1952

The geology of the Elliston phosphate district
Powell County Montana

Jerome Stone

The University of Montana

Let us know how access to this document benefits you.

Follow this and additional works at: https://scholarworks.umt.edu/etd

Recommended Citation

Stone, Jerome, "The geology of the Elliston phosphate district Powell County Montana" (1952). Graduate Student Theses, Dissertations, & Professional Papers. 7093.

https://scholarworks.umt.edu/etd/7093

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
THE GEOLOGY OF THE ELLISTON PHOSPHATE DISTRICT, POWELL COUNTY, MONTANA

by

Jerome Stone

B.S., City College of New York, 1950

Presented in partial fulfillment
of the requirements for the degree of
Master of Arts

MONTANA STATE UNIVERSITY

1958
This thesis has been approved by the Board of Examiners in partial fulfillment of the requirements for the degree of Master of Arts.

[Signatures]

Chairman of the Board of Examiners

Dean of the Graduate School

Date
This thesis has been approved by the Board of Examiners in partial fulfillment of the requirements for the degree of Master of Arts.

[Signatures]

Chairman of the Board of Examiners

Dean of the Graduate School

Date
# TABLE OF CONTENTS

LIST OF ILLUSTRATIONS .................................................. 11

INTRODUCTION ............................................................... 1
   Location and general geography .................................. 1
   Previous Work .......................................................... 3

ACKNOWLEDGEMENTS ....................................................... 3

GENERAL STRATIGRAPHIC FEATURES .................................... 3

STRATIGRAPHY OF THE ELLIOTON AREA ................................. 4

   Precambrian ............................................................ 4
   Paleozoic era ......................................................... 4
      Cambrian to Devonian System ................................... 6
      Mississippian System ............................................. 6
      Madison limestone ................................................ 6
      Pennsylvanian System ........................................... 7
      Amsden formation .................................................. 7
      Cuadrant quartzite ............................................... 7
      Permian System .................................................... 9
      Phosphoric formation ............................................ 9
   Mesozoic era .......................................................... 15
      Triassic System ................................................... 16
      Jurassic System ................................................... 16
         Ellis group ...................................................... 16
         Sawtooth formation ............................................ 17
         Swift(?) formation .............................................. 18
      Cretaceous System ................................................ 19
         Kootenai formation ............................................ 19
         Contact metamorphism of Kootenai formation .............. 20
   Cenozoic era ........................................................... 22
      Tertiary System .................................................... 22
      Quaternary System ................................................ 23
         Pleistocene deposits ........................................... 23
         Recent deposits ................................................ 23
      Igneous Rocks ..................................................... 23
         Sills and/or volcanic flow .................................... 23
         Pyroclite porphyry ............................................. 25
         "Basalt" .......................................................... 25
         "Granite" ........................................................ 26

STRUCTURE ................................................................. 26

   General features .................................................... 27
   Simple structure ..................................................... 28
   Complex structure ................................................... 28
   Descriptions of the faults ....................................... 29
   Faults roughly parallel to the axis of the anticline ......... 29
<table>
<thead>
<tr>
<th>Faults roughly perpendicular to the axis of the anticline</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other faults</td>
<td>31</td>
</tr>
<tr>
<td>Comparison of effect of structure and location of phosphate rock</td>
<td>31</td>
</tr>
</tbody>
</table>

**PETROLOGY OF THE PHOSPHATE ROCK**

<table>
<thead>
<tr>
<th>Definition of phosphate rock</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralogy of the phosphate rock</td>
<td>32</td>
</tr>
<tr>
<td>Minerals associated with phosphate</td>
<td>33</td>
</tr>
<tr>
<td>General megascopic description of the phosphate rock</td>
<td>33</td>
</tr>
<tr>
<td>General microscopic description of the phosphate rock</td>
<td>36</td>
</tr>
<tr>
<td>Plasticity</td>
<td>38</td>
</tr>
</tbody>
</table>

**ORIGIN OF THE PHOSPHATE ROCK**

<table>
<thead>
<tr>
<th>Geologic setting</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of the constituents of the phosphate minerals</td>
<td>40</td>
</tr>
<tr>
<td>Solubility and concentration of the phosphate</td>
<td>40</td>
</tr>
<tr>
<td>Formation of the oolites</td>
<td>44</td>
</tr>
</tbody>
</table>

**SUMMARY**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
</tr>
</tbody>
</table>

**BIBLIOGRAPHY**

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS

Fig.                                      Page

1. Index map showing the Elliston Phosphate Field...  2

2. Location of phosphate operations, Montana Phosphate Products Company.................... 12

3. Graph showing the solubility of (1) phosphate rock (2) dicalcium phosphate and (3) bone with respect to pH.......................................................... 41

4. Thin section of the phosphate rock at Elliston, showing resorption of some of the oolites........ 47

5. Thin section of the phosphate rock at Elliston showing development of bonding.................. 48

6. Thin section of the phosphate rock at Garrison showing collophaneite and quartz matrix........... 49

Plate

1. Map of the Elliston Field ................ Pocket
INTRODUCTION

Location and general geography

The Elliston Phosphate Field is in Powell County in western Montana (see index map, fig.1). The mapped area may be reached by driving 20 miles west of Helena, Montana on U.S. Highway 10 N to the town of Elliston in secs. 1 and 2, T.9N., R.7W. The mapped area includes parts of T.9N., R.6 and 7W.; T.10 N., R.6 and 7W.; T.11 N., R.6 and 7W.

Elliston lies in the Little Blackfoot valley east-south-east of the Garnet Range. The elevations of the area range from 4940 feet to 6840 feet above sea level. The area is in a late youthful stage of dissection with the average relief being 700 to 800 feet.

The Little Blackfoot River, the headwaters of which are on the Continental Divide, flows north to Elliston where it is diverted to the west. At Garrison, an important railroad junction of the Northern Pacific 20 miles west of Elliston, the Little Blackfoot joins the Clark Fork River.

The climate is semi-arid. Douglas fir and lodgepole pine grow in abundance on the hills. The chief industry is raising cattle and some sheep. The lime kilns east of Elliston are sporadically in operation. A few miles south of Elliston there are several mines which have yielded chiefly lead and zinc and some gold from veins cutting through granite or quartz monzonite. The details of these mines are given by Knopf (1913, p.77).
Fig. 1 Index map showing the Elliston Phosphate Field.
Previous Work

Little previous work has been done in this region. The only published material of the Elliston area was a brief report of the phosphate rock by Stone and Bonine (1913) and a reconnaissance of the geology by Knopf (1913). Other published papers, all of which are U.S. Geological Survey publications, deal with nearby areas: Helena, Knopf (1913); Garrison and Philipsburg, Pardee (1917); Melrose, Gale and Richards (1925); Maxville, Philipsburg and Avon, Pardee (1936); in areas south and west of Elliston, McKelyey (1948).

ACKNOWLEDGEMENTS

The author is indebted to Dr. L. V. Bell and to the Montana Phosphate Products Company of Garrison, Montana without whose material assistance this paper could not have been written and to Dr. F. S. Honkala, whose assistance and kindness was a great help in completing this paper.

The following were all in one way or another of assistance and their help is hereby acknowledged:

GENERAL STRATIGRAPHIC FEATURES

The stratigraphic sequence in the Elliston Phosphate Field include rocks with a range in age from Mississippian to Recent. Six formations of the Paleozoic and Mesozoic eras have a total thickness of at least 3,000 feet. The sediments are locally covered with Tertiary volcanics.
Marine sediments dominate the Paleozoic, while continental deposits become more important in the Mesozoic rocks. A table of the sedimentary formations is on page 6.

STRATIGRAPHY OF THE ELLISTON AREA

Precambrian

No Precambrian rocks crop out in the mapped Elliston area. The stratigraphy and structure of surrounding areas, however, suggest that late Precambrian Belt Series rocks underlie the Elliston area.

Paleozoic Era

The Paleozoic era was characterized by alternating periods of emergence and submergence in the Central Montana trough, which was an eastward projecting tongue from the Cordilleran geosyncline further to the west. After a long period of erosion of Precambrian rocks, submergence occurred and middle Cambrian sediments were deposited. Emergence and erosion took place in Ordovician and Silurian times while deposition was continuing in the Cordilleran geosyncline.

Submergence followed in upper Devonian time with deposition of limestone and shale. The seas widened in lower Mississippian time and the Madison limestone was deposited over the Rocky Mountain region. Emergence and erosion took place in upper Mississippian time in the Elliston area while deposition was taking place in central Montana.

Deposition of sandstone and shale occurred in lower Pennsylvanian time. Possible emergence and erosion was
followed by deposition of marine sandstone later in Pennsylvanian time.

Deposition of phosphate and chert occurred along the shelf of a relatively shallow sea in Permian time.

Cambrian to Devonian Systems

No rocks of Cambrian to Devonian age crop out in the Elliston area. The stratigraphy and structure of surrounding areas, however, suggest that several hundred feet of Cambrian and Devonian rocks underlie the Elliston area.

Mississippian System

Madison limestone- The Madison limestone of lower Mississippian age was named by Peale (1893, pp. 33-39) from the Madison Range in southwestern Montana. The formation is about 350-500 feet stratigraphically below the Permian phosphate rock and is important as a guide since it is resistant and usually forms prominent outcrops. The outcrops are either cliffs or in the form of low "domes", about 25 feet in length and 3 feet in height. Along U.S. Highway 10 N there are lime quarries in exceptionally pure phases of the Madison limestone.

A thickness of about 200 feet representing the upper part of the Madison limestone was observed in the field. The formation is a gray, massive limestone which weathers to a characteristic bluish hue. It ranges from dense to finely crystalline and locally contains fossils. A few thick beds of dolomite and a few widely separated limestone beds, about 3 inches thick, and containing chert nodules are interbedded.
<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Thickness</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent</td>
<td>Alluvium</td>
<td>Sand and gravel.</td>
<td></td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Glacial drift</td>
<td>15 ft</td>
<td>Sand, gravel and boulders.</td>
</tr>
<tr>
<td>Eocene</td>
<td>&quot;lake beds&quot;</td>
<td></td>
<td>Sand, gravel, clay and tuff.</td>
</tr>
<tr>
<td>Lower Cretaceous</td>
<td>Kootenai formation</td>
<td>700 ft</td>
<td>Interbedded red shale and quartzites overlain by blue-black shales with quartzites and limestones. A 50-foot thick lower limestone and a 5-foot thick upper limestone with abundant gastropods.</td>
</tr>
<tr>
<td>Argovian upper Jurassic</td>
<td>Swift? formation</td>
<td>80</td>
<td>Basal conglomerate with coarse-grained sandstones.</td>
</tr>
<tr>
<td>Bathonian</td>
<td>Sawtooth formation</td>
<td>250</td>
<td>Basal gray and bluish shales overlain by buff-weathering soft limestones and sandstones; fossiliferous.</td>
</tr>
<tr>
<td>Middle Permian</td>
<td>Phosphoria formation</td>
<td>0-25</td>
<td>Gray, oolitic phosphate rock underlain and overlain by chert or cherty quartzite.</td>
</tr>
<tr>
<td>Lower Pennsylvanian</td>
<td>Quadrant quartzite</td>
<td>350-500</td>
<td>Gray, fine to medium grained quartzite weathering to a characteristic rusty color. Forms bold outcrops. Locally coarsely brecciated. Massive.</td>
</tr>
<tr>
<td>Lower Pennsylvanian and/or Upper Mississippian</td>
<td>Amsden (?) formation</td>
<td>150?</td>
<td>Red, calcareous, soft, fine-grained, sandy shale.</td>
</tr>
<tr>
<td>Lower Mississippian</td>
<td>Madison limestone</td>
<td>1000</td>
<td>Gray, massive limestone which weathers a characteristically bluish hue. Locally fossiliferous, dolomitic with widely-separated beds containing chert nodules.</td>
</tr>
</tbody>
</table>
The Madison limestone in the Elliston area is about 1000 feet thick (Stone and Bonine, 1913, pp. 377). No stratigraphically lower rocks were observed in the field. It may be overlain by the Amsden formation but this was not actually proven by the author. The Quadrant quartzite disconformably overlies the Madison limestone wherever the two formations were seen.

**Pennsylvania System**

The Amsden formation of upper Mississippian to lower Pennsylvanian age was named by Darton (1904, pp. 394-401) from exposures on the Amsden branch of the Tongue River, west of Dayton, Wyoming.

**Amsden (?) formation**—The only place in which Amsden (?) was observed is in central sec.31,T.10N.,R.6W. It is a red, calcareous shale about 4 feet thick, apparently underlying the Quadrant formation. No exact correlation to other formations could be made in the field. The Amsden formation crops out in the Drummond area with an estimated thickness of 150 feet. Stone and Bonine (1913, p. 375) reported 150 feet of Amsden (?) shales underlying the Quadrant.

**Quadrant quartzite**—The Quadrant quartzite was named by Weed (1896) from exposures on Quadrant Mountain in the Gallatin Range in Yellowstone National Park. In Western Montana, a brightly-colored, usually red, series of limestones, shales and fine-grained sandstones overlain by gray quartzite and cherty quartzite was named the Quadrant formation. It was thus described by Calkins and Emmons,
(1919, p.9) in the Flint Creek Range with thicknesses of 100 to 300 feet and 220 to 350 feet.

H. W. Scott (1925, pp.1011-1036) concluded from fossil evidence that the

"red zone above the Madison in (western) Montana which is commonly classified as the base of the Quadrant, is in reality the Amsden. The Quadrant consists of the overlying quartzites."

The Quadrant quartzite of lower Pennsylvanian age, which is equivalent to the oil-producing Tensleep sandstone of Wyoming, crops out as a cliff just north of Elliston and is visible from U.S. Highway 10 N. The Quadrant quartzite is a marine, grey, fine to medium-grained, well-sorted and rounded quartzite weathering to a characteristic rusty and yellowish-brown color. In places it is either cherty or extensively brecciated and massive. The breccia consists of angular fragments up to 5 inches in diameter in a fine-grained quartzitic matrix. The Quadrant has well-developed jointing and tends to break off in large blocks, but it is generally resistant and often forms prominent outcrops. Locally the Quadrant is thin-bedded and pitted. The pitting is due to the solution of small calcareous (?) oolites. The thickness of the Quadrant is estimated at 350 to 500 feet.

The Quadrant rests disconformably on the Madison limestone with the Amsden formation usually missing due to erosion. The Quadrant is disconformably overlain by the Phosphoria, and since the Quadrant commonly forms
prominent outcrops it serves an excellent guide to the Phosphoria formation.

A partial section was measured by chain in E², sec. 1, T.10N., R.7W. on a cliff outcrop just north of Elliston by L. V. Bell, R. Hieta and the author.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Thickness (in feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphoria chert</td>
<td></td>
</tr>
<tr>
<td>6. Covered</td>
<td>10</td>
</tr>
<tr>
<td>5. Quartzite, white, flaggy,</td>
<td></td>
</tr>
<tr>
<td>calcearous, fine to medium</td>
<td></td>
</tr>
<tr>
<td>grained</td>
<td></td>
</tr>
<tr>
<td>4. Quartzite, gray, fine-granular, containing nodules up to 3 inches in diameter; weathering yellow-brown</td>
<td>16</td>
</tr>
<tr>
<td>3. Quartzite, white, flaggy,</td>
<td></td>
</tr>
<tr>
<td>fine to medium grained,</td>
<td></td>
</tr>
<tr>
<td>calcearous</td>
<td></td>
</tr>
<tr>
<td>2. Quartzite, breccia, gray</td>
<td></td>
</tr>
<tr>
<td>with fragments up to 0.3 inches in diameter in a fine grained quartzitic matrix and locally containing chert nodules up to 1/8 inch in diameter, weathering yellow-brown</td>
<td>5.5</td>
</tr>
<tr>
<td>1. Quartzites, gray, fine to</td>
<td></td>
</tr>
<tr>
<td>medium grained. Bluish</td>
<td></td>
</tr>
<tr>
<td>weathering quartzites are</td>
<td></td>
</tr>
<tr>
<td>interbedded with rusty-weathering quartzites. Beds roughly 1 foot thick</td>
<td>121.0</td>
</tr>
</tbody>
</table>

Total exposed thickness...166.5

Permian System

**Phosphoria formation**- Outcrops of the Phosphoria formation of middle Permian age (Miller and Cline, 1934, p. 284) are rare because it is thin and non-resistant. It was mapped mainly on evidence from float and pits dug by previous prospectors. It is a remarkably persistent formation being present in Montana, Idaho and Wyoming. Equivalents of the Phosphoria formation are present in Alberta and Utah. The formation probably
contains the world's largest reserves of high-grade phosphate and it is a possible future source of some constituents such as fluorine, vanadium, uranium, nickel and molybdenum.

The Phosphoria formation was named by Mansfield and Richards (1912, pp. 684-689) from Phosphoria Gulch in southeastern Idaho.

McKelvey (1948, pp. 272-274) described the variations in the thickness and lithology of the Phosphoria formation:

"At its type locality in southeastern Idaho, the Phosphoria formation consists of a lower phosphatic shale member about 180 feet thick, and an upper member, the Rex chert, 240 feet thick. The units are easily recognizable over a wide area in Idaho and in adjoining parts of Wyoming and Utah, but in central Wyoming...it is thinner...has more sand and carbonate, and much less phosphate and shale...In southeastern Wyoming, phosphate is absent and the formation tongues out into non-marine beds...As in Idaho, the Park City formation of Utah thickens markedly to the west and contains a greater thickness of chemical precipitates. Eastward, the phosphate is absent and the shale and upper limestone are more clastic and finally tongue out into non-marine beds in eastern Utah and western Colorado. In southwestern Montana, the Phosphoria formation has been divided into five members:

E-Chert
D-Phosphatic mudstone
C-Carbonate rock
B-Phosphate rock and phosphatic mudstone
A-Cherty carbonate and clastic rocks
(equivalent (?) to upper part of Wells formation and lower limestone member of Park City formation, Utah.)

"In the vicinity of Dell and Lima, Montana, the total thickness is 485 feet. Units A, B, C disappear in the Madison Range and northward in the Garrison-Drummond area."
As noted by McKelvey, the phosphate content diminishes eastward in Wyoming and Utah. Kazakov (1939) explains the "asymmetry" of the phosphorite facies of the Phosphoria sea as due to

"the opposite directions of bottom currents (compensation currents) supplying phosphatic solutions to the phosphatic accumulation on the shelf, and surface currents poor in phosphate, heading for the opposite shore, no longer capable of producing precipitate in the region of the shelf of this opposite shore."

The Montane Phosphate Products Company is operating several phosphate mines in northwestern Montana (see fig. 2). Among the important ones are the Graveley Mine and the Luke Mine in Avon and the Anderson Mine in Garrison, where the main office is located. The Luke Mine near Elliston is operating in south 1/2, sec. 35, T. 11N., R. 7W., just north of Trout Creek.

In the Anderson Mine, on the west limb of the Garrison anticline the author measured a section of the middle member of the Phosphoria formation with a chain in the 5036 feet South stope:

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Thickness (feet)</th>
<th>inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chert (hanging wall), dark gray</td>
<td>0</td>
<td>3 1/2</td>
</tr>
<tr>
<td>9. Phosphatic quartzite</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8. Phosphate rock, high-grade, oolitic, with two sets of fractures at right angles to each other. One set is parallel to the bedding.</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>7. Clay seam, sandy</td>
<td>0</td>
<td>3 1/2</td>
</tr>
<tr>
<td>6. Phosphate rock, oolitic, friable, sandy</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>5. Phosphate rock, oolitic, high-grade, with fractures as described in (4)</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>4. Phosphate rock, oolitic, high-grade, banded, interbedded with clay seams</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3. Clay seam, gray</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2. Phosphate rock, oolitic, low-grade</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Fig. 9. Location of phosphate operations, Montana
Phosphate Products Co., Symposium on Western
Phosphate Mining, A.I.M.E. Mining Transactions,
Seven miles east of the Anderson Mine the author measured another section at the Graveley Mine, Avon with a chain in the 5117 foot west stope on the east limb of the corresponding Luke-Graveley Syncline:

Lithology

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chert, dark gray (hanging wall)¹ (covered)</td>
<td>0 7</td>
</tr>
<tr>
<td>Quartzite, gray, fine-to medium grained, containing phosphate nodules</td>
<td>0 4</td>
</tr>
<tr>
<td>ranging from 1 to 12 inches in diameter. Phosphateoolites confined</td>
<td></td>
</tr>
<tr>
<td>within phosphate nodules. In places the nodules surround the quartzite.</td>
<td></td>
</tr>
<tr>
<td>Clay, yellow-weathering</td>
<td>0 1</td>
</tr>
<tr>
<td>Quartzite, gray, medium-grained</td>
<td>0 6</td>
</tr>
<tr>
<td>Phosphate rock, quartzitic, low-grade, oolites weather white</td>
<td></td>
</tr>
<tr>
<td>Phosphate rock, bluish, siliceous, high-grade, oolites are blue-black</td>
<td></td>
</tr>
<tr>
<td>Phosphate rock, high-grade, colitic, deeply weathered</td>
<td></td>
</tr>
<tr>
<td>Same as (4)</td>
<td>1 8</td>
</tr>
<tr>
<td>Clay seam, yellow-weathering</td>
<td>0 1 1/2</td>
</tr>
<tr>
<td>Quartzite, gray, cherty, with jasper nodules weathering dull yellow</td>
<td></td>
</tr>
<tr>
<td>and rusty red (covered) (footwall)</td>
<td></td>
</tr>
</tbody>
</table>

Total thickness of middle member 3 10

Another section at the Graveley Mine (together with a section at Elliston) is described in Table II; also see appendix.

At the Anderson, Luke, and Graveley Mines (see fig.2), phosphate rock is from 2.5 to 5 feet thick and is overlain

¹ Hanging wall is a mining term referring to the rocks overlying the phosphate rock. Footwall refers to the rocks underlying the phosphate rock.
and underlain by 12 to 30 feet of cherty quartzite. (Armstrong and McKay, 1948, p.287). This is thicker than at Elliston.

Throughout most of the Elliston area, the Phosphoria formation maintains a uniform thickness and lithology. It is absent due to erosion just south of Elliston, sec.12, T.9N.,R.7W. and north of Elliston in sec.26, T.11N., R.7W.

The Phosphoria formation at Elliston consists of three members: the basal member, or footwall, the phosphate rock, and the upper member or hanging wall. These units may be correlated with the C(?), D and E units (see p.10) in the Dell, Montana region.

The lowest member is dark gray chert weathering rusty red and yellowish brown, broken by thinly-spaced fractures. Locally the top of the beds of the lowest member have a bright-green stain. Cherty quartzite is often present, which makes it difficult to distinguish the lowest member from the underlying Quadrant quartzite. The thickness is estimated as ranging up to 10 feet.

The middle member is composed of any combination of high-grade phosphate rock$^1$, phosphatic chert, and phosphatic quartzite. The phosphate is present mainly as oolites, but is also present in the matrix. Generally the phosphate rock is bluish-black on a fresh surface and highly fractured.

---

1. Phosphate rock is a rock composed mainly of phosphate minerals (Pettijohn, 1949)
   High-grade phosphate rock has about 31.5% $P_2O_5$ which is equivalent to 67.7% $Ca_3(PO_4)_2$. The latter is known as "bone phosphate of lime" (abbreviated B.P.L.)
It may be deeply weathered with a light gray to white color with or without a bluish tinge, the "phosphate bloom". The rock has a specific gravity of about 2.9 and thus is noticeably heavy. When it is freshly broken, a strong, fetid odor is often noted probably because of the presence of organic remains. These properties produce an easily-recognized float. The thickness varies up to 5 feet.

The upper member is similar to the footwall member except that the green stain is not present on the tops of the beds. The member is a quartzite, cherty quartzite or chert. Where the middle member was not located, the author could not distinguish the hanging well from the footwall. The upper member is also difficult to distinguish from the Quadrant quartzite. Locally the upper member is conglomeratic or brecciated. The thickness ranges up to 10 feet.

MESOZOIC ERA

In Mesozoic time non-marine deposition became more important, especially during the Cretaceous. The Laramide orogeny began early in Cretaceous time and continued on into Tertiary time. The following is a brief outline of Mesozoic events of western Montana:

1. Deposition (?) of marine sediments early in Triassic time.

2. Lower Triassic (?) to middle Jurassic (Bathonian) emergence and erosion of Triassic (?) sediments and some of the Paleozoic rocks.
3. Submergence and deposition of shales, sandstones and limestones in the Sundance Sea in middle and most of upper Bathonian time.

4. Emergence and erosion in uppermost Bathonian, Callovian and lower and middle Divesian times.

5. Submergence and deposition of sandstones and shales (?) in upper Divesian (?) and Argovian (?) time in the Sundance Sea.

6. Emergence and erosion in Kimmeridgian, Portlandian and Tithonian times.

7. Submergence and deposition during lower Cretaceous time followed by uplift. Marine Cretaceous sediments grade upward into non-marine beds.

8. Laramide folding and faulting in late Cretaceous and early Tertiary probably with some vulcanism.

Triassic System

All Triassic (?) rocks and probably some of the Phosphoria were eroded when the Elliston Phosphate Field was emergent from lower Triassic (?) to middle Jurassic time. Gale and Richards (1925) reports Triassic (?) rocks 400 feet thick at Melrose, Montana which may be equivalent to Dinwoody formation of the Tendoy, Snowcrest and Madison Ranges, Montana.

Jurassic System

Ellis group—The Ellis formation was named by Peale (1893) from exposures near Fort Ellis, a few miles southeast of Bozeman in southwestern Montana. Cobban (1945,
PglëôA) wmpkimg la Arch, elevated the Ellis formation to group rank. He recognized three formations in the Ellis group. They are, from oldest to youngest, the Sawtooth (middle to upper Bathonian), the Kiordon (upper Bathonian and Callovian) and the swift (upper Dives- sian and Argovian). The author mapped the Elliston area as including two units of the Ellis which may be correlated to the Sawtooth and the Swift formations.

Sawtooth formation—Cobben (1945, p. 1262) named the Sawtooth formation after a section in Kiordon Gulch in the Sawtooth Range in northwestern Montana. The formation consists of:

"three members, a basal fine-grained sandstone; a medial dark gray shale contain- ing a few dark limestone beds and an upper member of light-gray, calcareous siltstone, fine-grained sandstone, or sandy, calcitic limestone. The Sawtooth is as little as 8 feet in the Levin-Sunburst dome. It thickens eastward to 300 feet in the Sweetgrass Hills and westward to about 300 feet along the Rocky Mountain Front...."

The Sawtooth formation in the Elliston area is generally non-resistant and does not form good outcrops. However, it can be readily traced by its abundant and distinctive float.

The formation consists of a basal gray or blue-black shale and a series of thin-bedded, soft, gray, fine- to medium-grained, flaggy, calcareous sandstones; soft, gray, flaggy, sandy limestone and grayish-green, medium- crystalline limestone. All beds may contain fossils. Weathered beds are characteristically buff-colored and form a distinctive float.
In the NE Sec. 2 Sec. 10 N.W., R. 6 W., a bluish oolitic limestone emitting a fetid odor when freshly fractured was found.

The thickness of the Sawtooth formation is estimated at from 250 to 450 (?) feet.

The Sawtooth formation rests disconformably on the Phosphoria formation and is disconformably overlain by the Swift (?) formation.

Knopf (1915, p. 82) submitted a collection of fossils from an outcrop of basal Sawtooth just north of Elliston to T. W. Stanton who identified them as follows:

"Pentacrinites astericus Meek and Hayden
Campionoceras pterodactylus Hall and
Whitfield
Pseudomonotis (Eumicronatus curta Hall)
Undetermined gastropod shells
Cardioconus sp. (small fragment)"

The Hierdon formation of the Ellis group was not found in this area. Cobben (1948) said that

"during early Divesian time the Sawtooth and Hierdon formations were locally thinned by erosion and possibly removed from some areas. Later in Divesian, marine waters transgressed the entire area and remained until the close of the Argovian."

Swift (?) formation- Cobben (1948, p. 1281) named the Swift formation from the Swift Reservoir on Birch Creek in northwestern Montana where the beds are well-exposed. He also describes the Swift formation in the Little Belt Mountains which is similar to the one found at Elliston.

The Swift formation is of upper Divesian and Argovian age. Just north of Elliston the Swift (?) formation
crops out as a ledge.

The Swift(?) formation consists of a basal conglomerate containing quartzite and chert pebbles, ranging from 1 to 3 inches in diameter in a matrix of gray, coarse-grained, hard sandstone with minute particles of black chert, weathering dull yellow and rusty brown. It has sharply-defined bedding and cross-bedding. This grades laterally and upward into a coarse-grained, hard sandstone and in the northwestern part of the field it grades into a quartzite. It typically forms coarse talus and is a good marker bed. The thickness is roughly estimated at 60 feet. It lies disconformably on the Sawtooth and is disconformably overlain by the Kootenai formation.

Knopf (1913) reports several hundred feet of coarse-grained sandstones about 1/2 mile northwest of Elliston. These may be similar to the Swift(?). In the Drummond, Montana area, about 35 miles to the west, a sequence similar to the Elliston sequence was observed by the author. Shales, containing an oolitic limestone of the Sawtooth formation, underlie a chert-pebble conglomerate of the Swift (?) formation.

Cretaceous System

Kootenai formation—C. A. Fischer (1909, pp. 28-35) sums up the history of the Kootenai formation in Montana showing it to be lower Cretaceous in age.

The Kootenai formation in the Elliston area is best exposed in the north half, sec. 35, T. 11N., R. 7W., where it
caps the divide between Dog and Trout Creeks.

The formation consists of interbedded red-purple shales and quartzites about 90 feet thick overlain by a thick sequence of blue-black, thin-bedded, soft shale, which is, in places, interbedded with thin, medium-gray, fine-grained, well-rounded, ripple-marked or banded quartzites. There are two limestone beds. The lower one is bluish, finely-crystalline, fossiliferous and may be 50 feet thick; the upper limestone is bluish-black, ranging from dense to medium-crystalline, contains abundant gastropods, is locally dolomitic and is about 5 feet thick.

Near the upper part of the exposed Kootenai is a thin bed of siltstone which contains abundant plant remains. The youngest rocks observed are bright green, medium-grained, soft, argillaceous sandstone interbedded with purple shale. In places the rocks are streaked with bright reds and greens. The thickness of the Kootenai is at least 700 feet and probably is over 1000 feet. The upper contact was not observed.

In the west sec.of T.6N., R.7W., red, buff, and gray sandstones with interbedded red shale (about 25 feet thick) are present in the lower Kootenai.

Contact Metamorphism of the Kootenai formation

The shales of the Kootenai formation have been metamorphosed by numerous dioritic flows or sills (see p.21) into hornfels in the area extending from the S2, sec.20, T.10N., R.6W. to the S2, sec.7, T.10N., R.6W. The metamorphism in this area has not previously been described.
In sec. 20, T. 10N., R. 6W., the metamorphosed rock is typically an extremely fine-grained, olive-green hornfels weathering greenish-gray. It was difficult to distinguish the rock from basalt in the field.

A thin section revealed that 30% of the rock is anhedral to subhedral quartz and orthoclase with some albite and leucoxene and minor amounts of biotite. The matrix, 70% of the rock, is extremely fine-grained quartz and possibly feldspar and sericite. Unidentified prismatic crystals, about 0.004 inches in length, have some lineation.

In Sec. 7, T. 10N., R. 6W., a typical specimen underlying the youngest bed of fine-grained quartzite is a black, hard, dense hornfels with needle-shaped crystals of chlortolite with a cross-sectional width of 0.02 inches. Twenty-five percent is anhedral to euhedral quartz about 0.008 inch in diameter. The matrix is fine-grained and stained with chlorite and hematite. There are minor amounts of pyrite and biotite.

The character of the rock gradually changes downward in the section from a hard chlortolitic hornfels to a soft hornfels which has poorly-developed fissility and less chlortolite and finally to a blue-black shale. The changing character of the rock suggests that the overlying quartzite blocked the magma (see section on next page) causing it to metamorphose the shale below the quartzite to relatively great depths. The effects of the metamorphism is seen to diminish gradually.
The following section was measured by L. V. Bell and the author.

### Lithology

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Thickness (in feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. Quartzite, fine-grained</td>
<td></td>
</tr>
<tr>
<td>7. Diorite porphyry sill</td>
<td></td>
</tr>
<tr>
<td>6. Chiaastolite hornfels, black</td>
<td>200</td>
</tr>
<tr>
<td>5. Shale, blue-black to black, fissile, locally weathering red. Well-developed joint sets with vertical dips.</td>
<td>38</td>
</tr>
<tr>
<td>4. Andesite porphyry, dark-gray with euhedral pyroxene crystals weathering light green.</td>
<td>2</td>
</tr>
<tr>
<td>3. Shale, as in (5)</td>
<td>12</td>
</tr>
<tr>
<td>2. Quartzite, dark gray and blue-black, weathering red, massive.</td>
<td>12</td>
</tr>
<tr>
<td>1. Quartzite, with shale partings.</td>
<td></td>
</tr>
</tbody>
</table>

### CENOZOIC ERA

Following the Laramide orogeny, "lake beds" were deposited in Eocene (?) time. In Miocene (?) time, extensive rhyolite and basalt (?) flows covered the landscape which was probably much like it is today. This was followed by uplift and erosion and deposition of Recent alluvium.

### Tertiary System

Stone and Bonine (1913, p. 376) reported

"deposits of sand, gravel, clay, and tuff, commonly known as Tertiary lake beds (occur) just north of Elliston."

Horizontal Tertiary sediments can be seen along the road to the Greavely Mine, Avon. These beds were not investigated in detail.

---

1. The thickness of the hornfels was determined by traversing it with a car odometer and using a barometer at significant points. The sedimentary rocks were measured with a tape.
Quaternary System

**Pleistocene deposits**—Glacial drift overlies some of the primary Tertiary sediments immediately south of the Little Blackfoot valley. A road out in the SE¼, SE½, sec. 1, T. 10N., R. 7W. exposes at least 13 feet of glacial drift. About 0.5 miles north of the Little Blackfoot River, glacial debris is on the tops and along the slopes of the ridges. The debris consists mainly of fragments of Swift(? sandstone and granite. Granite crops out about 2 miles to the east and according to Knopf(1913) it is present about 7 miles to the south. This suggests that the glacier came from the southerly or easterly direction.

**Recent deposits**—Sand and gravel cover the floors of the Little Blackfoot valley and the valleys of its tributaries.

**IGNEOUS ROCKS**

At Elliston and surrounding areas near Avon and Drummond, Montana are many remnants of the Tertiary lavas which were widespread in the western United States. Both rhyolitic and basaltic flows are present.

**Sills and/or volcanic flow**—A series of dioritic igneous rocks is intimately associated with Mesozoic sediments throughout the Elliston area. The rocks are particularly well exposed in E¼, sec. 1, T. 10N., R. 7W. and W½, sec. 6, T. 10N., R. 6W. just north of Elliston. The rock here is undoubtedly intrusive. The diorite(?) porphyry has concordant contacts above and below it with the Sawtooth formation.

Dioritic igneous rocks also crop out in SE¼, SE½, sec. 7, T. 10N., R. 6W and continue northwest paralleling the trend of
the Mesozoic sediments to sec.36, T.11N., R.7W. Here they are associated with the Kootenai formation. Examined megascopically, the rock has a dark green, fine-to medium-crystalline groundmass with phenocrysts of plagioclase and pyroxene and probably some amphibole. Locally, the crystals are euhedral and up to 0.5 inches in diameter. It was called an andesite porphyry in the field.

In E$	ext{ }$construction outcrop, covering the ridge and slopes, which resemble megascopically the rocks just described. These beds have a northward strike and dip steeply to the east, roughly paralleling the Kootenai formation in that area.

Possible sources of the dioritic magma crop out in NE$	ext{ }$construction and in NW$	ext{ }$construction. In the former outcrop, the coarsely-crystalline diorite can be traced into the porphyry. The diorite is a gray, coarsely-crystalline, massive rock consisting mainly of plagioclase and pyroxene.

Knopf(1913) and Stone and Bonine(1913) in describing dioritic rocks in the northern part of the Elliston Phosphate Field refer to them as a series of flows interbedded with Mesozoic sediments. The author is not fully convinced that they are all extrusive. The following evidence points to an intrusive origin of the igneous rocks:

1. Wherever observed, the contacts between the igneous rocks and the sedimentary rocks are concordant.

2. Contact metamorphism of the Kootenai sediments is believed to be too deep to be caused by a flow. Furthermore,
overlying quartzite apparently blocked the magma causing the metamorphism. (See pp.20-21).

3. Most of the igneous bodies seem to be only a few feet thick.

If these bodies are sills, their age is post-lower-Cretaceous.

The following evidence points to a flow origin:

1. The bodies are always porphyritic and often have a fine-crystalline groundmass.

2. The rocks are associated only with Mesozoic sediments.

If these bodies are flows, then they are contemporaneous with the deposition of the Kootenai sediments.

Hyolite porphyry—Hyolite porphyry is the most widespread of the volcanics, cropping out as knobs just west of Elliston, north and south of the Little Blackfoot Valley and westward to Avon. About 2 miles west of Elliston a dike 400 feet long is visible from U.S. Highway 10N.

The rhyolite rests disconcordantly on the rocks of the Ellis group. Stone and Bonine (1913,p.377) date the rhyolite as possibly Miocene in age, although they do not give any evidence for the age.

The rhyolite porphyry has a characteristic dark reddish hue on a fresh surface. It has a red groundmass (locally appearing like jasper) which may constitute up to 95% of the rock. The phenocrysts are usually weathered red and are quartz and feldspar up to 1/3 inch in diameter. Bedding is locally well developed. In place, the rhyolite has a light-gray groundmass with phenocrysts of orthoclase, quartz, and some biotite up to 1/4 inch in diameter.
At the corner of secs.1,2,11,T.9N.,R.7W. and in sec. 7,T.6N.,T.6W., south of Ellistor, rhyolite(?) porphyry has a characteristically greenish float. The rocks have a green, dense to finely-crystalline groundmass. The phenocrysts consist mainly of tabular, pale-orange orthoclase up to $\frac{1}{3}$ inch long and some dull-grey quartz. Stone and Bonine (1913, p.376) call the rock in this area diorite porphyry.

"Basalt"- In secs.17,20,T.10N.,R.6W. there is an outcrop of "basalt" weathering rusty brown and containing black amygdules weathering white.

Thin-section study shows that about 30% of the slide consists of phenocrysts of albite and quartz with some orthoclase and microlites in a fine-crystalline groundmass of what is probably sericite and quartz. Flow lines are distinctly developed. The amygdules (about 25% of slide) are filled with spherulitic chalcedony surrounded by a reddish rim, probably an iron stain. The rock name is dacite, with the thickness probably less than 20 feet.

"Granite"- Stone and Bonine (1913) mapped granite intrusions about 3 miles northeast of Elliston which were seen by the author. There are several places where the intrusion is probably a monzonite because it lacked sufficient quartz to be a granite. Knopf (1913) describes several mines a few miles south of Elliston which are getting their ore from veins in granite.

STRUCTURE

The structure of the area is a southeastward plunging
anticline on which the town of Elliston is situated. The
crest of the anticline is highly faulted while its south-
west limb and the trough of the corresponding syncline,
where studied, are relatively simple, unfaulted structures.

General Features

The rocks studied in reconnaissance range in age
from Mississippian to lower Cretaceous. Most of the
structure, however, was deduced from the Phosphoria form-
ation, which was studied in detail and whose thin beds
were excellent markers in the field.

The structure will be divided into two parts for ease
of discussion. The first part is the relatively simple
structure of the limbs of the broad folds in the area.
The second is the more complex structure found on the crest
of the anticline.

Essentially the beds strike northwest on the east
limb of the Elliston anticline. The crest of the anticline
is formed by the Madison limestone and in the correspond-
ing syncline to the east, the trough is capped by the
Kootenai rocks.

The folds are southeast plunging, broad and open, with
axes striking approximately N.55°W. The common limb of
these folds is about 6 miles long; the crest of the anti-
cline about 2 miles wide and the trough of the syncline
about 2.5 miles wide. The folds trend parallel to the
Garrison anticline and the Luke-Graveley syncline (see
fig. 2).
Simple Structure

In the southeastern part of the common limb, the beds strike north and dip steeply east. In the SW1/4, sec.17, T. 10N., R. 6W. and continuing for 3.5 miles northwest, the beds strike N. 45°W. The beds are alternately normal and overturned, but maintain a steep dip. Continuing northwest for little more than a mile starting in the NE1/4, sec.2, T. 10N., R. 7W., the beds, which are locally overturned, swing from an almost east strike to the north and then strike N. 45°W. The beds gradually assume a more gentle dip to the east.

In the NE1/4, sec.34, T. 11N., R. 7W., at the west end of the synclinal trough the beds strike N. 45°E. and dip about 25°E. This northeast strike continues to the SE1/4, sec.23, T. 11N., R. 7W. where the field work was concluded.

In the center of the syncline, the beds have a very gentle westerly dip.

Complex Structure

South of the area just described, the structure is generally complicated by faulting. In the E1/4, sec.31, T. 10N., R. 6W. on the crest of the Elliston anticline the beds strike east and dip 30°S. In the western half of the section, the beds change strike to N. 45°W. and dip 30°W. The Quadrant quartzite is coarsely brecciated in section 31 indicating intraformational movement probably due to shattering of the competent beds because of the compressional forces involved in the folding.

South and southwest of section 31 are numerous faults
such as often occur on the crest of a fold. The task of solving the geology is made more difficult because some of the pre-Tertiary rocks are covered by Tertiary flows, and glacial drift.

**Descriptions of the faults**— All of the major faults, except one, lie in the crest of the Elliston anticline. These faults are probably Laramide in age since some of them cut across all pre-Tertiary rocks. The faults are probably due to the same compressional forces which are responsible for the folding since the faults are mainly confined to the anticlinal crest and one set of faults is parallel to the axis of the anticline. Faulting of this type is usually of the high-angle, normal variety and this type is probably present in the area. There was no field evidence, however, which confirms this.

The faults generally strike in two directions which are mutually perpendicular. One set of faults strikes approximately N.65°W. to N.80°W. which is roughly parallel to the axis of the Elliston anticline. The other set strikes from N.10°E. to N.20°E. Two faults in the NE₄, sec. 6, T.9N., R.6W., about 80 feet long, strike N.30°W.

**Faults roughly parallel to the axis of the anticline**— In SE₄, sec. 31, T.10N., R.6W. there is a high-angle fault striking N.70°W. which has a length of 4000 feet.
A fault 2400 feet in length and with a strike of N. 80°W. is found in the Ne, sec. 32, T. 10 N., R. 6 W. bringing Madison limestone in contact with the Ellis group.

In the W, sec. 6, T. 9 N., R. 6 W., a high-angle fault strikes N. 80°W. and has a length of 350 feet and an estimated stratigraphic throw of 150 feet. The fault can be seen by the offset of the Phosphoria outcrops along an old road leading to Helena.

Faults roughly perpendicular to the axis of the anticline—

The largest mapped fault in the area is found mainly in the W, sec. 6, T. 9 N., R. 6 W. but extends north into sec. 31, T. 10 N., R. 6 W. and south into sec. 7, T. 9 N., R. 7 W. The fault plane is curved but it has an average strike of N. 20°E., a length of 9000 feet and an estimated stratigraphic throw of 750 feet bringing Quadrant quartzite in contact with the Sawtooth formation. About 1500 feet of the fault trace is hidden beneath the alluvium of the Little Blackfoot River and some glacial drift.

In the NE 1., sec. 2, T. 9 N., R. 7 W., a high-angle fault striking N. 10°E. has a length of at least 1800 feet with an estimated stratigraphic throw of 1200 (?) feet bringing Quadrant quartzite in contact with the Kootenai formation. Probably much of the fault trace is hidden beneath the alluvium of the Little Blackfoot River and perhaps even by the glacial drift found on the hilltops overlooking the valley.

Numerous small faults were seen in the field. Most of the faults were detected by following phosphate float.
In outcrops where the fault planes were actually observed the net slip was not greater than a few inches. As a rule, these minor faults are parallel to the major fault sets and all fault planes seen had vertical or nearly vertical dips. Other faults—Bell (1952) has reported a fault in the Collins tunnel in sec. 29, T.10N., R.6W. The fault strikes N.26°E and has a vertical (?) dip. Outcrops seen around the area suggest that the fault trace is 3000 feet long and that it probably has a stratigraphic throw of 1400 feet bringing Quadrant quartzite in contact with the Sawtooth formation.

Comparison of effect of structure and location of phosphate rock

There were no significant differences in the nature of the phosphate rock, either macroscopically or microscopically, when compared over different structures, such as the highly-faulted crest of the Elliston anticline and the corresponding relatively-undeformed anticlinal limb. Any microstructures noted had no apparent relation to the macrostructures. However, because phosphate rock is incompetent, there is some reason to believe that even the relatively-undeformed anticlinal limb was subject to enough compressional forces so as to deform the oolites. Comparison with completely undeformed beds as near to Elliston as possible would have to be done in order to confirm this. More work will have to be done on this problem before a really definitive statement can be made.

The comparison of the phosphate sections at Elliston and at Garrison also showed no appreciable differences in
the texture and structure of the rocks in these two areas, except that the bending seems to be less pronounced at Garrison than at Elliston.

PETROLOGY OF THE PHOSPHATE ROCK

Definition of phosphate rock- Phosphate rock, also called phosphorite or rock phosphate is a sedimentary rock composed mainly of phosphate minerals (Pettijohn, 1949, p. 348).

Mineralogy of the phosphate rock- The amorphous phosphate mineral which makes up most of the oolites is called collophanite, but this mineral is not a single species. Dana (1947, p. 703) says that collophanite is essentially Ca$_3$P$_2$O$_8$H$_2$O containing small amounts of CaCO$_3$, CaF, CaSO$_4$, etc. with an index of refraction from 1.57 to 1.63.

Emery and Dietz (1950, p. 8-9) described phosphate minerals found off the coast of California and Mexico and stated that francolite or dahllite is possibly the anisotropic phosphate mineral associated with collophanite.

Altschuler (1952) studying the mineralogy of the phosphate nodules in the rocks of the Phosphoria formation stated that:

"on the basis of X-ray studies and chemical analyses...the nodules are composed of carbonate-fluor-apatite. This is an apatite in which fluorine is slightly in excess and in which, carbon, probably as carbonate, occurs substituted in the structure. The exact occurrence of carbonate in the structure is not known, however, it presumably replaces phosphate as analyses of carbonate-fluor-apatite are deficient in P$_2$O$_5$."  

This suggests that the mineral present in the phosphate rock is collophanite, since its theoretical formula is similar to that found by Altschuler. Altschuler's
report also confirms the fact that there is probably no one mineral present, but a mixture of minerals, perhaps in isomorphous series.

Minerals associated with phosphate- The most common associates of the phosphate minerals are chalcedony and quartz. Megascopically these minerals are chert. Also present in many specimens is hematite. Some limonite, possibly magnetite, and in one specimen, gleuconite are present.

It is interesting to note that except for one slide containing secondary calcite and one limestone bed (1 to 2 inches thick), no carbonate has been found. Gilbert (1945), studied in detail the phosphate rock at Garrison and also noted the lack of carbonates in the rock.

General megascopic description of the phosphate rock- The phosphate occurs mainly as oolites, rarely as pisolites, and is often found in the matrix as collophanite. The rock is often so tightly cemented that the oolites are broken through by closely-spaced sets of fractures. Weathering takes place most readily around the oolites. The phosphate rock is noticeably heavier than ordinary sedimentary rocks since it has a specific gravity of 2.9. When struck with a hammer, the rock often emits a fetid odor which can be detected at distances for more than one foot.

1. Oolites range in size up to 0.1 inch in diameter. Pisolites are greater than 0.1 inch in diameter.
There is no correlation between the grade of the phosphate and the odor. The odor is probably due to organic remains.

Oolites compose 50 to 85 percent of the phosphate rock at Elliston. There is some concentric structure usually evident in them. The oolites have light-gray centers surrounded by medium-gray or dark-gray phosphate or dark-gray centers surrounded by light-gray or medium-gray phosphate. Occasionally there is distinct banding with concentric bands composed of various shades of gray. The banding is best seen with the microscope. The oolites are also composed of phosphate of one color. These are either white, light gray, medium gray, dark gray, or as in one specimen, a very pale orange.

The oolites usually weather with a bluish tinge, the so-called "phosphate bloom", but may also weather to a light gray or even a pure white. The weathered surface is highly characteristic and, once seen, makes phosphate float easily recognized. When iron is present, the rock weathers to various shades of yellow and orange.

The size of the oolites varies from 0.02 inch to 0.1 inch, above which they are called pisolites; the average oolite size is from 0.04 to 0.05 inches in diameter. The oolites are predominantly ellipsoidal, but they may be spherical. They are sometimes discoidal, triangular in

1. The percentage of the oolites in the phosphate rock was estimated in the microscope by using the quadrants of the cross-hairs. A representative section of the slide was studied and an estimation was made of the percentage of oolites in one quadrant.
section, and irregular. These shapes may result from plasticity due either to pressures of overlying sediments or by pressures applied during the Laramide orogeny.

Apatite or dahlite crystals are present in many oolites. They can be recognized by their hexagonal cross-section, vitreous luster and medium- to dark-gray color, although it may be necessary to study their optical properties in order to distinguish them from quartz. The crystals are probably not oolite nuclei because they are often not in the centers of the oolites. They are probably a product of recrystallization because these phosphatic crystals seem to be more common in the more structurally deformed parts of the phosphate bed, that is, in the anticlinal crests rather than in the limb. More sampling would have to be done before any definite conclusions are reached.

The matrix is composed of chert, fine-grained quartz and/or collophaneite. Regardless of the matrix composition, the color is usually dark gray and sometimes medium gray. It may be necessary to carry a solution of 1:1 nitric acid and ammonium molybdate in the field to distinguish the phosphate from the chert. The phosphate is soluble in the nitric acid and tiny yellow octahedral crystals reform on addition of the ammonium molybdate. It is sometimes difficult to distinguish the oolites from the matrix when the oolites are crowded together, because of their similarity of color.
General microscopic description of the phosphate rock-
The oolites are pale brown, sometimes dark brown in plane light and gray, sometimes bluish gray or pale yellow in reflected light. When crushed to a powder with an average size of 0.1 mm in diameter and studied in refractive oils, the oolites appear dark brown in plane-polarized light and bright yellow in reflected light.

Two types of concentric structure or banding are present. One type is of coarse, isotropic bands of various shades of brown which are conspicuous in plane-polarized light but are barely discernable under crossed nicols. This is probably due to a slight change in chemical composition (or change in impurity) of the phosphate with little change in crystallinity. The other type, which is less often present, is of alternating, very thin, anisotropic bands and much thicker isotropic pale brown bands. This type is conspicuous under crossed nicols and is barely discernable in plane-polarized light. It seems, therefore, that the thin bands vary in crystallinity with possible chemical changes and resulting anisotropism. In one slide, some bands were part isotropic and part anisotropic.

Nuclei, which are rare, consist of subangular quartz grains which are secondarily enlarged. Apatite or dahlite crystals are present as small hexagonal prisms scattered throughout the oolite. Although some of these crystals may be in the center of the oolite, it is probable that they are not nuclei since the axes of the oolites do not coincide with the axes of the crystals. The number of the
crystals vary from a few which may be seen only under high power to so many that they fill almost the entire oolite. Sometimes the crystals are present in the matrix. These phosphate crystals are probably the result of recrystallization of collophanite since they are found within the oolites without orientation. This recrystallization may be due to pressures of the overlying sediments or to orogenic forces acting upon the unstable collophanite.

In one slide are two oolites partially or wholly replaced by chalcedony and quartz.

The following is a description of the intra-oolitic crystals:

- **index of refraction:** slightly less than 1.61
- **color:** colorless to very pale brown in plane light, steel blue in reflected light.
- **habit:** minute, euhedral, hexagonal prisms. Some are tabular, which sometimes show one crystal growing out of another (not as a result of twinning).
- **birefringence:** highest color is pale gray-0.007. Cross-sections are dark.
- **extinction:** length fast, parallel to prisms and tabular crystals.
- **inclusions:** most have tiny crystals(?) and bubble inclusions in them.
- **interference figures:** figures are difficult to determine because the crystals are very small. Some figures were biaxial, probably due to strain, with a small 2V and with no rings.

Mineral name—probably daillite although the index is a little too low and the tabular crystals are length fast unlike daillite.

The matrix of the phosphate rock is collophanite which has the same properties as the collophanite within
the oolites. The matrix also contains chalcedony, quartz, hematite, some limonite, magnetite(?), and in one, slide, glauconite. The quartz averages 0.004 inch in diameter, has wavy extinction, bubble inclusions, is often secondarily enlarged and sometimes fused.

All of the matrix minerals may be found in fractures except collophanite. Some of the collophanite present in the matrix may be due to the solution of part or all of the oolites and later redeposition. For further details see Tables II and III and appendix.

Plasticity- There is little doubt that the oolites were plastic at one time. This is indicated by:

1. deformation of the oolites- Some oolites have highly irregular curved surfaces as a result of compression. These oolites may have assumed the shape of more competent adjacent oolites (see figs.). The oolites may be crowded together to such an extent that there is difficulty in distinguishing them from a phosphate matrix. The ellipsoidal form may be a deformed sphere. In places, part of the oolite has been compressed into the matrix.

2. deformation of the bands within the oolites- Bands of some ellipsoidal oolites appear to have been thickened parallel to the long axis of the ellipsoid and thinned perpendicular to the long axis (See fig. 5). This suggests that the compression was perpendicular to the long axis.

The plasticity is a result of original deposition or later metamorphism.

In several slides orientation of the oolites is noted, sometimes parallel to the bedding, but more often
at about 45 degrees to the bedding (See appendix). The orientation may change in the same slide two or three times and, therefore, may be explained by original deposition only if it is cross-bedding on a microscopic scale. If it is assumed that the oolites were plastic when they were formed then the weight of the overlying sediments may have produced some orientation. There is some evidence, however, that metamorphism played a role in the deformation of the oolites. In one slide there is a fusion of several quartz grains evidently caused by the pressure of the oolites because the quartz grains now assume the shape of the oolites. The sphericity of the oolites may have made them more competent than the harder quartz. The presence of "quartzite" was noted in one other slide. One slide, however, shows that sets of fractures cut across at various angles to the orientation.

ORIGIN OF THE PHOSPHATE ROCK

A complete origin of the phosphate rock should explain:

1. The geologic setting for phosphate deposition including nature of nearby lands and containing sea.

2. The source of the constituents of the phosphate minerals.

3. How the phosphate is made insoluble.

4. The formation of the oolites.

Geologic setting—Mansfield (1927,p.372) discusses the physiographic conditions under which the phosphate was
"...lowlands or peneplaned lands adjacent to the sea are suggested and also the abundance of sandy and quartzitic material in Pennsylvanian terranes, possibly exposed to erosion, is indicated."

The lowlands or peneplaned lands seem to be necessary in order to produce phosphate rock, otherwise any phosphate that is deposited would be diluted with other sedimentary materials. Megascopic and microscopic examination of the phosphate rock near Elliston shows very little clastic material present.

Sources of the constituents of the phosphate minerals—
Igneous rocks contribute phosphate mainly from apatite with some xenotime and monazite. There are many other phosphate minerals in igneous rocks which contribute to the supply.

The phosphate is used by animals to form their teeth and skeletons (either endo- or exoskeletons). After the death of the animals, the phosphate is returned to the sea. Guano is also an important source of phosphate.

Solubility and concentration of the phosphate—Phosphate deposition is taking place in the oceans today (Emery and Dietz, 1950; Murray, 1873-1876). Clarke (1924, p. 127) shows that phosphate, with silica and iron make up 0.02 to 0.08 percent of the ocean salts. Therefore, relatively little phosphate is necessary to produce a deposit.

One of the most important problems concerning phosphate deposition is what makes the phosphate insoluble.

Pardee (1917, pp. 225-228) said that the phosphate precipitated out directly to form oolites. He assumed that
Fig. 3 Graph showing the solubility of (1) phosphate rock (2) dicalcium phosphate and (3) bone with respect to pH. Solid line represents calcium alkalinity; dashed line represents sodium alkalinity. Solubility in parts per million.

(After McGeorge, 1932)
a certain amount of phosphate has been precipitating continuously in geologic time, but that calcium carbonate which is ordinarily precipitated with the phosphate, was made more soluble in cold water due to glacial conditions elsewhere in the world. The glaciation cooled the waters which helped retain carbon dioxide and thus prevented the calcium carbonate from depositing.

The cooling of the waters would help explain the absence of calcium carbonate in the Elliston area. Kazakov (1938) also considers the concentration of carbon dioxide important. However, he does not consider glaciation:

"accumulation of phosphate occurs on the shelf, at the expense of the chemical precipitation of calcium phosphate from ascending deep (bottom) currents, which can contain up to 300-600... mg P₂O₅ per cubic meter. Owing to the lessening in partial pressure of CO₂ in these ascending layers, the sea water finally becomes supersaturated-first of all with respect to CaCO₃, which must precipitate first; somewhat later, in the upper half of the shelf, the crystallization of calcium phosphate occurs combined with the final crystallization of CaCO₃."

The Elliston phosphate may represent the upper shelf deposits after all of the calcium carbonate has been precipitated as calcite.

However, a lowering of the pH would also make calcium carbonate more soluble. In the phosphoria formation, south of the Elliston area into southwestern Montana, Wyoming, and Idaho, carbonate is often associated with the phosphate rock. Therefore, it seems that the lack of carbonate is a local phenomenon.
It should be mentioned that an increase of carbon dioxide or decrease of pH makes both the carbonate and the phosphate more soluble. However, since phosphate is ordinarily much less soluble than the carbonate, it is probably much less affected by an increase of carbon dioxide.

The roles of pH and carbon dioxide in the precipitation of phosphate have until recently, (Krumbein and Garrels, 1952), been overlooked by American geologists. Kazakov (1938), a Russian geologist and McGeorge (1932), an American chemist have recognized the importance of the roles of pH and carbon dioxide for some time.

McGeorge (1932, pp. 593-630) prepared a chart (see fig. 3) showing the relationship of pH on the solubility of phosphate rock, chemically pure dicalcium phosphate, and bone. It is interesting to note that at the pH range of present-day oceans where phosphate precipitation is taking place (about 8.1 to 8.25- McClendon, 1918, p. 254) the solubility of phosphate, as in apatite and in bone, is very low. However, although the solubility of bone is low, it is more soluble than the phosphate rock. This suggests that bone will dissolve under the same conditions which will precipitate phosphate rock.

Other investigators such as Murray, 1873-76, Blackwelder, 1915 and Honkala, 1949 present theories of phosphate deposition based on wholesale destruction of organisms, which in turn yields a rapid accumulation
of phosphate.

Mansfield (1918 pp. 591-598) thought that the phosphate oolites were replacements of calcareous oolites.

Another problem concerning the phosphate deposits is the presence of fluoride. Mansfield (1940, pp. 863-873) suggests that volcanic activity which is associated with the principal deposits of the United States was the source of the fluoride (in the form of fluoride) found in phosphate rock.

Formation of the oolites—Hardley (1936, pp. 1359-1372), working with calcareous oolites in Great Salt Lake, is one of the few authors who stress physical chemistry in the formation of the oolites. He says that carbonate is precipitated as minute crystals near the surface due to evaporation. These crystals sink and since they are more soluble than the larger carbonates (the oolites) already forming, they are redissolved.

"At the same moment molecules of carbonate come out of solution and build on the larger particles which are less soluble. The theory involves the phase rule and is based on the observation of the variable solubility of a substance depending on the degree of combination. (Thus) the larger particles grow at the expense of the smaller..."

"Distinct layers instead of one continuous growth ring are the rule because of seasonal climatic variations which alter the rate of carbonate precipitation."

Although Hardley was studying calcareous oolites, the author believes that the process of growth of the phosphate oolites is similar. The theories of Hardley
explain the lack of visible nuclei and the well-developed bending in the phosphate oolites. It must be noted, however, that Hardley requires constant agitation for the formation of the oolites, which does not apply to the phosphate rock at Elliston. The black color and the fetid odor emitted by the phosphate rock when struck suggest that the phosphate was deposited under stagnant conditions.

**SUMMARY**

The following is a list of the more significant contributions made in this paper.

1. Rocks previously assigned to the Ellis formation have been separated into the Sawtooth and Swift(?) formations of the Ellis group.

2. The phosphate occurs in the Phosphoria formation in the form of oolites and is often present in the matrix.

3. The oolites are composed of collophanite, an amorphous form of a carbonate-fluor-apatite, and apatite or dahllite, and possibly francolite. The apatite or dahlite is a result of recrystallization.

4. The matrix is mainly collophanite, but chaledony and quartz are also important. Carbonates are conspicuously absent. The lack of carbonates may be due to an increase of carbon dioxide or decrease in pH, both of which make carbonate more soluble than phosphate.

5. Bending of the oolites, which is common, consists of two types:
(a) bands composed of alternating light and dark shades of brown isotropic phosphate. This type is plainly visible only in plane light.

(b) bands composed of alternating thin, anisotropic phosphate and coarser isotropic phosphate. This type is plainly visible only under crossed nicols.

6. Nuclei, which are rare, are made of secondarily-enlarged quartz.

7. Experiments by McGeorge (1931) show that the pH and the concentrations of carbon dioxide and calcium carbonate have profound effects on the solubility of phosphate. To the author's knowledge, the results of these experiments have not been emphasized before in American literature. Consideration of McGeorge's results indicates his results have an important bearing on the precipitation of phosphates.

8. Other contributions:

   a. the geology of the Elliston Phosphate Field was mapped and described.

   b. the petrography of the rocks of the Elliston region, with emphasis on phosphate rock, was studied, described and tabulated.
Fig. 4. Thin section of the phosphate rock at Elliston. Sample No. 1-2-4. Note resorption of some of the oolites. The opaque mineral is hematite. Picture taken in plane light. X 20
Fig 5. Thin section of phosphate rock at Elliston. Banding made of alternating pale and dark brown isotropic bands. Most of the lighter-colored grains are quartz, but there are several apatite or dehllite crystals visible in the matrix. Note thinning and thickening of some of the bands. Picture taken in plane light. X 22
Fig 6 Thin section of phosphate rock at Garrison. Sample No. G-5124-E-b. Collophaneite is the matrix in the upper right-hand corner; chalcedony and quartz are the matrix in the remainder of the picture. Note the plastic effect on some of the oolites.

Picture taken in plane light. X 20
BIBLIOGRAPHY OF REFERENCES CITED IN TEXT

Altschuler, Z. S. (1952) Personal communication


Bell, L. V. (1952) Personal communication


