Contributions to Economic Geology 1952-53

GEOLOGICAL SURVEY BULLETIN 982

DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1953

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

CONTENTS

The letters in parentheses preceding the titles are those used to designate the papers for separate publication]

ILLUSTRATIONS

[All plates in pocket]

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Phosphatic Rocks in the Deer Creek-Wells Canyon Area Idaho

By WAYNE RUSSELL LOWELL

CONTRIBUTIONS TO ECONOMIC GEOLOGY, 1952

GEOLOGICAL SURVEY BULLETIN 982-A

A study of the phosphatic shale member, Phosphoria formation of Permian age

DEPARTMENT OF THE INTERIOR
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CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO ECONOMIC GEOLOGY, 1952

PHOSPHATIC ROCKS IN THE DEER CREEK-WELLS CANYON AREA, IDAHO

By Wayne Russell Lowell

ABSTRACT

The phosphatic shale member of the Phosphoria formation of Permian age in the Deer Creek-Wells Canyon area consists of interbedded shales, siltstones, limestones, and phosphate rock of marine origin. Shales are the dominant type of rock.

Detrital quartz, muscovite, and clay minerals, as well as organic matter, are present in varying amounts in all the rocks of the phosphatic shale member. Calcite, in addition to that in the limestones, is present in the matrix of some shales, siltstones and phosphate rock. Collophane (cryptocrystalline fluorapatite) is the common phosphate mineral. Francolite is present in the gray and brown phosphate rock. The terms "ovules" and "ovulitic texture" are proposed for the phosphatic pellets that do not show concentric laminae and for the texture of the phosphate rock, respectively. Collophane ovules are common in shale, siltstone and limestone, and with collophane cement compose most of the phosphate rocks. Collophane ovules may be spherical, elliptical, irregularly elongated, or disklike in form and are generally structureless, but they may show concentric laminae or consist of an aggregate of smaller ovules.

Continuity of beds between trenches is based on textures, structures, sequence of beds, lithology, and tricalcium phosphate content. Many of the beds in the phosphatic shale member of the Phosphoria formation are continuous throughout the prospected parts of the area, but some appear to be local lenses. The lithology of some individual beds is remarkably constant; others change vertically and laterally. The mineral composition of some beds grades from any one to any other of the rock types. Beds may show either gradational or abrupt contacts with overlying and underlying beds.

Petrographic study indicates that the phosphate rock may be a chemical precipitate.

Three zones of phosphate rock, one high-grade zone (lower phosphatic zone) and two medium-grade zones (middle and upper phosphatic zones), are of economic interest. The chief impurities of the phosphate rocks are quartz, calcite, clay minerals, and organic matter. Beneficiation of the lower grades of phosphate rock is possible.

INTRODUCTION

LOCATION OF AREA

The Deer Creek-Wells Canyon area is in Caribou County 25 to 30 miles by road north of Montpelier and 15 miles by road northeast of Georgetown, Idaho (fig. 1). The area is in the Crow Creek

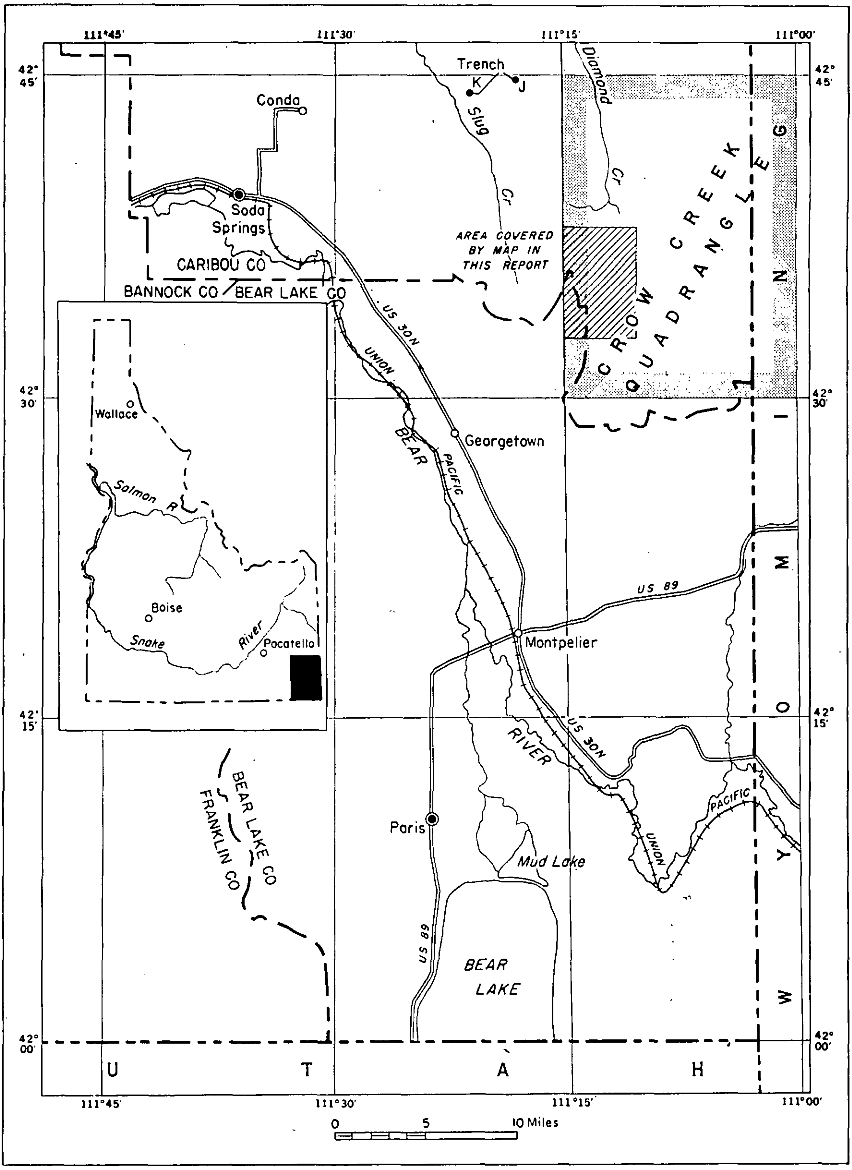

FIGURE 1.—Index map showing location of Deer Creek-Wells Canyon area, Caribou County, Idaho.

quadrangle, included in secs. 19–22 and 27–34, T. 9 S., R. 45 E., and secs. 3–10 and 15–18, T. 10 S., R. 45 E., Boise meridian. Geologic and topographic maps of the Crow Creek quadrangle have been published (Mansfield, 1927, pp. 7, 8).

PURPOSE OF THE STUDY

The Geological Survey, U. S. Department of the Interior, investigated the phosphate deposits of the Deer Creek-Wells Canyon area, southeastern Idaho, in 1944. The writer assisted Charles Deiss, geologist in charge, during part of August and September 1944. Petrologic problems that arose during the progress of the work were the mineral composition of the various rock types in the phosphatic shale member of the Phosphoria formation, lateral and vertical changes of lithology, the continuity of individual beds from one trench to another, and the effects of weathering on exposed phosphate rock beds.

The objective of this study was to obtain data that could be applied to these problems. A detailed examination was made of 702 rock specimens representing one complete and eight incomplete stratigraphic sections (pls. 2, 3) across the phosphatic shale member of the Phosphoria formation, and 100 thin sections were studied to identify minerals and determine grain sizes and mineral relationships.

ACKNOWLEDGMENTS

The Geological Survey provided the opportunity of making this study, made 100 thin sections, and gave permission to use the chemical analyses representing the channel samples taken by Charles Deiss. Analyses of phosphorus pentoxide (P_2O_5) in the samples were made in the Chemical Laboratory of the Geological Survey, in the Chemical Research Laboratory of the Tennessee Valley Authority, and in the Chemical Laboratory, Fertilizer Department, Anaconda Copper Mining Co., Conda, Idaho. Montana State University provided laboratory facilities, equipment, and stenographic help. Alan King, University of Utah, made the X-ray diffraction patterns of fluorapatite, collophane, and francolite.

GEOLOGY

STRATIGRAPHY

The Phosphoria formation (Richards and Mansfield, 1912, pp. 684–689), of Permian age, is underlain by the Wells formation (Richards and Mansfield, 1912, pp. 689–693) of Pennsylvanian age and is overlain by the Woodside shale (Mansfield, 1927, p. 86) of Triassic age. The geologic map of the Deer Creek-Wells Canyon area (pl. 1) shows the distribution of the formations within the district. The Phosphoria formation is comprised of two lithologic members, the Rex chert member and a lower unnamed phosphatic shale member. The Rex chert member ranges from 240 to 450 feet in thickness (Mansfield, 1927, p. 78) and forms prominent outcrops and ledges.

The phosphatic shale member overlain by the Rex chert member of the Phosphoria formation ranges from 179 feet (trench I, pls. 2, 3) to 200 feet in thickness, weathers more readily than the Rex chert member, and generally does not crop out at the surface. All the valuable phosphate rock in the area is in the phosphatic shale member, which is the part of the Phosphoria formation discussed in this paper. The phosphatic shale member consists of interbedded black, brown, and gray shales and siltstones, brownish-gray to gray-black, impure limestones, and gray and black phosphate rock. Many beds are intermediate in mineral composition between these types, which commonly intergrade.

STRUCTURE

The rocks in the area have been deformed into three major folds trending slightly northeast (pl. 1). The east and west folds, known as the Webster syncline and the Georgetown syncline, are separated by the Snowdrift anticline (Mansfield, 1927, pp. 139, 141–142). Secondary folds and local thrust and normal faults are present on the limbs of the major folds (pl. 1).

The Georgetown syncline, the most complex of the major folds, is a synclinorium overturned to the east. The east limb is characterized by broken minor folds and the west limb by closed folds overturned to the east. Both limbs are broken by minor faults. The overturned westward dip of the west limb varies from 35° to 86°. The east limb dips 39° to 88° west (pl. 1, structure sections *A–A′*, *B–B′*). The limestone of the Thaynes group (Triassic), the youngest unit in the district, crops out along the axis of this fold (Mansfield, 1927, p. 87).

The Webster syncline is much less deformed than the Georgetown syncline. The west limb of the Webster syncline dips 55° to 88°, and the east limb dips 6° to 30°. Both limbs are broken by small faults. The Phosphoria formation in the trough of the syncline is nearly truncated by erosion in Deer Creek valley and Wells Canyon (pl. 1).

The steeply dipping limbs of the deeply eroded Snowdrift anticline form the east limb of the Georgetown and the west limb of the Webster synclines. The Mississippian Brazer limestone (Mansfield, 1927, p. 63) crops out along the axis of the Snowdrift anticline and is the oldest formation in the district.

PHOSPHATIC SHALE MEMBER OF PHOSPHORIA FORMATION

TERMINOLOGY

The following definitions of rock terms are used in this report.

Shale: A rock composed dominantly of detrital mineral grains ranging from 1/256 to 1/16 mm in diameter and having fissility parallel to the bedding.

Siltstone: A rock composed dominantly of detrital mineral grains ranging from 1/256 to 1/6 mm in diameter and lacking fissility parallel to the bedding.

Limestone: A rock containing 30 percent or more calcite.

Phosphate rock: A rock composed of 13.8 percent or more P_2O_5. Other single minerals, or constituents, generally make up less than 30 percent of the total composition. Following the practice of Gardner (1944, pp. 12–13), phosphate rock is divided into three types: high-grade rock that contains 32 percent or more P_2O_5 or 70 percent or more phosphate of lime (B. P. L.); medium-grade rock that contains 23 to 32 percent P_2O_5 or 50 to 70 percent B. P. L.; and low-grade rock that contains 13.8 to 23 percent P_2O_5 or 30 to 50 percent B. P. L.

Collophane: "Collophane" will be used as a varietal designation for the submicrocrystalline fluorapatite (McConnell, 1942, p. 656; Frondel, 1943, p. 220) which is the dominant constituent of the phosphate rocks of the Deer Creek-Wells Canyon area.

Francolite: "Francolite" will be used for the microcrystalline variety of fluorapatite which is commonly associated with collophone in this rock (McConnell, 1942, p. 256).

Ovule: "Ovules" refers to the phosphatic pellets that lack concentric structure.

Ovulitic texture: "Ovulitic texture" refers to the texture of those rocks composed of phosphatic ovules.

Oolite: "Oolite" refers to those ovules that have concentric banding, radial structure, or both.

METHODS OF EXAMINATION

SAMPLING

The phosphatic shale member of the Phosphoria formation was sampled in nine trenches (pl. 1) by Deiss (1949, pp. 66–76), who examined and described the exposed stratigraphic sections and subdivided each section into lithologic units (pls. 2, 3). Some units necessarily included two or more kinds of rock. In trench I the phosphatic shale member was divided into 74 lithologic units, 57 of which were chemically analyzed (table 1). Lithologic units measured in trenches A to H represent only parts of the phosphatic shale member. Hand specimens representing each lithologic unit and variation within the unit were collected by the writer. The orientation of each specimen was marked and the position of the specimen was recorded by measurement from the base or top of the stratigraphic unit. The stratigraphic sections for trenches A to I (pls. 2, 3) represent the combined data from Deiss' field notes and the results of the laboratory examination of the specimens.

TABLE 1.—*Analyses of samples from trench I*

[Units numbered from top to bottom of stratigraphic section]

Unit no.	Rock name and description	Thickness		P_2O_5	B. P. L.	Fe_2O_3	Al_2O_3	CaO	V_2O_5	F_2	Acid insoluble	Moisture 105° C.	Ignition loss
		Ft.	*In.*										
74	Phosphate rock, dark gray, hard, ovulitic, fossiliferous. Collophane, francolite, calcite, quartz, organic matter		4	24.1	52.5	0.7	1.8	41.4	0.01	2.51	14.9	1.0	12.3
73	Shale,[1] brown-gray, platy, fissile. Quartz, calcite, muscovite, clay	3	7	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
72	Siltstone and shale,[1] brown-gray, thin- and thick-bedded. Quartz, calcite, muscovite, clay	4	9	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
71	Shale and limestone,[1] brown-gray, dark gray, thin-bedded, interbedded hard limestone and shale. Quartz, calcite, muscovite, collophane	6	8	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
70	Limestone,[1] dark gray, thick-bedded, hard, finely crystalline. Calcite, clay, quartz	2	4	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
69	Siltstone and shale,[1] brown-gray, dark gray, thin-bedded, tough, ovulitic, fossiliferous. Quartz, calcite, collophane, clay, muscovite, francolite	5	2	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
68	Phosphate rock, dark gray, massive, hard, ovulitic, nodular. Collophane, quartz, muscovite, organic matter, francolite		10	35.5	77.4	.4	.3	50.8	.05	3.84	4.4	.6	4.6
67	Phosphate rock, dark gray, thin- and thick-bedded, hard, ovulitic. Collophane, quartz, clay, organic matter, limonite		4	33.8	73.7	.6	1.3	47.6	.13	3.57	6.8	1.0	6.5
66	Siltstone, brown-gray, massive, hard, ovulitic. Quartz, clay, collophane, calcite, organic matter		10	9.0	19.6	2.9	5.2	11.6	.07	.84	61.8	1.1	6.4
65	Limestone,[1] brown-gray, massive, hard, finely crystalline, fossiliferous. Calcite, quartz, clay, collophane		11	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
64	Phosphate rock, dark gray, thin-bedded, hard, calcareous, ovulitic phosphate rock, interbedded brown-gray shale. Collophane, quartz, clay, muscovite, organic matter, calcareous nodules	2	4	21.8	47.5	1.8	3.6	31.7	.05	2.22	30.5	.9	5.3
63	Phosphate rock, dark gray, thin-bedded, hard, ovulitic. Collophane, quartz, muscovite, clay, organic matter	1	8	32.0	69.8	.6	1.2	47.5	.13	3.53	6.4	1.1	7.3
62	Shale and phosphate rock, interbedded thin beds, brown-gray shale and dark gray phosphate rock. Quartz, collophane, muscovite, clay, francolite, organic matter, limonite stain	1	9	17.0	37.1	1.9	4.2	24.8	.11	1.80	40.7	1.5	8.4
61	Phosphate rock, medium and dark gray, thin-bedded, hard, ovulitic. Collophane, organic matter, quartz, clay	1	1	34.4	75.0	.6	1.0	48.7	1.16	3.63	4.7	1.0	5.9
60	Phosphate rock, dark gray, thin-bedded, fissile, hard, ovulitic. Collophane, organic matter, quartz, clay	2	0	34.3	74.8	.5	1.2	47.2	.25	3.51	4.6	1.3	8.6
59	Phosphate rock and limestone, medium gray, thin-bedded, hard, ovulitic. Collophane, calcite, organic matter, quartz, clay, secondary limestone nodules as much as 14 by 25 by 34 in	2	6	20.1	43.8	.9	2.5	38.3	.44	1.90	11.1	3.1	21.1

58	Phosphate rock, brown-black, thin-bedded, soft and hard, ovulitic. Collophane, organic matter, quartz, clay, calcite	3	6	25.4	55.4	1.0	2.4	37.0	.36	2.53	12.5	3.1	16.8
57	Shale and phosphate rock, brown-black, thin-bedded, phosphatic shale in basal half, silty phosphate rock in upper half, calcareous nodules. Collophane, organic matter, quartz, clay, calcite	3	9	18.1	39.5	1.7	3.5	27.6	.16	1.86	29.6	3.3	17.8
56	Limestone and shale, brown-gray, silty, clayey limestone, brown-black calcareous, chunky, fissile shale. Calcite, quartz, clay, organic matter, collophane	2	6	2.3	5.0	1.6	2.1	22.6	.04	.22	35.1	1.0	28.1
55	Phosphate rock and shale, brown-black, interbedded. Collophane, quartz, clay, organic matter, calcite, muscovite	1	9	16.7	36.4	2.0	3.9	25.3	.06	1.63	32.2	3.1	17.1
54	Shale and phosphate rock, interbedded, brown-gray, calcareous nodules. Quartz, clay, collophane, organic matter, *calcite, muscovite, fluorite*	4	3	13.0	28.3	2.5	3.6	19.8	.03	1.43	47.1	2.0	12.6
53	Phosphate rock, medium gray, ovulitic, nodular, hard. Collophane, quartz, muscovite, clay, organic matter		11	28.0	61.0	1.7	1.9	39.6	.01	3.10	18.7	.7	5.9
52	Siltstone, light brown-gray and gray-black, chunky, massive, spheroidally weathered. Quartz, clay, muscovite, collophane, organic matter, fluorite, francolite	1	5	6.0	13.1	2.8	2.5	10.2	.01	.80	69.8	1.1	7.7
51	Phosphate rock, brown-black, thin-bedded, hard, ovulitic; shaly partings. Collophane, quartz, clay, organic matter, muscovite, limonite stain, fluorite		6	24.2	52.8	1.2	2.5	34.2	.03	2.61	22.8	1.8	11.4
50	Shale, brown-gray and brown-black, phosphatic, ovulitic, fissile. Quartz, clay, muscovite, collophane	2	5	10.7	23.3	2.2	3.0	14.8	.02	1.12	59.5	1.5	9.0
49	Limestone,[1] brown-gray, massive, hard, finely crystalline. Calcite, quartz, clay, collophane	1	0										
48	Siltstone, brown-gray and brown-black, calcareous, phosphatic, tough. Quartz, clay, muscovite, collophane, calcite	1	4	3.2	7.0	2.1	2.9	12.6	.02	.37	59.3	1.5	17.5
47	Shale and phosphate rock and limestone, interbedded, brown-black and gray-black and thin-bedded, ovulitic. Quartz, clay, collophane, calcite, organic matter, muscovite	1	10	14.6	31.8	1.9	3.4	23.8	.04	1.59	39.9	1.9	13.8
46	Shale, brown-gray, spheroidally weathered, tough. Quartz, clay, organic matter, muscovite, collophane	2	3	2.2	4.8	2.5	3.1	4.3	.02	.29	78.7	1.7	9.7
45	Shale, brown-black, phosphatic, fissile. Quartz, clay, organic matter, muscovite, collophane	1	6	4.7	10.2	2.7	4.2	7.7	.09	.53	64.5	2.7	16.8
44	Shale and siltstone, brown-black, chunky and thin-bedded, phosphate in upper 12 in. Quartz, organic matter, muscovite, clay, collophane	2	9	2.6	5.7	2.9	4.0	4.7	.04	.24	76.3	2.0	11.9
43	Phosphate rock and shale, dark gray and brown-black, interbedded ovulitic phosphate rock and fissile shale. Collophane, quartz, organic matter, muscovite, clay, limonite stain	1	6	13.4	29.2	2.8	4.6	19.4	.07	1.29	43.8	2.5	15.2
42	Phosphate rock and shale, dark gray and gray-black, interbedded, ovulitic and nodular. Collophane, quartz, organic matter, clay, muscovite, francolite, limonite stain	1	3	22.6	49.3	2.0	2.8	32.4	.04	2.41	25.8	1.9	11.3

[1] Not analyzed.

TABLE 1.—*Analyses of samples from trench I*—Continued

[Units numbered from top to bottom of stratigraphic section]

Unit no.	Rock name and description	Thickness		P_2O_5	B. P. L.	Fe_2O_3	Al_2O_3	CaO	V_2O_5	F_2	Acid insoluble	Moisture 105° C.	Ignition loss
		Ft.	*In.*										
41	Siltstone and shale, pale brown and brown-black, thin- and thick-bedded, hard, brittle. Quartz, organic matter, muscovite, clay, calcite, collophane	7	4	2.4	5.2	3.0	2.1	9.0	0.01	0.20	66.5	1.0	13.6
40	Phosphate rock, brown-black, thick-bedded, massive, ovulitic and nodular. Collophane, quartz, clay, calcite	1	3	17.5	38.2	5.0	2.6	25.6	.01	1.90	42.9	1.2	8.6
39	Shale, brown-gray, thin-bedded, hard, brittle, phosphatic, calcareous. Quartz, clay, organic matter, muscovite, calcite		8	9.6	20.9	3.8	4.7	13.8	.02	1.00	58.2	1.9	10.9
38	Shale and phosphate rock, black, interbedded calcareous, ovulitic, fissile. Quartz, collophane, organic matter, calcite	1	5	12.6	27.5	2.5	4.8	21.0	.08	1.47	27.4	5.4	30.2
37	Limestone,[1] dark gray, weathers pale brown, hard, massive, finely crystalline. Calcite, quartz, clay		4										
36	Shale, phosphate rock, and limestone, dark gray, interbedded, fissile, phosphatic shale and thin-bedded, hard, finely crystalline limestone. 6-in. bed, black, ovulitic phosphate rock. Quartz, muscovite, clay, calcite, collophane, organic matter	3	4	9.6	20.9	2.4	3.8	21.5	.03	1.10	39.7	3.3	22.2
35	Shale, brown-black, thin-bedded, phosphatic, calcareous, ovulitic; limestone nodules present. Quartz, clay, muscovite, calcite, collophane, organic matter	2	1	7.9	17.2	2.4	4.1	26.5	.04	.84	30.4	3.1	28.5
34	Shale and limestone, brown-black, fissile, ovulitic, calcareous, phosphatic shale and interbedded, dark gray limestone nodules. Quartz, calcite, collophane, clay, muscovite, organic matter	3	8	9.4	20.5	2.4	4.2	25.1	.02	.96	35.6	2.6	21.6
33	Siltstone and limestone,[1] basal 8 in. dark brown, massive, calcareous silt-stone grades into brown-gray, massive, hard, finely crystalline fossiliferous limestone. Calcite, quartz, clay, organic matter, muscovite	3	0										
32	Shale, brown-gray, calcareous, phosphatic, thin-bedded, fossiliferous. Quartz, clay, calcite, organic matter, collophane	1	10	2.0	4.4	3.1	5.1	9.6	.02	.20	65.1	1.9	15.6
31	Shale, brown-black, ovulitic, calcareous, phosphatic, fossiliferous. Quartz, clay, organic matter, collophane, calcite, muscovite	2	1	9.2	20.1	2.9	6.2	14.6	.02	1.04	53.3	2.6	31.5
30	Limestone,[1] dark gray, weathers gray-brown, hard, massive, fossiliferous, finely crystalline, collophane, limestone. Calcite, collophane, clay, quartz	2	3										
29	Shale, dark gray, hard, fissile. Quartz, clay, muscovite, collophane	1	3	2.0	4.4	3.8	6.2	3.9	.02	.24	76.5	1.3	10.2
28	Limestone, brown-gray, hard, massive, fossiliferous. Calcite, clay, organic matter	4	4	.3	.7	.5	.4	28.8	.01	04	17.2	.4	39.3

27	Shale and siltstone, brown-gray and brown-black, calcareous, phosphatic, spheroidally weathered. Quartz, clay, muscovite, organic matter, collophane, calcite	4	3	2.5	5.4	3.1	4.4	5.3	.05	.37	74.0	1.9	12.3
26	Limestone,[1] dark gray, massive, hard, finely crystalline. Calcite, clay		6	------	------	------	------	------	------	------	------	------	------
25	Shale and siltstone, interbedded, brown-black, fissile shale and massive siltstone. Quartz, clay, muscovite, organic matter, collophane	5	3	2.4	5.2	3.2	3.5	5.5	.02	.20	74.0	1.6	11.9
24	Shale and limestone, interbedded, thin-bedded brown-black fissile shale and dark gray, hard limestone. Quartz, calcite, clay, organic matter, collophane	4	6	7.3	15.9	2.9	5.2	15.3	.03	.67	53.7	2.3	15.7
23	Limestone,[1] dark gray, hard, massive, fossiliferous, finely crystalline. Calcite, clay, collophane	1	2	------	------	------	------	------	------	------	------	------	------
22	Shale and limestone, interbedded, thin-bedded, dark gray, fissile, ovulitic, phosphatic, calcareous shale and dark gray limestone. Quartz, clay, organic matter, collophane, calcite, muscovite	3	5	13.6	29.6	1.9	4.5	27.6	.02	1.49	29.2	3.2	21.3
21	Limestone,[1] dark gray, hard, massive, finely crystalline. Calcite, collophane, clay	1	2	------	------	------	------	------	------	------	------	------	------
20	Shale and limestone, interbedded, brown-black fissile, ovulitic, nodular, calcareous, phosphatic shale and dark gray limestone. Quartz, organic matter, collophane, clay, calcite	4	4	12.0	26.2	2.3	4.3	23.2	.03	1.31	37.9	2.8	19.2
19	Limestone,[1] dark gray, massive, hard, finely crystalline. Calcite, clay	1	2	------	------	------	------	------	------	------	------	------	------
18	Shale, brown-black, fissile, ovulitic, calcareous, phosphatic. Quartz, collophane, organic matter, calcite, clay	2	5	10.2	22.2	2.9	6.1	17.8	.02	1.18	47.0	3.0	16.8
17	Phosphate rock, dark gray, chunky, massive, ovulitic, nodular. Calcite nodules in upper 5 in. Collophane, quartz, calcite, organic matter	1	3	20.4	44.5	1.4	3.4	34.6	.02	2.08	22.2	2.0	15.6
16	Phosphate rock, black, fissile, crumbly, massive, ovulitic. Collophane, organic matter, quartz, calcite	1	6	23.3	50.8	1.2	3.8	34.8	.03	2.33	14.5	3.3	19.4
15	Phosphate rock, brown-black, hard, massive, fissile, ovulitic, silty, calcareous. Collophane, organic matter, quartz, calcite, clay	2	10	23.9	52.1	1.4	3.1	35.8	.03	2.84	17.0	2.9	16.7
14	Phosphate rock, black, massive and fissile, ovulitic, silty. Collophane, quartz, organic matter, clay, calcite, fluorite	1	11	23.9	52.1	1.5	3.1	34.6	1.13	2.57	17.6	2.9	16.0
13	Limestone, brown-black, thin-bedded, hard, spheroid, weathered, phosphatic. Calcite, organic matter, collophane, quartz, clay	3	1	5.1	11.1	1.0	1.4	27.8	.01	.61	20.9	1.0	32.2
12	Shale, brown-black, fissile, ovulitic, calcareous, phosphatic. Quartz, collophane, organic matter, calcite, clay, muscovite	2	9	9.2	20.1	2.0	4.5	18.0	.03	.98	45.8	2.1	16.9
11	Limestone,[1] brown-gray, massive, hard, ovulitic, dolomite, finely crystalline. Calcite, clay, quartz, dolomite, collophane	2	6	------	------	------	------	------	------	------	------	------	------

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[1] Not analyzed.

TABLE 1.—*Analyses of samples from trench I*—Continued

[Units numbered from top to bottom of stratigraphic section]

Unit no.	Rock name and description	Thickness		P_2O_5	B. P. L.	Fe_2O_3	Al_2O_3	CaO	V_2O_5	F_2	Acid insoluble	Moisture 105° C.	Ignition loss
		Ft.	*In.*										
10	Phosphate rock, black, thin-bedded, hard, ovulitic, silty, calcareous. Collophane, quartz, calcite, organic matter, clay	2	8	25.2	54.9	0.9	2.2	36.3	0.41	2.43	18.4	2.2	14.5
9	Phosphate rock and shale, basal 14 in. brown-black, fissile, ovulitic, phosphatic shale, upper 28 in. black, platy and fissile, ovulitic phosphate rock. Collophane, quartz, organic matter, clay, calcite	3	6	18.7	40.8	1.6	3.3	26.8	.49	1.69	34.9	2.0	12.0
8	Phosphate rock and shale, basal 13 in. brown-black fissile, ovulitic, phosphatic shale, upper 78 in. black, platy, massive, hard, ovulitic, calcareous, phosphate rock. Collophane, quartz, organic matter, clay, calcite, francolite	7	7	25.4	55.4	1.0	2.4	37.5	.24	2.51	17.6	2.0	12.4
7	Limestone, shale, and phosphate rock,[1] dark gray, hard, massive, limestone and interbedded shale and phosphate rock. Calcite, quartz, clay, organic matter, muscovite, collophane	2	11										
6	Phosphate rock, brown-gray-brown-black, thin- and thick-bedded, ovulitic, nodular, silty, calcareous. Collophane, quartz, organic matter, clay, calcite, francolite	3	0	21.9	47.7	1.0	3.3	33.9	.07	2.39	24.6	1.9	11.7
5	Limestone,[1] dark gray, hard, massive, ovulitic, fossiliferous, phosphatic. Calcite, collophane, quartz, organic matter, clay	1	7										
4	Phosphate rock, black, thin-bedded, hard, ovulitic, Collophane, organic matter, quartz, calcite, clay, francolite		10	28.0	61.0	.5	1.9	44.2	.14	3.24	8.1	1.3	10.9
3	Phosphate rock, black, thin-bedded, hard, ovulitic. Collophane, organic matter, calcite, quartz, clay, limonite stain	3	3	32.1	70.0	.5	1.1	46.4	.23	3.18	4.1	1.3	11.3
2	Phosphate rock, black, thin- and thick-bedded, hard, massive, ovulitic. Collophane, calcite, organic matter, quartz, clay	1	6	33.0	71.9	.6	.7	47.4	.22	3.28	3.9	1.1	8.9
1	Phosphate rock, gray-brown, thin-bedded, ovulitic. Collophane, quartz, clay, organic matter, muscovite. Wells formation		7	2.9	6.3	3.4	6.6	4.6	.51	.24	71.8	2.7	11.3

[1] Not analyzed.

CHEMICAL ANALYSES

The content of phosphorus pentoxide (P_2O_5) was determined for each of the 187 samples collected from the Phosphoria formation. The percentage of tricalcium phosphate ($Ca_3(PO_4)_2$) in the 187 channel samples is given in plates 2 and 3. The samples for which complete analyses are given were analyzed in the Chemical Research Laboratory of the Tennessee Valley Authority. The analyses of P_2O_5 in the samples from trenches A to D, G, and H were made by S. H. Cress, J. G. Fairchild, or M. K. Carron in the Chemical Laboratory of the Geological Survey in Washington, D. C. Complete analyses were made for all samples taken from trench I (table 1). The B. P. L. (bone phosphate of lime) content, or $Ca_3(PO_4)_2$, was computed for each sample by multiplying the percentage of P_2O_5 by 2.18 (Gardner, 1944, p. 12).

Chemical analyses for MgO content in the carbonate rocks were made by Vance Fallon and William Newman, graduate students in geology, Montana State University.

The chemically analyzed samples represent stratigraphic units that range from ⅓ to 12⅓ feet in thickness. (See columnar sections, pls. 2, 3.) The analyses, therefore, furnish an excellent chemical check on the mineral composition determined by using immersion oils and the petrographic microscope.

MINERALOGY

The identified minerals of the lower phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area are collophane, francolite, quartz, calcite, muscovite, clay minerals, chalcedony, and fluorite. The optical properties of these minerals are listed in table 2. Phosphate minerals other than collophane and francolite may be present, but were not recognized. The relative abundance of each mineral varies with the rock type.

COLLOPHANE

The sedimentary phosphate rocks of the Phosphoria formation of the Western States are composed of a submicrocrystalline calcium phosphate substance known to be an impure massive variety of apatite, but generally called collophane in the literature.

Sanberger in 1870 gave the name "collophane" (Kollophan) to a layered, opallike, amorphous material collected from phosphate deposits on the island of Sombrero in the West Indies. Rogers (1922, p. 276) expressed the belief that collophane was entitled to species rank.

TABLE 2.—*Optical properties of the identified minerals*

Name	Group	Index	Relief	Color	Remarks
Calcite	Uniaxial (−)	Ne = 1.486; Nw = 1.658.	Low-high	Colorless	
Chalcedony	?	Less than canada balsam.	Low	do	Fibrous; spherulitic crosses abundant; lower relief and indices of refraction than francolite.
Collophane	Isotropic (?)	1.591 to 1.630; average 1.618.	Moderate	Colorless; light to dark brown, black.	
Fluorite	Isotropic	Less than canada balsam.	High	Colorless; pink, purple	Cleavage lines at angles of 70° and 110°.
Francolite	Uniaxial (−)	1.598 (brown grains) 1.610 (colorless grains)	Moderate	Colorless; pale brown	Wavy extinction and spherulitic crosses common.
Muscovite	Biaxial (−)	Not determined		Colorless	2 V approximately 40°; extinction parallel to cleavage traces.
Quartz	Uniaxial (+)	Ne = 1.553; Nw = 1.544.	Low	do	

Recent research work by Hendricks, Hill, and others (1931, p. 1417) and Frondel (1943, p. 220) has shown that the phosphate substance of the continental phosphate rock is crystalline and gives the X-ray diffraction pattern of apatite. Collophane ovules separated from the phosphate rock of unit 68, trench I, gave an X-ray diffraction pattern similar to that of fluorapatite (fig. 2).

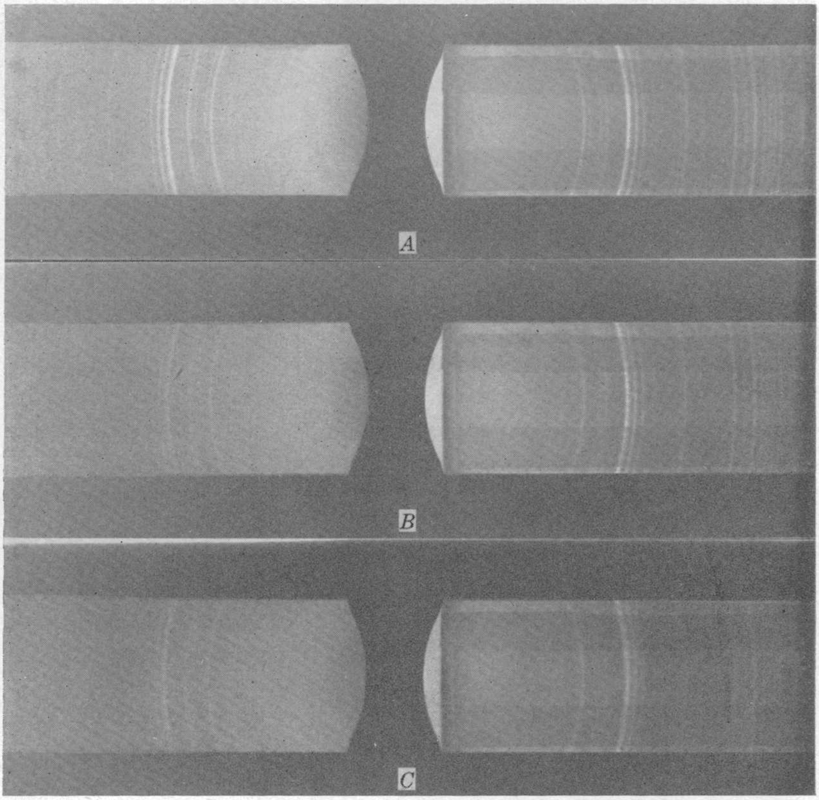

FIGURE 2.—Powder-diffraction photographs of fluorapatite, collophane and francolite.

Frondel (1943, p. 220) considers collophane to consist of a submicroscopic aggregate of crystallites of apatite and believes that it is structurally identical with apatite. The structural formula of $Ca_{10}F_2(PO_4)_6$ is given by Hendricks, Hill, and others (1931, p. 1417) and McConnell (1938, p. 17). The latter indicates, also, that some of the excess fluorine substitutes for oxygen. Frondel (1943, p. 220) states that essential (OH) together with absorbed and capillary water are present in collophane. The chemical formula may be variable and uncertain. An approximate formula of $10CaO.3P_2O_5.CaF_2.CO_2.H_2O$

for collophane is used by the U. S. Geological Survey in the Western phosphate project.

A chemical analysis was not obtained for the collophane of the phosphatic rocks of the Deer Creek-Wells Canyon area. The chemical analyses given in table 1 are for bulk samples of rock units.

The identification of collophane, examined in thin sections and immersion oils, is based upon the following data: colorless, light to dark brown, and black; isotropic; moderate relief; index of refraction ranges from 1.591 to 1.630, with most readings approximately 1.618.

The color shades of the collophane in thin sections correlate closely with those of the hand specimen. Thin sections of black phosphate rock are nearly opaque owing to the dark-brown or black collophane. Thin sections of light-colored phosphate rock show gradational boundaries between colorless, light- and dark-brown, and black collophane areas.

Microscopic aggregate structure is present in the colorless and light-brown collophane (figs. 3, 4, and 6). The isotropic character is shown in figure 5. Some thin sections of light-gray phosphate rock in which colorless collophane is present, show a microscopic aggregate of isotropic collophane and anisotropic francolite.

FRANCOLITE

"Francolite" was selected as the name of a mineral occurring in microscopic, anisotropic grains in the phosphatic rocks under discussion because of its optical properties, its association with collophane, and the presence of fluorine as shown in the chemical analyses of the rocks.

The name "francolite" was given to small crystalline stalactitic and minute curving crystals from the Wheal Franco mine, Travistock, Devonshire, England, by H. J. Brooke prior to 1850.

Lacroix (1910), on the basis of published reports, considered francolite and staffolite to be identical. Several workers since have shown these two minerals to be identical. Sandell, Hey, and McConnell (1939, pp. 396–401) analyzed a specimen from Wheal Franco and found it to be francolite. Francolite gives the X-ray diffraction pattern of apatite (Frondel, 1943, p. 220). A white mineral, enclosed in a phosphate-rock specimen from the Montpelier area, Idaho, identified as francolite by using immersion oils, gives an X-ray diffraction pattern similar to apatite (fig. 2). The d/n values of francolite and fluorapatite, obtained by X-ray analysis, are listed below. Additional lines present on the francolite X-ray film were not calculated.

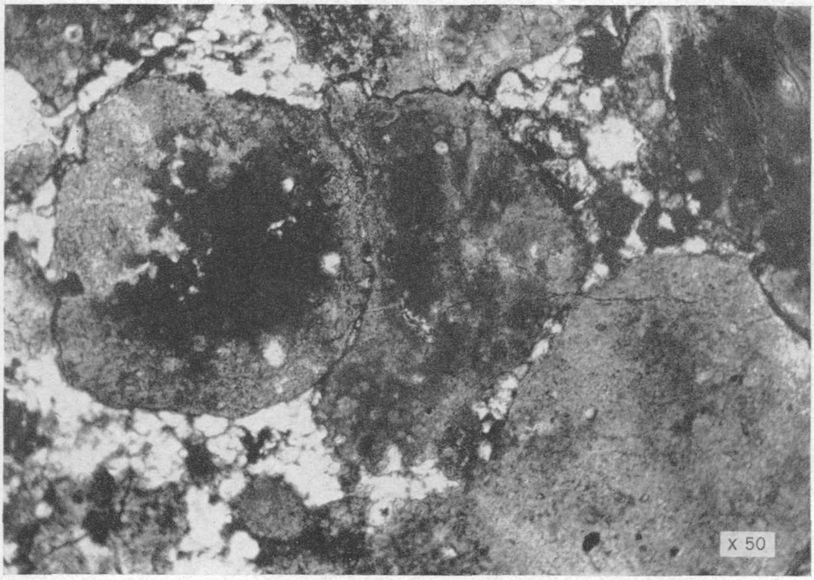

FIGURE 3.—Gray phosphate rock. Shows adjustment of collophane ovules embedded in collophane cement and quartz grains (white). Bleaching of collophane has advanced inward from peripheries. Bleached areas show granulose texture and consist of aggregates of submicroscopic grains of collophane and francolite. Transmitted light.

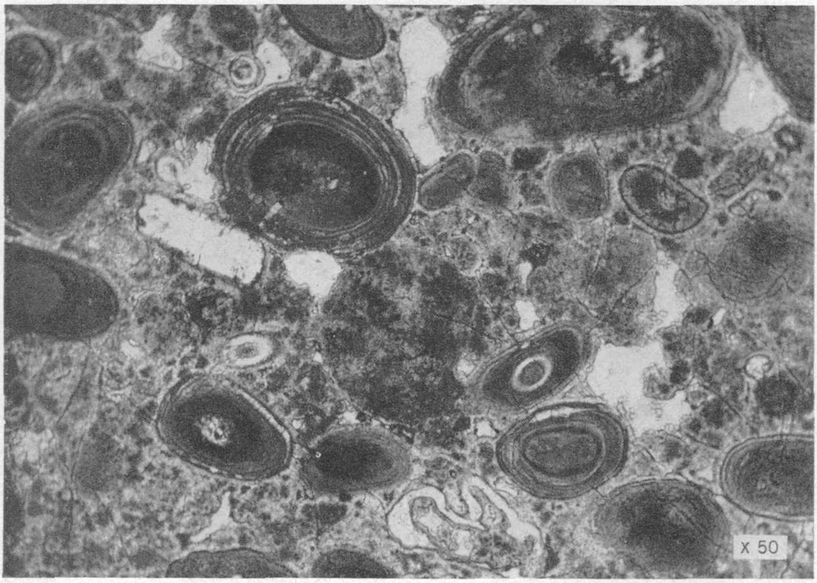

FIGURE 4.—Gray phosphate rock. Oolites and ovules embedded in phosphate matrix. Oolites consist of collophane and francolite layers. Quartz grains (white) are enclosed by ovules, oolites and matrix. Ribbon-like form (bottom center) is composed of chalcedony. Matrix consists of an aggregate of submicroscopic collophane and francolite grains. Bleaching is more pronounced in matrix than in ovules and oolites. Collophane ovule (bottom right) is partly replaced by collophane-francolite aggregate. Transmitted light.

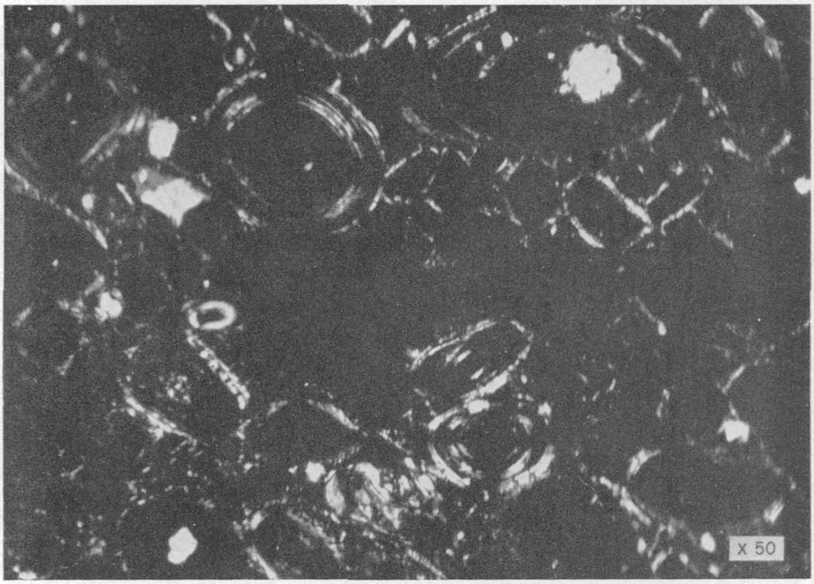

FIGURE 5.—Same gray phosphate rock as shown in figure 4; crossed nicols. Francolite layers in oolites are anisotropic. Oolites show spherulitic crosses.

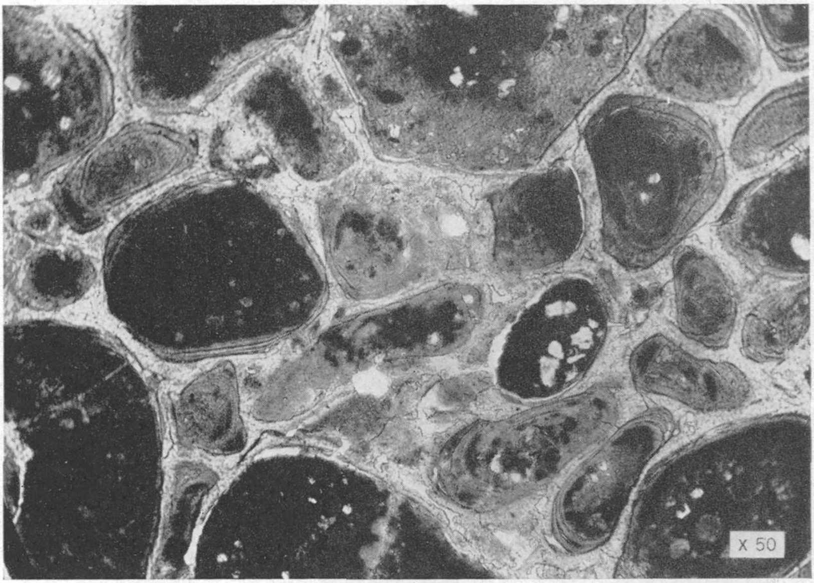

FIGURE 6.—Gray phosphate rock. Bleaching has occurred in matrix, and at peripheries and along fractures in collophane ovules and oolites and is more pronounced in matrix than in ovules and oolites. Matrix consists of submicroscopic collophane and francolite grains. Quartz grains (white) enclosed by ovules. Oolite in upper right has francolite band that passes through residual dark area. Thin black lines in oolites may be organic matter. Transmitted light.

d/n values for francolite and fluorapatite obtained by X-ray analysis

[Interpretation supplied by Alan King]

Francolite from film	*Fluorapatite from ASTM index, of X-ray diffraction pattern*
3.44	3.44
2.79	2.78
2.69	2.69
2.62	2.61
2.24	2.64
1.93	1.93
1.88	1.87
1.84	1.83

Francolite is a variety of the fluorapatite series (Ford, 1932, p. 704; Larsen and Berman, 1934, p. 228). The latter gives the chemical formula as $10CaO.3\,P_2O_5.CaF_2.CO_2.H_2O$. McConnell (1938, p. 9) believes francolite to be a suitable name for an apatite containing an appreciable amount of CO_2 and more than 1 percent fluorine; OH-ions may or may not be present, depending upon the various amounts of other ions. McConnell believes, also, that francolite should include both a carbonate-fluorapatite and a carbonate-hydroxy-fluorapatite (where F=1 percent). He gives the structural composition as $(Ca_3F)_2\ (P,C)_6\ (O,OH,F)_{24}\ (Ca,C)_4$.

Attempts to separate sufficient francolite from the host rocks collected in the Deer Creek-Wells Canyon area for a chemical analysis were not successful.

The optical properties of the francolite grains are colorless and slightly brownish; moderate relief; uniaxial negative; wavy extinction in the larger grains; spherulitic crosses common.

Similar grains, present in a phosphate rock specimen collected in the Montpelier area, Idaho, by V. E. McKelvey, were large enough to examine in immersion oil. Most of the grains are slightly brownish, uniaxial negative, and have an index of refraction of approximately 1.598. Colorless grains have indices as high as 1.610. These values for the index of refraction are lower than that (1.625) given by Larsen and Berman (1934) or those (W–1.629, e-1.624, both ±0.002) given by Sandell, Hey, and McConnell (1939, p. 397).

DOLOMITE

Dolomite was not identified in thin sections or in grains studied in immersion oils. All of the carbonate rock specimens were analyzed chemically for MgO. Most of the limestones show a trace and some as much as 10 percent MgO.

CHALCEDONY

Chalcedony grains were not successfully isolated for determination of indices of refraction. Most of the grains in the thin sections show spherulitic structure and spherulitic crosses are prominent. Chalcedony in spherulites is similar to fibrous francolite and was distinguished from francolite by its low relief and index of refraction.

MUSCOVITE

Muscovite flakes were not successfully isolated for the determination of the indices of refraction.

FLUORITE

Fluorite was observed in four thin sections of phosphate rock. Grains were not successfully isolated for determination of the index of refraction.

CLAY MINERALS

The clay minerals were not identified. They occur as microscopic, colorless, and light-brown flakes and aggregates disseminated through the matrix of all the rock types. Flakes have low birefringence.

LIMONITE

Limonite, as yellow and brown stains, is present but not common in the phosphate rock, shale, and siltstone beds.

PARAGENESIS

The occurrences, relationships, and structures of the identified minerals in the phosphatic shale member of the Phosphoria formation are described in this section. The primary minerals include detrital quartz, muscovite, and clay minerals as well as the chemically precipitated collophane and calcite. The observed relationships of the above minerals indicate contemporaneous deposition during the period of sedimentation. Some of the secondary minerals may represent diagenetic changes during lithification; some, however, were deposited at a later period.

COLLOPHANE

Collophane is a primary mineral occurring as ovules, oolites, and cement in the phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area. As ovules, oolites, and cement it is the dominant constituent of the phosphate rocks, which, generally, contain minor amounts of detrital quartz, muscovite, and clay minerals. As ovules and oolites, it is disseminated in the matrix or concentrated in discontinuous lenses, or both, in the shales, siltstones and limestones. Collophane (?) veinlets and cavity fillings are present in some limestones.

The relationships of collophane to calcite, detrital quartz, muscovite, and clay minerals show that these minerals were deposited simultaneously in a marine environment. Collophane ovules, oolites and cement of the phosphate rocks enclose quartz grains (fig. 6) and muscovite flakes. Collophane oolites may have quartz grain nuclei (fig. 7). Collophane cement encloses flaky clay minerals. The same relationships of collophane to the detrital minerals are present in phosphatic shales and siltstones.

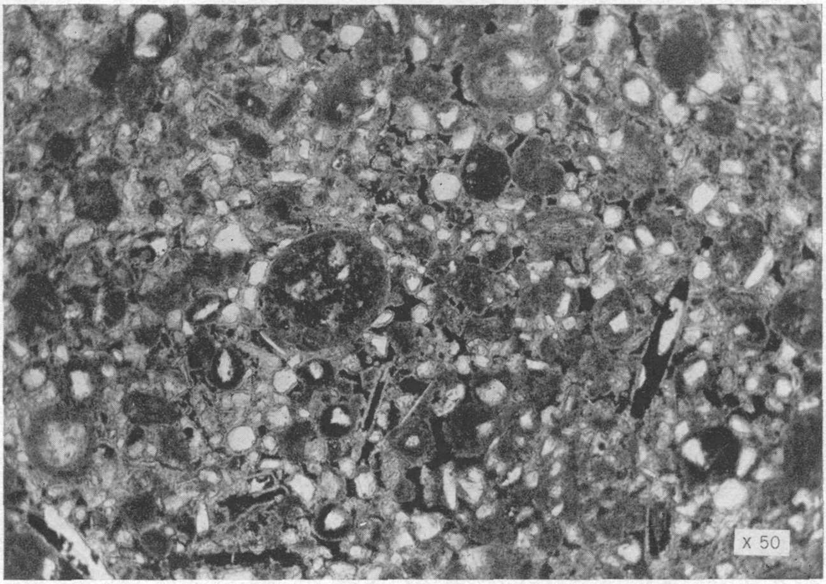

FIGURE 7.—Section of part of phosphatic nodule, 60 mm in diameter. Consists of an aggregate of collophane ovules, oolites and fossil fragments. Many of the oolites have quartz grain nuclei (white). Dense black areas may be organic matter. Transmitted light.

The collophane ovules disseminated in the matrix of the limestone beds and the thin discontinuous lenses of ovules enclosed by limestone are evidence of contemporaneous deposition. Evidence was not found to indicate that the collophane ovules were secondary replacement features in the limestone beds.

The collophane in the limestone beds appears to be less stable than it is in the phosphate rock or phosphatic shales. Collophane ovules in the latter beds show little evidence of replacement that is accompanied by removal of the collophane.

FRANCOLITE

Francolite is common in thin sections of light-colored phosphate rocks. Only a few occurrences were observed in thin sections of dark-colored phosphate rock.

Francolite occurs as alternating concentric laminae with collophane in oolites, as crusts or layers on collophane, as isolated grains, as an aggregate mixture of submicroscopic collophane and francolite grains, in shell fragments, and as microscopic veinlets cutting collophane.

The most striking occurrence of francolite is as concentric fibrous laminae in oolites, where it may form remarkably uniform concentric layers (figs. 4, 5). All stages of development ranging through the formation of microscopic grains in an incomplete concentric band, to a complete band or to several alternating francolite and collophane bands are present in oolites in the thin sections. Dietz, and others (1942, p. 818) describe francolite laminae in oolites of Tertiary phosphorites dredged from the California coastal area.

Concentric francolite bands in oolites generally show spherulitic interference figures (fig. 5).

Some well-outlined oolites were observed in which a lacy network of francolite had developed as crustified layers on collophane in which residual black collophane remains within the central area (fig. 8).

A few isolated francolite grains of odd shapes were observed (fig. 9). These grains show wavy extinction parallel to the outlines of the grains. They may represent an initial stage in the development of spherulites (Morse and Donnay, 1936, p. 396).

The common development of francolite is in the aggregates of submicroscopic collophane and francolite. This aggregate structure is best developed in collophane cement, but often transgresses ovule and oolite boundaries and also, develops along fractures within ovules (figs. 4, 6).

The francolite in shell fragments may be primary or secondary. Direct evidence of francolite replacement of calcite in shell fragments was not observed. Most of the shell fragments observed in the thin sections are composed of calcite; however, some of the fossils originally may have had phosphatic shells.

Francolite in the phosphatic shale member of the Phosphoria formation in this area is interpreted, in most of its occurrences, as a secondary mineral which has developed by crystallization of the submicrocrystalline collophane. Dietz (1942, p. 818) reached the same conclusion for the francolite in the phosphorites dredged from the ocean bottom off southern California. The secondary origin is based upon the frequent occurrence of francolite in the light-colored

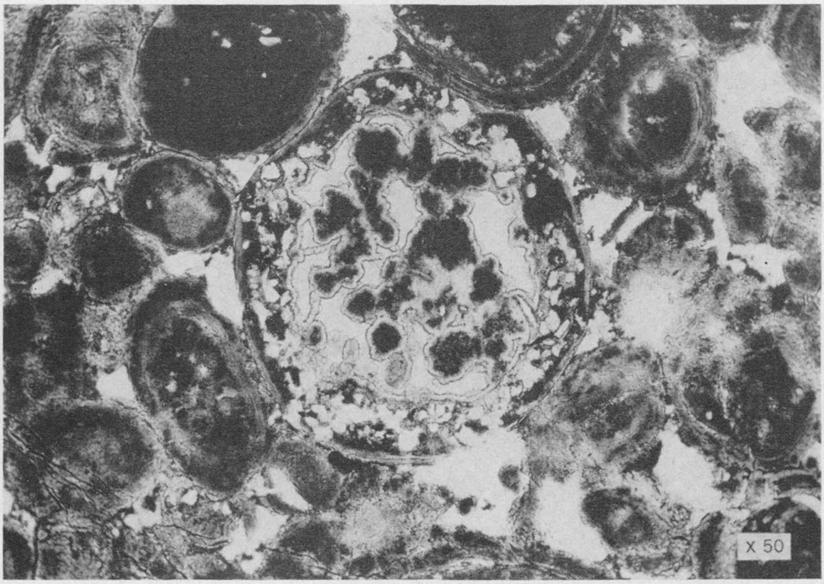

FIGURE 8.—Gray oolitic phosphate rock. Oolitic structure resulting from bleaching of collophane. Light colored layers consist of mixture of collophane and francolite. Large oolite (center) shows irregular development of francolite as crusts (gray layers) on collophane (black). Quartz grains (white) enclosed in outer rim of collophane. Large irregular white areas (holes). Transmitted light.

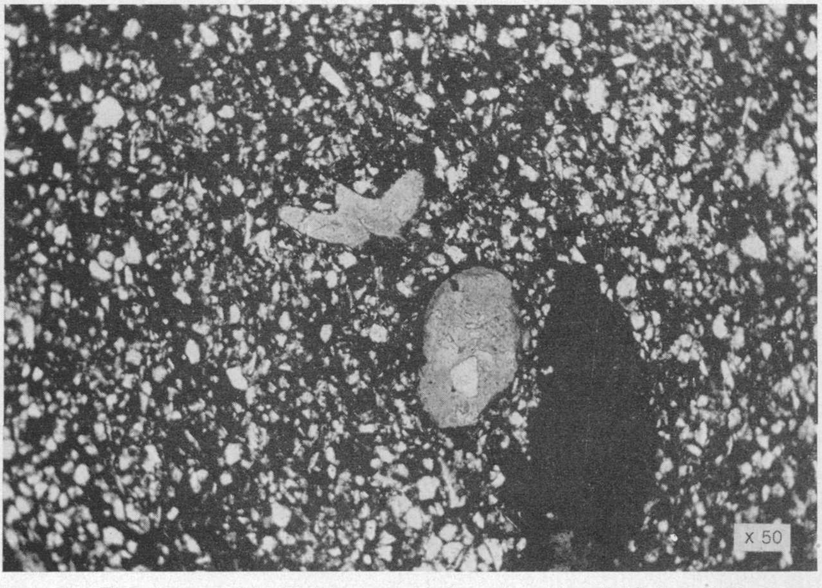

FIGURE 9.—Phosphatic shale. Matrix consists of quartz grains (white), collophane, and organic matter (black). Collophane ovule (center) enclosing quartz grain. Irregular form (center) is an uncommon type of francolite development, possibly an initial stage in growth of a spherulite. Transmitted light.

phosphatic rock specimens where it is best developed in the well-bleached areas as: (1) an aggregate of microscopic grains of collophane and francolite and the transgression of the aggregates from cement into ovules and oolite boundaries, (2) crusts surrounding residual collophane areas, (3) incomplete concentric rings in collophane oolites, and (4) its nearly complete absence in the dark-colored phosphate rocks.

QUARTZ

Quartz, as angular grains, is the dominant mineral in the shale, siltstone, and phosphatic shale and siltstone of the Phosphoria formation (fig. 10). It may be nearly as abundant as the collophane in the low-grade phosphate rocks, and it is the most abundant of the accessory minerals in most medium- and high-grade phosphate rocks.

Quartz grains are scattered irregularly through the collophane matrix (fig. 3) and in many of the ovules and oolites (figs. 6, 7) of the phosphate rocks. The matrix of some phosphate rock may include as much quartz as collophane (fig. 3).

The quartz grains are angular to subrounded and are mostly silt size, $\frac{1}{16}$ to $\frac{1}{256}$ mm, (fig. 10). Generally less than 5 percent of the quartz grains are $\frac{1}{16}$ to $\frac{1}{8}$ mm in diameter. The quartz grains are colorless when not coated with carbonaceous matter or collophane.

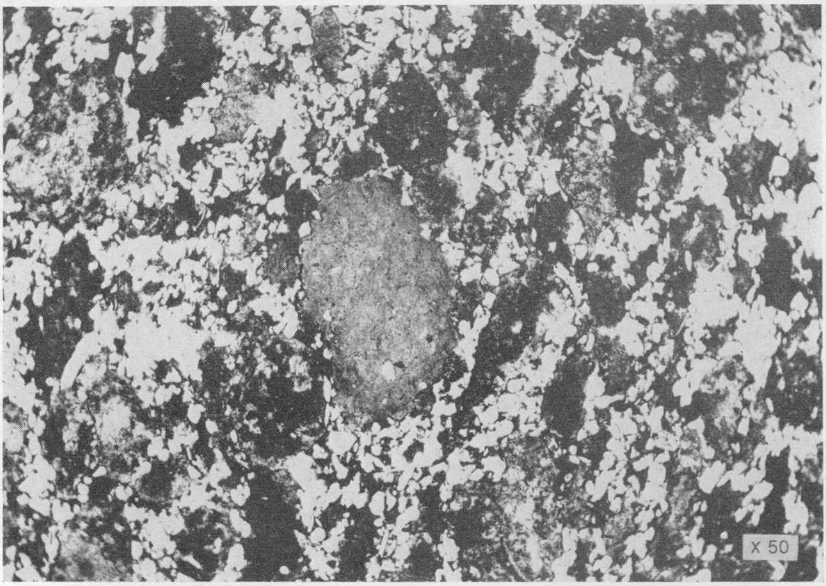

FIGURE 10.—Phosphatic shale. Irregular collophane ovules (black) enclosed by quartz grains (white). Larger collophane ovule (center) with enclosed and partly enclosed quartz grains. Transmitted light.

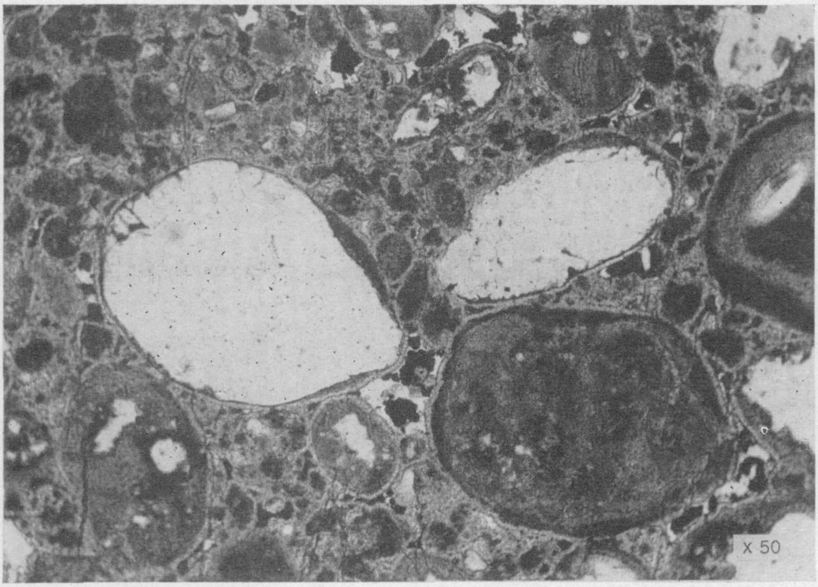

FIGURE 11.—Gray phosphate rock. Collophane shows differential bleaching. Francolite crusts (gray rims) surround collophane ovules. Secondary quartz (large white areas) has replaced central areas of collophane ovules. Transmitted light.

In the thin sections studied only three occurrences of secondary quartz were recognized. In the phosphate rock bed of unit 69, trench I, subhedral quartz grains exhibiting growth zones are associated with francolite and dense black bitumin (?) in the centers of altered collophane oolites. A phosphatic limestone nodule at the base of unit 11, trench H, contains collophane oolites having nuclei of quartz grains, some of which show growth rims that have developed euhedral outlines. Secondary quartz was observed as replacement centers in oolites (fig. 11). Quartz veinlets cut the phosphate rock of unit 11, trench E.

Francolite-secondary quartz relationships are not sufficiently conclusive to determine their relative ages. Generally quartz fills cavities in and between ovules that are lined with francolite crusts. Part of the secondary quartz, at least, appears to be later than some francolite.

CALCITE

Calcite is both a primary and a secondary mineral in the phosphatic shale member of the Phosphoria formation in this area. It is the dominant mineral in the limestone beds. It is probably a primary and a secondary mineral in some shales, siltstones, and phosphate rocks. Limestone beds in trench I are ½ to 5 feet thick, and some beds appear to be continuous for at least 2 miles or more. In these beds the calcite undoubtedly is a primary precipitate.

The calcite is very fine grained, ranging from 0.015 to 0.06 mm in diameter (fig. 12). The calcite of veinlets and some recrystallized calcite in the matrix of the rocks occur in grains as much as 1 mm in long diameter (fig. 13). Recrystallized calcite is abundant in the "Cap lime" (unit 5, trench I). Calcite veinlets, approximately 1 mm in width, occur in most of the rocks.

Calcite replacement of collophane ovules is common in the phosphatic limestone beds (fig. 12), where many collophane ovules have been at least partly replaced by calcite. Nearly complete replacement of the collophane has taken place in some beds where thin black rims or stained patches of angular calcite grains indicate the former presence of collophane ovules (fig. 14). The collophane has been more or less completely removed from some of these limestone beds. In other beds the collophane is concentrated as irregular fillings between recrystallized calcite grains or as thin veinlets in fractures in the limestone.

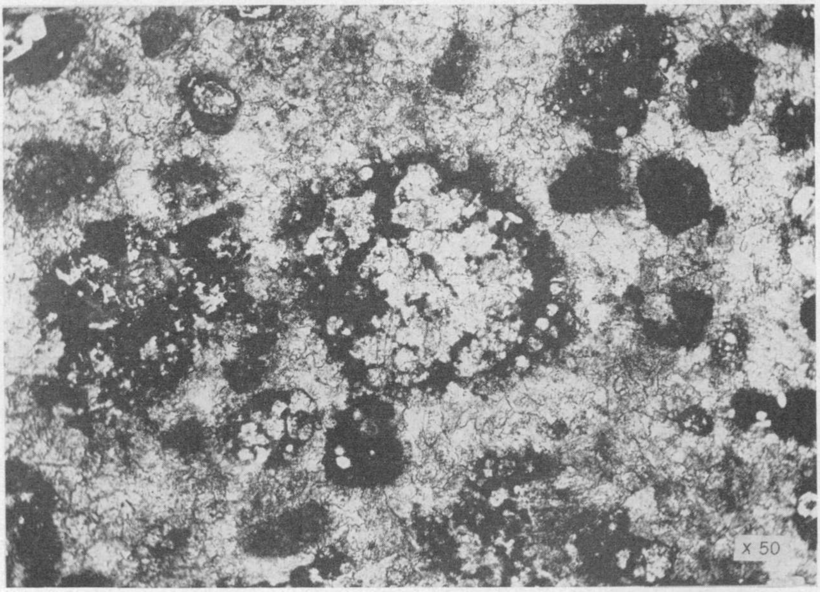

FIGURE 12.—Phosphatic limestone. Collophane ovules (black) enclosed by crystalline calcite matrix (white). Calcite has replaced central area of collophane ovules (center). Some ovules are almost completely replaced. Transmitted light.

Slight etching of detrital quartz grains by calcite has occurred in some silty limestone beds.

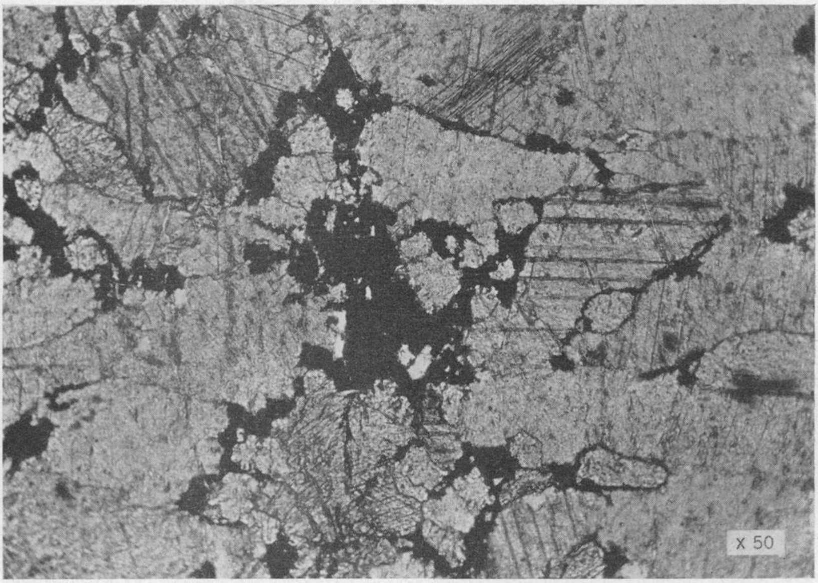

FIGURE 13.—Recrystallized calcite in phosphatic limestone. Collophane (black) reconcentrated in irregular areas between calcite grains (white). Transmitted light.

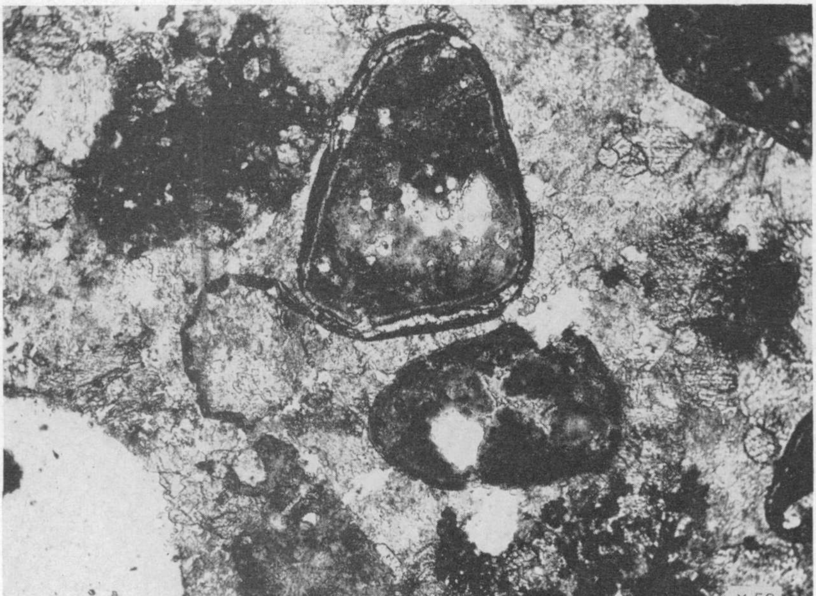

FIGURE 14.—Phosphatic limestone. Collophane ovules and oolites (black) enclosed by crystalline calcite (white). Ovules and oolites show calcite replacement in central areas and concentric layers. Collophane shows granulose texture. Transmitted light.

MUSCOVITE AND CLAY MINERALS

Muscovite and clay minerals are common constituents in the matrix of shales and siltstones and are minor constituents of the phosphate rock. Both minerals were deposited simultaneously with collophane and detrital quartz grains.

CHALCEDONY

Chalcedony occurs as spherulites, as irregular grains and ribbonlike forms, and as a partial replacement in shell fragments. Most of the chalcedony occurs in spherulites and exhibits spherulitic crosses; some occur as "salt and pepper" aggregates.

The best development of chalcedony was observed in a thin section of the "Cap lime" (unit 5 trench I), where it replaces coarsely crystalline calcite (figs. 15, 16). It also replaces central areas of collophane ovules (fig. 17).

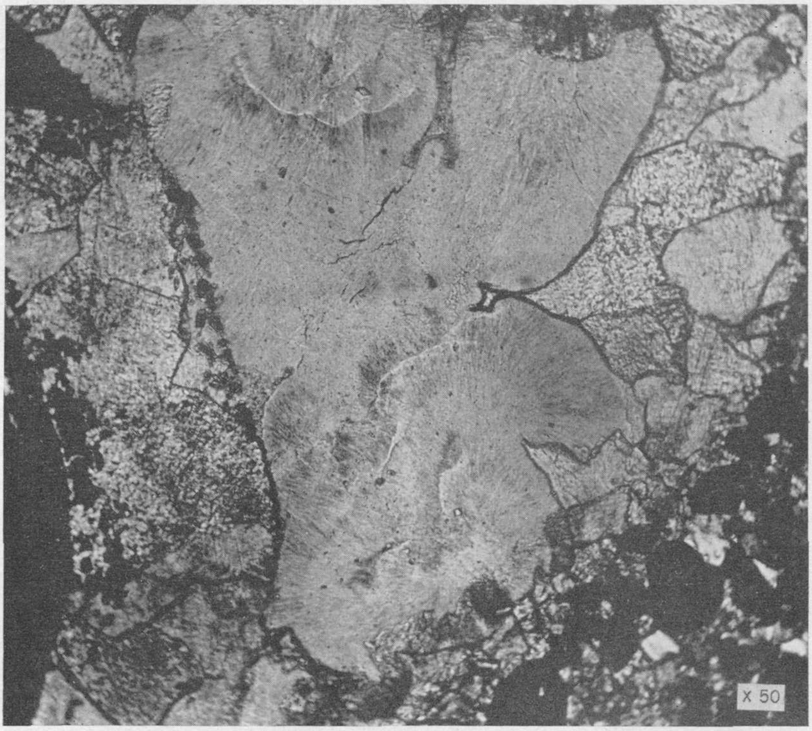

FIGURE 15.—Phosphatic limestone. Four intergrown spherulites of chalcedony (large gray area) enclosed by calcite (mottled area). Collophane ovules (black) in lower right. Chalcedony has replaced calcite, and shows concentric and radial structure. Transmitted light.

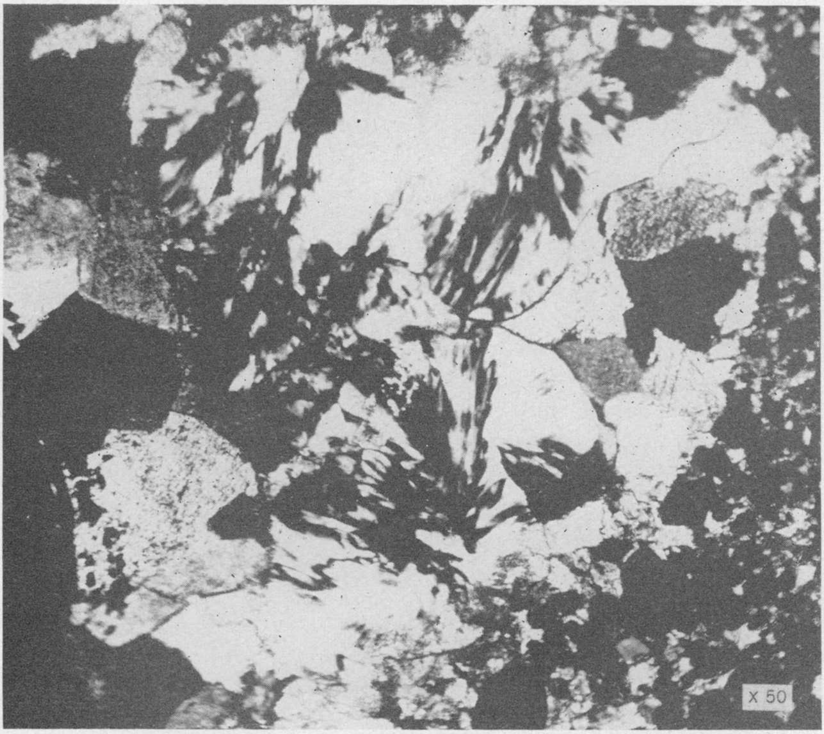

FIGURE 16.—Same phosphatic limestone as figure 15. Crossed nicols.

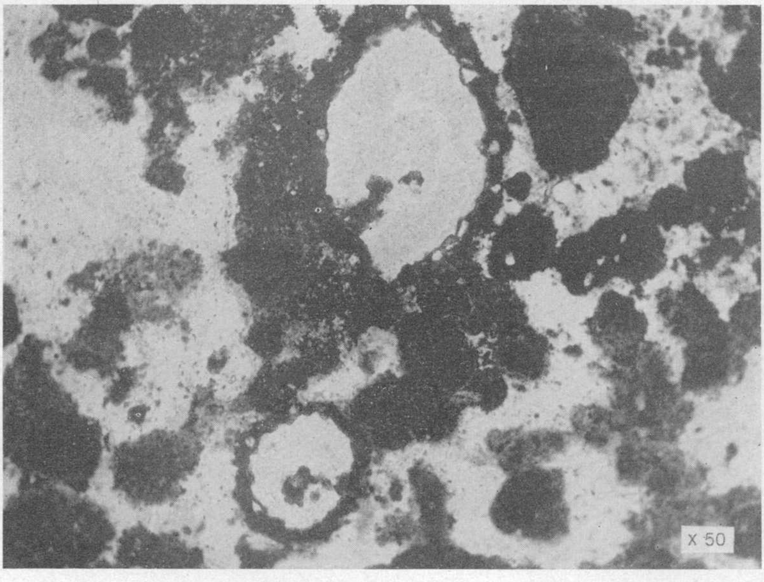

FIGURE 17.—Chalcedony (gray) replacement of central areas in collophane ovules. Chalcedony shows poor concentric laminae and radial structure. Collophane (black) residuals remain in chalcedony. Quartz grains (white) enclosed by black collophane rims. Irregular gray areas (open space). Transmitted light.

An odd ribbonlike structure consisting of chalcedony is developed in a collophone-francolite matrix (fig. 4). This structure, which does not resemble a fossil or shell fragment, is interpreted as a replacement in the collophane-francolite matrix.

Some chalcedony may be nearly contemporaneous with collophane and detrital quartz in the phosphatic shale member of the Phosphoria formation; some is definitely of secondary origin, as shown by its replacement relationships to collophane and calcite.

FLUORITE

Fluorite was not observed in any of the hand specimens collected from the phosphatic shale member. It is present in four thin sections as irregular grains, veinlets in oolites, and cavity fillings (?). It occurs in the light-colored phosphate rock of units 14 and 51 and in the light-colored phosphatic shales of units 52 and 54, trench I.

The cavity fillings may represent fluorite replacement of central areas; however, evidence for replacement was not observed. Many hand specimens of phosphate rock contain ovules having central cavities. Similar cavities might well have been filled by deposition of fluorite.

Fluorite also occurs as irregular grains in collophane cement and as a microscopic veinlet in a collophane ovule. Several small structures that have the appearance of fossil fragments are composed of fluorite. The fluorite is interpreted as a secondary mineral. The source of the fluorine is probably the collophane, which has undergone some replacement by other minerals and some solution.

Fluorite was not observed in contact with the other secondary minerals.

PETROLOGY

The phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area consists of shale, siltstone, phosphate rock, and limestone beds. All the rocks are well bedded. Beds range from less than one-tenth of an inch to 5 feet in thickness.

The lithology of any rock type may grade laterally or vertically into another type. A shale may grade into a fine-grained fissile phosphate rock by the gradual increase of collophane and decrease of detrital grains. A similar gradation between siltstone and limestone occurs as calcite increases and detrital grains decrease and between phosphate rock and limestone with increase of calcite and decrease of collophane.

The combined laboratory and field data and the chemical analyses were necessary to construct stratigraphic sections that would show most of the lithologic changes within each section (pls. 2, 3). Stratigraphic sections of phosphatic rocks constructed solely on field observations may contain errors, because black chippy phosphate rocks and black shales are difficult to distinguish. Some lithologic units thought in the field to be phosphatic shales prove upon microscopic study to be high-grade phosphate rock, and some rocks considered to be phosphate rock actually are black shales.

PHOSPHATE ROCK BEDS

Phosphate rock beds make up about 30 percent of the stratigraphic section in trench I, where they are interbedded with shale, siltstone, or limestone beds. Phosphate rock occurs in beds $1/10$ to 6 inches thick and constitutes the greater part of the high-grade zones which are as much as 7 feet thick (pl. 2, trench C).

Ovulitic texture is characteristic of the medium- and high-grade phosphate rock. Oolitic texture is present in some light-colored phosphate rock beds. The ovules may be remarkably uniform in size in some beds, very few ovules being smaller or larger than the average for such beds. In other beds sizes range from microscopic ovules to as much as 60 mm in long diameter. The ovules occur in spherical, elliptical, and irregular shapes. In some beds ovules may be so tightly cemented by massive collophane similar to that in the ovules that the ovulitic texture is not visible. Some phosphate rock beds cropping out at the surface reveal little if any cement between the ovules.

The phosphate rock beds are black, gray-black, brownish-gray and gray. The lighter-colored specimens display various stages of bleaching of the cement and ovules from black to brown and gray. The color change in many ovules is irregularly to well zoned in light and dark concentric bands.

Collophane comprises the ovules and cement which in turn constitute the phosphate rock beds. The accessory minerals are quartz, muscovite, and calcite. Carbonaceous matter is present in all the phosphate rocks. Quartz as subangular grains, $1/16$ to $1/256$ mm in diameter, is the most abundant accessory mineral and may be accompanied by rounded muscovite flakes. These two minerals are scattered between and enclosed in ovules and cement of high-grade phosphate rock and constitute part or much of the matrix between ovules in the medium- and low-grade rock. Calcite is abundant locally. Finely crystalline calcite fills spaces between ovules and constitutes thin films and veinlets on fracture surfaces.

In contrast with ovulitic phosphate rock, two basaltlike phosphatic rock beds, each 2 to 3 inches thick, occur in the middle of unit 6, trench I, and at the top of unit 7, trench E (pl. 2). In thin section these phosphate rocks have an indistinct, finely ovulitic texture.

The phosphate beds appear to have acted as a lubricant during the deformation of the region. Slickensides are strongly developed parallel to the bedding and are poorly developed across the bedding. Many beds of phosphate rock were brecciated and crushed. Ovules in such beds are polished and brecciated, and the collophane cement is flaky.

Spheroidal weathering has produced poorly rounded nodules in some low-grade phosphate rock. Most fracture surfaces of nodules display brown Liesegang rings parallel to joint surfaces.

Phosphatized shells are abundant in the *Omphalotrochus* zone at the top of the phosphatic shale member.

SHALE AND SILTSTONE BEDS

The shale and siltstone beds make up approximately 50 percent of the stratigraphic section in trench I and range from less than one-tenth of an inch to several inches in thickness. The siltstones are massive, generally hard and brittle, but some are rather soft, though tough.

Black, gray, and brown colors are characteristic of the dry shale and siltstone beds. The original dark colors tend to lighten as the rocks weather. Bleached zones of varying thickness, parallel to fracture, joint, and bedding surfaces, emphasize the effects of weathering on the colors. Most of the light colors of the shale and siltstone beds probably depend on the degree of weathering of the carbonaceous matter. Iron oxide stain is scarce.

The shale and siltstone beds consist of the detrital minerals (quartz and muscovite) and the clay minerals. Carbonaceous matter is present in varying amounts. Collophane, francolite, and calcite may be present. Quartz, the dominant mineral, occurs as angular and subangular grains $1/16$ to $1/256$ mm (silt size) in diameter (fig. 10). Generally less than 5 percent of the quartz is $1/8$ to $1/16$ mm in diameter (fine-sand size). The quartz grains are coated with carbonaceous matter, which in many samples is so thick that the separated quartz grains remain nearly dark under the microscope. Muscovite constitutes less than 10 percent of most of the shales and siltstones. The muscovite flakes are of silt size, transparent, and rounded at the corners and are evenly distributed throughout the matrix

The collophane in some shale and siltstone beds ranges in abundance from a trace to nearly as much as the dominant mineral and occurs as ovules and irregular blebs (fig. 10). Ovules may be uniformly disseminated throughout the matrix or concentrated in lenses a few tenths of a millimeter in thickness and 20 to 30 mm in length, or a combination of both. Flat ovules seemingly are restricted to narrow zones parallel to bedding planes.

Many shale and siltstone beds are calcareous, and calcite may be primary in most of these rocks. Secondary calcite occurs in narrow veinlets and small to large nodules.

Most of the structures observed in the shale and siltstone beds are secondary in origin and have resulted from deformation or weathering. Slickensides in the shales and siltstones are few in comparison with their abundance in the phosphate rocks. White and gray calcite veinlets, ranging from 0.1 mm to several millimeters in thickness, may occur along fractures, joints, and bedding surfaces. Some calcite veinlets are bordered on one or both sides by a thinner zone of black collophane(?). Calcareous nodules and some siliceous nodules are distributed irregularly through the beds. The secondary origin of some calcareous nodules is shown by bedding planes that pass from enclosing rock through the nodules and by shale beds that have been forced aside by the growth of the nodules.

Spheroidal weathering is well developed in the siltstone beds. The resulting nodules may have soft or hard cores which are bounded by well-developed concentric shells that mask the original bedding. Most of the spheroidal nodules, when broken either parallel or normal to bedding planes, display yellow and brown Liesegang rings separated by rings the normal color of the rock.

Fossils are scattered throughout the shale and siltstone beds, but in most beds are not well preserved. Imprints of shells are the most common type of preservation.

LIMESTONE BEDS

Limestone, in beds 1 to 12 inches thick and in lenticular nodules ½ to 25 inches thick and 3 to 60 inches long, constitutes approximately 20 percent of the stratigraphic section in trench I. The limestone beds and nodules are sparsely interbedded with the shale, siltstone, and phosphate rock beds.

The limestone beds are light to dark gray and gray-black, but weather to brownish gray and light brown The contact between weathered and unweathered limestone generally is abrupt.

The limestone beds of the Deer Creek-Wells Canyon area are fine-grained (0.016–0.061 mm in diameter), thin-bedded to massive, hard, and impure. Quartz grains and clay minerals may be present as accessory minerals which are more or less evenly distributed throughout the matrix. Quartz, occurring in angular grains and less than $1/16$ mm in diameter, is in general the most abundant detrital mineral. In two or three limestone beds collophane is abundant and quartz scarce. Collophane ovules as much as 25 mm in long diameter are common in the "Cap lime" (pl. 2, trench I, unit 5). Francolite is common in the "Cap lime," where it occurs as laminae in collophane oolites and in shell fragments. Most of the limestone beds contain a trace of dolomite, and some units contain as much as 10 percent MgO. The dolomitic units are unit 20, trench A; units 14 and 15, trench E; unit 2, trench H; and units 11, 13 and 30, trench I (pls. 2, 3).

Calcite veinlets, one-half to several millimeters thick, transect the massive limestone beds and some, like those in the shale and siltstone beds, have bordering films of black and dark-brown collophane (?).

The best-preserved fossils in the phosphatic shale member are found enclosed in the limestone beds and nodules. Most shells and shell fragments are composed of calcite.

ORIGIN

DESCRIPTION OF THE OVULES AND OOLITES OF THE DEER CREEK-WELLS CANYON AREA

Most of the phosphatic rocks of the western United States are described in published papers as oolitic. The rock specimens collected from the phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area contain spherical, elliptical, and irregular phosphatic ovules as much as 60 mm in long diameter. Black, freshly fractured ovules from this area are solid, massive and apparently structureless when examined under the binocular microscope, whereas the light-colored ovules may or may not show concentric and nonconcentric gray, light- to dark-brown or black laminae.

Only 48 of the 342 phosphate rock specimens and 1 of 95 phosphatic rock specimens collected from the area show concentric banding in the ovules that could be interpreted as oolitic structure. Gardner noted the fact that many of the oolites and pisolites from the Teton Basin also do not appear laminated when observed with a hand lens Gardner (1944, p. 15) says:

> Of 58 samples of rock from the Teton Basin area that contained 30 percent or more of B. P. L., ovules were found in 49, but radial or concentric structure characteristic of oolites could be seen in only 7 of these, even with the aid of a hand lens. In the other 42 samples the ovules appeared to be structureless pellets, although thin sections may show that many, perhaps all, of them have oolitic structure. Such pellets, ranging from one-fourth centimeter to 10 centimeters in diameter, occur in samples having as little as 8.4 percent and as much as 72–5 percent of B. P. L. Ovules were present in almost 90 percent of the samples of phosphate rock and in about 30 percent of the samples of phosphatic shale and siltstone. The pellets in some rocks have such vague outlines that they are very hard to see. This holds for some high-grade phosphate rock as well as for low-grade rock.

Petrographic study of 75 thin sections containing fine to coarse collophane ovules shows that most ovules have a microgranulose texture and lack concentric laminae (fig. 2). Table 3 shows the estimated percentage of oolites present in each of the 75 thin sections of light- and dark-colored phosphate rock from the Deer Creek-Wells Canyon area, Idaho. A representative group of 100 rock specimens was selected for thin sectioning. Seventy-five thin sections contain ovules and oolites; twenty-five did not contain either ovules or oolites. The percentage refers to the relative abundance of oolitic structures in comparison to structureless ovules in each thin section.

The tabulated data (table 3) show that 31 thin sections of light- and dark-colored phosphatic rock consist entirely of structureless ovules. Twenty-one thin sections contain as much as 10 percent oolitic structures and 90 percent or more structureless ovules; 16 of these thin sections are light-colored and 5 are dark-colored phosphate rock. Of the remaining 23 thin sections, all represent light-colored specimens. Five of these specimens contain as much as 25 percent oolitic structures, nine contain as much as 50 percent oolitic structures, and nine contain 50 to 100 percent oolitic structures.

Some of the 12 thin sections of dark-colored phosphate rock contain a few oolites; the others contain none. Of the 63 thin sections of light-colored phosphate rock 38 percent contain no oolites, 25 percent contain as much as 10 percent oolites, and 37 percent contain 10 to 100 percent oolites. The above data show that oolitic structures are almost entirely confined to the light-colored phosphate rocks, but are dominant in only a few of the specimens which were collected from the top of section I.

The collophane ovules in thin section may show microgranulose texture, concentric laminae, or a combination of both. Thin sections of light-colored phosphate rock consist of ovules having microgranulose texture and oolites having concentric laminae; some sections consist almost entirely of oolites. Mansfield (1927, pls. 63, 65–66, 69, 70) published several plates in which most of the oolites and pisolites show concentric laminae, but some of them are structureless and are more or less microgranulose in texture. The laminae of the oolites and pisolites shown in Mansfield's plates appear to be similar to the laminae of the oolites in figure 4, which are alternating bands of francolite and isotropic collophane. The thin section represented by figure 4, was made from a light-gray phosphate rock. Mansfield does not state whether the specimens represented in his plates were light- or dark-colored.

Microgranulose texture is characteristic of small ovules (fig. 3) and central areas of oolites (fig. 4). The ovules, in thin section, consist of an aggregate of isotropic collophane granules each having a submicroscopic dark spot at the center. Quartz grains and fossil fragments when present are generally disseminated irregularly through the ovules. The large collophane ovules, 5 mm in diameter and larger, consist of an aggregate of small ovules and oolites cemented by massive collophane (fig. 17).

TABLE 3.—*Number of thin sections of light- and dark-colored phosphate rock from the Deer Creek-Wells Canyon area, Idaho, in groups based on estimated percentage of oolites present*

Trench	Percentage range												Total number of thin sections
	0		1–10		10–25		25–50		50–75		75–100		
	Light	Dark	Light	Dark	Light	Dark	Light	Dark	Light	Dark	Light	Dark	
E	5	2	2	1	1	0	0	0	1	0	0	0	12
H	0	3	2	2	3	0	2	0	0	0	2	0	14
I	19	2	12	2	1	0	7	0	1	0	5	0	49
Total	24	7	16	5	5	0	9	0	2	0	7	0	75

The laminae of the oolites result from colorless, light- to dark-brown and black bands of collophane, alternating laminae of collophane and francolite, alternating laminae of collophane and calcite, collophane enclosing quartz grain nuclei, and collophane enclosing central cores of secondary minerals. The bands may or may not be concentric.

The color-band type of structure usually has the colorless or light-brown zone at the periphery with progressively darker bands inward (figs. 3, 4). Occasionally, however, this sequence is reversed. The color change is generally gradational, but abrupt changes are common. The color bands are irregular in width, and within a single band the color may not be uniform, as areas of lighter or darker collophane may be present (fig. 6).

Nearly all the oolites that show color banding have central areas of microgranulose texture. The color bands have a microgranular texture similar to the texture of the enclosed central area and both are similar to the microgranular texture of ovules lacking concentric laminae. This type of oolite is interpreted as resulting from the removal of organic matter (bleaching) during the weathering process.

Laminae resulting from alternating layers of francolite and collophane are common. Either francolite or collophane may form the peripheral zone. The collophane layers generally are in shades of brown, occasionally nearly colorless or black, and the francolite is colorless to light brown. Concentric layers of francolite pass through residual dark areas in some oolites (fig. 6). Francolite laminae in many oolites are only partly developed and are confined to bleached areas at the periphery (fig. 4) or occur in irregularly bleached central areas (figs. 6, 8).

Thin black lines may occur between francolite and collophane layers (fig. 6) and in oolites composed of collophane and calcite laminae. They were observed only in oolites in the light-colored phosphate rock in which there is pronounced bleaching, accompanied by the development of francolite, and in phosphatic limestone in which calcite has replaced collophane. These relationships point to a secondary origin which may be accounted for by exclusion of organic matter with accumulation in thin zones during the alteration and/or crystallization of collophane.

A primary origin of the black lines as representing former surfaces during growth of the oolite should not be disregarded (Dietz and others, 1942, p. 837), as primary growth zones may have provided control for the even development of francolite in concentric laminae.

The collophane-francolite laminae in oolites are interpreted as resulting from the removal of organic matter and crystallization of microcrystalline collophane to francolite.

Oolites consisting of alternating collophane and calcite laminae (fig. 14) were observed only in phosphatic limestone beds. This type of oolite is interpreted as resulting from replacement because of its association with structureless ovules which show all stages from partial to complete replacement by calcite. Residual black rings of organic matter (?) are all that remain of many ovules.

Two examples of quartz grains concentrated in a concentric ring were observed (figs. 18, 8). These oolites are interpreted as primary structures in which the quartz grains were incorporated by the collophane as the oolites grew.

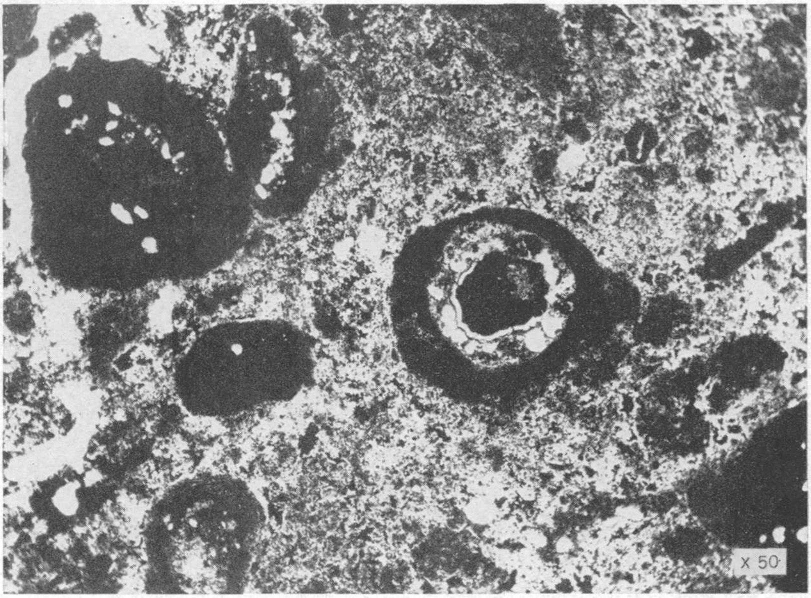

FIGURE 18.—Section of part of a phosphate ovule 5 mm in diameter. Composed of small collophane ovules and oolites (black) enclosed by collophane-francolite matrix. Larger white areas are quartz grains. Collophane oolites (right center) with concentric layer enclosing quartz grains and discontinuous inner layer of chalcedony. Transmitted light.

Some oolites have peripheral zones of collophane enclosing cores of chalcedony (fig. 17), quartz (fig. 11), calcite (figs. 12, 14), francolite and collophane in a lacy network (fig. 8), and fluorite. These oolites are interpreted as secondary structures in which the core material has replaced collophane. Oolites having fluorite cores are interpreted as cavity fillings.

Quartz-grain nuclei were observed in a phosphatic nodule collected from unit 40, trench I. The nodule, 60 mm in long diameter, is composed of microscopic ovules and oolites cemented in part by black collophane cement (fig. 7). These are interpreted as primary structures which resulted from the deposition of collophane around quartz grains. The nodule may be the result of wave action on a fragment of indurated phosphate rock.

PREVIOUS VIEWS OF THE ORIGIN OF OOLITES

The origin of oolites has been explained as resulting from both organic and inorganic action. The chemical origin of oolites has been recognized by many workers. Seeley (1888) suggested that oolites resulted from direct chemical precipitation. Linck (1903) grew oolites in the laboratory by chemical means. Vaughn (1914) grew oolites from strained shoal-water mud. Bucher (1918, p. 593) grew spherulites by using hydrated iron chloride and in the same paper expressed the belief that Schade's principles are involved in the formation of nearly all sedimentary oolites, spherulites, and concretions. These principles are quoted from Bucher (1918, p. 594) as follows: (1) "The spherical shape of spherites is due to the tendency of the droplets, forming during the separation of the dispersal phase of an emulsoid to coalesce. (2) The difference between spherites of radial and concentric structure depends on the amount of other substance thrown out simultaneously with and mechanically enmeshed in the growing structure." Bucher's survey of naturally occurring oolites led him to the conclusion that nearly all oolitic and spherulitic grains were formed by at least one constituent changing from an emulsoid to that of a solid and that oolites grew in free suspension.

Bradley (1926, p. 126) described oolites from the Green River formation as having been formed by algae or bacteria. After a restudy of the oolites, Bradley (1928, p. 221) decided that the oolites in some beds had formed by inorganic action and had formed in suspension in the matrix when it was an ooze. He believed the growth of these oolites agreed with the principles of Schade. Bradley (1928, p. 222) also summarized evidence to show the possibility of the growth of oolites in natural environments in which the media of growth are as fluid as lake or marine waters. He concluded that lake water might be saturated with calcium carbonate and contain colloidal components so dispersed that the increased viscosity of the solution would not hold nuclei and small oolites in suspension. Such conditions, he believes, better account for the formation of most of the oolites of the Green River formation.

Eardley (1938, pp. 1372–1377) believes the calcareous oolites of Great Salt Lake to be the result of inorganic precipitation of calcium and magnesium carbonate and a "base exchange" relation between the colloidal clay particles and the aragonite crystals. Constant wave agitation of the growing oolites permits equal accretion to take place. Eardley found the oolites only along open shore lines where waves were active.

Mansfield (1927, p. 364), after considering the possibility of an organic origin for the oolites of the Western phosphate deposits (Permian age), decided they were the result of chemical and physical causes. He concluded that the oolites were formed directly from solutions rich in phosphate or phosphatic colloids partly by chemical precipitation and partly by physical or mechanical accretion.

The phosphates have been classified with the "gelatinous salts" (Ostwald, 1915, p. 51). Rogers (1917, pp. 530–533), Bucher (1918, p. 596), and Dietz and others (1942) consider collophane to be of colloidal origin.

Dietz and others (1942, pp. 831–833) have summarized previous views on the origin of phosphate. These authors also discuss the chemistry of phosphate in the ocean and the possibility that the ocean is essentially saturated with tricalcium phosphate at depth. They state that "such saturation may allow the existence of a colloidal phase of tricalcium phosphate in equilibrium with the dissolved phase." Their conclusion is that the phosphorite dredged from the ocean off southern California is the result of direct precipitation in place.

DEPOSITION OF PHOSPHATE

Collophane, the primary constituent of these phosphate rocks, may have replaced preexisting ovules and oolites, may have been formed elsewhere and been transported to the present site, or may have been deposited in place. The following data collected from a study of the thin sections indicate that the phosphate is a primary precipitate and has not undergone significant reworking:

1. Evidence was not found in this study that organisms were active in the formation of the ovules and oolites. The microgranules, however, which are responsible for the microgranulose texture of the ovules may be interpreted as being of organic origin (E. S. Larsen, personal communication).
2. In thin sections, the microgranules have the appearance of having been submicroscopic droplets of phosphatic gel. Each granule appears to have had a nucleus. Granules show adjustment of boundaries to each other, and the adjustments apparently were made while the granules were more or less plastic.
3. Unsupported collophane ovules in shales, siltstones, and limestones are common. Similar occurrences of oolites have been explained as growth during suspension in a more or less "gel-like" or ooze matrix (Bradley, 1928, p. 221). Enclosed quartz grains are irregularly distributed as though enmeshed during the growth of the ovules. Evidence was not obtained to indicate collophane replacement of preexisting oolites. The lack of oolites composed of nonphosphatic minerals in the nonphosphatic rocks is suggestive that the collophane of the ovules and oolites is not a replacement phenomenon.
4. High-grade phosphate rock is composed of collophone ovules pressed closely together with very little collophane cement; some ovules, however, are suspended in collophane cement. Irregular shapes and adjustment of some ovules to ad-

jacent ones are common. The adjustment of some ovules to others may have resulted during growth as a result of interference at contacts. Interference during growth of ovules may also account for the irregular and elliptical shapes.

5. Collophane ovules and cement enclose quartz grains and some fossil fragments. The quartz grains are irregularly distributed in collophane cement and matrix. The fossil fragments, if elongated, are essentially parallel to bedding planes whether enclosed by cement or ovules.

6. Many hand specimens of phosphate rock appear to be equigranular (ovulitic). The wide variation in sizes of ovules, as shown in thin sections, is evidence that reworking and sorting has not occurred.

7. Current bedding and ripple marks were not observed.

The following data suggest that a few phosphate beds, at least, have undergone some reworking by wave or current action. Many lenses, laminae, and thin beds show poor to excellent grading, but the lateral extent of individual lenses and laminae generally is not great. The possibility of a turbidity-current origin deserves study (Keuhnen and Migliorini, 1950).

1. Several beds are composed of ovules and nodules ranging from microscopic sizes to 40 mm in long diameter. Nearly all ovules of 5 mm in diameter or larger are composed of smaller ovules and nodules and may represent indurated or partly indurated phosphate rock broken and rounded by wave or current action.

2. Some occurrences of fragmented ovules and oolites surrounded by unbroken ovules and oolites were observed. As much as half an ovule may be missing. The relationships of broken to unbroken ovules and oolites show that both types were deposited simultaneously. Some transportation is indicated for the broken ovules and oolites.

3. Many phosphate-rock specimens are composed, as shown in thin sections, of nearly quartz-free ovules enclosed in a quartz-rich collophane matrix (fig. 3). If these ovules developed in place, the quartz grains must have been excluded. This process does not seem likely, as in many phosphate-rock specimens the quartz grains are distributed in both matrix and ovules. Wave disturbance of previously formed thin beds of quartz-free collophane ovules alternating with beds rich in quartz grains seems to be a logical explanation.

4. A characteristic feature of many low-grade phosphate rock and phosphatic shale and siltstone beds is the interbedding of lenses, laminae, and beds of these materials. Individual lenses, laminae, and beds range from 0.1 mm to several millimeters in thickness, and each type is essentially parallel to the major bedding planes. The resulting appearance is similar to sorted and graded sediment. This feature may be the result of current or wave action, or both.

CONCLUSIONS: CONTINUITY AND PHOSPHOROUS CONTENT

The calculation of phosphate reserves in the phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area depends upon the lithologic continuity of particular beds or zones from one trench to another and upon the content of phosphorus pentoxide within the beds or zones. A knowledge of the quantity and kinds of impurities and the relationships of the impurities to the phosphate minerals is essential for beneficiation of the phosphate rock. Nine trenches were dug and sampled to collect data to be used in determining the thickness, lateral extent, and phosphorous pentoxide content of phosphate rock zones in the area.

The location of the trenches is shown on plate 1. The location of each trench is as follows:

Trench A. S½NE¼ sec. 32, T. 9 S., R. 45 E., on the south bank of the small creek south of Black Dugway, and on the east limb of the Georgetown syncline. Altitude, 7,375 feet.

Trench B. S½NE¼ sec. 32, T. 9 S., R. 45 E., on the north side of the ridge north of Black Dugway, 300 to 350 feet north of trench A, and on the east limb of the Georgetown syncline. Altitude, 7,350 feet.

Trench C. S½NE¼ sec. 32, T. 9 S., R. 45 E., east of trench A and S. 45° W. of Black Dugway, and on the east limb of the Georgetown syncline. Altitude 7,325 feet.

Trench D. W½NE¼ sec. 5, T. 10 S., R. 45 E., on a spur at the south side of the South Fork of Deer Creek, approximately 280 feet south of the road, and on the east limb of the Georgetown syncline. Altitude, 7,375 feet.

Trench E. NW¼NE¼ sec. 9, T. 10 S., R. 45 E., in Wells Canyon, and on the east limb of the Webster syncline. Altitude, 7,275 feet.

Trench F. SW¼SW¼ sec. 9, T. 10 S., R. 45 E., on the south bank of the second large gully 1 mile southwest of Wells Canyon, and on the west limb of the Webster syncline. Altitude, 7,650 feet.

Trench G. SW¼SW¼ sec. 9, T. 10 S., R. 45 E., on the south bank of the second large gully 1 mile southwest of Wells Canyon, approximately 200 feet east of trench F, and on the west limb of the Webster syncline. Altitude, 7,570 feet.

Trench H. NW¼NE¼ sec. 9, T. 10 S., R. 45, E., in Wells Canyon approximately 75 feet west of Trench E, and on the east limb of the Webster syncline. Altitude, 7,300 feet.

Trench I. S½SW¼ sec. 34, T. 9 S., R. 45 E., on the north side of Deer Creek, and on the east limb of the Webster syncline. Altitude 7,000 feet.

CONTINUITY OF MINOR PETROLOGIC UNITS

Stratigraphic sections at the base of the phosphatic shale member of the Phosphoria formation are exposed in trenches C to F and I (pl. 2). Stratigraphic sections at the top of the member are exposed in trenches A, B, G, H, and I (pl. 3). Trench I (pls. 2, 3) contains the only stratigraphic section of all the beds between the underlying limestone of the Wells formation and the overlying Rex chert member.

Trench I is 1½ and 2½ miles north of trenches E and F, respectively, and 1½ and 1¾ miles east of trenches C and D, respectively (pl. 1). Although the distances involved are not long, many lithologic differences exist between trenches. Folding and faulting have caused duplication and possibly omission of beds in this area.

The correlations indicating presence or absence of continuity of beds between the sections shown on plates 2 and 3 are based on lithology, texture, structures, and stratigraphic sequence.

The upper and lower limits of the phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area are defined by two easily recognized zones. They are the "*Omphalotrochus* zone" at the top and the lower phosphatic zone at the base.

The *Omphalotrochus* zone, a 4- to 8-inch phosphate bed, was recognized in each section in the Deer Creek-Wells Canyon area (pl. 3) at the top of the phosphatic shale member. The numerous individuals of *Omphalotrochus* sp. (gastropods) and the ease of locating the bed readily define the top of the phosphatic shale member in the area. The phosphate rock is light brownish gray to dark gray in color, silty, locally calcareous, and ovulitic; ovules range from 0.10 to 20 mm in diameter. Large ovules are irregular to elliptical in shape and consist of smaller ovules. Approximately 25 percent of the phosphatic pellets display concentric laminae.

The lower phosphate zone, exposed in trenches C, D, I, E, and F (pl. 2), is continuous throughout the Deer Creek-Wells Canyon area. The phosphate rock occurs in ¹⁄₁₀- to 6-inch beds separated by a few shale laminae. Ovulitic textures are well developed. Ovules range from 0.05 to 2.0 mm in long diameter. Hand specimens have an equigranular texture. The phosphate rock is gray black and black in trench I and medium gray to medium dark gray in Trenches C, D, and E. The lower phosphate zone is high-grade phosphate rock (70 percent or more B. P. L.). A sandy shale layer, 2 inches thick in trench E and 8 inches thick in Trench I, separates the lower phosphate zone from the underlying Wells formation. The shale is absent in trenches C, D, and F.

Two medium-grade phosphate zones (50 percent or more B. P. L.) are present above the lower phosphate zone. These are designated the middle and upper zones.

The middle phosphate zone was exposed in only two of the trenches (pl. 2). The phosphate rock is thin-bedded, silty, locally calcareous, ovulitic grains (0.05 to 2.0 mm in long diameter), medium dark gray and brownish black in trench E, gray black in trench I. The zone in trench I contains a limestone bed 5 inches thick near the middle and microscopic fluorite grains near the base.

The upper phosphate zone is continuous within the prospected parts of the Deer Creek-Wells Canyon area (pl. 3). High-, medium-, and low-grade phosphate beds and several thin beds of shale, siltstone, and limestone constitute the upper phosphate zone. The medium- and low-grade phosphate rock beds are silty.

All of the beds, except the limestone bed of unit 65, trench I, and unit 22, trench H, are continuous in the upper phosphate zone. The phosphate rock of the upper zone is thin-bedded, hard, brittle, silty, locally calcareous, ovulitic grains (0.05 to 2.0 mm in diameter). Ovules as much as 35 mm in long diameter occur in the upper phosphate bed of the zone, oolites are common. The large ovules consist of smaller ovules, generally 0.5 in diameter or less. Medium dark gray is the dominant color. Francolite is common. Quartz grains are common in the matrix of high-, medium-, and low-grade phosphate rock beds, but scarce in the ovules. Small interbedded lenses of siltstone and phosphate rock are abundant, and generally the boundaries are gradational.

Many beds and zones shown on plates 2 and 3 are similar in most respects and undoubtedly are continuous. However, some units having similar stratigraphic positions are unlike in lithology, texture, structures, and B. P. L. content and probably represent lensing beds or lateral changes in lithology. The discussion in the following paragraphs will deal primarily with the dissimilar units.

One bed, the fossiliferous "Cap lime," is widely recognized in southeastern Idaho and northeastern Utah. According to Mansfield (1927, p. 76), it is 2 to 3 feet thick in the Montpelier area, but it was identified only in trench I (pl. 2) in the Deer Creek-Wells Canyon area, where it is 1.7 feet thick.

The "Cap lime" overlies the lower phosphate zone and consists of fine to coarse ovules and fossils embedded in a calcite matrix. The lower 12 inches of unit 6, trench I, is similar to the "Cap lime" and grades upward into noncalcareous phosphate rock. The lower part of unit 6, trench I, may represent local addition of secondary calcite to the original beds. Unit 6, trench E, consists of pale-brown, porous, friable, medium and coarsely ovulitic phosphate rock, which has been considerably leached. Much calcite may have been removed from this unit. Unit 3, trench F, consists of pale yellowish-brown, thick-bedded, hard, fossiliferous, silty, calcareous, finely to coarsely ovulitic phosphate rock. Unit 2, trench D, consists of pale-brown mud which may be residue of a leached limestone bed. The position of these units on top of the lower phosphate zone indicates that they may represent a former, more calcareous zone, the "Cap lime," that has been leached.

A black, dense, hard, aphanitic phosphate bed 2 to 3 inches thick is present in the middle of unit 6, trench I, and at the top of unit 7, trench E. Similar phosphate rock was not observed in trenches D and F, however; so the specimens may represent a local lens or a bed that changes laterally.

Unit 8, trench E, consists of dark-gray, finely crystalline limestone nodules embedded in brownish-gray, porous, chunky, finely ovulitic, silty mud. The nodules weather to brownish-gray material similar to the enclosing silty mudstone and containing bedding planes that imply a weathered limestone bed. A 5-inch layer of brownish-gray mudstone in the middle of unit 4, trench F, at the same stratigraphic position, may be the equivalent of the limestone and mudstone of unit 8, trench E. The limestone bed apparently lenses out between trenches E and I, as similar material was not observed in trenches I and D.

Unit 7, trench I, consists of 3 feet of thick-bedded, massive, hard, grayish-black, finely crystalline limestone with a thin bed of shale and another thin bed of phosphate rock occurring near the center of the unit. The limestone seems to be a local lens, as similar material was not present in trenches E and F.

Unit 6, trench F, and the lower 15 inches of unit 8, trench I, are characterized by spheroidally weathered, slightly micaceous, brownish-gray siltstone, which grades upward into thin-bedded, hard, ovulitic, low-grade phosphate rock. The lithology, textures, and tricalcium phosphate content are similar, except that siliceous nodules as much as 24 mm in diameter occur in unit 6, trench F. Similar material is missing in trench E. The zone may lens out toward trench E or may be cut out by faulting.

A dark-gray and pale-brown, chunky-bedded siltstone makes up unit 8 and the lower 20 inches of unit 9, trench F, and that part of unit 11, trench E, 11 to 22 inches below the top of the unit; it does not appear in trench I. The decrease in thickness of the silt-stone indicates a lensing bed.

The lower 14 inches of unit 9, trench I, and unit 12, trench E, consists of a grayish-black, pale brown-weathering, thick-bedded, silty limestone and calcareous siltstone. The upper 19 inches of unit 9, trench F, consists of pale-brown to brownish-black, slightly calcareous siltstone that is considerably weathered. The lithology shows a change between trenches E and F if the limestone and calcareous siltstone represent a single zone.

The silty phosphate rocks of units 13 and 14, trench F, do not have recognizable equivalents in trenches E and I.

Unit 11, trench I, consists of dark-gray, thick-bedded, massive, hard limestone that is phosphatic at the base. Units 14 and 15 and the lower 30 inches of unit 16, trench E, consist of calcareous siltstone. These units may represent a local lens-shaped bed that shows a lateral lithologic change and thickening.

The remainder of the units in trenches E and I are correlative and are shown on plate 2.

A series of shales, siltstones, limestones, and phosphate rock 19 to 25½ feet thick lies between the *Omphalotrochus* zone and the upper phosphate zone (pl. 3). Unit 27, trench H, and unit 25, trench G, consist of a 6-inch zone of silty, medium dark-gray, finely to coarsely ovulitic phosphate rock. The ovules are as much as 40 mm in long diameter. This phosphate zone was not observed in the other trenches. The limestone bed of trenches A, B, H, and I is not present in trench G.

A 7-inch zone of black, chunky-bedded, siliceous, ovulitic, phosphate rock occupies the base of unit 23, trench A; the base of unit 19, trench B; an interval 20 to 24 inches above the base of unit 69, trench I; the base of unit 25, trench H; and the base of unit 23, trench G. The ovules, as much as 20 mm in long diameter, are composed of collophane cement enclosing ovules as much as 2 mm in long diameter. The thickness of the zone and the texture are remarkably constant.

Correlations below the upper phosphate zone could not be made with certainty between trenches B and I, and only a few correlations could be made between trenches I, H, and G.

A "wedge" of phosphate rock, siltstone, and shale (units 13 to 16) appears just below the upper phosphate zone in trench A (pl. 3). A similar series of beds is not present in trench B, which is 300 to 350 feet to the north. The "wedge" may have resulted from faulting, although the specimens collected from these units show no more evidence of movement than the average specimens of the district. The remaining beds in trench A correlate closely with beds of the same stratigraphic position in trench B.

EFFECT OF WEATHERING ON GRADE OF PHOSPHATE ROCK

Weathering processes have been active on the exposed parts of the phosphate rock beds. The available data indicate that slight enrichment probably has occurred at the surface, but the evidence is not conclusive. A definite statement regarding enrichment is not warranted because a suite of phosphate rock specimens representing the lower and upper phosphate zones at depth could not be collected and compared with the specimens collected from the trench sites.

It is probable that the same conditions are present in the phosphate zones of the Deer Creek-Wells Canyon area that Norris (1944, p. 481) describes for the phosphatic beds at Conda, Idaho. He states: "At depth the beds are highly carbonaceous and are brownish-black to blueblack in color. Near the surface the beds have been oxidized and weathered to a lighter color, varying from light-gray to cream through darker shades of gray and brown. Weathering reduces the carbonaceous and calcareous content of the beds, thereby increasing the percentage of tricalcilm phosphate through residual effect."

Solution and redeposition of collophane and the bleaching of organic matter accompanied by the development of francolite have occurred in the phosphatic rocks of the area.

Some phosphate rock displays textural variations within the exposed part of the bed. A bed may consist in part of collophane ovules without cementing material and in part of ovules enclosed in collophane cement. The areas of uncemented ovules grade into adjacent solid phosphate rock, thus indicating that selective solution of collophane cement in minor amounts has occurred in favorable areas. Some redeposition of phosphate within the beds is shown by collophane veinlets and reconcentration of collophane between calcite grains (fig. 13).

Black phosphate, in thin sections, consists of dark-brown to opaque black collophane. Light-colored phosphate rock, in thin sections, consists of colorless to dark-brown collophane. In the latter type the color change is gradational (pl. 2, fig. a) and may have resulted from the removal of organic matter. The removal of organic matter would enrich the phosphorus pentoxide (P_2O_5) content of the phosphate rock.

The P_2O_5, CaO, and organic-matter (ignition-loss) contents and the color of the rock for the lower and upper phosphate zones are assembled in tables 4 and 5. The percentage of CaO in excess of that needed to use up all the P_2O_5 content to form collophane

$$(10CaO.3P_2O_5.CaF_2.CO_2.H_2O)$$

is shown. It has been assumed that collophane is the only phosphate-bearing mineral present. Francolite is present in some of the specimens. It has nearly the same formula, but as has been shown on page 17, C can substitute for Ca and P, F and OH can substitute for O. Loss on ignition is an approximate measure of the organic matter content if the rock does not contain carbonates. Moisture loss at 105° C. was determined. The colors were based on the rock-color chart distributed by the National Research Council, 1948.

The assembled data for the lower phosphate zone in trenches C, D, E, F, and I, table 4) offer some evidence of enrichment resulting from bleaching. The specimens from trenches C, D, E, and F are medium to dark gray in color, and those from trench I are black. The lower phosphate zone in trench I is just a few feet above the water level of Deer Creek (pl. 1). The same zone in trenches C, D, E, and F is considerably above the adjacent stream levels.

The lower phosphate zone in trench I contains the least phosphorus pentoxide (P_2O_5) and the highest organic-matter content of any of the trenches sampled (table 4). The average organic content (trench I) is approximately 10 percent, which is 1.5 to 3.4 percent more than the organic content for the same zone in trenches C, D, E, and F. The lower percentage of organic matter associated with the gray color of the phosphate rock indicates the removal of some organic matter from the lower phosphate zone of trenches C, D, E, and F.

TABLE 4.—*Comparison of organic content and excess CaO in samples representing lower phosphate zone*

Trench	Unit no.	Percent P_2O_5	Percent CaO	Percent excess CaO	Percent ignition loss	Rock color
I	2	33.0	47.4	4.5	8.9	Black (N1).
	3	32.1	46.4	4.7	11.3	Black (N1).
	4	28.0	44.2	7.8	10.9	Black (N1).
C	1	33.1	47.6	4.6	6.8	Medium gray (N6).
D	1	33.0	45.4	2.5	8.5	Medium dark gray (N5).
E	2	34.4	49.5	4.8	6.6	Medium gray (N6).
	3	32.2	46.2	4.3	7.7	Medium gray (N6).
F	1	35.5	48.0	2.0	8.2	Medium to dark gray (N5-N6).

A loss of calcareous content is possible in the weathering process. The chemical analyses (table 1) should indicate any significant loss of CaO when the mineralogy of the various samples has been determined. Most of the units of the lower phosphate zone show an excess of 2.0 to 4.8 percent CaO (table 4). Unit 4, trench I, has an excess of 7.8 percent CaO, but the thin section for the unit contains calcite. Calcite was not observed in the other units. A significant loss of CaO content in the lower phosphate zone is not shown by the available data.

Similar data are compiled for the upper phosphate zone of Trenches A, B, G, H, and I (table 5). The phosphate specimens representing this zone are light to dark gray in color. The percentage of organic content is considerably lower throughout the upper phosphate zone than in the lower phosphate zone of trench I. A loss of CaO content in the upper phosphate zone is not shown by the data in table 5.

Available information on phosphate rock of the Phosphoria formation in the Montpelier district, Idaho (Mansfield, 1927, p. 213), and in the Montana areas (Gale, 1910, p. 5; Pardee, 1916, p. 218), indicates that weathered phosphate rock may contain as much as 5 percent more phosphorus pentoxide than the unweathered rock. The exposed phosphate rock beds of the Deer Creek-Wells Canyon are likely to contain slightly more phosphorus pentoxide than the unweathered parts of the same beds.

TABLE 5.—*Comparison of organic content and excess CaO in samples representing upper phosphate zone*

Trench	Unit no.	Percent P_2O_5	Percent CaO	Percent excess CaO	Percent ignition loss	Rock color
I	60	34.3	47.2	2.6	8.6	Dark gray (N3).
	61	34.4	48.7	4.0	5.9	Medium and dark gray (N6–N3).
	63	32.0	47.5	5.9	7.3	Medium and dark gray (N6–N3).
	67	33.8	47.6	3.7	6.5	Medium and dark gray (N6–N3).
	68	35.5	50.8	4.6	4.6	Medium and dark gray (N6–N3).
A	18	33.9	48.8	3.7	7.0	Medium and dark gray (N6–N3).
	21	35.6	50.2	3.9	4.8	Medium and dark gray (N6–N3).
B	13	33.1	47.1	4.1	8.6	Dark gray (N3).
	17	34.1	50.1	5.8	4.5	Med. and med. dark gray (N6–N5)
G	21	34.9	49.5	4.1	5.4	Light and med. dark gray (N8–N5).
H	15	34.3	47.8	3.2	6.7	Med. and dark gray (N6–N3).
	23	32.2	49.2	7.3	4.5	Med. and dark gray (N6–N3).

ECONOMIC POSSIBILITIES

The phosphate rock of possible economic interest in the phosphatic shale member of the Phosphoria formation in the Deer Creek-Wells Canyon area is in the lower and upper phosphate zones (pls. 2, 3). Thick phosphate zones of medium and low grade occur above the lower phosphate zone and below the upper phosphate zone. Since the middle phosphate zone (pl. 2) was exposed only in trenches E and I, its lateral extent is not known; therefore it is not described.

Most of the phosphate rock mined in southeastern Idaho has been converted into superphosphate fertilizer by acidulation with sulfuric acid. For this process phosphate rock containing a minimum of 68.7 percent tricalcium oxide (31.5 percent P_2O_5) is desired. Phosphate rock containing approximately 52 percent tricalcium phosphate (24 percent P_2O_5) is being utilized in electric furnaces by Westvaco at Pocatello, Idaho.

Lower Phosphate Zone.—The lower phosphate zone is the only one mined in most of southeastern Idaho (McKelvey, 1949, p. 274). In the Deer Creek-Wells Canyon area the lower phosphate zone is 4 to 7 feet thick and contains 70 percent or more tricalcium phosphate. The phosphate occurs in thin beds separated by clay partings. Ovulitic texture is characteristic. Collophane is the important phosphate mineral. The impurities include quartz grains and clay minerals (approximately 4 percent) and organic matter (approximately 10 percent).

Of economic interest, in addition to the phosphate, is vanadium and fluorine. Approximately 0.2 percent V_2O_5 and 3 percent fluorine (trench I) are present. Vanadium-bearing minerals have not been identified in the phosphate rocks of the area. The fluorine occurs in the phosphate minerals, collophane and francolite.

A medium-grade phosphate zone (approximately 50 percent tricalcium phosphate) overlies the lower phosphate zone in trenches E, F, and I (pl. 2) and may be present in the areas of trenches C and D. The zone is 13 feet thick in trench F (units 3–7), 20 feet thick in trench E (units 6–13), and 14 feet thick in trench I (units 8–10). The tricalcium phosphate content is approximately 48 percent in trench F and 50 percent in trenches E and I. Unit 12, trench E, is averaged into these figures as containing zero percent tricalcium phosphate.

The vanadium content averages approximately 0.40 percent (V_2O_5) for units 8–10, trench I. Analyses for V_2O_5 were not made for the zone in trenches E and F.

The impurities are quartz grains and clay minerals (acid insoluble, approximately 22 percent), organic matter (approximately 12.5 percent for trench I), and calcite.

Upper Phosphate Zone.—The upper phosphate zone is mined at Conda, Idaho (Russell, 1949, p. 279). The upper phosphate zone in the Deer Creek-Wells Canyon area (pl. 3) varies from 8 feet in thickness in trench A (units 18–21) to 14 feet in trench H (units 15–23) and includes several high-grade and two to four low- and medium-grade phosphate rock beds and thin interbedded phosphatic shales, siltstones, and limestones.

The tricalcium phosphate content of the upper phosphate zone is approximately 64 percent in trench A, 53 percent in trench B, 55 percent in trench I, 50 percent in trench H, and 54 percent in trench G. Units 60 to 68, trench I, contain approximately 0.2 percent V_2O_5. The impurities are quartz grains, clay minerals, calcite, and organic matter.

A low- and medium-grade phosphate zone underlies the upper phosphate zone. The zone is 21 feet thick and averages 42 percent tricalcium phosphate in trench A; it is 18 feet thick and averages 48 percent tricalcium phosphate in trench B, it is 9.5 feet thick and averages 46 percent tricalcium phosphate in trench I, it is 11 feet thick and averages 53 percent in trench H; and it is 7 feet thick and averages 50 percent tricalcium phosphate in trench G. Units 57 to 59, trench I, contain approximately 0.3 percent V_2O_5.

The combined upper phosphate zone and the underlying low- and medium-grade phosphate zone is 29 feet thick and averages 49 percent tricalcium phosphate in trench B; it is 22.5 feet thick and averages 51 percent tricalcium phosphate in trench I; and it is 25 feet thick and averages 55 percent tricalcium phosphate in trench G. This zone in trench I contains approximately 0.25 percent V_2O_5.

The combined phosphate zone in trench I contains approximately 20 percent quartz and clay minerals (acid insoluble) and 10 percent organic matter (ignition loss). Complete chemical analyses were not made for the samples from trenches A, B, G, and H.

BENEFICIATION METHODS

Beneficiation of the phosphate rock of all grades present in the area will increase the tricalcium phosphate content by a few percent.

Beneficiation methods that have been successfully applied to phosphate rock are calcining, washing, and flotation. Calcining and washing have been used on the Idaho phosphate rock and washing and flotation on Florida phosphate rock.

Calcining.—Phosphate rock mined at Conda, Idaho, is shipped to Anaconda, Mont., for processing. The high-grade phosphate rock from the lower phosphate zone is calcined to burn off excess organic matter (Caro, 1949, p. 282).

Grinding and washing.—Newton and Finklenburg (1947) describe experiments in beneficiating medium-grade phosphate rock from Fort Hall and Montpelier, Idaho. The phosphate rock was ground to separate collophane pellets and cementing matrix. Attempts were made not to crush the collophane pellets. Tests were made of phosphate rock ground to minus 20 and minus 48 mesh. The low-grade portion of the rock, which probably included quartz grains, clay minerals, and possibly carbonate, formed a brown slime, and the pellets were collected as black, high-grade phosphatic sand. Separation of pellets and matrix was accomplished by washing and desliming.

Phosphate rock mined from the upper phosphate zone at Conda, Idaho, will be beneficiated in a washing plant at Anaconda, Mont. (Caro, 1949, p. 282). The phosphate rock will be crushed to minus three-eighths inch and treated in a scouring mill to separate shale particles having a high alumina and iron but a low P_2O_5 content. The operation will increase the P_2O_5 content by 3 percent. The beneficiated rock will be calcined to remove excess organic matter.

Washing plants have been in use in Florida (Swainson, 1944) and Tennessee (Grissom, 1944) for some years.

Flotation.—Flotation as a process for concentration of low-grade phosphatic sands is being applied commercially in Florida by several companies (Swainson, 1944).

Application or calcining, washing and flotation methods to the concentration of low and medium-grade phosphate rock of the Western field should be possible. Experimental work will be required to work out a suitable flotation process for the phosphate rock of any particular area.

REFERENCES CITED

Bradley, W. H., 1926, Shore phases of the Green River formation in northern Sweetwater County, Wyoming: U. S. Geol. Survey Prof. Paper 140, p. 126.

——— 1928, Algae reefs and oolites of the Green River formation: U. S. Geol. Survey Prof. Paper 154.

Bucher, W. H., 1918, On oolites and spherulites: Jour. Geology, vol. 18, pp. 593–609.

Caro, R. J., 1949, Anaconda phosphate plant, beneficiation and treatment of low grade Idaho phosphate rock: Mining Engineering, vol. 1, no. 8, pp. 282–284.

Dana, E. S., 1932, A textbook of mineralogy, 4th ed., revised and enlarged by W. E. Ford, p. 704, New York, John Wiley & Sons, Inc.

Deiss, C. F., 1949, Phosphate deposits of the Deer Creek-Wells Canyon area, Caribou County, Idaho: U. S. Geol. Survey Bull. 955–C.

Dietz, R. S., Emery, K. O., and Shepard, F. P., 1942, Phosphorite deposits on the sea floor off southern California: Bull. Geol. Soc. Amer., vol. 53, pt. 1, pp. 815–847.

Eardley, A. J., 1938, Sediments of Great Salt Lake, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 22, no. 10, pp. 1305–1411.

Frondel, Clifford, 1943, Mineralogy of the calcium phosphates in insular phosphate rock: Am. Mineralogist, vol. 28, pp. 215–232.

Gale, H. S., 1910, Phosphates in Montana: U. S. Geol. Survey Bull. 470–A.

Gardner, L. S., 1944, Phosphate deposits of the Teton Basin area, Idaho and Wyoming: U. S. Geol. Survey Bull. 944–A.

Grissom, R. J., 1944, Mining and washing phosphate rock in Tennessee: Mining and Metallurgy, vol. 45, no. 454, pp. 477–480.

Hendricks, S. B., Hill, W. L., Jacob, K. D., and Jefferson, M. E., 1931, Structural characteristics of apatite-like substances and composition of phosphate rock and bone as determined from microscopical and X-ray diffraction examinations: Ind. and Eng. Chemistry, vol. 23, pp. 1413–1418.

Kuenen, Ph. H. and Migliorini, C. I., 1950, Turbidity currents as a cause of graded bedding: Jour. Geology, vol. 58, no. 2, pp. 91–127.

Lacroix, A., 1910, Acad. sci. Paris Comptes. rendus, vol. 150, p. 1213.

Larsen, E. S., and Berman, H., 1934, The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 848, 2d ed.

Linck, G., 1903, Die Bildung der Oolithe und Rogensteine: Neus Jahrb., Beilage-Band 16, pp. 495–513.

Mansfield, G. R., 1927, Geography, geology, and mineral resources of part of southeastern Idaho: U. S. Geol. Survey Prof. Paper 152.

———, 1928, The Idaho phosphate field: Mining and Metallurgy, vol. 9, no. 253, pp. 19–20.

McConnell, Duncan, 1938, A structural investigation of the isomorphism of the apatite group: Am. Mineralogist, vol. 23, no. 1, pp. 1–19.

———, 1942, X-ray data on several phosphate minerals: Am. Jour. Sci., vol. 240, pp. 649–657.

McKelvey, V. E., 1949, Geological studies of the western phosphate field: Mining Engineering, vol. 1, no. 8, pp. 270–279.

Morse, H. W., and Donnay, J. D. H., 1936, Optics and structure of three-dimensional spherulites: Am. Mineralogist, vol. 21, no. 7, pp. 391–426.

Newton, J., and Finkelnburg, O. C., 1947, Beneficiation of Idaho phosphate rock: Idaho Univ., School of Mines, Min. Resources Rept. 3.

Norris, E. M., 1944, Underground mining of phosphate rock at Conda, Idaho: Mining and Metallurgy, vol. 25, no. 454, pp. 481–485.

Ostwald, Wolfgang, 1919, Handbook of colloidal chemistry, translated by Martin H. Fischer, p. 51, Philadelphia, P. Blakiston's Son & Co.

Richards, R. W., and Mansfield, G. R., 1912, The Bannock overthrust, a major fault in southeastern Idaho and northeastern Utah: Jour. Geology, vol. 20, pp. 681–709.

Rogers, A. F., 1917, A review of the amorphous minerals: Jour. Geology, vol. 25, pp. 515–541.

———, 1922, Collophane, a much neglected mineral: Am. Jour. Sci., 5th ser., vol. 3, no. 16, pp. 269–276.

Russell, T. C., 1949, Mining of phosphate rock at Conda, Idaho: Mining Engineering vol. 1, no. 8, p. 279.

Sandell, E. B., Hey, M. H., and McConnell, D., 1939, The composition of francolite: Mineralog. Mag., vol. 25, no. 166.

Seeley, H. G., 1889, On the oolitic texture in rocks: Brit. Assoc. Adv. Sci., 58th Ann. Meeting, [1888], Rept., pp. 674–675.

Swainson, S. J., 1944, Washing and concentrating Florida pebble phosphate: Mining and Metallurgy, vol. 45, no. 454, p. 469–474.

Vaughan, T. W., 1914, Preliminary remarks on the geology of the Bahamas, with special reference to the origin of the Bahaman and Floridian oolite: Carnegie Inst. Washington Pub. 182, pp. 51–53.

INDEX

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