip, only the edge of the formation is exposed.

The Iron Dike, as a formation, is divided into three members, which are grouped together because of their close association. The lower, and stratigraphically older portion, consists of a thin, gray, buff, or iron-stained quartzite. The middle layer is a thin, banded slate, and the upper part a thick, highly pyritized graphitic slate. The graphite member is divided into
two parts which would scarcely be associated on first sight. On the hills, for about 150 feet below their crests, the formation is highly silicified. The pyrite which was in the slate has been oxidized and partly removed, and its place has been taken by quartz. Iron oxide has stained portions of the rock a deep red, while the graphite has colored the rest black. The quartz gives the whole a hard, glossy appearance. Below this siliceous cap, the Dike is a bed of unweathered pyritized graphitic slate from thirty to sixty feet thick.

Geography of The Region

The Black Hills are located in the central western portion of South Dakota and north eastern Wyoming. The Hills form an irregular, elongated dome, rising abruptly from the flat surrounding plains and attaining, at the highest point, an elevation of 7216 feet. A Tertiary uplift has brought the Hills above the general level of the Great Plains. Erosion has removed much of the uplifted sediments and exposed a core of pre-Cambrian crystalline rocks surrounded by a nearly complete sequence of truncated sedimentary formations ranging in age from Cambrian to Cretaceous and overlain unconformably by more recent deposits.

The Lead-Deadwood region is located at the north eastern edge of the northern Black Hills. This reg-
ion shows a mature stage of erosional development. It is drained by Whitewood Creek and its tributaries, of which Whitetail Creek and Deadwood Creek are the most important. The region has wide daily and annual ranges in temperature, in common with most elevated regions of the temperate zone, and has an abundance of rainfall, averaging 36 inches a year. Dense vegetation is limited to the valleys and the northern slopes of the hills, where it serves as an effective check to erosion.

The region contains the two cities of Lead and Deadwood and numerous small stations or villages. Railroad connections are very good. Deadwood is the terminal for the Black Hills divisions of both the Chicago and Northwestern and the Chicago, Burlington and Quincy railroads. Both have wide gauge freight and narrow gauge passenger connections with Lead.

The region is important for its great mineral wealth and has been a mining center for many years. The Homestake mine, the largest gold mine in the world, is located at Lead, and the Trojan Company, one of the larger gold mining companies in the United States, has its offices in Deadwood. The other mineral resources include tungsten deposits and workable pyrite prospects. Farming is not important on account of the rough topography and long cold winters. There
are forests over most of the Hills, which supply lumber for the surrounding territory. Water is available for electric power and irrigation.

Field Work

The field work for this thesis was done in the Lead-Deadwood region of the northern Black Hills of South Dakota, during the summers of 1921 and 1922, under the direction of Prof. J. J. Runner of the State University of Iowa.

Previous Work in The Region

Much geological work has been done in the region. A few of the publications referred to in writing this thesis are, U.S. Geol. Surv., Prof. Paper 26; articles by Sidney Paige and J. J. Runner in Bull. Geol. Soc. Am.; B. M. O'Hara in Eng. & Min. Jour.; W. J. Sharwood in Econ. Geol.; and Wright and Hastead in Eng. & Min. Jour. A complete, accurate, and serviceable bibliography of the Geology and Mining interests of the Black Hills was prepared in 1917 by Cleophas C. O'Harra, and was published as Bull. 11 of the South Dakota School of Mines. More recent articles may be found in the columns of the recent technical and geological journals.
Acknowledgements

The writer wishes to express his appreciation for the kind assistance of Prof. J. J. Runner of the State University of Iowa as an aid and director in the field and laboratory, and to his classes in the Black Hills, to Lawrence Wright, and to Olaf Seims for aid in the field.
CHAPTER II
GENERAL GEOLOGY

Description of Beds

The pre-Cambrian rocks of the northern Black Hills consist of a thick series of sedimentary formations. These were highly dynamometamorphosed, hydrothermally altered by ascending or descending ground water, and eroded to much their present form before the beginning of Cambrian deposition. At present the beds stand at high angles and are complexly folded.

Around Lead and Deadwood, where the pre-Cambrian is well exposed, it has been possible to work out the general structure by tracing certain key formations. From west to east, or from bottom to top, the following sequence of key beds was observed:

4. The Iron Dike (east)
3. Two or three layers of quartzite
2. Two layers of the cummingtonite series
1. A thick, non-pyritiferous, graphitic slate (west)

These sets of beds are separated by slates, schists, and pre-Cambrian and Tertiary intrusions. These formations are inclosed in a thick series of slates and schists in which no folds of importance can be observed. Similar sequences of key beds are exposed at Rochford and Nemo, south east of Lead. At these two
places the sequences are opposed to each other as if they were on opposite sides of a fold. The formations will be described here, with the exception of the Iron Dike which will be taken up in a later chapter.

The lower graphitic slate

The oldest member of the pre-Cambrian series exposed in the Lead-Deadwood region is a thick layer of graphitic slate. This slate, being the oldest pre-Cambrian exposed, is found in the cores of the larger anticlines. The bed is soft and easily eroded, and for this reason the outcrops are covered with talus and soil, so that good exposures are hard to find. Since the slate is plastic and non-resistant the bed varies greatly in thickness. In the narrow fold west of the DeSmet syncline the graphitic slate is not more than ten feet thick, while further west, opposite the mouth of Poor Man Gulch, the bed is approximately 600 feet thick. This great thickness is due to duplication by folding. In spite of the poor exposures the slate can be traced along much of its course by the presence of graphite. The graphite is a minor constituent of the slate, but because of its persistent color, it appears to be more important than it is. The main mineral is probably quartz. This bed contains no observable pyrite, and is locally called
the "Calcareous Black Slate Series". It is very porous, and because of its softness and plasticity, none of the original structure and very little of the imposed structure is retained.

The cummingtonite series

The cummingtonite schists are of particular interest because they contain the ore body of the Home-stake mine. The rock is probably the metamorphic equivalent of a cherty magnesian limestone or dolomite. The series consists of two, or possibly three, layers of schist. The third layer, if there is a third layer, is very thin and outcrops very irregularly. The two lower members which vary in thickness from a few feet to several hundred feet, are separated by thick beds of slate. Neither the thickness nor the separation is uniform, owing to the shearing, crushing, and folding of the rock, and to the pre-Cambrian and Tertiary intrusions. The cummingtonite schist is dark colored, varying from green to black when unweathered. The rock contains numerous long, lens shaped quartz stringers. These quartz lenses lie parallel to the original bedding of the schists and have been folded with it. They are composed of coarse, granular quartz and usually are less than two inches thick. The lenses are numerous and fairly continuous. That is, any one
lens runs out in a few feet, but there are others parallel to it a few inches away which continue so as to shingle the breaks. By means of these lenses it is possible to gain a good idea of the amount of folding which has taken place in the bed.

In the Lead-Deadwood region the cummingtonite schists, with the overlying quartzites, have been repeated several times by folding. These folds have been worked out in detail because of their association with the gold ore. West of Lead the series contains less cummingtonite, the quartz veins become rare, and the formation appears to be very impure. This is probably due to a change in the original sediment, which here may have been a calcareous shale instead of a limestone.

The rock breaks up on weathering, into blocky fragments. It is easily iron stained and rapidly loses the crystalline structure of the cummingtonite. The history of this rock is very complex¹. It was probably altered to a schist during the first period of pre-Cambrian deformation which followed its deposition. Probably at this time crystalline carbonates, quartz, phlogopite, chlorite, graphite, garnet,

---

¹. J.J. Runner  Personal communication
and chloritoid were developed. At a later period it was hydrothermally altered, probably by the Harney Peak granite. At this time lime was removed and new minerals were developed. This later action consisted in the replacement of the minerals already formed, first by tourmaline, and later by cummingtonite, quartz, chlorite, magnetite, pyrite, pyrrhotite, and arsenopyrite, in the order named. The gold, which determines the value of the rock, was probably introduced with the arsenopyrite, with which it is closely associated.

The quartzites

The quartzites are the horizon markers of the pre-Cambrian of the Lead region. As a rule these quartzites have been only slightly changed by the folding and metamorphism, and because of their hardness their courses across the pre-Cambrian areas are marked by prominent ridges. The two thick quartzites of the Lead region have been repeated several times by folding, and this makes the quartzites appear very numerous. Usually the color of the quartzites is a steel gray, but on some exposures it is red, and on others, where iron is especially abundant, it is almost black. The bedding planes have been lost but the rock has a cleavage parallel to the sides of the
bed. The quartzites were so brittle that they were broken rather than bent at the folds.

West of Lead the number of quartzites is increased to three, and the first two are of greater thickness. The increase in number and thickness of the quartzites to the west is taken as proof of the fact that the sediments which compose them were derived from land exposed in that direction. This assumption is apparently correct because other beds in the region, notably the cummingtonite series, seem to indicate the same thing. However, none of the other beds illustrate this theory as well as the quartzites.

The slates and schists

Slates and schists make up the greater part of the pre-Cambrian rock of the northern Black Hills. They inclose the key beds, but because of their plasticity, thickness, and uniformity they are not important in tracing the structure. Their importance lies in their great thickness and in their ability to absorb deformation. The whole series contains many drag folds. Some of these folds are small enough to be observed in the structure of the schist, others can be traced with the assistance of the quartz veins which were folded with the rock. The slates and schists grade insensibly into each other. Originally the rocks
west of the Iron Dike were separated and designated as slates or schists. More recent study has shown the inapplicability of this classification here, and the same probably applies to the rocks east of the Dike. Further study may separate the rocks on some other basis, but at present the data all points to a similar sedimentary origin for all of them.

The minerals of these rocks are those typical of highly schistose formations. The micas are important because they are formed by pressure and shearing and because they combine density and small volume. Black mica, probably biotite, is the common variety in this region. Garnets are very common. They are usually very small and generally are scattered very thickly through the schists. They are often developed in crusts along the large shear planes, at the contact of the schists and quartzites, and along the surfaces of the pre-Cambrian igneous rocks. On exposed surfaces the garnets are usually weathered out and removed. This leaves the surface of the schist covered with small pits. The garnets are usually black or dark red due to the presence of iron or manganese. Garnets, chlorite, calcite, pyrite, feldspar, hematite, siderite, kaolinite, mica, and graphite occur scattered and in masses through the schists and slates.
Quartz is probably the most important mineral in the rock. From a quantitative analysis, Sharwood determined that the slates and schists contained from 50% to 66% silica and from 12% to 16% aluminum.

Pre-Cambrian Structure

The pre-Cambrian structure of the Lead region consists of a series of close set, steeply pitching anticlines and synclines. These folds, some of which are miles in length, are but minor folds near the northern apex of the large, southeastward plunging syncline which forms the major pre-Cambrian structural feature of the northern Black Hills. The folds of the Lead region are shown on the accompanying map. The major structure of the Hills was worked out by tracing the key beds to determine the minor folds, and then by using the minor folds to determine the major ones. Rock cleavage is of little use in determining the structure because the cleavage is, in general, parallel throughout the region.

According to Wright and others, the Black Hills show what appears to be the cross section of a huge syncline of pre-Cambrian age, with an east-west axis.

---
2. Sharwood, W.J. Econ. Geol. Vol. 6 1911 p. 729
3. Wright, Lawrence Personal communication
through the central Hills. They suppose that it was caused by the uplift of the southern part of the Hills at the time of the intrusion of the Harney Peak granite. Field evidence does not support this theory.

In general the structure of the Iron Dike is the same as that of the other pre-Cambrian beds of the region. It is the youngest of the key formations, and with them, dips steeply to the east. The bedding, except for the quartzite-slate-graphite contacts, is highly distorted. Small drag folds are abundant and are especially well shown in the upper silicified cap, the folding having apparently preceded the silicification. In the lower, unweathered portions small drag folds can be traced by following the distorted pyrite veins, and larger folds can be traced by following the pre-Cambrian quartz veins which are abundant through most of the Dike.

Pre-Cambrian History

The pre-Cambrian history of the Black Hills is divided into two periods, both of uncertain age.

4."The older system of sediments outcrops within an oval area approximately three miles by two miles in extent and occupies the center of a slightly elongated domical structure. The intrusion of

igneous rocks into both systems is thought to have had an effect in producing the structure.

The older formation comprises quartzites, quartz-sericite schists, and iron formations consisting of alternate bands of quartz and specular hematite or magnetite. Completely surrounding the older system is a younger one. The contact between the two is in some places clearly an erosional one. The basal member of the younger system is generally a conglomerate containing in places huge boulders of precisely the same character of rock that is found in the older, only a few feet distant, and at some of these points the older beds are clearly truncated.

The existence of boulders within the conglomerate containing drag folds and brecciated structures, of firmly cemented quartzite pebbles within a chloritic matrix, and the considerable angle between the bedding planes of the two systems is evidence of the time required in the unconformity.

The pre-Cambrian of the remainder of the Hills area probably belongs to the younger system.

In the later period mentioned above, the quartzite, iron formations, limestones, and various schists and slates were deposited as sediments, apparently derived from land lying to the west or north west of the present position of the Hills. The greater thickness of the quartzites and the greater impurity of the other formations are the main evidences of this shore line in the Lead-Deadwood region.

After the deposition of these sediments they were cut by numerous basic intrusions. According to Irving these intrusions were followed, by the folding of the strata of the region to approximately their present form. Probably the intrusion and the folding were

5. Irving, J.D., Contrib. Geol. Northern Black Hills
almost simultaneous. Accompanying or preceding this folding the country rock of the whole Hills area was ramified by quartz veins. Late in the pre-Cambrian the rocks were compressed to give them their present slatey cleavage. During this period structures of such magnitude were developed that the large folds in the northern Hills were of but very minor importance. Accompanying or preceding this second period of folding the Harney Peak granite was intruded as a large batholith under the whole region. Probably accompanying this second intrusion the region was again ramified by quartz veins. These can be distinguished because they are less folded than the earlier veins. 5J.J.Runner, in speaking of the Harney Peak granite, says:

"Certain crystalline cummingtonite schists, derived from calcareous rocks, in the Lead and Rochford regions indicate the proximity of some agent of thermal metamorphism other than the basic intrusions in those regions. Apparently accompanying this thermal metamorphism, occurred the introduction of quartz, sulphides, and gold and the formation of valuable ores. The date of this mineralization appears to have been pre-Cambrian, after the folding of the sediments and the development of the schistose structure."

During the last chapter of the known pre-Cambrian history the whole area was raised to a considerable height and the rocks were exposed to the agencies of

weathering. The erosion continued for a long time and an enormous amount of rock was removed. Erosion ceased before the region had been reduced to base level, subsidence followed and the Cambrian sediments were deposited over the pre-Cambrian hills and valleys.

Age of The Pre-Cambrian in The Black Hills

The crystalline rocks of the Black Hills are definitely known to be of pre-Cambrian age, because they underlie the Cambrian unconformably. Pre-Cambrian geologists of the Lake Superior region believe them to be equivalent to the Upper Huronian. The lack of absolute correlation between the two regions is due first, to the fact that there are no fossils; second, to the absence of connecting outcrops; and third, to differences in original sedimentation and degree of metamorphism. The name Algonkian is applied to the pre-Cambrian rocks of the Black Hills by the U.S. Geological Survey because the majority are of sedimentary origin. In this thesis, however, on account of the lack of absolute data, the rock formations will be designated simply as pre-Cambrian.

Igneous Intrusions

Several times in the past the Black Hills have been the seat of great igneous activity. At least
two periods preceded the final metamorphism and one followed it. In the first period the basic sills and dikes of the northern Hills were intruded in great numbers. In the second period the Harney Peak granite and pegmatite were intruded beneath the whole area. The third period, during which the porphyries and rhyolites of the northern Hills were intruded, did not come until the close of the Mesozoic era. From their separation in time and composition it seems probable that these three were in no way genetically related. As far as is known there was no extrusion during any of these periods of igneous activity.

The pre-Cambrian igneous rocks exposed in the northern Black Hills are of both basic and acidic types. The basic intrusions are represented by altered amphibolite sills and dikes which were intruded in the pre-Cambrian sediments and metamorphosed with them.

They consist of meta-gabros whose chief components are plagioclase feldspar, hornblende of the variety uralite, and accessory ilmenite, calcite, apatite, and quartz. Cores of large dikes show uralite masses with augite kernels, furnishing a clew to the original character of the rock. Such cores pass toward the periphery with increasing schistosity, proceeding by insensible gradations into chlorite and hornblende schist."

No features were noted in the field, which showed

the metamorphic effect of these basic intrusives. They apparently accompanied or preceded the first period of folding and they may have an important bearing on the geology of the region. In many places these basic sills are in contact with the Iron Dike, and in others they are separated from it by Tertiary intrusions. From a survey of the relations of the igneous rock and the Iron Dike in the exposed areas, one can say that originally these basic intrusives were in contact with the Dike through most, if not all, of its course through the Lead-Deadwood region. Heat and pressure are necessary for changing carbon to graphite, and since these were furnished at the time of intrusion it is possible that the graphite was formed by them. These intrusives were undoubtedly important in the metamorphosing of the rocks adjacent to them, although this does not show at present, and they may have been important in the mineralization of the region.

Granites are exposed in several places in the northern Black Hills. Usually they occur as inclusions in the Tertiary intrusions. Such inclusions are exposed in the Bear Lodge Mts., in the Nigger Hill Laccolith, and in the Whitewood Canyon Laccolith northeast of Deadwood. In texture and minerals they re-
semble the Harney Peak granite or pegmatite. If they are connected with this granitic intrusion, which seems probable, the Harney Peak granite must underlie most of the northern Black Hills. Although no outcrops of the granite, in place, are exposed around Lead and Deadwood it undoubtedly underlies this area at no great depth and its effect on the mineralization of the region has been important.

The last period of igneous activity in the Hills occurred at the close of the Cretaceous or early in the Tertiary. During this period of intrusion porphyries and rhyolites were injected as dikes, sills, and laccoliths in all the formations of the northern Hills. These intrusions were apparently dry; and although their temperature may have been high, their effect on the mineralization of the pre-Cambrian is not apparent.

**Erosional History**

The erosion which followed the Tertiary uplift of the Black Hills uncovered the pre-Cambrian-Cambrian contact over much of the region. This marked unconformity, which almost everywhere separates the Cambrian from the pre-Cambrian, is well illustrated in the Lead region. The top of the pre-Cambrian here represents an old erosion surface which was formed after thousands of feet of rock had been removed.
During this early erosional period the area was reduced almost to grade. Some of the original features of this surface have been removed by subsequent erosion, but enough remain to show the original contour.

It is evident that the region was near grade at the beginning of the Cambrian, but the surface certainly was not a plain. There are numerous low pre-Cambrian hills exposed. Some of the irregularities of the pre-Cambrian surface may have been developed by Tertiary intrusions. Most of the hills however are due to variations in the hardness of the pre-Cambrian beds. The hard beds, the quartzites and the Iron Dike, form ridges in the exposed areas and their courses under the Cambrian sandstone are marked by slight anticline which appear to be due to differential settling. The Cambrian sandstone was originally deposited in horizontal beds over the pre-Cambrian surface. Settling due to the presence of overlying sediments took place upon consolidation. This settling was greater over the thicker deposits, and consequently anticlines were formed over the ridges. The traces of these anticlines are lost as the thickness of the overlying beds increases. The average maximum dip of these anticlines is about 5°.

The conclusion is drawn that settling took place with sedimentation and that equalization came shortly after deposition began. The effect of the settling is lost
to a great extent wherever the Cambrian sandstone is underlain by Tertiary sills.

The present exposure of the pre-Cambrian rocks in the Black Hills is due to the erosion which followed the early Tertiary uplift. As a result of this uplift reduction was rapid and by Oligocene times the streams had cut through the Paleozoic and Mesozoic sediments into the underlying pre-Cambrian rocks. Apparently the region was reduced almost to grade during the Oligocene. Erosion ceased to be the dominant factor and fresh water lakes and swamps were formed. Some of these occurred in stream valleys well below the tops of the present pre-Cambrian hills. No known Miocene, Pleiocene, or Pleistocene (?) deposits are found. Probably the crests of many of the ridges were silicified by descending ground water during these periods. The Pleistocene or Recent gravels which occur abundantly on some of the divids and in the stream valleys are the result of renewed uplifts which inaugurated a new period of erosion, of which the present topography is the result.
CHAPTER III
GEOLOGY OF THE IRON DIKE

Description of The Formation

The name "Iron Dike" or "Great Iron Dike" is given to a prominent sedimentary member of the pre-Cam­brian formations of the northern Black Hills. This formation is divided into three parts by the nature of the original sediments. The first or lower mem­ber of the Iron Dike is a thin buff or gray quartzite. It is composed of firmly, fine grained sand. The bedding, although indistinct, is parallel to the strike of the bed. The thickness is relatively uniform, averaging about 8 feet. This uniformity is probably due to the fact that the quartzite was inclosed in softer rocks which absorbed the deformation. The quartzite is friable and apparently is less resist­ant to weathering than the inclosing schists. For this reason exposures are poor except in fresh cuts. One exception to this rule is the outcrop on the "Powder House" hill just south of Gold Run and east of the city limits of Lead. Here the quartzite is well exposed at the base of the silicified graphite. In general the quartzite is not highly iron stained, and contains no graphite. However, one specimen taken from the outcrop in the Chicago and Northwest-
ern cut just south of the 5377 foot hill, in the S.W. 1/4 of Sec. 27, R.3 E., T.5 N., had graphite along the bedding planes. Pyrite is present in very small quantities. The color of the quartzite varies. In general it is darkest near the tops of the hills and lightest in the valleys. On the weathered surfaces it is usually a reddish brown, but on the slope north of City Creek the outcrop is a deep red due to iron stain. On fresh surfaces the color is usually gray, buff, or yellow.

The second or middle member of the Iron Dike is a thin layer of slate or schist. It is well marked in some of the outcrops near the northern end of the Dike. This member is composed of thin, alternating layers of light and dark material, indicating that the original deposit was a varicolored shale. The thickness varies. In some places the bed has been completely pinched out by infolds of the graphitic slate, while in other places it is six or eight feet thick. It is best exposed in the fresh cuts in the valleys, but is often marked in the silicified portions of the Dike by its light and dark banding. It is probably continuous over the entire region, but becomes very thin to the south, where it is very seldom exposed.
Faults in The Banded Slate of The Iron Dike

(X 10)
The third or upper member of the Iron Dike is a thick, pyritized graphitic slate. This graphitic member is divided into two parts along the dip of the bed. In the Lead-Deadwood region the Iron Dike dips eastward at an angle of about 70°. For this reason the width of the outcrop is only a little greater than the thickness of the formation. On the slopes of the hills, for from 150 to 200 feet below the crests, the formation is highly silicified. The pyrite which was originally contained in the slate has been oxidized and partly removed and its place has been taken by quartz. The iron oxide formed from the pyrite has stained portions of the rock deep red, while the graphite has colored the remainder black. In the valleys the lower portion of the upper member is exposed. Here the pyrite forms the bulk of the rock, but the graphite colors the whole black. The upper member of the Dike, which has been folded, faulted, and mashed until very little of the original structure is retained, varies from 35 to 50 feet in thickness.

Areal Distribution

The outcrops of the Iron Dike extend as a more or less continuous single band, for about eight miles across the Lead-Deadwood region. A graphitic slate
Black Nodules in The Iron Stained Portion of The Siliceous Cap
with stratigraphic relations similar to those of the Iron Dike, is exposed in the vicinity of Englewood. Assuming these to be exposures of the Iron Dike, it can be traced northward from near Englewood to the north bank of City Creek, just west of the city limits of Deadwood. It can not be traced further because it is covered at both ends by caps of Cambrian sandstone. According to Runner, formations similar to the Iron Dike in structure and stratigraphic relations are exposed at Rochford and Nemo, to the south and southeast of Lead. He supposes that they are continuations of this formation. However, they will not be discussed here.

In the exposures at Englewood the relations of the quartzite and the graphite are reversed in the two outcrops, probably indicating that they are on opposite sides of a fold. From east of Englewood, the Iron Dike runs northward along the divide between Whitewood Creek and Yellow Creek. Most of the divide is capped by Cambrian sandstone or the underlying Tertiary sills, and the Iron Dike rarely outcrops. The only exposure of the graphitic slate along this ridge is at an old mine dump a half mile southwest

---
Runner, J.J., Personal communication---
The Iron Dike North East of Lead
of Kirk. From here the outcrop extends southward again and crosses Yellow Creek a mile south of Kirk. From the east bank of Yellow Creek the Dike turns north along the west slope of the divide between Yellow Creek and Grizzely Gulch. This reversal of strike is due to a fold which is observable in all the key beds of the region. From Yellow Creek to Whitewood Creek the outcrops are obscured by vegetation and the overlying rocks. The Dike crosses Whitewood Creek about three quarters of a mile west of the mouth of West Strawberry Creek, and from here to City Creek its course is easy to follow. From Whitewood Creek to Gold Run it lies almost parallel to and only a few hundred yards east of the city limits of Lead. The Dike is well exposed in the railway cut in the north bank of Whitewood Creek. The following section measured from west to east (oldest to youngest) was taken at this place.

1. Hard, buff, slightly brecciated quartzite 12
2. Soft, porous, slaggy graphitic slate with lenses of nearly pure graphite  5
3. Hard, graphitic slate 2
4. Yellow, slaggy, schistose rock 22
5. Hard, graphitic slate 4
6. Slightly iron stained, slaggy, graphitic slate 8
The Dike, at this outcrop, appears to be in two thin parts with a layer of foreign material between. This does not seem to be a repetition by folding because the quartzite is on only one side.

A typical exposure of the silicified portion of the Iron Dike occurs on the "Powder House" hill, south of Gold Run and east of Lead. It was impossible to get an accurate section here, but the thickness was estimated at about 65 feet. The basal quartzite is well exposed in this outcrop as a grayish buff band along the foot wall of the Dike. At the southern edge of the outcrop the thickness of the Dike is exaggerated by the intrusion of a thick Tertiary sill or dike which cuts across it.

In the valley of Gold Run and on the slopes on either side, the Iron Dike is mostly covered. In one exposure on the south bank of Gold Run the formation is cut into narrow strips by the younger quartz veins. In some of these quartz veins comb structures were well developed and the interstitial spaces were open. In the first gulch north of Gold Run, in the N.W.1/4 of Sec.34, T.5 N., R.3 E., there is an abandoned prospect in the lower, unsilicified portion of the Dike.
The formation here contains a large amount of pyrite. The formation outcrops continuously from the bottom of this gulch to the top of the 5377 foot hill in the S.W. 1/4 of Sec. 27, T. 5 N., R. 3 E. The following section was taken about half way up the hill, along the Chicago and Northwestern railroad track. The section reads from west to east:

1. Massive, buff quartzite ------------------- 9
2. Thin bedded slate ------------------------ 6
4. Impure, massive, graphitic slate--------- 12

Total ---------------------- 54

At the top of the hill the outcrop is typical of the silicified portion of the Dike. The great width of the silicified rock here may be due to repetition of the Dike by folding or faulting, or to the silicification of the inclosing beds. The quartzite is of little importance compared to the great mass of silicified rock. There is a sharp break in the Iron Dike from the northern slope of this hill to the southern slope of the next hill, a half mile to the north. This gap may have been formed by a fold or a block fault which shifted the outcrop of the Dike about a half mile to the west. From the north end of this gap, on the eastern slope of the small hill in the
N.E.1/4 of the S.W.1/4 of Sec.27, T.5 N., R.3 E., the Dike runs north to Deadwood Creek. The outcrop in Deadwood Creek is east of the general course of the Dike, probably because erosion has carried it down the dip and not because of folding, although it is possible that there is a small fold.

The outcrop in Deadwood Creek is typical of the unsilicified portion of the Dike. The graphitic slate is soft and highly pyritiferous and is bordered on both sides by igneous rock. Owing to the presence of igneous rocks and quartz veins it was impossible to measure the true thickness of the slate. Mr. Seim², who owns a deserted mine on the north side of the valley, says that the Dike is 80 feet thick here, but this is exaggerated by at least 20 feet due to the presence of igneous rocks and quartz veins in the section.

From the north bank of Deadwood Creek, the Iron Dike outcrops continuously, to the top of the divide between Deadwood Creek and City Creek. The northern slope of this divide is covered with vegetation but the Iron Dike outcrops again on the north side of City Creek. There is an abandoned mine in the unsilicified portion of the Dike.

-----
2. Olaf Seim, Personal communication
-----
icified portion of the Iron Dike on the north bank of City Creek, from which much pyrite ore has been removed. From this mine, outcrops are continuous to the base of the Cambrian sandstone cap near the top of the north wall of the valley. The following section, measured from west to east, was taken just below the Cambrian sandstone:

1. Dark red, iron stained quartzite. ------- 8
2. Light gray and black banded slate ------- 3
3. Iron stained, highly silicified, graphitic slate with black nodules and alternating patches of black and red ------- 57

Total------------------- 68

This is the thickest section taken and probably is the nearest normal, because all the other outcrops were bordered on at least one side by igneous rocks.

Topographic Expression
And Resistance to Weathering

The Iron Dike dips steeply to the east throughout its course, except for a few minor reversals due to drag folding. The present streams which cross the Dike are superimposed on the pre-Cambrian topography. Sufficient time has elapsed however, since the uncovering of the pre-Cambrian to allow most of the streams to adjust their courses to the pre-Cambrian structure.
All the streams which cross the Iron Dike cross it at right angles because of the hardness and resistance of the siliceous cap. Where the large streams have cut through this hard cap into the softer portions below, the Dike seems no more resistant than the inclosing schists. The prominent ridge which is formed by the silicified portion of the Iron Dike is made conspicuous by its continuity and isolation. The quartzite which accompanies the graphitic slate is so thin and friable that it neither forms ridges on the hills nor rapids in the creek beds. This friability is probably due to the great porosity which makes the rock easily accessible to the agents of disruption. The quartz which occurs in the silicified portion of the graphitic slate was deposited from solution, and almost completely fills the pores of the rocks, thus excluding disruptive agents. This and the original texture are the important factors in determining the relative resistance of these two members of the Dike.

In most places, the exposed surface of the Dike below the cap, is covered by a hard, dark brown, porous crust totally unlike the silicified cap. This crust is probably due to the leaching of the pyrite and the formation of some iron oxide in its place, rather than to the introduction of silica. In this
regard Emmons says:

"Sulphide ores, exposed to weathering, at or near the surface of the earth, break down to form soluble salts and minerals that are stable under surface conditions. No metallic sulphide that is long exposed to the air and water remains unaltered. Iron sulphides which are present in practically all sulphide ores, are changed on weathering, to iron oxide, and the changes are attended by the liberation of sulphuric acid.

The chemical reactions would probably be as follows:

\[
\begin{align*}
2\text{FeS}_2 + 70 + 2\text{H}_2\text{O} &\rightarrow \text{FeSO}_4 + 2\text{H}_2\text{SO}_4 \\
6\text{FeSO}_4 + 30 + 3\text{H}_2\text{O} &\rightarrow 2\text{Fe(SO}_4)_3 + 2\text{Fe(OH)}_2 \\
\text{Fe}_2(\text{SO}_4)_3 + 6\text{H}_2\text{O} &\rightarrow 2\text{Fe(OH)}_3 + 3\text{H}_2\text{SO}_4 \\
4\text{Fe(OH)}_3 - 2\text{Fe}_2\text{O}_3 + 6\text{H}_2\text{O} &\rightarrow 2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O} + 3\text{H}_2\text{O}
\end{align*}
\]

Economic Features

The economic importance of the Iron Dike is due to the high percent of pyrite which it contains. Although gold and copper occur with the pyrite, they are present in such small quantities that they do not materially increase the value of the ore. These metals may be profitably extracted as by-products in any process utilizing the pyrite. Pyrite forms about 60% of the rock in the unweathered outcrops of the Dike in the Lead-Deadwood region. Some of this pyrite has been mined for use as flux in smelting and for the manufacture of sulphuric acid.

Sections of Drill Cores

Showing the Large Percentage of Pyrite
There are two deserted pyrite mines in the Iron Dike on Deadwood Creek, about a mile west of Deadwood. These mines were originally developed to supply the Golden Reward Co. of Deadwood with pyrite for flux in the smelting of gold ore. Pyrite mining was profitable until the smelter closed down early in 1918. The closing of the smelter came during the last year of the war. At that time there was a great demand for pyrite in the manufacture of chemicals. After the closing of the smelter mining was continued in the Seim mine on the north side of the valley and the pyrite was shipped to a sulphuric acid plant in Chicago. Freight rates were raised after a few hundred thousand tons had been shipped, mining became unprofitable and was discontinued.

High grade pyrite free from lead, zinc, arsenic, antimony, and selenium is necessary for the manufacture of sulphuric acid. Only that pyrite with a sulphur content of at least 38% is used. The ore from the Iron Dike yields, after concentration, a high grade of pyrite, free from objectionable metals, and averaging about 40% sulphur. Ore appears to be present in immense quantities, and because of the soft gangue it can be easily mined. For these reasons Mr. Seim believes that if it were possible to estab-
lish a sulphuric acid plant at the mine, mining could carried on profitably. The advisability of establishing such a plant will be considered after a summary of the prospects for pyrite mining has been given.

Since the close of the war, in 1918, there has been a great decrease in the demand for pyrite. This is best shown by the following tables taken from Mineral Resources of The United States:

<table>
<thead>
<tr>
<th>Year</th>
<th>Production</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Tons</td>
<td>Value</td>
</tr>
<tr>
<td>1913</td>
<td>341 338</td>
<td>$1 286 084</td>
</tr>
<tr>
<td>1914</td>
<td>335 662</td>
<td>1 283 346</td>
</tr>
<tr>
<td>1915</td>
<td>394 124</td>
<td>1 674 933</td>
</tr>
<tr>
<td>1916</td>
<td>439 132</td>
<td>2 038 002</td>
</tr>
<tr>
<td>1917</td>
<td>482 662</td>
<td>2 593 035</td>
</tr>
<tr>
<td>1918</td>
<td>464 494</td>
<td>2 644 515</td>
</tr>
<tr>
<td>1919</td>
<td>420 647</td>
<td>2 558 172</td>
</tr>
<tr>
<td>1920</td>
<td>310 777</td>
<td>1 596 961</td>
</tr>
<tr>
<td>1921</td>
<td>157 118</td>
<td>7 11 432</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Imports</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1913</td>
<td>850 592</td>
<td>$3 611 137</td>
</tr>
<tr>
<td>1914</td>
<td>026 617</td>
<td>4 797 326</td>
</tr>
<tr>
<td>1915</td>
<td>964 634</td>
<td>4 817 977</td>
</tr>
<tr>
<td>1916</td>
<td>244 662</td>
<td>6 728 318</td>
</tr>
<tr>
<td>1917</td>
<td>967 340</td>
<td>5 981 457</td>
</tr>
<tr>
<td>1918</td>
<td>496 792</td>
<td>2 741 676</td>
</tr>
<tr>
<td>1919</td>
<td>388 973</td>
<td>2 176 565</td>
</tr>
<tr>
<td>1920</td>
<td>332 606</td>
<td>1 660 832</td>
</tr>
<tr>
<td>1921</td>
<td>216 229</td>
<td>818 852</td>
</tr>
</tbody>
</table>

From this table it can be seen that the peak of production came in 1917, and the peak of imports in 1916. The tables show the production and imports of 1921 to be the lowest in nine years. The cause
of this decrease in the production is the fact that free sulphur can be mined at less expense. The following table, showing the increase in the sulphur industry, was taken from Mineral Resources of The United States, for 1921:

<table>
<thead>
<tr>
<th>Year</th>
<th>Mined</th>
<th>Shipped</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Tons</td>
<td>Long Tons</td>
<td>Value</td>
</tr>
<tr>
<td></td>
<td>649 683</td>
<td>766 835</td>
<td>$12 246 000</td>
</tr>
<tr>
<td>1916</td>
<td>649 683</td>
<td>766 835</td>
<td>12 246 000</td>
</tr>
<tr>
<td>1917</td>
<td>134 412</td>
<td>120 378</td>
<td>23 987 000</td>
</tr>
<tr>
<td>1918</td>
<td>353 525</td>
<td>266 907</td>
<td>27 368 000</td>
</tr>
<tr>
<td>1919</td>
<td>190 575</td>
<td>678 257</td>
<td>10 252 000</td>
</tr>
<tr>
<td>1920</td>
<td>255 249</td>
<td>517 625</td>
<td>30 000 000</td>
</tr>
<tr>
<td>1921</td>
<td>879 150</td>
<td>954 344</td>
<td>17 000 000</td>
</tr>
</tbody>
</table>

It is evident that, unless some valuable by-products can be recovered from pyrite, the mining of this mineral will not be important as long as Louisiana sulphur supplies the market, as it has done in the last few years. There is a possibility of recovering iron from the pyrite, but no satisfactory process has as yet been perfected, and since the gold and copper in the Iron Dike are not abundant enough to materially increase the value of the ore, the idea of establishing a sulphuric acid plant to use the pyrite of this formation is not advisable at present.

Siliceous Cap

A review of the geology of the Iron Dike would be incomplete without a discussion of the age and origin
of the siliceous cap which crowns the exposed, weathered portions of the Dike. Most of the quartz in this cap is undoubtedly of secondary origin. Secondary quartz may be introduced in two ways. It may be deposited either by ascending magmatic waters, or by descending ground waters. The age as well as the origin of this silica is in question. It appears that the folding of the region took place before the introduction of the quartz, because the smooth, regular folds of the graphitic slate are retained undisturbed in the silicified deposit. If the quartz had been introduced before the folding, the bed would have been brecciated, and it is highly improbable that the silicified cap would bear as close a relation to the surface as it does. From this association of the silicification with the pre-Cambrian surface of the region, it seems probable that the quartz was introduced after or accompanying the period of erosion which preceded the deposition of the Cambrian.

The quartz in this siliceous cap completely fills the pores and cavities formed by the oxidation of the pyrite. It appears that the deposition of the quartz was related chemically and chronologically with the destruction of the pyrite which it replaces. Weak sulphuric acid formed by the oxidation of pyrite
Residual Boulder on Siliceous Cap

The Iron Dike South of The Powder House
will precipitate finely crystalline quartz from silicic acid solutions, and if any long period of time had elapsed between the oxidation and removal of the pyrite and the introduction of the silica, it is probable that the nonresistant graphitic slate would have been compressed to fill the open spaces.

Silicification is very common in connection with igneous intrusions. In many places in the northern Black Hills the country rock was silicified at the time of the Tertiary intrusions. The most important deposits formed at this time are the siliceous gold ores in the Cambrian dolomites. These deposits are noted for their economic value, but the same processes which formed them seem to have formed similar deposits, without the gold, in the pre-Cambrian slates. Through most of its course, the Iron Dike is bordered by Tertiary intrusions. The pyritic portion of the Iron Dike, below the siliceous cap, is very porous. A silicic solution may have moved outward and upward from the intrusive magma into the graphitic slate and have been precipitated when its upward course was checked by the overlying Cambrian sandstone. This does not seem probable because the pyrite must have been oxidized but a short time before the introduction of the quartz. At the time of the intrusions
the region was covered by a thick mantle of sediments and oxidation could not have taken place from the surface. Although the magmatic solution might have dissolved the pyrite, it could not have oxidized it.

There is a close association between the silicification of the Iron Dike and the pre-Cambrian topography of the region. This relation seems to indicate that the secondary quartz in the siliceous cap was deposited by descending ground waters during the period of erosion in which the pre-Cambrian was exposed. There have been two such periods of erosion in the Lead region. The first one came sometime between the folding of the pre-Cambrian beds and the beginning of Cambrian deposition. The second probably began in the late Eocene and has continued to the present. Arguments may be advanced to prove that the silicification took place in each of these periods.

Silicification and oxidation take place above the ground water surface. The thickness of the siliceous cap of the Iron Dike is between 100 and 200 feet. This means that at some period the ground water surface stood that far below the present tops of the hills. As shown in the discussion of the erosional history, beds of Oligocene age are found in depressi-
ions or old valleys below the present top of the pre-Cambrian surface. These beds, which are swamp or lake deposits, occur about on a level with the bottom of the siliceous cap. They probably represent almost the top of the ground water surface at the time of their deposition. If the silicification took place at this time or at a later period the lower surface of the siliceous cap should be curved to conform to the present surface. In the Olaf Seim mine this appears to be the case. Here the siliceous cap curves gently upward and inward, following in a very modified form, the contour of the hill.

There are indications that at least the upper part of the siliceous cap is of pre-Cambrian age. Although the silicification seems to be roughly dependent upon the present topography, it seems to be more dependent upon the topography of the pre-Cambrian surface. In other words, silicification is marked to the same depth in those hills which are covered by several hundred feet of Cambrian sandstone or Tertiary porphyry as in the hills on which the Iron Dike outcrops at the surface. The flat anticlines in the basal Cambrian sandstone, which occur along the ridges show that the Iron Dike was hard enough at the beginning of Cambrian deposition, to stand above the
inclosing schists. The thin quartzite which accom­
panies the graphitic slate is too thin and friable
to form such a prominent ridge. For these reasons
it appears that the silicification of at least the
upper part of the cap took place during the inter­
val preceding the beginning of the Cambrian depos­
iton, although the lower part was probably formed
at a more recent date.
CHAPTER IV
ORIGIN OF PYRITIZED GRAPHITIC SLATES

Association of Pyrite and Graphite

The origin of bedded deposits of pyritized graphitic slates is of great interest. This question will be taken up in detail in this thesis. A brief resume of the commonly accepted theories will be given and the principles developed will be applied to the Iron Dike.

In studying the literature, one is impressed with the common association of pyrite and graphite. As shown by Harder, conditions which favor the deposition of carbonaceous material also favor the deposition of pyrite and other iron compounds. Iron compounds are slowly altered to pyrite by the action of sulphur bacteria in the decaying carbonaceous matter. In many deposits, it is evident that the association is not one of primary deposition. It is usually believed that pyrite, when it is very abundant in graphite deposits, has been introduced after the formation of the graphite. The mode of introduction may vary. The secondary pyrite may be introduced as iron disulphide or any other iron com-

1. Harder, E.C., U.S. Geol. Surv., Prof. paper 113, 1919
pound which can be altered to pyrite by metamorphism. The fact that graphite, as such, or as organic car-
bon, has the ability to precipitate pyrite has been pointed out by Jenny\(^2\) and Allen\(^3\). Smyth\(^4\), in speak-
ing of this subject, says:

"Thus for the graphite, a history somewhat sim-
ilar to that of the pyrite is indicated, but with the difference that most of the former is thought to be carbon that was original in the sediments, which has undergone some concentration and may have received minor additions from magmatic sources, while, in the case of the pyrite, the relative im-
portance of the sources is reversed. Thus the ev-
idence furnished by the pyrite would add support to the contention that the carbon was present in
the sediments as an original constituent."

Any discussion of the graphite or pyrite of a bed in which they both occur would be lacking in comple-
teness if it did not consider the origin of both, be-
cause as shown above, the association is common and may be either primary or secondary. In this thesis the relation of the graphite and the pyrite in the Iron Dike will be considered before any conclusions are drawn.

\(^3\) Allen, E.T. Min. & Sci. Press, Vol.103, 1911, p.413
Origin of Graphitic Slates

A study of the principal graphite deposits of the world shows that the various deposits may differ in origin. For this reason some classification of the many types of deposits is necessary, but so little is known about the origin of graphite that, to the present, none has been proposed. The following was copied from Clark. He describes it as "simple and complete enough to cover every case known in sedimentary rocks."

1. Bedded deposits
2. Disseminated deposits
3. Vein or vein-like deposits
   - Fissure deposits
   - Contact deposits
   - Pegmatite deposits
4. Deposits with native iron and in meteorites

As described by Clark, the graphitic slate of the Iron Dike is distinctly a bedded deposit. A genetic classification of such deposits would be somewhat similar to the following:

1. Pneumatolytic or magmatic deposits
2. Deposits of original graphite

5. Clark, T. H. Econ. Geol. Vol. 16, 1921, p. 167
3. Metamorphosed coal beds

4. Metamorphosed carbonaceous shales or bituminous deposits other than coal beds

5. Metamorphosed and altered limestones

Each of these will be taken up in the order named and a discussion as to its applicability to the Iron Dike will be given. Jensen, in speaking of pneumatolytic graphite deposits, says:

"My opinion is that graphite is deposited pneumatolytically from iron carbonyl which is produced by the interaction of metallic iron with carbon monoxide under conditions of high temperature and pressure. . . . The carbonyls of iron are mostly clear, oily liquids soluble in petroleum and insoluble in water, but decomposed by moist, hot air with the production of metallic iron hydroxide and CO. They are unstable, volatile compounds and under slightly varying conditions decompose spontaneously yielding different products, thus iron carbonyl may yield iron and CO, or iron oxide, CO₂ and graphite.

Sulphur and oxygen are chemical equivalents and yield similar compounds with the metals, hence it is probable that under the temperature-pressure conditions existing in a cooling magma, thio-carbonyls would also form and would pass away in the gaseous form, and as the temperature and pressure conditions change, deposit pyrite and graphite, thus Fe(CS)₄ → FeS₄ + 4 CO₂ or FeS₂ + 4 CS₂ + 4 C₂.

Some carbonyls on contact with moist air yield metallic carbonates and hydroxides and CO.

The latter under conditions of relieved temperature and pressure may yield carbon dioxide and carbon.

The CS₂ formed in the decomposition of thio-carbonyl would form thio-carbonates. Carbonates are high temperature compounds. Thio-carbonates are probably also formed under high temperature condi-

ions. They tend under normal conditions to decom­
pose into metallic sulphides and CS₂. However K₂CS₃,
a thio-carbonate of polyvalent potassium, decom­
poses into K₂S₃ + C. As iron is also polyvalent it is possible that the thio-carbonate will behave similarly, yielding pyrite and graphite."

The main objection to this theory is that it seems impossible for a deposit so formed to replace a bed over a large area. Jensen states, in the same article, that graphite deposited in this way forms bedded de­
posits, but that they are of small extent and are lim­
it to shear zones and fissure lodes. This theory does not apply to the Iron Dike because it extends over large areas and does not follow a faulted zone. The same objections apply to the theory of magmatic origin for the graphite in the Iron Dike.

Graphite is supposed to be a product of original sedimentation because it is found in unmetamorphosed sediments. Such occurrences are rare although de­
position may logically follow the erosion of some pre-existing graphite deposit. The deposition of graphite in such cases is due to mechanical proces­
ses and the eroded deposit may have been either ig­
neous or sedimentary in origin. No localities are noted in which such deposition is going on at the

   Emerson, B.K. Mon. XXIX, U.S. Geol. Surv. p. 365
present time, but such an origin is theoretically possible.

The pre-Cambrian intrusions exposed in the Black Hills are all younger than the Iron Dike and therefore could not have been eroded to furnish the graphite. A thick graphitic slate is exposed west of the Iron Dike and lies parallel to and about 3000 feet below it. The origin of this slate is unknown. It is improbable that the graphite of the Iron Dike was derived from this formation, first because dynamic or thermal metamorphism or both are necessary in the formation of graphite and there are no marks of any such metamorphism having intervened between the deposition of the two graphite bearing beds. This indicates that graphitization took place simultaneously in the two beds. And second, because there is no unconformity between the two beds, the lower one could not have been upturned and deeply eroded to furnish the graphite for the Iron Dike.

Many authorities believe that bedded graphite deposits are formed by the metamorphism of coal beds. Clark, in speaking of such beds, says:

"All writers agree that this type of graphite is the result of the metamorphism of carbonaceous

Page numbering in the original document skips page number 48.
sediments, and in fact, in most cases, of coal beds. Either contact or regional metamorphism may be re­sponsible for the change, but static metamorphism does not seem to have been active in transforming coal beds into graphite. Of all the agents of meta­morphism, heat seems to have been the most impor­tant factor, since all the volatile constituents of the original coal must be dispersed in order to al­low the formation of graphite. Even in contact metamorphism of sediments, pneumatolytic processes seem to play no part in the production of this type of graphite."

No one doubts that graphite can be produced from coal. But this theory for the origin of all bedded graphite deposits brings up the question of pre-Cam­brian coal. It is generally believed that there were no fibrous plants in the pre-Cambrian but the plant life necessary for coal beds may have been furnished by algae or other organisms. According to White9, European botanists and paleobotanists have found that some Paleozoic coals are preponderantly composed of micro-algae. Such beds are common in the Cretaceous and Tertiary but the occurrence ofOrdovician beds composed of these organisms places the range of their importance much farther back in geologic time. White9 suggests them as a possible source for the bedded graphite deposits of the pre-Cambrian. The name "saprolitic coal" has been applied to such deposits10.

The term bituminous might be applied to such beds but its use is generally restricted to deposits formed from higher organisms. There are several objections to the algal theory of the origin of coal. Some of those given by White and Thiessen\textsuperscript{11} will be quoted:

"Living gelosic algae contain 98.5\% to 97\% water and only 1.5\% to 3\% solid matter. The algae of the coal times are supposed to have been of about the same consistency. Like the gelosic algae, the brown fundamental jelly also contains only about 1.5\% solid matter to 98.5\% water. . . . It becomes evident therefore that neither the gelosic algae nor the fundamental jelly was able to furnish directly the 'hydrocarbon' represented in algal coal. The algae were therefore supposed to have a great affinity for bituminous substances, and were therefore impregnated with those substances and thus enriched to the extent now disclosed by analyses. No satisfactory explanation is offered as to the origin of the bituminous substances."

These arguments are not conclusive enough to prove that algae do not occur abundantly in Paleozoic coals, and they show nothing concerning pre-Cambrian coal beds. From the low carbon content of the formation it does not seem probable that the Iron Dike is an altered coal bed.

The exact point at which a bituminous shale becomes an impure coal is not well defined. Although no data is at hand, it is entirely possible that a very short period of pre-Cambrian time would have been sufficient

\textsuperscript{11} White, D. & Thiessen, R. U.S.B.M. Bull. 38:199, 1913
for algae to deposit a bituminous shale such as the Iron Dike may have been, even though the algae contain only 2% carbon. Ideal conditions for the formation of thick carbonaceous algal deposits would probably include:

1. Warm climate facilitating rapid growth
2. Shallow water in inclosed bays, lakes or lagoons, free from heavy wave action
3. Gradually submerging bottoms keeping the deposits continually under water
4. Optimum amount of clastic sediments
5. Abundant supply of carbon in available form
6. Rapidly reproducing gelosic algae
7. Freedom from competition and natural enemies

A shale with a high content of finely divided carbonaceous material might be altered to an amorphous graphitic slate. In this case, unless the carbon content of the shale was very high, the graphite would occur as disseminated flakes through the resulting slate or schist. Shales do not, as a rule, contain more than 5% carbonaceous material, and usually much less. The average for a shale would probably be less than 1% free carbon or hydrocarbon. The composition of the average shale is about 60% silica, 15% alumina, 8% lime, less than 5% iron, and the remainder small quantities of numerous other elements. With an in-
crease in the carbon content of a shale, the percentage of the other constituents naturally decreases.

The alteration of a highly carbonaceous shale to a graphitic slate which contains 60% pyrite, 20% silica, and 15% graphite requires an important exchange of components. Such a change could take place only in a region which had suffered such complete igneous or hydrothermal metamorphism as would alter all the rocks. There are evidences that such alteration has taken place in the northern Black Hills.

Most of the pre-Cambrian meta-sediments of the Black Hills contain small amounts of graphite. This was probably formed from an original constituent of the rock. The percentage of graphite in these slates and schists should furnish a rough estimate of the average amount of carbon which was present in the original shale. Several analyses made by Sharwood\textsuperscript{12} show that the slates compare chemically with modern shales, and that where graphite is present it comprises less than 1% of the rock. If the Iron Dike is a metamorphosed carbonaceous shale, it must have been deposited under different conditions than the other slates of the region. Owing to the intense metamorphism of the rocks of the region, it is im-

\textsuperscript{12} Sharwood, W. J. Econ. Geol. Vol. 6, 1911, p. 729
possible to tell from field evidences whether this is the correct explanation of the origin of the graphite in the Iron Dike.

A graphitic slate may be formed by the silication of a limestone or other carbonate rock. The alteration of calcite or dolomite to lime silicate minerals is common, especially in regions of hydrothermal metamorphism. A graphite bed, if formed in this way, should contain such lime silicate minerals as epidote, pyroxine, scapolite, tourmaline, and garnet. Quartz and pyrite are usually present in such beds. In the Port Elmsly District of Quebec, where extensive silication has taken place in the Grenville limestone, the graphite is most abundant where the silication has proceeded to completeness.

Jensen says that graphite and lime silicate minerals may be derived from limestone or mixed carbonate rocks, under conditions of great heat and pressure, in the presence of magmatic waters. He suggests the following set of reactions:

\[ \text{M}_2\text{CO}_3 \rightarrow \text{M}_2\text{O} + \text{CO}_2 \]

\[ \text{M}_2\text{O} + \text{SiO}_2 \text{ (magmatic solution)} \rightarrow \text{MSiO}_3 \text{ (silicate mineral)} \]

\[ 2\text{CO}_2 + \text{H}_2\text{S} \rightarrow \text{H}_2\text{O} + \text{SO}_2 + 2\text{C} \]

The same reactions would hold in mixed rocks for $MCO_3$ and $M_2(CO_3)_3$. Some of the phenomena of the Iron Dike could be readily explained if the original rock had been an iron carbonate, because this would furnish the graphite, and the iron for the pyrite.

The formation of graphite by silication is due to the fact that the CO or $CO_2$ freed by the reaction may be deoxidized by hydrogen or any other reducing agent, leaving free carbon. The partial reduction of CO occurs in the absence of any reducing agent, at temperatures below 900°C. $2CO \rightarrow C + CO_2$. At higher temperatures, and in the presence of free hydrogen, the deoxidation would probably proceed by one of the following reactions:

$$2H_2 + CO_2 \rightarrow 2H_2O + C$$
$$H_2 + CO \rightarrow H_2O + C$$

This carbon may be altered to graphite by heat. Acheson\textsuperscript{15} concludes, from experiments, that:

"Graphite is the form that carbon assumes when freed from chemical associations under conditions of low pressure and protection from chemical influences."

The objection to this theory in nature, is that the freeing of the carbon must take place at abysmal depths; otherwise the gas escapes before it can be deox-

\textsuperscript{15}Acheson,E.G. Jour.Franklin Inst. June 1899 p.1
idized. High pressures exist at great depths, and the change from carbon to graphite takes place under these conditions.

Many graphite deposits in altered limestones have been described. Alling\textsuperscript{16}, in his paper on the Adirondack Graphite Deposits, cites 17 regions, in 12 of which graphite occurs in limestone. Winchell\textsuperscript{17} describes graphite deposits in a limestone at Dillon, Montana. Wilson\textsuperscript{18} believes that the Port Elmsly graphite and the accompanying lime silicate minerals were formed from the Grenville limestone in which they occur. Tilly\textsuperscript{19} describes graphite deposits at Sleaford Bay, in West Australia, where the graphite occurs in an altered limestone or dolomite, in connection with garnets and other lime silicate minerals.

Clark\textsuperscript{20}, in speaking of the formation of graphite by the silication of limestone, says:

"It is entirely a problem as to how it can be done and not one as to whether it can be accomplished. The geological setting consists princip-

\textsuperscript{16} Alling,H.L. N.Y. State Mus. Bull. 199 1918
\textsuperscript{17} Winchell,A.N. Econ. Geol. Vol. 6 1911 p. 218
\textsuperscript{18} Wilson, M.E. Summary Rep't. Can. Dep't. Mines 29E 1917
\textsuperscript{19} Tilly, C.E. Econ. Geol. Vol. 16 1921, p. 4
\textsuperscript{20} Clark, T.H. Econ. Geol. Vol. 16 1921, p. 419
ally of carbonates subjected to metamorphosing influences, and the inability of the oxides of carbon to escape. The problem, as I see it, is two fold. In the first place, is the chemical setting appropriate for the transformation of the residual CO\textsubscript{2} to graphite? Secondly, is there sufficient CO\textsubscript{2} evolved to form the graphite now known to exist in the rock? It does not appear that as much graphite as 10\% is incompatible with the view that it was derived from the carbonate of the original rocks, for, 10\% graphite (assuming it to be pure carbon) would demand an original content of 37\% CO\textsubscript{2} or 83\% calcite or 77\% dolomite."

Wilson\textsuperscript{21} finds that where the silication has been complete, from 15\% to 20\% of the rock is composed of graphite. The variations between these figures and those given above may be due to several reasons. The deposits may represent the silication of an almost pure limestone or dolomite; they may be due to the metamorphism of a carbonaceous limestone, with a resultant increase in the graphite content; or the high percentage of graphite may be due, locally, to concentration by folding.

Graphite deposits formed in this way, unless they are formed from an iron carbonate rock, should contain free silica and a large amount of lime or magnesian silicate minerals. The Iron Dike contains from 10\% to 20\% graphite, about 20\% quartz, and from 60\% to 70\% pyrite. There are no complex silicates associated with the graphite of this formation. If the

Iron Dike was originally a carbonate rock which did not contain iron, the high percentage of pyrite must be the result of very unusual conditions of metamorphism. The most plausible explanation of this unusual condition is that the complex silicates originally formed, have been replaced by secondary pyrite. In this regard, Lindgren\textsuperscript{22} says "All sulphides replace all silicates as well as quartz." The fact that some of the pyrite of the Iron Dike is of secondary origin, and that it occurs in about the right proportion to have replaced all the complex silicates, bears out this theory.

Origin of Pyrite
In Meta-sedimentary Deposits

Pyrite deposited in a meta-sedimentary formation may originate in several ways. The classification of mineral deposits proposed by Lindgren\textsuperscript{22} will be followed in the discussion of the origin of the pyrite in the Iron Dike. The first main division includes the primary deposits which have been concentrated by mechanical processes. This is not important in the formation of pyrite deposits because the pyrite weathers to soluble iron salts.

\textsuperscript{22} Lindgren, W. Mineral Deposits 2nd Ed. 1917
Normal Pyrite Bands in The Graphitic Slate
The second main division of Lindgren's classification includes all the deposits which have been formed by chemical processes. This main division is further subdivided. The first subdivision includes those deposits formed by organic or inorganic agents in bodies of surface water. Harder23 groups the processes for the formation of sedimentary pyrite under four heads:

1. The source and manner of obtaining the iron
2. The transportation of the iron
3. The manner of deposition of the iron
4. The conditions under which pyrite is deposited

Iron is very abundant in the earth's crust, where it occurs in nearly all rocks. It forms an important constituent of igneous and metamorphic rocks, where it is present as iron silicates in the ferromagnesian minerals, biotite, amphibole, pyroxine, epidote, garnet, olivine, and chlorite; as iron oxide in magnetite, ilmenite, and hematite; as iron sulphide in pyrite, marcasite, and the more basic pyrrhotite; and occasionally as the carbonate, siderite. In sedimentary rocks iron is present in the undecomposed silicates which occur in shales and graywacke, and

Its oxides, sulphides, carbonates, and secondary silicates are common in all sediments.

When rocks containing iron are broken up by disintegration and decomposition, the iron compounds which they contain are dissolved by the acids which are present in the surface and ground waters. Carbonic acid, $\text{H}_2\text{CO}_3$, and some other organic acids are abundant in the soil. Most iron compounds, and especially iron carbonate, are quickly dissolved by carbonic acid. The iron is taken into solution as the carbonate or bicarbonate, and remains as long as the water contains an excess of carbon dioxide. Ferric oxides are almost insoluble in carbonic acid, but they are readily dissolved by various other soil acids. The iron, once dissolved by organic acids, is carried in solution as salts of these acids. It is usually carried as the soluble iron carbonate but it may also be carried as a sulphate.

Iron may be precipitated, in nature, under ordinary conditions of sedimentation, by either chemical or biological agents. The iron precipitate may occur as any one of the following: hydroxide, carbonate, silicate, phosphate, sulphate, sulphide, or disulphide. The precipitation usually takes place in the quiet waters of bogs, marshes, lakes, and lagoons.
Doss\textsuperscript{24} has the following explanation for the sedimentary origin of pyrite: Iron is dissolved from iron bearing minerals and carried in solution by surface waters, to inclosed bays or lagoons in which decaying organic matter is abundant. Here the iron is precipitated, either directly as black, colloidal ferrous sulphide by the reaction with hydrogen sulphide, or as ferric hydroxide by iron bacteria. Ferric hydroxide, upon reduction in the presence of hydrogen sulphide, is changed slowly to ferrous sulphide. By the addition of sulphur which occurs free in the mud, the sulphide is changed to the disulphide, melnikowite (FeS\textsubscript{2}). Polished sections show that the black, finely crystalline melnikowite alters gradually to the stable form, pyrite. If the pyrite is not important in the sediment it is scattered in the resulting rock, but where the precipitate is concentrated, bedded pyrite results on solidification.

Pyrite may be precipitated from iron bearing solutions, by simple chemical reactions, with other materials in the solution or in contact with the solution. These conditions are met most generally in deposits which contain organic matter. Peat bogs

\textsuperscript{24}Doss, B. \textit{Zeitschr. prakt. Geol.} Jahrg. 20 1912 p. 460
and forming coal beds are rich in decaying organic matter and pyrite is usually abundant in them. In discussing the sedimentary origin of pyrite, Harder says:

"Much of the iron sulphide occurring in sedimentary rocks, has been formed by chemical processes, but the chemical action is, for the most part, the result of the decomposition of organic matter by bacteria. Decomposing organic matter may cause the formation of iron sulphide, (1) by the direct reduction of iron sulphate in solution, owing to the removal of oxygen by the oxidation of carbon, or (2) by the action of hydrogen sulphide, produced during the decomposition, on the various iron salts in solution. Much of the iron sulphide also is deposited directly by the bacteria which have the power of reducing iron sulphates to iron sulphide. . . ."

Under the second sub-heading of Lindgren's classification come those secondary deposits formed in preexisting rocks. The first group in this class includes the deposits which are important because of the concentration of minerals which were previously contained in the rock. Pyrite may be secondarily enriched by descending ground waters. Iron sulphide is abundant in sedimentary rocks, where it occurs both as disseminated crystals and as beds and lenses. Pyrite is the common form although melnikowite is sometimes present. Emmons says:

"Sulphide ores exposed to weathering at or near

the surface of the earth break down and form solu-
stable salt and minerals that are stable under sur-
face conditions. No metallic sulphide that is long
exposed to the air and water remains unaltered.
The iron sulphides, which are present in practic-
ally all sulphide ores, are changed by weathering,
to iron oxides, and the changes are attended by
the liberation of sulphuric acid. Many metals form
soluble sulphates with sulphuric acid, and when
the conditions favor their migration downward, they
are carried in solution to depths where air is ex-
cluded. Unoxidized rocks are, in general, alkaline.
Acid solutions that encounter such rocks in the
region where air is excluded will lose acidity, and
as the solution approaches a neutral or alkaline
condition some of the metals it contains are depos-
ited. If the solution of metallic sulphates encoun-
ters metallic sulphides in depth, precipitation may
take place or there may be an interchange between
the metals in solution as sulphates and the metallic
sulphides. Thus as a result of precipitation or
chemical interchange new metals are deposited and
certain portions of the ore body become enriched."

The oxidation and precipitation of the pyrite in
this case may be expressed by one of the following
hypothetical equations:

\[
2\text{FeS}_2 + 2\text{H}_2\text{O} + 7\text{O}_2 \rightarrow 2\text{FeSO}_4 + 2\text{H}_2\text{SO}_4
\]

\[
\text{FeSO}_4 + \text{H}_2\text{S} + \text{S} \rightarrow \text{FeS}_2 + \text{H}_2\text{SO}_4
\]

\[
2\text{FeS}_2 + 2\text{H}_2\text{O} + 7\text{O}_2 \rightarrow 2\text{FeH}_2(\text{SO}_4)_2
\]

\[
15\text{FeH}_2(\text{SO}_4)_2 + \text{FeS}_2 \rightarrow 2\text{FeS}_2 + 7\text{Fe}(\text{SO}_4)_3 + 7\text{H}_2\text{SO}_4 + 8\text{H}_2\text{O}
\]

The reaction according to the first equation re-
quires hydrogen sulphide and free sulphur. The pres-
ence of hydrogen sulphide is assumed because it is
found in nearly all the assays of mine waters. The
free sulphur can be produced by the following reaction
which is known to take place in nature:

\[
12\text{FeSO}_4 + 3\text{O}_2 + 6\text{H}_2\text{O} \rightarrow 4\text{Fe}_2(\text{SO}_4)_3 + 4\text{Fe(OH)}_3
\]

\[
\text{FeS}_2 + 4\text{Fe}_2(\text{SO}_4)_3 \rightarrow 3\text{Fe}_2\text{SO}_4 + 2\text{S}
\]

According to these equations the enrichment of pyrite by descending ground water would not be rapid because both processes require that some of the original pyrite be broken down in the formation of the secondary deposit. It is evident however, that enrichment will take place.

The concentration of the pyrite in the Iron Dike may be due to secondary enrichment. Judging from the size of the folds and the intensity of the folding, a great amount of erosion must have taken place to reduce the pre-Cambrian hills to the level of the pre-Cambrian surface of the present time. The pyrite from the eroded portion of the Iron Dike would have been sufficient to have greatly enriched the remainder of the Dike. Secondary enrichment is not necessarily a surface phenomena, but the enriched zone may extend for several thousand feet below the exposed surface. If the pyrite of the Iron Dike has been secondarily enriched, the enrichment must have taken place in pre-Cambrian time. No deep explorations have been made in the Iron Dike, and for this reason it is impossible to tell whether the high pyrite content
decreases uniformly with depth.

According to Allen²⁷, the two factors which determine whether the iron disulphide mineral formed by descending ground water will be marcasite or pyrite are temperature and pressure. Marcasite is formed by the action of hydrogen sulphide on ferric sulphate or any other ferrous or ferric salt, in the presence of air, provided that the solution contains at least 1% of sulphuric acid and is at a temperature of less than 100°C. In other words, marcasite is a surface mineral formed from surface solutions at low temperatures. The mineral is common because surface waters, if they carry iron, usually carry sulphuric acid as well. Both the iron and the acid originate from the oxidation of preexisting deposits of pyrite or marcasite.

Pyrite is formed from neutral or alkaline solutions by the action of polysulphides on ferrous salts, and by the action of hydrogen sulphide on ferric hydroxide. Pyrite, rather than marcasite, is always deposited by hot water, although either may be deposited by cold waters. Hot or warm terrestrial waters are usually alkaline, and above 300°C it is impossible

to form marcasite no matter what the acidity of the solution may be. In fact, if marcasite is heated to 450°C under conditions which preclude oxidation, it changes to pyrite.

If any of the pyrite of the Iron Dike was deposited near the surface by cool acid water, it was deposited as marcasite and later altered to pyrite, or if it was deposited below the zone of oxidation, by warm neutral or alkaline water, it was deposited as pyrite. The available evidence is not sufficient to prove that any of the pyrite was deposited by descending ground waters.

Lindgren's second group of epigenetic deposits includes those deposits in which the minerals introduced were foreign to the rocks in which they are now concentrated. The first division of this group includes the deposits formed at moderate or shallow depths by atmospheric waters, and does not apply to the Iron Dike because, while the Iron Dike itself is highly pyritiferous, the inclosing beds are barren. The second group of this division includes those deposits which are dependant on igneous activity.

The pyrite of the Iron Dike may be an epigenetic deposit formed shortly after the intrusion of the Harney Peak granite, in which the pyrite was present as a mineralizer. A magma, cooling slowly enough
Folding and Brecciation of The Pyrite Bands
(x30)
to form the Harney Peak pegmatite, would allow sufficient time for the escape of its fluxes. The fluxes which were driven off would be in an aqueous solution, and would be deposited as the solution cooled. According to both Spurr and Kemp, each mineral or set of minerals is precipitated in a regular order from the cooling solution. Spurr distinguishes six concentric zones of characteristic ore and vein minerals, only the first two of which are present in the Black Hills. The others, if they were present, have been removed by erosion.

The first of these groups includes such minerals as tin, molybdenum, and tungsten, and such gangue minerals as tourmaline, beryl, muscovite, and quartz. These are formed at the contact with the country rock, or in quartz veins just outside the cooling magma. The zone containing these minerals is present and is exposed near the contact of the Harney Peak granite, in the southern Hills. In the second zone, quartz veins are common, but as a rule, the characteristic minerals are deposited in the country rock. The minerals of this second group are gold, auriferous pyrite, pyrite, and possibly chalcopyrite.

Spurr puts the chalcopyrite in the third group, while Kemp includes it with the pyrite. If the deposits in the northern Black Hills were formed from the Harney Peak granite, they follow Spurr's classification because, although gold and pyrite are common, chalcopyrite is rare. Since the distance from the Lead-Deadwood region to the outcrops of the Harney Peak granites in the southern Hills seems too great for the mineralization to have been due to the granite, it can be explained by the fact that the granite pegmatite underlies the northern Hills at no great depth. This theory would explain the presence of such high temperature minerals as arsenopyrite and pyrrhotite in these deposits.

Each mineral given off from a cooling magma is concentrated in that formation which is best suited to precipitate it from the original solution. The schists, slates, and quartzites of the northern Black Hills are apparently inert. The cummingtonite rock seems especially suitable for the precipitation of gold, and the Iron Dike for the precipitation of pyrite.

Probably the concentration of the pyrite precipitate in the Iron Dike was due to the presence of carbon, or of hydrogen sulphide in an acidic rock. Ac-
According to Allen\textsuperscript{30} pyrite is slowly precipitated from solution when the solution comes in contact with carbon or hydrogen sulphide. According to Knox\textsuperscript{31} and Turner\textsuperscript{32} all the large epigentic pyrite deposits in the world are in siliceous rather than calcareous rock. The slates, schists, and quartzites of the Lead-Deadwood region are mostly siliceous, and the pyrite would probably have been disseminated through them if it had not been for the especially favorable conditions encountered in the Iron Dike. The main objection to this theory for the origin of the pyrite in the Iron Dike is that the lower graphitic slate, which seems to offer identical advantages for the precipitation of pyrite, is essentially barren.

Pre-Cambrian amphybolite dikes occur in contact with the Iron Dike through much of its course. According to Irving\textsuperscript{33} these dikes are altered gabros which were intruded as sills, before the folding and metamorphosing of the slates and schists. Since pyrite deposits are commonly associated with basic igneous rocks, these amphybolites may have been the

---

32. Turner, H.W. Econ.Geol. Vol.7 1912 p.709
33. Irving, J.D. Contrib.Geol.Northern Black Hills
Polished Sections Showing Mineral Associations.
P, pyrrhotite; Py, pyrite; Q, quartz; G, graphite
source of the pyrite in the Iron Dike. According to Sharwood\textsuperscript{34} these dikes do not contain much pyrite. This would naturally be expected because, although pyrite is an igneous product, it is seldom found in igneous rocks. As mentioned above, the Iron Dike is especially suitable for the precipitation of pyrite from solution. This explains the concentration of the pyrite in one formation. The amphibolites were nowhere observed in contact with the lower graphitic slate, and this may explain the absence of pyrite in that formation.

Samples of the unweathered portion of the Iron Dike were obtained from drill cores from the abandoned mine on the south bank of Deadwood Creek. These cores were cut and polished for microscopic and microchemical examination. Polished sections show that the pyrite usually occurs in thin bands along the bedding planes or the planes of schistosity of the slate. The pyrite, in the sections, shows evidences of faulting, folding, segregation, and brecciation. From the amount of distortion of the banded pyrite, it would seem that the pyrite had been present from the begin of the folding. This evidence supports the theory

\textsuperscript{34} Sharwood, W.J. Econ. Geol. Vol. 6 1911 p. 729
Polished Section Showing Mineral Association

P, pyrrhotite; Py, pyrite; G, graphite
that the basic intrusives were the source of the pyrite.

Magnetic portions of the drill cores were tested for pyrrhotite and the presence of this mineral was determined by microchemical tests. The presence of pyrrhotite has an important bearing on the interpretation of the geologic history of the Iron Dike. All authorities agree that pyrrhotite is formed only under conditions of high temperature and pressure. It is found in deep veins, igneous segregations, and contact deposits. Pyrrhotite may also be formed by the intense metamorphism of pyrite. The pyrite and pyrrhotite of the Iron Dike are intimately associated. The pyrrhotite seems to be the younger, and to have replaced the pyrite, during or after the period of deformation which preceded or accompanied the intrusion of the Harney Peak granite. This relation may be the result of either of two processes. The pyrrhotite may have been formed by the metamorphism of the pyrite, or it may have replaced the pyrite during some period of pre-Cambrian igneous activity. In either case the presence of this secondary pyrrhotite supports the theory that the pyrite was present in the Iron Dike before the intrusion of the Harney Peak granite, and was probably formed by the basic intrusions of an earlier date.
CONCLUSIONS

In this paper, theories have been advanced to explain the origin and history of the Iron Dike. The following conclusions have been drawn.

The Iron Dike is of sedimentary origin.

The siliceous cap along the exposed edges of the Iron Dike is due to a precipitation of quartz from ground water by the action of sulphuric acid which was formed by the oxidation of the pyrite. Silicification, causing the Dike to resist erosion, produced the prominent ridge which marked the course of the Dike on the pre-Cambrian surface. Part of the silicification may be of post-Eocene age.

The rock which has been altered by heat and pressure, to form the graphite in the Iron Dike, was probably either a carbonate rock or a carbonaceous shale.

The concentration of the pyrite in the Iron Dike is mainly a secondary feature, and was probably due to the presence of the graphite. The pyrite is mostly of igneous origin. It may have been introduced during several successive periods of pre-Cambrian mineralization.
The presence of pyrrhotite, which is intimately intergrown with the pyrite, is one of the most important geological features of the Iron Dike. It may have been formed from the pyrite, by dynamic metamorphism, or it may be of igneous origin. It is later than the earliest pyrite, but the exact date of its formation is uncertain. Under the microscope, it appears that the pyrrhotite and some of the pyrite were formed simultaneously.

Thin sections of the rock of the Iron Dike were returned too late to be discussed in the body of this thesis. These sections show tourmaline, carbonates, and complex silicates in minor quantities. The presence of primary tourmaline with the pyrrhotite furnishes almost absolute proof that the mineralization of the Iron Dike was due to contact metamorphic processes.
BIBLIOGRAPHY

Acheson, E.G. Jour. Franklin Inst. 1899 p. 1

Sulphides of Iron and Their Genesis

Alling, H.L. N.Y. State Mus. Bull. 199 1917
The Adirondack Graphite Deposits

Bastin, E.S. Econ. Geol. Vol. 5 1910 p. 134
Origin of Certain Adirondack Graphite Deposits

Clark, T.H. Econ. Geol. Vol. 16 1921 p. 167
The Origin of Graphite
Econ. Geol. Vol. 16 1921 p. 419
Graptite of Sleaford Bay

Geology and Water Resources of the Northern Portion of The Black Hills and Adjoining Regions in South Dakota and Wyoming

Doss, Bruno Zeitschr. prakt. geolog. Jarg. 20 1912 p. 460
Melnikowit, ein neues Eisenbisulphid, und seine Bedeutung fur die Genesis der Kieslagerstatten

Emmerson, B.K. U.S. Geol. Surv. Mon. 29 1898 p. 365
Geology of Old Hampshire County, Mass.
The Enrichment of Sulphide Ores

Harder, E.C. U.S. Geol. Surv. P.P. 113 1919
Iron Depositing Bacteria and Their Geologic Relations

Irving, J.D. N.Y. Acad. Sci. Vol. 12 No. 9 p. 248
Contributions to The Geology of The Black Hills
U.S. Geol. Surv. P.P. 26 1904
Economic Resources of The Black Hills
Econ. Geol. Vol. 6 1911 p. 527
Criteria of Replacement Deposits

The Chemistry of Ore Deposition

Jensen, H.I. Econ. Geol. Vol. 17 1922 p. 55
The Origin of Graphite

Kemp, J.F. Econ. Geol. Vol. 16 1921 p. 474

Knox, H.H. Econ. Geol. Vol. 7 1912 p. 295
Criteria for Replacement Ore Bodies

Larsen, Allen, Crenshaw, & Johnston
The Disassociation Pressure of Purite
Lindgren, W. Mineral Deposits 2nd Ed. 1919
Econ. Geol. Vol. 17 1922 p.292
Terminology of Mineral Deposits

Black Hills Gold-Bearing Iron-Quartz-Tremolite Belt

Pre-Cambrian Structure of The Northern Black Hills as Bearing on The Homestake Ore Body

Mechanics of Intrusion of The Black Hills Pre-Cambrian Granite

Potonie, H. Die Entstehung der Steinkohle und der Kaustobolitthe überhaupt, wie des Torfes der Braunkohle, des Petroleums U.S.W. 5th Ed. 1910

Evidences of an Unconformity Within the Pre-Cambrian of The Black Hills of South Dakota

Pahasapa Quarterly Vol. 10 1920 p.17
Some Problems of Black Hills Pre-Cambrian Geology

Sharwood, W.J. Econ. Geol. Vol. 6 1911 p.729
Analysis of Some Rocks and Minerals from the Homestake Mine Lead South Dakota
Origin of Certain Adirondack Pyrite Deposits

Spurr, J.E. Econ. Geol. Vol. 2 1907 p. 791
A Theory of Ore Deposition

Tilly, C.E. Econ. Geol. Vol. 16 1921 p. 184
Graphite Deposits of Sleaford Bay West Australia

Turner, H.W. Econ. Geol. Vol. 7 1912 p. 709
Replacement of Siliceous Rocks by Pyrite

Review of the Evidence Concerning the Fossiliferous Character of Certain Pre-Cambrian Strata

Wherry, E.T. Econ. Geol. Vol. 7 1912 p. 764
Quoted

White, David Econ. Geol. Vol. 3 1908 p. 292
Problems of Formation of Coal

White, David and Theissen, R.
U.S. Bureau of Mines Bull. 38 1913 p. 199
The Origin of Coal


Winchell, A.N. Econ. Geol. Vol. 6 1911 p. 218
Theory of The Origin of Graphite Exemplified in the Graphite Deposits Near Dillon Mont.