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PHOSPHATE ROCK IN THE THREE FORKS-YELLOWSTONE PARK REGION MONTANA

BY

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INTRODUCTION

PREPARATION OF THE REPORT

The following report includes part of an unpublished manuscript written by D. Dale Condit and E. H. Finch shortly after their field examination, in 1916, of a large area in southern Montana. Before their report was prepared for publication these authors severed their connection with the United States Geological Survey. The part of that manuscript relating to the phosphate deposits and their closely related geology has been assembled and reviewed by J. T. Pardee, who, in 1924, visited some of the localities described. In this work, except for rearranging the material, no noteworthy change has been made in the text. Likewise the accompanying map (pl. 12) showing the phosphate outcrops is taken with few changes from the manuscript geologic map of the region prepared by Messrs. Condit and Finch. A summary and a bibliography prepared by Mr. Pardee have been added.

SUMMARY

The region described is about 7,000 square miles in area. It includes most of Gallatin and Madison Counties, in Montana, and some contiguous parts of Idaho and Wyoming. Within it are several broad fertile valleys and a number of prominent mountain ranges. A considerable part is underlain by a bed of phosphate rock which occurs in the Phosphoria formation, of Permian age, and is elevated to the surface of the mountainous area. In most of the middle and southwestern parts of the region this deposit is about 2 feet thick; locally it is 3 feet or more. Outcrops of beds in which the deposit is more than 6 inches thick aggregate more than 200 miles in length. Toward the northeast the deposit thins out, and its limit in that direction is represented fairly accurately by a line drawn from

Yellowstone Park northwestward through Salesville to Willow Creek, on Jefferson River. Its thicker parts contain 45 to 65 per cent of tricalcium phosphate.

In this region the phosphate deposit is thinner and of poorer quality than in the adjoining parts of Montana on the west and northwest, where it is commonly 4 feet thick and contains 65 to 70 per cent of tricalcium phosphate. In southeastern Idaho the deposit is still thicker and richer.

NATURE AND SCOPE OF THE REPORT

It has been known for a number of years that important phosphate fields lie to the west and southwest of Helena, Mont., near Elliston, Garrison, and Drummond, and also to the south at Melrose,[1] through reports of Gale, Pardee, Richards, and Stone. The extensive fields in Idaho, Utah, and western Wyoming have been mapped by Gale, Richards, Schultz, Blackwelder, Mansfield, Richardson, Condit, and others. There remained unexplored a large intervening area in southwestern Montana and the western part of Yellowstone Park, comprising some 7,000 square miles, which showed extensive outcrops of the Phosphoria formation, suspected of containing beds of phosphate rock. It was with the object of ascertaining the extent and value of the phosphate beds in this area that the field work summarized in this report was undertaken. The location and extent of the area studied are shown in Figure 11.

EARLIER EXAMINATIONS AND MAPS

Prior to the field work of 1916 almost nothing was known of the occurrence of phosphate within this area. Reconnaissance surveys of the Livingston and Three Forks quadrangles and of the Yellowstone National Park were made more than 30 years ago and the results were published.[2] Outside these areas little was known of the geology, especially in the southern part, along upper Madison River, Centennial Valley, and the Continental Divide, and in the Snowcrest Mountains, west of Ruby River.

The topographic maps of the Livingston, Three Forks, and Gallatin quadrangles based upon the old surveys, though fair maps of the reconnaissance type, need revision. A partial revision of the Gallatin map was effected in 1910, when a new map of Yellowstone National Park was prepared. The Forest Service has made a topo-

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[1] See Nos. 8, 13, 15, and 22, in bibliography, pp. 154, 156, 157, 159.

[2] U. S. Geol. Survey Geol. Atlas, Livingston folio (No. 1), 1894; Three Forks folio (No. 24), 1896; Yellowstone National Park folio (No. 30), 1896. Hague, Arnold, and others, Geology of the Yellowstone National Park: U. S. Geol. Survey Mon. 32, pt. 2, 1899.

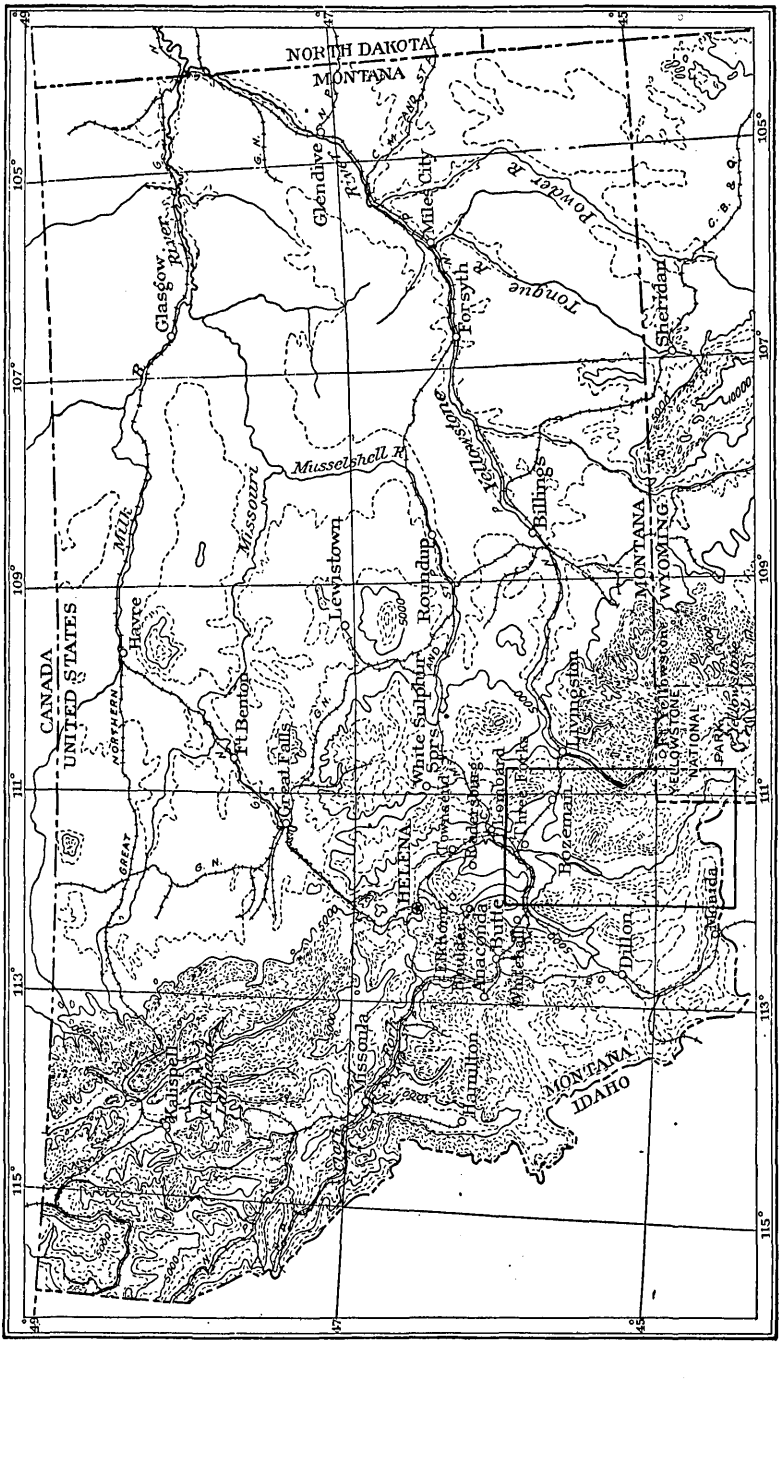

FIGURE 11.—Index map showing location of Three Forks-Yellowstone Park region, Montana

graphic survey of the Targhee National Forest, and the maps are published in the Targhee Forest atlas. Similar maps have been prepared for a portion of the Madison National Forest, including most of the Gravelly Range and Snowcrest Mountains. Township plats by the General Land Office are available for most of the remaining areas.

The southern portion of the field west of Yellowstone National Park had not been previously mapped.

FIELD WORK

Field work was started early in June, 1916, and was continued until September 15, the latest date that geologic work is ordinarily practicable in the mountainous part of this region, because of snowfall. The examination was begun in the vicinity of Helena and extended southward through the Elkhorn and Radersburg mining region to Cardwell and Three Forks. The route followed from those points was southward to Norris, eastward to the Gallatin Valley, and up it into Yellowstone National Park, thence westward down Centennial Valley, and again northward down Madison Valley, the mountain slopes on both sides being worked. Ruby Valley and Snowcrest Range, to the west, were reached by pack horse from Madison Valley. Throughout the entire itinerary supplies were hauled by camp wagon along the principal wagon routes, from which they were carried by pack horse to the camps in the mountains.

At the time the earlier geologic work was done the presence of rock phosphate was not known and the Phosphoria formation had not been defined. Nevertheless, the geologic folios available were of great assistance in the detailed examination of the Phosphoria, and, except for the mapping of that formation and the making of minor corrections in a few places, no attempt was made to revise their geology. Some readjustment of geologic boundaries was necessary, however, in order to tie the phosphate outcrops to the section corners of the General Land Office surveys.

In areas where no good maps were available plane-table and alidade surveys were made and the control established by triangulation from the principal peaks. In areas covered by land surveys the phosphate exposures were tied to section corners.

The map accompanying this report is a compilation based upon the sources mentioned, supplemented by the surveys made by the field party.

In August, 1924, parts of the Madison Range and some adjacent areas were reviewed in the field by J. T. Pardee.

Mention should be made of the uniform hospitality of the inhabitants and of the many courtesies extended by officials of the Forest Service, who permitted the use of ranger stations and furnished a number of excellent maps.

BIBLIOGRAPHY

The principal reports describing the western phosphate fields are listed below and numbered in the order of their publication. After each title is a summary of some of the more interesting features described. The character, composition, thickness, and geologic associations of the phosphate beds are treated more or less fully in nearly all the reports. Information on special subjects is given in the reports indicated by the numbers following:

Discovery of the western phosphate deposits	5, 8, 11, 13, 19, 31
Examination of the western phosphate lands by the Geological Survey with relation to their classification as mineral lands	2, 3, 7, 9, 12, 15, 16, 18, 22, 24, 25, 29, 30, 38
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Publications of the Geological Survey for which a price is given can be purchased, as long as the supply lasts, from the Superintendent of Documents, Government Printing Office, Washington, D. C. Other Survey publications listed here as out of print are not available for distribution but may be consulted at the larger public libraries and at the libraries of the larger educational institutions throughout the country.

1. Weeks, F. B., and Ferrier, W. E. Phosphate deposits in the western United States: U. S. Geol. Survey Bull. 315, pp. 449–462, 1907. Out of print.

Within the few years just prior to 1906 oolitic beds containing a variable precentage of phosphoric acid (P_2O_5) were found in the upper Carboniferous rocks over considerable areas in southeastern Idaho, southwestern Wyoming, and northeastern Utah. The phosphatic series, which in places is about 90 feet thick, consists of alternating layers of phosphate rock, shale, and limestone. The phosphate beds range in thickness from a few inches to 10 feet; the richest bed is 5 or 6 feet thick.

2. Gale, H. S., and Richards, R. W., Preliminary report on the phosphate deposits in southeastern Idaho and adjacent parts of Wyoming and Utah: U. S. Geol. Survey Bull. 430, pp. 457–535, 1910. Out of print.

Lands in this region supposed to contain phosphate deposits having been withdrawn from entry, the United States Geological Survey in 1909 began their examination and classification.

The sedimentary rocks of the areas covered in this report are described as ranging in age from the Mississippian Madison limestone to the Cretaceous Bear River formation, and as including the Park City formation [Pennsylvania and Permian], which is made up of cherty limestone, phosphatic beds, and limestone, mentioned in descending order. The phosphate member, which is as much as 200 feet thick, consists of phosphatic shale and beds of phosphate rock with some limestone and chert. In Georgetown Canyon, Idaho, the exposed phosphate-bearing strata have an aggregate thickness of 140 feet, practically all of which is phosphatic. Of these beds 73 feet, or slightly more than half, contains more than 40 per cent of tricalcium phosphate, and about 21 feet of this contains more than 60 per cent. The main phosphate bed, which is 6 feet thick, contains 80 per cent of tricalcium phosphate. Four other beds in the same section, which aggregate nearly 14 feet in thickness, contain from 64 to 82 per cent. At several other places the deposits are comparable in size and composition, though the phosphatic member is less rich.

The phosphate rock is characterized by an oolitic texture, being usually a mass of small rounded grains of concentric structure, more or less cemented together with phosphate or foreign material. Its color ranges from coal black to dull gray or rusty brown. Its weathered surface is charecteristically coated with a thin bluish-white film. When struck with a hammer the rock gives off a fetid odor. This feature and the black color are due to the presence of bituminous matter. In some places a little fluorite occurs as an associated mineral.

An estimate covering part of the field shows the amount of phosphate rock available in beds 5 feet or more thick and containing at least 70 per cent of tricalcium phosphate to be 266,000,000 tons. In addition there is a much larger amount of lower grade rock present.

3. Blackwelder, Eliot, Phosphate deposits east of Ogden, Utah: U. S. Geol. Survey Bull. 430, pp. 536–551, 1910. Out of print.

A continuation of the examination of western phosphate lands by the United States Geological Survey. Deposits of phosphate rock have been found at two horizons in the Paleozoic rocks of the district. The lower bed, which is in the Mississippian limestone, comprises black and brown shale distributed through 100 to 200 feet of the vertical section. Analyses of some of the black shale show less than 20 per cent of tricalcium phosphate, but pieces of much richer oolitic phosphate rock have been found along the outcrop of the shale zone.

The upper and richer deposit occurs in the Park City formation [Pennsylvanian and Permian; includes at the top the equivalent of the beds later named Phosphoria formation]. It includes two beds, each of which averages 7 or 8 feet in thickness and several beds that range from 1 to 3 feet in thickness. The stratigraphic section exposed near Robison's ranch, in Weber Canyon, shows 1,200 feet of limestone with some sandstone, chert, and shale. Here the principal beds of phosphate rock are 10 and 13 feet thick, and contain 39 and 46 per cent, respectively, of tricalcium phosphate.

4. Girty, G. H., The fauna of the phosphate beds of the Park City formation in Idaho, Wyoming, and Utah: U. S. Geol. Survey Bull. 436, 82 pp., 1910. 20c.

The fauna includes 45 species, 2 of which are worms and the remainder invertebrate shellfish. It possesses a remarkable individuality but can be recognized as belonging to a Carboniferous fauna, widely dispersed over the West and traceable even into Alaska, Asia, and eastern Europe. On the other hand, it appears quite unrelated to any of the faunas of the Mississippi Valley. Some of its peculiarities are the entire absence of Protozoa, corals, and Bryozoa, which are well represented in most American Carboniferous faunas, and the rather rare and restricted occurrence of brachiopods, except for the genus *Chonetes*, which ordinarily is not very plentiful. The scarcity of *Productus* and the Spiriferidae is noteworthy. The gastropods, pelecypods, and goniatites, on the other hand, are somewhat unusually well represented. The most common and characteristic types of the phosphate fauna are *Chonetes ostiolatus* and its varieties, *Pugnax weeksi*, *P. weeksi* var. *nobilis*, *Omphalotrochus ferrieri*, and *O. conoideus*. *Nucula montpelierensis*, *Yoldia mcchesneyana*, and *Gastrioceras simulator* also deserve mention. (See also No. 10.)

5. Richter, A. Western phosphate discovery: Mines and Methods, vol. 2, No. 9, May, 1911, p. 207.

The writer claims to have discovered in 1889 phosphate rock in the La Plata district, 50 miles northeast of Ogdon, Utah, and to have traced the deposit from that locality to Bear Lake, Idaho. In this work he came upon old workings and location notices claiming parts of the deposit for gold, silver, etc., but no evidence that any of his predecessors had recognized the material as phospate rock. In 1910 he submitted samples of the phosphate rock which analyzed as much as 70 per cent of tricalcium phosphate to leading fertilizer manufacturers of Chicago, but his efforts to interest them in developing the deposit were unsuccessful.

6. Breger, C. L., Origin of Lander oil and western phosphate: Min. and Eng. World, vol. 35, pp. 631–633, 1911.

The black shales [of the phosphatic series] and the phosphate beds are [in the western field] everywhere bituminous, and in the Lander field they are the source of oil. The bitumen and the phosphate are regarded to have a common origin in Carboniferous time from a submarine ooze or slime of microorganic nature, probably composed largely of bacteria. These organisms are thought to have extracted the calcium phosphate from sea water and deposited it in the present phosphatic beds. The slime, entombed by sediments, has in time generated the petroleum.

7. Richards, R. W., and Mansfield, G. R., Preliminary report on a portion of the Idaho phosphate reserve: U. S. Geol. Survey Bull. 470, pp. 371–439, 1911. Out of print.

The examination of phosphate lands in the western field by the United States Geological Survey begun in 1909 was continued in 1910. This report covers portions of Bear Lake and Bannock Counties, Idaho.

The phosphate-bearing member [later named Phosphoria formation] of the Park City formation consists of 77 to 140 feet of phosphatic sandy shale and beds of phosphate rock with some limestone and bands of chert. Locally the phosphate beds are inferior in quality and quantity to those of the Georgetown Canyon section (see No. 2), but in general they are comparable in richness and volume. The main structural features of the region are broad synclinal troughs, broken intervening anticlinal ridges, and the great folded and overthrust mass composing the Bear River Range. The phosphate beds were included in the folding, and the parts of them that have escaped subsequent erosion are confined chiefly to the synclines. The amount of phosphate rock available in the nine townships reviewed is estimated at more than a billion tons.

8. Gale, H. S., Rock phosphate near Melrose, Mont.: U. S. Geol. Survey Bull. 470, pp. 440–451, 1911. Out of print.

Phosphate rock discovered by the author at this locality is of the same type as the deposits in southeastern Idaho. (See also No. 2.) The deposit occurs in Pennsylvanian rocks which overlie the massive quartzite of the Quadrant formation. It is correlated with the deposits in Idaho, Wyoming, and Utah. At one place a trench exposes two beds of phosphate each a little more than 3 feet thick and containing about 30 per cent of phosphoric acid (P_2O_5), equivalent to about 65 per cent of tricalcium phosphate. One of the beds may be a repetition of the other, due to faulting.

9. Blackwelder, Eliot, A reconnaissance of the phosphate deposits in western Wyoming: U. S. Geol. Survey Bull. 470, pp. 452–481, 1911. Out of print.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The strata that include the phosphate beds lie between two conspicuous horizon markers. The lower marker is a sandy series which comprises the Weber quartzite in Idaho and Utah and the Tensleep sandstone in central Wyoming. Its basal portion has been called the Morgan formation in Utah, and corresponding beds in north central Wyoming were named Amsden by Darton. The outcrops of these rocks are resistant to erosion and usually form ridges, peaks, or cliffs. The upper horizon marker is a bright-red series of sandstone and shale with gypsum called the Chugwater formation in north-central Wyoming. In southeastern Idaho it is probably represented by the Nugget sandstone and the Ankareh shale. Between the two markers lie less resistant strata which include the phosphate beds. In north-central Wyoming these strata are relatively thin and have been named Embar formation. Farther west, in the Hoback and Salt River Ranges, they are thicker and somewhat different in character, and there they may be divided into several formations, representing probably the Park City, Woodside, and Thaynes formations of Idaho and Utah. The phosphate beds are associated with dark shale and fossiliferous limestone and lie near the base of the Embar formation to the east and the Park City formation to the west.

In the canyon of Snake River, in western Wyoming, the total thickness of phosphate beds exceeds 40 feet. Of this 29 feet contains more than 30 per cent of tricalcium phosphate, and some beds exceed 70 per cent. On the north side of the Wind River Range the beds have dwindled in thickness to 3 or 4 feet and contain only 35 to 40 per cent of tricalcium phosphate. In the Shoshone and Owl Creek Mountains the deterioration is still more marked. In general the rocks associated with the phosphate deposit are folded mildly toward the east and much more intensely toward the west.

10. Richards, R. W., and Mansfield, G. R., The Bannock overthrust: Jour. Geology, vol. 20, pp. 681–709, 1912.

The stratigraphy of southeastern Idaho and the adjoining part of Utah includes beds ranging in age from Middle Cambrian to Quaternary, including the phosphate-bearing Phosphoria formation, provisionally regarded as Permian. The Phosphoria formation, named from Phosphoria Gulch, a branch of Georgetown Canyon near Meade Peak, Idaho, ranges from 75 to 627 feet in thickness and averages 350 feet. Included in the Phosphoria is the Rex chert member, which ranges from a feather-

edge to 450 feet in thickness. As measured in detail in the neighborhood of Phosphoria Gulch the phosphate shale beds are 175 feet thick and the Rex chert 240 feet. The Phosphoria is equivalent to the two upper members of the Park City formation, namely, the "overlying chert" and the phosphate shale, as heretofore mapped in this region. It is also correlated with the upper part of the Embar formation of Wyoming and the phosphatic beds above the Quadrant formation in southwestern Montana.

The Rex chert is generally nonfossiliferous, but locally it contains sponge spicules and casts of crinoid stems. The following species are listed by Girty as the most characteristic:

Productus multistriatus.
Productus subhorridus.
Spirifer aff. S. cameratus.
Spiriferina pulchra.
Composita subtilita var.

From the extensive fauna of the phosphate shale Girty has selected the following as characteristic species: (See also No. 4.)

Lingula carbonaria?
Lingulidiscina missouriensis.
Chonetes ostiolatus.
Productus geniculatus.
Productus eucharis.
Productus montpelierensis.
Productus phosphaticus.
Pugnax weeksi.
Pugnax osagensis var. occidentalis.
Ambocoelia arcuata.
Leda obesa.
Plagioglypta canna.
Omphalotrochus ferrieri.
Omphalotrochus conoideus.
Hollina emaciata var. occidentalis.

In this region a great fault, named the Bannock overthrust, causes older rocks to overlie the Phosphoria and associated formations. The trace of this fault, which trends in general a little west of north, is exposed at intervals from the vicinity of Woodruff, Utah, nearly to Idaho Falls, Idaho, a distance of 270 miles. In general the fault plane dips slightly westward, and the mass of rocks above it was shoved eastward and over the mass below for a distance of at least 12 miles and probably 35 miles or more. The fault plane has been deformed by later faults and folds, and portions of the overthrust block have been separated from the main mass by erosion.

11. Jones, C. C., The discovery and opening of a new phosphate field in the United States: Am. Inst. Min. Eng. Bull. 82, pp. 2411–2435, October, 1913.

In 1897 an outcrop of phosphate rock on Twelvemile Creek, a branch of Woodruff Creek, Rich County, Utah, on which there was an old working, was located by R. A. Pidcock, who believed it to be gold ore. Afterward the property came into the possession of the Alice Mining Co., which did considerable development work and, finding no gold, sent a sample of the deposit (sometime during or after 1899) to Thomas Price & Sons, of San Francisco, whose analysis revealed the fact that it contained among other things phosphoric acid equivalent to 70 per cent of tricalcium phosphate. In 1903, after an examination by the author, the property was purchased by the Mountain Copper Co., of Keswick, Calif. During this and the following year the author examined the phosphate deposits near Montpelier, Idaho, and at several places in the neighboring parts of Wyoming and Utah. Fossils which he collected at these places and sent to the United States Geological Survey were determined by Girty as upper Carboniferous. In January, 1907, phosphate rock was being mined and shipped from Montpelier, Idaho, and Cokeville, Wyo. Rock mined in Utah was shipped from Sage Station, Wyo.

12. Schultz, A. R., and Richards, R. W., A geologic reconnaissance in southeastern Idaho: U. S. Geol. Survey Bull. 530, pp. 267–281, 1913. Out of print.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The area covered lies mostly along Snake River, north of the lands examined in 1909 and 1910. The rocks are described as including, in ascending order, the Madison limestone, 1,000 feet or more thick, an upper Mississippian limestone about 1,100 feet thick, the Wells formation (Pennsylvanian) of sandstone and limestone, aggregating 2,400 feet in thickness, the Phosphoria formation [Permian], and the Woodside, Thaynes and Ankareh formations, all assigned to the Lower Triassic. [The Wells and Phosphoria formations include equivalents of the Park City formation of the earlier reports.] The Phosphoria formation carries the economically valuable deposits of phosphate of the general region. It consists of an upper member, called the Rex chert member, which commonly ranges from 100 to 240 feet in thickness and consists mainly of chert, and a lower member, which consists of 75 to 600 feet or more of alternating shale, sandstone, and limestone with one, two, or three zones bearing beds of high-grade oolitic phosphate rock that range from 1 to 7 feet in thickness and contain 70 per cent or more of tricalcium phosphate.

13. Pardee, J. T., Some further discoveries of rock phosphate in Montana: U. S. Geol. Survey Bull. 530, pp. 285–291, 1913. Out of print.

In 1911 phosphate rock was discovered near Garrison, Philipsburg, and Elliston, western Montana. The deposits are of the same type as the phosphate found near Melrose (see No. 8) and in the Idaho-Wyoming field (see No. 2). The phosphate occurs in the upper part of the Pennsylvanian Quadrant formation, a few feet above a massive quartzite and beneath beds of chert. Near Garrison a bed 4 feet thick contains, as sampled at the outcrop, 70 per cent of tricalcium phosphate. Samples of float (loose fragments in the surface mantle) from Philipsburg and Elliston yielded more than 60 per cent of tricalcium phosphate.

14. Schultz, A. R., Geology and geography of a portion of Lincoln County, Wyo.: U. S. Geol. Survey Bull. 543, pp. 31, 132–135, 1914. Out of print.

The Carboniferous rocks of this area are described as consisting of 8,000–9,000 feet of undifferentiated Mississippian and Pennsylvanian limestone, above which is 1,000 feet of Weber quartzite. The Weber is overlain by 1,400 feet of limestone, shale, and sandstone that make up the Park City formation [Pennsylvanian and Permian], near the middle of which are the phosphate deposits. Above the Park City is the Woodside formation of red and brown sandstone and shale. The beds are bent into folds that trend north or northwest and are cut by some large faults of similar trend.

In many places the Park City formation may be divided into three members. The upper member consists of chert and limestone, the lower of limestone, and the middle of phosphate rock, shale, and limestone. Brown and black phosphate beds on Fontenelle Creek are about 50 feet thick (composition not given). Samples from other places (thickness not given) contained from 25 to 34 per cent of tricalcium phosphate.

15. Stone, R. W., and Bonine, C. A., The Elliston phosphate field, Mont.: U. S. Geol. Survey Bull. 580–N, pp. 373–383, 1914. 5c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The Madison limestone is overlain by about 700 feet of later Carboniferous rocks, of which the upper 80 feet is correlated with the Phosphoria formation of Idaho. Above these rocks are sandstone, shale, and limestone of Mesozoic age. The beds are bent into an arch and a trough and are cut by faults. At the base of the rocks correlated with the Phosphoria is a bed of phosphate rock that ranges from 3 to 6 feet in thickness and carries from 60 to 72 per cent of tricalcium phosphate. An area of 8½ square miles is estimated to be underlain by the phosphate bed, which averages 4 feet in thickness and contains an available amount of 86,000,000 tons.

16. Richards, R. W., and Mansfield, G. R., Geology of the phosphate deposits northeast of Georgetown, Idaho: U. S. Geol. Survey Bull. 577, 76 pp., 14 pls., 1914. Out of print.

A continuation, in 1911, of the geologic examination of the western phosphate field carried on by the United States Geological Survey in 1909 and 1910. (See Nos. 2 and 7.) The area covered comprises portions of Bear Lake and Bannock Counties and lies mostly north and east of the lands previously examined. The authors give descriptions of the stratigraphy and structure which are much more detailed but otherwise similar to the earlier descriptions. The sections of the phosphate shales measured in 1909 in Georgetown Canyon (see No. 2) is the most satisfactory one obtained so far in the western fields and shows the maximum phosphate content. The several new sections measured in different places show more or less variation in thickness and quality of the phosphate. In general a bed of phosphate rock not more than 3 feet thick occurs near the top of the phosphate shale, and at the base there is usually a bed as much as 8 feet thick, containing about 70 per cent of tricalcium phosphate.

17. Blackwelder, Eliot, Origin of the Rocky Mountain phosphate deposits: Geol. Soc. America Bull., vol. 26, pp. 100–101, 1915 (abstract).

Special conditions of temperature and currents in the ocean, together with other factors not yet understood, may have induced the wholesale killing of animals over large areas and the accumulation of putrefying matter on the sea floor at moderate and shallow depths. Decomposition through the agency of bacteria produced ammoniacal solutions which dissolved the calcium phosphate present in bones, shells, etc. Abundant carbonic acid arising from decay probably dissolved most of the calcareous shells descending from the surface. For physicochemical reasons the phosphatic material was quickly redeposited as hydrous calcium carbophosphates, locally replacing shells, etc., but especially forming granules of colophanite and finally a phosphatic cement among all particles.

18. Mansfield, G. R., A reconnaissance for phosphate in the Salt River Range, Wyo.: U. S. Geol. Survey Bull. 620–O, pp. 331–349, 1916. 15c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The area examined includes sedimentary rocks ranging in age from early Carboniferous (Madison limestone) to Quaternary. The Phosphoria [Permian] consists of the Rex chert member, 250 to 300 feet thick, and underlying phosphate shales 65 to 150 feet thick, which contain several beds of phosphate rock. The structure is complex and involves at least two great folds and a number of faults. The phosphate shales have a thickness comparable to that of the same formation in the Idaho field. The phosphate deposits are probably inferior but contain a considerable amount of medium-grade rock. Samples of float (loose pieces in the surface mantle) indicate the presence of a bed, which may not exceed 1 foot in thickness, containing as much as 70 per cent of tricalcium phosphate.

19. De Schmid, H. S., Investigation of a reported discovery of phosphate in Alberta: Canada Dept. Mines, Mines Branch, Bull. 12, 1916.

In the neighborhood of Banff, Alberta, about 350 miles north of Elliston, Mont. (see No. 15), a phosphate bed which occurs in the upper part of the Rocky Mountain quartzite (Pennsylvanian) is, together with some associated chert, quartzite, and shale, correlated with the Phosphoria formation of Idaho and neighboring States. The phosphate rock is black, fine grained, and compact, resembling somewhat an igneous rock. It does not show the oolitic texture or bluish-gray "bloom" characteristic of the Montana and Idaho deposits. Analyses show from 20 to 63 per cent of tricalcium phosphate, and the average of nine samples from the main bed was 44 per cent. The chief impurity is silica in the form of quartz grains, which locally are so abundant that the rock becomes a phosphatic quartzite. The main phosphatic bed averages about 1 foot in thickness, and all the phosphatic layers are confined within a part of the stratigraphic section about 3 feet thick.

20. De Schmid, H. S., A reconnaissance for phosphate in the Rocky Mountains: Canada Dept. Mines, Mines Branch, Summary Rept. for 1916, pp. 22–34, 1917.

The phosphate bed previously discovered near Banff (see No. 19) was traced south as far as Tent Mountain, near Crowsnest, B. C. (about 120 miles south of Banff, 35 miles north of the international boundary, and 200 miles north of Elliston, Mont.). Contrary to expectation the field work indicates that the phosphate bed thins out in a southeasterly direction from Banff and at the same time becomes poorer in phosphoric acid. At Tent Mountain the bed is a thin layer of small phosphatic nodules in a quartzite matrix. South of Tent Mountain no outcrops of phosphate were found in either the Livingstone or Macdonald Ranges. In the area examined the phosphate bed, in addition to becoming thinner and poorer, assumed a conglomeratic character.

21. Condit, D. D., Relations of the Embar and Chugwater formations in central Wyoming: U. S. Geol. Survey Prof. Paper 98, pp. 263–270, 1916. Out of print.

The Embar formation has in recent years attracted attention on account of its yield of petroleum in the Wind River Basin and also on account of its phosphate beds, which have been traced and mapped by the United States Geological Survey throughout the Wind River and Owl Creek Mountains. In its typical development the Embar consists of an upper shale part and a lower limestone part, but it includes phosphatic and calcareous shale and nodular chert. The lower part is identified with the Park City formation of Utah by Blackwelder, who has suggested the name Dinwoody formation for the upper shale part. Somewhat meager evidence indicates that the Dinwoody beds are of Triassic age and are to be correlated with the Woodside shale and Thaynes limestone of southeastern Idaho.

In the Wind River and Owl Creek Mountains the Park City part of the Embar consists in general of dolomitic and shaly limestones, shale, cherty limestone, phosphatic shale and phosphate rock, phosphatic chert, and limestone, mentioned in ascending order. A section on the northeastern slope of the Wind River Mountains shows an upper phosphate bed about 3 feet thick, containing 41 to 44 per cent of tricalcium phosphate, and a lower bed about 2 feet thick, containing 36 to 48 per cent.

Eastward the Dinwoody and Park City gradually change in character and composition. The Dinwoody becomes thinner and increasingly gypseous, and the Park City shows increasing amounts of red shale, the appearance of beds of unmixed gypsum, the disappearance of beds of concentrated phosphate rock, and other changes. A nodular chert member, however, is common to all localities. The equivalent of these formations, except the lowest limestone bed, is the lower part of the Chugwater red beds as exposed in the Big Horn Mountains. [Recent unpublished work by W. T. Lee throws doubt on some of these correlations.]

22. Pardee, J. T., The Garrison and Philipsburg phosphate fields, Mont.: U. S. Geol. Survey Bull. 640-K, pp. 195–228, 1917. 10c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. In addition to other rocks, a series of sedimentary beds ranging in age from Cambrian to Cretaceous is exposed, which includes the Madison limestone, the Quadrant (?) quartzite, and the Phosphoria formation. In the Garrison field, near the base of the Phosphoria and from 450 to 550 feet above the Madison limestone, is a bed of phosphate rock 4 feet thick that contains 65 to 75 per cent of tricalcium phosphate. Toward the west this deposit thins out and gives place to a bed of sandstone containing phosphate nodules. In the Philipsburg field the phosphate bed lies 350 to 650 feet above the Madison limestone. At Philipsburg it is made up of several layers of varying richness that aggregate about 15 feet in thickness. The richest layer, which is 1 foot 4 inches thick, contains nearly 70 per cent of tricalcium phosphate. In both fields the bed is steeply inclined and favorably situated for mining. In the Garrison field 97,000,000 tons is estimated as available.

The deposit is of marine origin and is thought to have accumulated because of low temperature of the sea water at that time, which produced conditions unfavorable to the growth of coralline limestone.

23. Mansfield, G. R., Origin of the western phosphate of the United States: Am. Jour. Sci., 4th ser., vol. 46, pp. 591–598, October, 1918.

Available knowledge indicates that (1) the sea in which the phosphate was deposited was separated from the main ocean to the east, south, and west, but may have been open to the north and northwest; (2) detrital material from the land is largely absent from the deposit; (3) the period of deposition may have been long; (4) the oolitic texture characteristic of much of the western phosphate is doubtless connected with the origin of the rock, like the oolitic texture of certain beds in Pennsylvania, for example, which is regarded by Brown (see Geol. Soc. America Bull., vol. 25, pp. 745–780, 1914) as derived from calcareous oolites composed of the mineral aragonite, which originally formed the beds, the aragonite having since been replaced by other minerals without destroying its oolitic texture. Phosphates resembling those actually found have been produced experimentally by the reaction upon mineral substances of ammonium phosphate, a compound which results from the ordinary process of bacterial decay. Calcareous oolites, composed largely of aragonite precipitated by denitrifying bacteria, are now forming in tropical waters, and it has been concluded that great limestone formations were laid down in waters that were warm, at least near the surface.

From these facts it is deduced as a tentative working hypothesis that the phosphatic oolites and matrix were deposited originally as aragonite in the warm shoal waters of a sea bordered by land that furnished little sediment. Afterward cooling of the waters checked the activities of denitrifying bacteria, and hence the conditions became unfavorable for the formation of oolitic limestone. At the same time plant and animal life increased and furnished the decaying matter necessary to phosphatize the oolitic limestone already accumulated. As suggested by Blackwelder (see No. 17), this process may have been hurried by wholesale killings of marine animals, due to abrupt changes in temperature. Recurrence of the conditions outlined would account for the successive beds of phosphate rock. [As given in U. S. Geol. Survey Prof. Paper 152, the author's views have been modified since publication of this paper.]

24. Schultz, A. R., A geologic reconnaissance for phosphate and coal in southeastern Idaho and western Wyoming: U. S. Geol. Survey Bull. 680, 84 pp., 1918. 10c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. This area, which was examined in 1912, includes about 2,000 square miles in the vicinity of Big Bend of South Fork of Snake River and lies north and east of lands previously examined for phosphate by the Geological Survey. The rocks range in age from pre-Cambrian to Quaternary and include the Phosphoria formation (Permian), which is from 75 to 100 feet thick and is composed of the Rex chert member and, below it, sandstone, shale, limestone and phosphate rocks. The structure is complex, involving large folds and great thrust faults.

Phosphate rock was recognized at several places, at most of which the principal bed is from 2 to 4 or 5 feet thick and contains 60 to 75 per cent of tricalcium phosphate. In addition beds of lower-grade material are present. In several places a little work has been done along the phosphate outcrop by prospectors looking for coal.

The field work was not sufficiently detailed to permit tonnage estimates, but the author concludes that parts of the region contain a large amount of phosphate rock.

25. Schultz, A. R., A geologic reconnaissance of the Uinta Mountains, northern Utah, with special reference to phosphate: U. S. Geol. Survey Bull. 690–C, pp. 31–94, 1918. 15c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. Phosphate deposits are found both north and south of the Uinta Mountains in the Park City formation (Pennsylvanian and Permian), which is equivalent to the Phosphoria formation and the Wells formation of eastern Idaho. The beds crop out along the flanks of the Uinta anticline along a flat-topped east-west fold and are included in secondary folds and faults.

The phosphatic series is about 35 feet thick but varies from place to place. Individual beds in this series contain from 1 to 70 per cent of tricalcium phosphate. These beds vary in character and richness but in some respects are rather uniform throughout the field. Generally the richest portion of the series is dark colored and contains tarlike hydrocarbon compounds. Certain layers are filled with disk-shaped fossils (*Lingulidiscina*) and specimens of *Nucula* and other small pelecypods. The richest beds range from 1 to 6 feet in thickness, and samples from a number of places, some of which represent the bed in place and some of which are float, are shown by analyses to contain 40 to 67 per cent of tricalcium phosphate. No tonnage estimates were made, but the author concludes that a large amount of phosphate is present.

26. Bowen, C. F., Phosphatic oil shales near Dell and Dillon, Beaverhead County, Mont.: U. S. Geol. Survey Bull. 661, pp. 315–320, 1918. Out of print.

A bed of oil shale which occurs in the Phosphoria formation at nearly the same horizon as the extensive beds of phosphate rock elsewhere in the western phosphate field was sampled at two places. Analyses of the samples show the recovery of 7½ and 24 gallons of oil per ton, by dry distillation, and the presence of about 34 and 6 per cent, respectively, of tricalcium phosphate. The phosphate is not driven off by distillation or burning of the shale. The author suggests that a method for obtaining ammonium phosphate from this shale might be developed. The extent of the deposit was not determined, but reports indicate that it may be widely distributed.

27. Condit, D. D., Relations of late Paleozoic and early Mesozoic formations of southwestern Montana and adjacent parts of Wyoming: U. S. Geol. Survey Prof. Paper 120–F., pp. 111–121, 1918. 10c.

Formations from the Madison limestone (Mississippian) to the Kootenai formation (Lower Cretaceous) are discussed, including the Phosphoria. The Quadrant quartzite of Yellowstone Park is approximately equivalent to the Amsden and Tensleep formations of Wyoming. The Park City (Pennsylvanian and Permian), Dinwoody (Lower Triassic), and Chugwater (largely Triassic) of Wyoming are in part represented by the Teton formation of Yellowstone Park. The quartzitic cherty basal beds of the Teton, containing the phosphate rock, are equivalent to the Phosphoria formation of Idaho, which corresponds to the upper part of the Park City formation.

The Phosphoria consists of 100 to 250 feet of dark-gray cherty quartzite and layers of nodular chert and shale with one or more beds of phosphate rock. In Yellowstone Park and to the west along the Idaho State line the irregular layer of phosphate rock at the base is made up of fragments of phosphatized shells of *Lingulidiscina* and fossil bones. In places the phosphatic material is a resinous brown cement binding the quartz sandstone. At 30 to 60 feet above the base of the Phosphoria are other phosphate beds consisting of black oolitic phosphorite associated with dark shale and chert. Northeast of a line drawn from Helena to the northwest corner of Yellowstone Park both the shale and the phosphate beds are lacking.

Prior to the encroachment of the sea from the northwest in late Jurassic time erosion to base level occurred over much of the Rocky Mountain region. From the Idaho State line near Yellowstone Park northward to the vicinity of Helena this erosion surface cuts across beds of Triassic and Carboniferous age through a stratigraphic range of about 1,000 feet. North of latitude 45° 30′ (a little south of the latitude of Bozeman) the Triassic was completely removed, and the Ellis formation (Upper Jurassic) rests on the partly eroded Phosphoria formation.

28. Condit, D. D., Oil shale in western Montana, southeastern Idaho, and adjacent parts of Wyoming and Utah: U. S. Geol. Survey Bull. 711, pp. 15–40, 1919. Out of print.

The Phosphoria formation, which appears to extend through a considerable part of the Dillon-Dell area, Beaverhead County, Mont., has been observed in several places to contain oil shale and phosphate rock closely associated with one another. The oil shale occurs in beds 3 feet or more thick, yields 25 to 30 gallons of oil to a ton, and is also more or less phosphatic. The beds of phosphate rock range from 3½ to 5½ feet in thickness, contain 42 to 52 per cent of tricalcium phosphate, and yield 2 to 4 gallons of oil to a ton. The details of a section measured at Daly spur, on the Oregon Short Line Railroad, in an old tunnel driven under the supposition that the oil shale and phosphate deposit was coal, are given below.

Section at Daly spur, in T. 9 S., R. 10 W.

[Analyses by E. T. Erickson, R. C. Wells, and Benedict Salkover]

Character of beds	Thickness	Oil	Tricalcium phosphate (equivalent of P_2O_5 determined)	Ammonium sulphate (theoretical equivalent of the nitrogen determined)
	Ft. in.	*Gallons per ton*	*Per cent*	*Pounds per ton*
Shale, cherty, phosphatic	9+			
Shale, dark brown, bony	4 8	14	7.11	47.1
Phosphate, dark, oolitic, interbedded with oolitic shale	4 7		42.31	18.9
Shale, black, bony	14	17	3.85	72.6
Shale, brownish gray	1			
Shale, dark brown, bony	10	13		
Lower strata not exposed.				

29. Mansfield, G. R., Geography, geology, and mineral resources of the Fort Hall Indian Reservation, Idaho: U. S. Geol. Survey Bull. 713, pp. 28–30, 61–66, 105–114, 1920. 50c.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The sedimentary rocks, except for the Cretaceous and some of the Tertiary, which are missing, present a rather full sequence from early Cambrian to Quaternary. The Phosphoria (Permian) includes about 350 feet of flinty shale and chert composing the Rex chert member and about 150 feet of phosphate shale. The geologic structure is complex and involves both folding and faulting. The main phosphate bed occurs near the base of the Phosphoria formation, is about 6 feet thick, and contains 71 to 75 per cent of tricalcium phosphate.

The amount of phosphate available in the five townships examined is estimated at more than 738,000,000 tons. This estimate relates only to the main bed and thus excludes some workable high-grade rock and much lower-grade rock that may eventually become workable. Estimates to date for the western fields, including the Elliston and Garrison fields in

Montana, make a total of nearly 5½ billion tons. From areas for which estimates have not yet been made or which have not yet been surveyed large amounts will eventually be added to this total.

30. Pardee, J. T., Phosphate rock near Maxville, Granite County, Mont.: U. S. Geol. Survey Bull. 715, pp. 141–145, 1921. Out of print.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The phosphate bed, together with the inclosing rocks, is bent into several tightly squeezed folds, one of which is partly buried by an overthrust mass of older rocks. As a result of the folding and the erosion that produced the present surface the outcrop of the phosphate bed winds back and forth, forming long loops. The bulk of the phosphate that has escaped erosion remains in the synclines. In the several exposures examined the phosphatic formation (the lower member of the Phosphoria) is 15 to 30 feet thick. The main phosphate bed, which is a little more than 4 feet thick, contains 64 to 68 per cent of tricalcium phosphate. In addition beds that contain about 60 per cent have an aggregate thickness of 2 or 3 feet. The amount of phosphate rock available in the main bed in part of the area is estimated to be more than 100,000,000 tons.

31. Kirkham, V. R. D., Idaho phosphate industry (abstracted from History of phosphate mining in Idaho, article in University Argonaut, Moscow, Idaho): Am. Fertilizer, vol. 57, No. 13, pp. 76–78, December 30, 1922. (See also Nos. 5 and 11.)

In 1907 the black rock near Montpelier, Idaho, which had erroneously been regarded as coal, was determined by W. F. Ferrier and J. J. Taylor to be phosphate rock. Under their direction the deposit was developed and worked for phosphate as the Waterloo mine.

32. Mansfield, G. R., Phosphate rock in 1922: U. S. Geol. Survey Mineral Resources, 1922, pt. 2, pp. 109–132, 1923. 5c.

The total area of public land in the western field that may be regarded as containing workable phosphates amounts to more than 2,300,000 acres. Not all this territory contains high-grade rock, but conservative and incomplete estimates show that nearly 5½ billion tons may be expected in the different areas as follows:

	Tons
Idaho	4,997,809,000
Montana	273,785,000
Wyoming	115,754,000
Utah	96,750,000
	5,484,098,000
Less the quantity mined, 1916–1922	106,000
Estimated quantity available	5,483,992,000

This total may be compared with the total amount remaining in the eastern field (Florida, Arkansas, Kentucky, South Carolina, and Tennessee), which is estimated at 326,700,000 tons. Analyses of the western rock have shown 0.08 to 0.23 per cent of chromic oxide (Cr_2O_3) and 0.11 to 0.52 per cent of vanadium oxide (V_2O_5) in typical samples. The green color of some of the sulphuric-acid solutions of the rock may be due to these substances. In 1920 the Anaconda Copper Mining Co. put in operation at Anaconda, Mont., a process for producing a concentrated phosphatic fertilizer from western phosphate rock.

33. Nighman, C. E., Phosphate mines at Conda, Idaho: The Anode, vol. 9, No. 9, pp. 1–6, Butte, Mont., Anaconda Copper Mining Co., September, 1923.

The mines are in the Aspen Range, about 9 miles northeast of Soda Springs, Idaho, at an altitude of more than 6,000 feet. The phosphate-bearing formation is from 130 to nearly 200 feet thick, but only the lower 7 to 10 feet is considered to be of minable grade, the rest being low-grade phosphatic shale and limestone with some thin layers of high-grade phosphate. The beds are tilted and folded so that on the company's property there are two anticlines and three or more outcrops of the phosphate. The deposit is opened by two adit levels half a mile apart. Each of these entries is half a mile long, heavily timbered, electrically lighted, and equipped for electric storage-battery haulage. Raises and intermediate levels have been made and the total underground work amounts to nearly 3 miles. Backs (ore blocked out for stoping) extend from 300 to 700 feet above the main levels. The mined rock is crushed to ¾-inch size, dried, and stored for shipment, most of it going to the company's fertilizer plant at Anaconda, Mont.

34. Johnson, R. M., and Cole, Frank, The phosphate plant [at Anaconda, Mont.]: The Anode, vol. 9, No. 10, pp. 1–4, Butte, Mont., Anaconda Copper Mining Co., October, 1923.

Sulphuric acid, a by-product of the company's smelting operations, is used to make phosphoric acid from phosphate rock. To the phosphoric acid dry ground phosphate rock is added, producing a soluble monocalcium phosphate that is sold under the trade name Anaconda Treble Superphosphate. The phosphate rock is obtained from the company's mines at Conda, Idaho. It contains 32 to 33 per cent of phosphorus pentoxide (P_2O_5), equivalent to about 70 to 72 per cent of tricalcium phosphate, about 6 per cent of insoluble matter (chiefly silica), 2 per cent of iron and alumina ($Fe_2O_3+Al_2O_3$), and varying small amounts of sodium, potassium, magnesium, manganese, chromium, sulphur trioxide, fluorine, and chlorine. In addition, the rock contains organic matter which gives it a dark color and a fetid odor. Calcining eliminates this organic matter, resulting in about 7 per cent loss in weight of the rock and a consequent increase in the phosphoric acid content to about 35 per cent.

In addition to calcining, the various operations include grinding, treating with sulphuric acid, decanting the phosphoric acid and washing the residue, concentrating the phosphoric acid by evaporation, mixing with dry phosphate rock, drying the mixture, and grinding and sacking it for shipment to market. Since August, 1922, the product has amounted to 800 to 1,200 tons a month, most of which has been marketed in the Middle Western States and on the Pacific coast. Construction of a new plant with a daily output of 100 to 120 tons of "treble superphosphate" is in progress.

35. Anaconda Copper Mining Co., Report for 1923 (by the president and the chairman of the board of directors), New York, 1924.

A new plant for the manufacture of superphosphate at Anaconda, Mont., was constructed at a cost of nearly $550,000. The mines at Conda, Idaho, produced about 31,500 tons of phosphate rock, averaging 32.6 per cent of phosphoric acid (P_2O_5). Most of this was shipped to Anaconda and made into "treble superphosphate," of which nearly 7,600 tons was produced, averaging about 45 per cent phosphoric acid.

36. Mansfield, G. R., Phosphate rock in 1923: U. S. Geol. Survey Mineral Resources, 1923, pt. 2, pp. 239–273, 1924. 5c.

The production of phosphate rock in the Western States has ranged from 1,700 tons in 1916 to 55,600 tons in 1920. In 1923 the amount was 30,335 tons, which had a value at the mine of $5.79 a ton, or a total of $175,713. The mining of phosphate at Conda, Caribou County, Idaho, and the manufacture of fertilizer at Anaconda, Mont., by the Anaconda Copper Mining Company, are summarized from the company's publications. (See Nos. 33, 34, and 35.)

37. Condit, D. D., Phosphate deposits in the Wind River Mountains near Lander, Wyo.: U. S. Geol. Survey Bull. 764, 39 pp., 1924. 15c.

The sedimentary formations range from pre-Cambrian to Quaternary and include the Phosphoria, which is 200 to 300 feet thick and contains two principal phosphate beds, one 60 to 75 feet below the top and the other 40 to 50 feet above the base. The Phosphoria rests upon the Tensleep sandstone and is in turn overlain by the Dinwoody formation, consisting of shale and limy sandstone. The upper part of the Phosphoria is divided into three rather distinct members, called the upper bryozoan limestone, the phosphatic shale, and the lower bryozoan limestone. The phosphatic shale member contains the upper phosphate bed. The fourth or lowest member of the Phosphoria generally consists of two shaly zones, each underlain by beds of dolomite, sandstone, and chert. The lower phosphate bed occurs in this member, just beneath a ledge of gray limestone. It is filled with the disk-shaped shells of *Lingulidiscina utahensis*, and at a number of places in the Wind River Range it has been found to contain fossil fish. Throughout the area the beds show a moderate dip toward the northeast.

The lower phosphate bed varies greatly in thickness and richness, and in one place—the Sheep Mountain uplift—it is absent. This bed is at its best in the neighborhood of Usher Creek, south of Lander, where it is 4 feet thick and contains 61 per cent of tricalcium phosphate. The upper phosphate bed contains large amounts of sand and clay and is generally made up of several layers of phosphate interbedded with shale. Some of the layers a foot or so thick may be found to contain as much as 60 per cent of tricalcium phosphate, but samples representing layers that aggregate several feet commonly show no more than 40 per cent. The upper bed is most favorably developed from Baldwin Creek opposite Lander southeastward to Usher Creek. It ranges in thickness from 27 inches on Baldwin Creek to 86 inches on Little Popo Agie River and at both places contains 35 per cent of tricalcium phosphate. On Willow Creek, 7 miles south of Lander, it is 5 feet thick and contains 49 per cent of tricalcium phosphate.

The high-grade phosphate rock of the Wind River Mountains, like other phosphate deposits in the Rocky Mountain region, is oolitic, of high specific gravity, dark brown to black when freshly exposed, and bluish gray on weathered surfaces. The shale, limestone, and chert that are closely associated with the upper bed are likewise similar to those in the phosphate fields of southeastern Idaho and adjacent parts of Utah. The Wind River Range phosphate, however, occurs at a lower horizon not known to be represented in Idaho and Utah.

Large fossil brachipols of the genus *Productus* are plentiful in the basal part of the upper phosphate bed. In places this bed grades into the underlying limestone. The lower bed is more largely made up of phosphatized fossil shells. *Lingulidiscina*, the most abundant fossil, has a shell of essentially phosphatic composition and appears to have furnished a large part of the phosphatic material of this horizon.

The freshly broken phosphate rock generally has an oily odor, and the same rock under cover is productive of oil in this part of Wyoming. The chief impurities in the rock are sandy, clayey, more or less calcareous sediments. Analyses show from 1.33 to 2.66 per cent of iron and alumina.

Though the deposits described are less rich than those of southeastern Idaho, their position some 150 miles east of the main barriers of the Rocky Mountains gives them an advantage over the Idaho deposits in respect to transportation to the wheat belt of the Great Plains region.

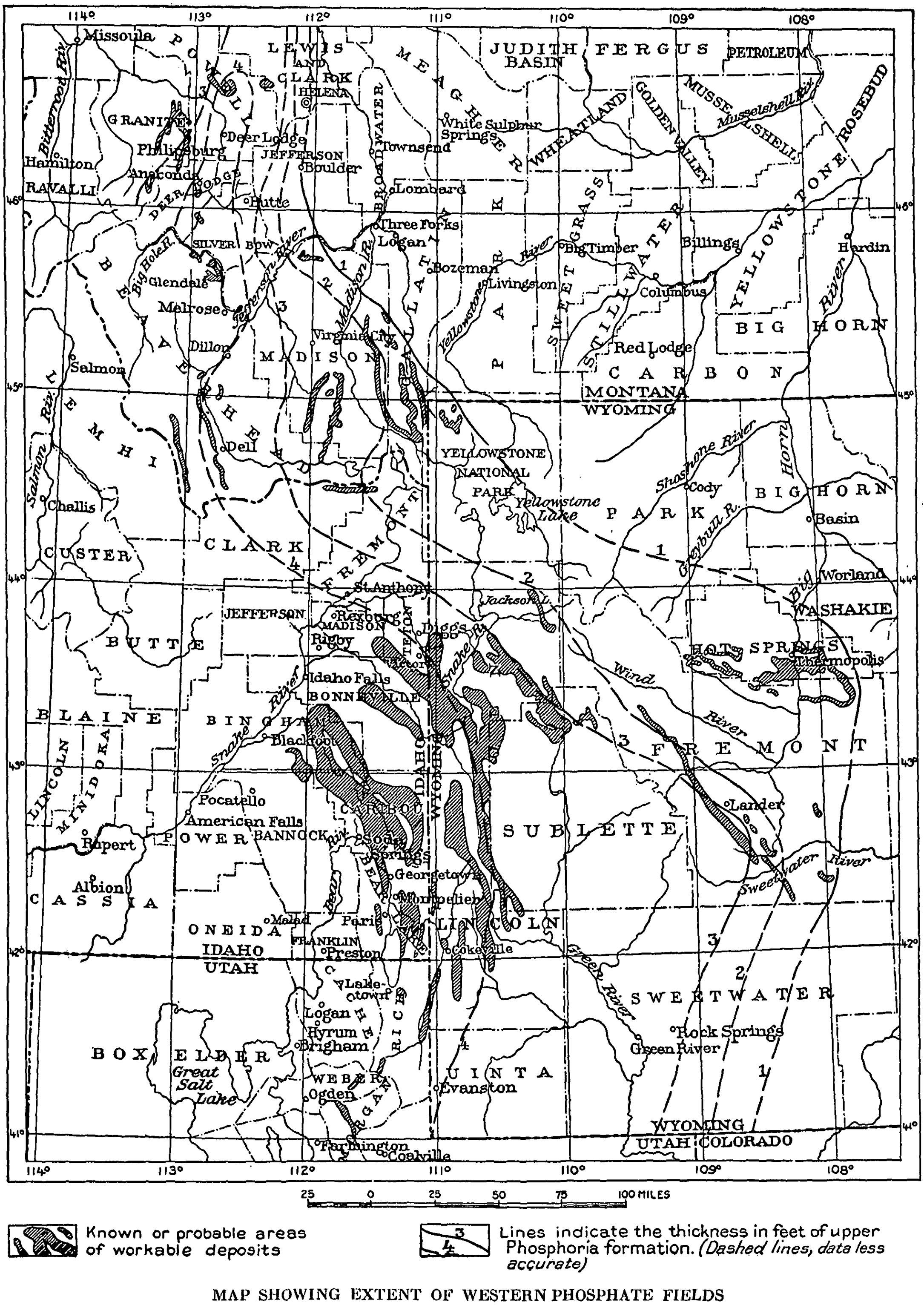
38. Richards, R. W., and Pardee, J. T., The Melrose phosphate field, Montana: U. S. Geol. Survey Bull. 780, pp. 1–32, 1925. Out of print.

A continuation of the examination of western phosphate lands by the United States Geological Survey. The field work on which this report is based was mostly done by R. W. Richards in 1912. The sedimentary series ranges from Algonkian to Tertiary and includes the Madison limestone, Quadrant formation, Phosphoria formation, and beds of Triassic age that are correlated with the Woodside formation of Idaho. Rocks of Jurassic age are absent.

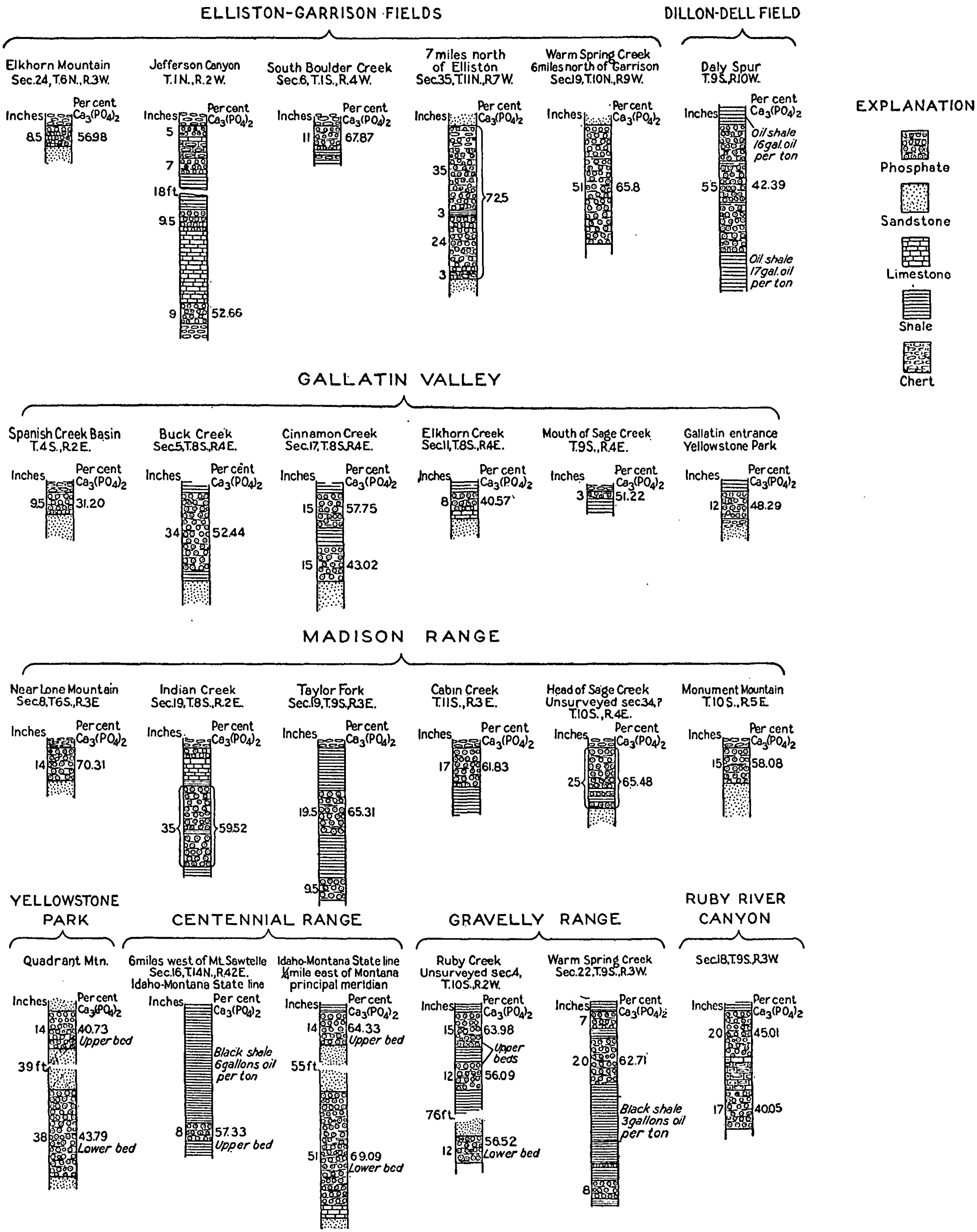
The formations are compressed in a series of folds that have a northwesterly trend. The phosphate-bearing rocks are eroded away from the anticlines but form narrow belts along the synclines. One or more beds of phosphate rock occur in the lower part of the Phosphoria formation, between a layer of limestone below and a layer of chert above. Near Melrose phosphatic layers that aggregate 12 to 20 feet or more in thickness contain 20 to 66 per cent of tricalcium phosphate, and layers 3 to 6 feet in thickness contain 60 per cent or more of tricalcium phosphate. In one place, in the neighborhood of McCarthy Mountain the phosphate bed is 6 feet thick and contains 58 to 64 per cent of tricalcium phosphate.

REVIEW OF THE ROCKY MOUNTAIN FIELDS

In southwestern Montana and western Wyoming phosphate rock occurs at two principal horizons in the Phosphoria formation, one near the base and the other 20 to 60 feet higher, stratigraphically about the middle of the formation. The beds of the upper horizon are by far the more extensive, being persistent over at least 25,000 square miles in southwestern Montana and extending through southeastern Idaho, western Wyoming, and northeastern Utah. In the most valuable fields of southern Idaho, western Wyoming, and southwestern Montana the principal bed is a black or gray, finely oolitic layer 4 to 5 feet thick, containing more than 70 per cent of tricalcium phosphate. From these rich areas the beds gradually thin eastward and also deteriorate in quality. Plate 10 shows the principal phosphate fields of Montana, Idaho, Wyoming, and northern Utah. The lines represent approximately the eastern limits of the upper bed where it is 4 feet, 3 feet, 2 feet, and 1 foot thick, respectively.



MAP SHOWING EXTENT OF WESTERN PHOSPHATE FIELDS



COLUMNAR SECTIONS OF THE PHOSPHATE BED IN THE THREE FORKS-YELLOWSTONE PARK REGION, MONTANA

It should be explained that although the beds of the upper horizons have been traced over parts of several States, the persistence of the individual layers is less certain. The upper phosphate member is in most places made up of several layers of phosphate rock separated by phosphatic shales that range from cherty to sandy and more or less carbonaceous and petroliferous over large areas. In fact, the entire upper portion of the Phosphoria formation is noticeably phosphatic, even the coarse quartzitic cherty sandstones, which are speckled with the grayish oolites. The expansion of the upper member into several beds of concentrated oolitic phosphate associated with 50 feet or so of black or brown carbonaceous shale is characteristic in all exposures from northern Utah across Idaho and as far north as Dillon, Mont. At Dillon the shale is rich in oil, some beds yielding on distillation 30 gallons to the ton. Farther north in Montana and also to the east in the area covered by this report the shale is thin or lacking and the phosphate layers are reduced in number to one or two that lie between sandstone beds. Still farther east, where the phosphate is missing, there is no shale marking the horizon, which shows continuous chert and sandstone. Along Gallatin Valley near the northwest corner of Yellowstone National Park the phosphate bed and its associated shale thin within a distance of 3 miles from an aggregate thickness of about 3 feet to a few inches of oolitic phosphate. In this place the thinning of the beds eastward may have been caused by erosion, but elsewhere it seems evident that no such beds were deposited.

The beds of the lower phosphate horizon are, as stated above, far less extensive than the upper ones. They lie near the base of the Phosphoria formation, only a few feet above the Quadrant quartzite. In western Wyoming the lower phosphate horizon of the Phosphoria formation (in earlier reports called Park City formation) is about 25 feet above the Tensleep sandstone. The lower bed wherever observed differs from the upper one in that it consists almost entirely of phosphatized shells of certain mollusks, of which the most plentiful is a *Lingulidiscina*. This bed was recognized at Quadrant Mountain, Yellowstone Park, and at one point to the west, in the Centennial Range, and it appears in excellent development with the usual characteristics farther east along the Wind River Mountain front, south of Lander. In southeastern Idaho the main phosphate bed is at or within a few feet of the base of the Phosphoria formation. The fossil *Lingulidiscina* is common in this bed at some localities in this region, but it is not certain that the main bed of southeastern Idaho corresponds with the lower bed as found in the Wind River Range and elsewhere in Wyoming.

Phosphate deposits in the Rocky Mountain region are not limited to the Phosphoria formation, others having been found in northern Utah in strata of Mississippian age several thousand feet lower stratigraphically. The deposits investigated near Logan and Ogden, Utah, do not, however, indicate that discoveries of much value will be made at this horizon.

PRINCIPAL FEATURES OF THE LOCAL FIELDS

A summary of the principal features of the local fields in this area will be useful for comparison with those of other areas in southwestern Montana. The outcrops of the phosphate bed where it is more than 6 inches thick are represented on Plate 12. The bed is missing at the upper end of Gallatin Canyon, in T. 6 S., R 3 E., but appears near Lone Mountain, 7 miles farther northwest. It is thin or missing to the northeast, just south of Bozeman, and is likewise missing in the Bridger Range and westward in the hills north of Logan. The excellent exposures in Jefferson Canyon were measured in detail, and the thickest of several layers of phosphate was found to be only 9 inches. A line representing the eastern limit of the phosphate bed can therefore be drawn fairly accurately across the map. Southwest of this limit the principal bed thickens gradually to a maximum of about 3 feet of black, finely oolitic phosphate containing phosphorus pentoxide (P_2O_5) equivalent to 45 to 65 per cent of tricalcium phosphate. The bed is generally divided into two parts by a layer of shale 2 to 8 inches thick.

Plate 11 shows the sections of the phosphate beds measured throughout the area, with the percentage of tricalcium phosphate in each. The exposures in the upper bed that appear to be the richest are those of Indian Creek and Buck Creek (Nos. 10 and 5 on the map), on opposite slopes of the Madison Range, in which the thickness is only an inch or two short of 3 feet. The percentage of tricalcium phosphate is 59.52 at Indian Creek and 52.44 at Buck Creek. In all other exposures the bed is at best barely 2 feet thick, or if more is divided into two benches, each a foot or so thick, separated by 4 to 12 inches of phosphatic shale. The bed in the Gravelly Range is not so good as in the Madison Range, being divided by a layer of shale into two parts, neither of which is more than 18 inches thick. To the west, in Ruby River canyon (No. 22), the bed is slightly thicker.

The lower phosphate bed is much less extensive than the upper one. It is about 3 feet thick at Quadrant Mountain, Yellowstone Park, and 4 feet thick at one point to the west in the Centennial Range, but less than 1 foot thick where observed elsewhere in Montana.

Several sections of the upper phosphate bed as found at the richest localities in Montana to the northwest and west of this area are given in Plate 11 for comparison. In the Elliston-Garrison fields, west of Helena, the bed at its best is 4 feet thick and generally shows on chemical analysis 65 to 70 per cent of tricalcium phosphate. Near Melrose and McCarthy Mountain the richer parts of the phosphate bed range from 2 to 6 feet in thickness and contain from 60 to 66 per cent of tricalcium phosphate. In the Dillon-Dell field, in Beaverhead County, the phosphate bed was found to be 4 feet thick at a number of localities but contains shale laminae; in the best exposures sampled there the content of tricalcium phosphate ranges from 42 to 52 per cent. The associated oil shale is also phosphatic. The section measured at Daly spur, along the Oregon Short Line Railroad (see No. 28 in bibliography), is regarded as representative of the field. In the fields of southeastern Idaho, where phosphate rock has been mined for several years in a commercial way, the bed is 5 feet or more thick and contains 70 per cent of tricalcium phosphate.

It is evident that the phosphate beds of the district covered by this report are of little present economic value, being inferior in thickness and quality to those of other fields. The small areas underlain by a bed of fair thickness are in high mountains difficult of access and far from railroads. The extent of the richer deposits in other fields is so enormous that it will be many generations before they are exhausted.

PHOSPHATE ROCK

OCCURRENCE AND CHARACTER

Throughout the Rocky Mountain region the phosphate rock of the Phosphoria formation occurs as a sedimentary or bedded deposit in stratified rocks, chiefly shale and chert.

The upper phosphate bed is readily distinguished by its bluish-white color on weathered surfaces, heavy specific gravity, and peculiar oily or fetid odor when freshly broken. The rock is generally oolitic, consisting of an aggregate of small rounded grains suggesting fish roe, more or less firmly cemented by a matrix of the same or some other material. The oölites vary greatly in diameter, ranging from microscopic size to the size of a pea. The oolitic particles are generally well assorted, there being no great variation in any individual layer. In still coarser gravelly phosphate rock many of the pebbles are as much as an inch in diameter but do not show oolitic structure. Some of the coarser-textured specimens are made up of pebbles that appear to be travel rounded. Other specimens have a brecciated appearance, being made up of slightly rounded, poorly assorted pebbles of phosphorite in a matrix of the same material. The phosphorite ranges from black to light gray and generally has a dull luster.

In some localities the oolites have slick, shiny surfaces, possibly induced by shearing. In the loosely cemented rock, which may be open textured with interspaces resembling those of sandstone, the fracture passes around the oolites, but in some of the more compact varieties the fracture passes through the oolites, which are so firmly cemented by a bond apparently of secondary phosphorite that there are almost no interspaces.

The chief impurities present in the deposits are clay, lime, particles of quartz sand, and more or less bituminous material. Silicification is noticeable in some specimens, which on examination under the microscope show minute growths of chalcedonic character.

The lower phosphate bed of the Phosphoria formation differs from the upper in that it is made up for the most part of phosphatized shell fragments with less oolitic material. The bed is essentially clastic in origin, and this alone explains in large part its lack of continuity. The shell fragments are mostly a brachiopod of the genus *Lingulidiscina*, a phosphate-secreting organism, and, in fact, the comminuted particles of this same shell make up the bulk of the 4-foot phosphate bed found in the Centennial Mountains along the Idaho-Montana State line. The nearly circular, flat, disklike shells are about the size of a 5-cent piece. With their concentric markings they appear in cross section as vitreous gray, finely laminated arcs in the rock specimen. The shells of coin thickness, although preserving the shell markings on each side, are believed to have been thickened through replacement of the original shell substance by a mineral of the tricalcium phosphate group. In the Quadrant Mountain exposures the bed contains, in addition to the *Lingulidiscina* shells, quartz grains, a few brown phosphate oolites, and a green unidentified mineral that may be glauconite.

The high specific gravity of the phosphate rock, as compared with that of the associated chert, limestone, sandstone, and shale, is a property that aids in distinguishing the richer rock. The specific gravity of specimens containing 70 per cent of tricalcium phosphate averages 2.9.

Phosphate rock on and near the surface shows evidence of the leaching effect of ground water, which has removed the more soluble constituents, such as lime and pyrite. The result has been that the weathered outcrop contains a higher percentage of phosphoric acid than the same bed far below the surface. The degree of enrichment, however, is generally insufficient to affect the commercial quality of the rock.

MINERAL AND CHEMICAL COMPOSITION

A close examination of the phosphate rock reveals the fact that the phosphatic material occurs in three principal forms—oolites or irregular pebbly masses; deposit replacing fossils, chiefly molluscan forms; and secondary growths filling interspaces between mineral grains or forming irregular veinlets. Many of the smaller oolites are made up of concentric layers, as shown by the banded appearance seen in cross section under the microscope, and some contain central nuclei of foraminiferal shells of the genus *Textularia?* and less frequently *Globigerina.* More commonly such shells are absent, and as a rule no specific nucleus is distinguishable.

The *Lingulidiscina* shell fragments, seen in cross section, show a finely laminated structure, are brownish to white, have a waxy luster, and show no distinct cleavage. The fracture is regular, giving even, smooth faces. The hardness is considerably less than that of apatite. W. T. Schaller, who made a qualitative examination of shell fragments collected from the Wind River Mountains near Lander, makes the following statement:

> The mineral is essentially a phosphate of calcium but contains also water (H_2O), carbonate (CO_3), and sulphate (SO_4). The refractive indices are approximately 1.598 (parallel to laminae) and 1.602 (normal to laminae), which are lower than those of the known related minerals.

The precise mineral composition of the oolitic phosphate is especially difficult of determination owing to the mode of occurrence of the mineral constituents. Cross sections viewed under the microscope commonly show the concentrically banded oolites to consist of an aggregate of cryptocrystalline mineral particles with inclusions of quartz flakes and other foreign substances. Some of the banded zones show a crystalline, fibrous structure with isotropic bands of a phosphatic mineral having an index of refraction suggesting collophanite, the formula of which is given as

$$x(Ca_3PO_4)_2 \text{ or } x[(CaF_2)Ca_3PO_4)_6+yCaCO_3+H_2O].$$

A large number of analyses made by R. M. Kamm in the laboratory of the United States Geological Survey on samples of the phosphate rock from this region show the presence of different amounts of phosphoric acid (P_2O_5) up to 33 per cent. Apparently most if not all of this substance exists in combination with lime (CaO) as tricalcium phosphate ($Ca_3P_2O_8$). From microscopic examinations it is evident that the bulk of the residue is silica (SiO_2). As a rule small amounts of iron oxides (reckoned as Fe_2O_3) and alumina (Al_2O_3) are present. The analyses of four samples show from 0.33 to 1.42 per cent of iron oxides and from 0.38 to 3.51 per cent of alumina. Qualitative tests on a composite of the same four samples showed some water remaining after the material had been heated to 100° C., considerable carbon dioxide (CO_2), a little fluorine, sulphate (SO_3), sodium, and potassium, and traces of chlorine, lithium, and barium. No strontium or rare earths were detected. Two separate samples contained 0.31 and 0.58 per cent of fluorine.

These analyses indicate the presence of the minerals calcite, apatite, and barite, which would yield, respectively, the carbon dioxide, the fluorine, and the sulphate and barium. Probably the sodium, potassium, and lithium are present as chlorides, though they may occur also as silicates.

ORIGIN

Ever since the discovery of the bedded phosphate deposits of the Rocky Mountain region their unique character has led to much speculation about their origin, as they represent a type previously not recognized in America. The beds differ from the residual phosphate of the Carolinas and the phosphate of secondary origin in Florida in that they are sedimentary deposits occurring in stratified rocks in a manner similar to coal. They are of enormous extent, reaching from northeastern Utah northward into Canada, a distance of more than 600 miles. The eastern limits of the beds are fairly well defined, but of the westward extent less is known. It is probable, however, that the original area of the beds, 1 foot or more thick prior to mountain making and destructive erosion, was more than 175,000 square miles. Of this area at least half was underlain by two or three beds, each 1 to 5 feet thick. It is estimated that if the phosphate rock known to have originally covered the Rocky Mountain region were spread out over the surface in a layer 1 foot thick, it would cover all of the United States east of Mississippi River.

The beds of the Phosphoria formation were for the most part laid down in the sea. Marine fossils, chiefly brachiopods, are plentiful in strata underlying the phosphate beds, and it is not uncommon to find them also embedded in the lower beds of the phosphate rock itself. One particular bed described as the "lower bed" in Yellowstone Park and the Centennial Range is literally a coquina made up of shell fragments of a phosphate-secreting species of *Lingulidiscina*. The lenticular character of the bed and its lateral variation within short distances lead to the belief that it is almost entirely of clastic origin and was laid down along a sea beach. The deposit displays all gradations from a richly phosphatic almost clean shell bed to a leanly phosphatic quartz sand. The chief uncertainty is concerning the extent to which the rock has been enriched through replacement of the calcium carbonate portion of the shells by phosphate minerals.

The origin of the oolitic phosphorite is less easily explained. In its various forms it ranges from oolites, thoroughly assorted and with but little foreign material, to gravelly conglomerates made up solely of phosphorite or of a heterogeneous mixture of phosphorite, quartz pebbles, and clay, with a cementing bond of calcium carbonate. The coarser phosphorite pebbles show no concretionary or oolitic structure and they may well have been deposited as a phosphatic mud and subsequently broken into particles either by exposure of the mud flats to desiccation under the sun's rays or by water currents, or probably through both agencies.

The ultimate source of the phosphoric acid (P_2O_5) was the igneous rocks,[3] in which it is present in an average proportion of 0.29 per cent. Sedimentary rocks, especially limestones, contain appreciable amounts, and their disintegration delivers a constant supply to the sea waters, from which it is either precipitated chemically or incorporated into the skeletons of marine organisms.

Most observers agree that the western phosphate deposits are original—that practically no addition or concentration of phosphatic material has taken place since the beds were laid down. Mansfield,[4] however, in a recent paper, after reviewing the principal theories advanced to explain the origin of the western phosphate deposits, has set forth as a tentative hypothesis the suggestion that the phosphatic oolites and their matrix were originally deposited as carbonate of calcium in the form of aragonite. He mentions as evidence the studies of Drew [5] and Vaughan,[6] who have investigated the problem of oolite formation in the region of the Florida Keys and have reached the conclusion that marine oolites are largely due to the action of marine bacteria. Drew has shown that large quantities of calcium carbonate in the form of aragonite are precipitated by denitrifying bacteria. Vaughan has found that this chemically precipitated calcium carbonate tends to accumulate as balls or spherulitic growths of true oolitic structure forming around a variety of nuclei. Drew's observations show that these denitrifying bacteria are most prevalent in shoal waters of the Tropics.

Mansfield's hypothesis for the origin of the western phosphates, based on deductions from the work of Drew, Vaughan, and others,

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[3] U. S. Geol. Survey Bull. 770, p. 28.

[4] Mansfield, G. R., Origin of the western phosphates of the United States: Am. Jour. Sci., 4th ser., vol. 46, pp. 591–598, 1918. See also U. S. Geol. Survey Prof. Paper 152, pp. 361–367, 1927.

[5] Drew, G. H., On the precipitation of calcium carbonate in the sea by marine bacteria, and on the action of denitrifying bacteria in tropical and temperate seas: Carnegie Inst. Washington Pub. 182, Papers from Tortugas Laboratory, vol. 5, pp. 9–53, 1914.

[6] Vaughan, T. W., Preliminary remarks on the geology of the Bahamas, with special reference to the origin of the Bahaman and Floridan oolites: Carnegie Inst. Washington Pub. 182, Papers from Tortugas Laboratory, vol. 5, pp. 47–54, 1914.

supposes that the phosphatic oolites and their matrix were deposited originally as carbonate of calcium in the form of aragonite in shoal warm waters. The neighboring land areas were low and contributed little sediment to the sea. The phosphatization of the oolitic deposit is believed to have been subsequent to its deposition, for the reason that the activities of the denitrifying bacteria, as shown by Drew, reduce the nitrate content of the sea water and hence the growth of marine plants and of animals dependent upon them, and such conditions are favorable for the deposition of the carbonate but not of the phosphate of calcium. It is supposed that there followed a period of cooler temperature in the waters of deposition, which reduced the activities of the denitrifying bacteria but favored the increase of plant and animal life. The phosphatization of the oolitic limestone shortly after its deposition may have been brought about by a wholesale killing of certain marine animals, with the subsequent decomposition of their remains and redeposition of the phosphatic material, as suggested by Blackwelder. (See Nos. 17 and 23, bibliography.) If there had been a pronounced increase in plant and animal life at this time, as supposed by Blackwelder, the shale interbedded with and closely overlying the phosphate beds should be a mass of fossils, but such is generally not the case. The black shale examined at dozens of places reveals few remains of brachiopods and only here and there individual pelecypods. Fish teeth are fairly common in the shale and also in the quartzitic sandstone beds of the Phosphoria formation but are not nearly so plentiful as would have been necessary had the fish skeletons furnished any considerable portion of the phosphoric acid.

Any theory which shall satisfactorily explain the origin of phosphate beds of the Rocky Mountains must take into consideration the conditions of sedimentation that permitted the deposition over large areas of the associated black carbonaceous shale, singularly poor in animal fossils and containing but little limestone.

Though the precise conditions of deposition in the area are not certain, it is probable that extensive marine carbonaceous shale beds, such as those of the Phosphoria, were laid down in shallow, quiet waters and that the carbonaceous material was derived from plants whose decomposition products formed black oozes that settled to the sea bottom. Hydrogen sulphide, carbon dioxide, and ammonia evolved by the decomposing plant material could hardly be favorable for the precipitation of calcium carbonate. The hydrogen sulphide might have produced a state of toxicity almost if not quite prohibitive of animal life, and such a condition might explain the general scarcity of fossils in the phosphate beds and associated shales. Similar conditions of toxicity in the depths of the Black Sea have been described by Murray.[7]

The field relations of the phosphate beds in the Dillon district are of interest in this connection. The richest and thickest phosphate bed lies in the midst of a thick dark shale that is richer in shale oil than any other part of the section. Yet this shale and the phosphate bed contain few fossils and are only slightly calcareous. The little limestone present in associated beds occurs largely in nonfossiliferous concretionary lenses, denoting secondary origin.

In Mansfield's hypothesis, as already stated, the two stages in the formation of the phosphate are precipitation of oolitic calcium carbonate (aragonite) and subsequent replacement by phosphorite. It seems improbable that oolitic calcium carbonate was precipitated in the midst of conditions producing black shale, such as are recorded in the beds of the Dillon district. On the contrary it seems highly probable the oolitic phosphorite was deposited directly as such from the sea water.

The waters charged with hydrogen sulphide, though inimical to animal life, might act together with the carbon dioxide as a ready solvent of phosphatic skeletons on the neighboring sea bottom, producing certain acid phosphate salts such as $CaHPO_4$ or $CaHPO_4.2H_2O$, which although far more soluble than the normal tricalcium phosphate are not less soluble than calcium bicarbonate.

Just what factors or conditions may have been active in intermittently causing precipitation of the burden of acid phosphate salts carried in solution in the sea water is a matter of conjecture. A concentration of the phosphoric acid above the normal for sea water may have taken place in temporarily restricted basins. The variable structure of any individual phosphate bed, noticeable even over a small area, is noteworthy in this connection. Its thickness changes, shaly layers appear and disappear in its midst, and some oolitic layers are lost entirely in the shale. Evidence favoring an origin through evaporation in restricted basins has been observed at several points where there are desiccation conglomerates consisting solely of phosphorite. Although we are not warranted in assuming that bacterial action was a factor in the deposition of the oolitic phosphorite, such action may well be suspected in view of the part known to be taken by bacteria in the formation of certain oolites. Phosphatic nodules are being deposited at the present time on the bottom of the sea,[8] and in some places the quantity is so great that the product has been recovered in a commercial way by dredging. With

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[7] Murray, John, Deposits of the Black Sea: Scottish Geog. Mag., vol. 16, pp. 683–684, 1900.

[8] Murray, J., and Renard, A. F., *Challenger* Rept., Deep-sea deposits, pp. 397–400, 1891.

Foraminifera and other minute organisms present to act as nuclei oolitic beds might have accumulated in a similar manner on the sea bottom in Phosphoria time.

LOCAL DETAILS

The following pages present details regarding the local stratigraphy and structure that are not included in the general discussion, with chief reference to the economic aspect of the phosphate beds of various localities. As the search for phosphate rock was the principal object of the field work, most of the discussion bears on the Phosphoria and Quadrant formations. It seems best to present the account under headings that designate the sections as traversed in turn by the field party, beginning with Lombard, the Elkhorn mining district, and the Bull Mountains, which are outlying localities, north of the main area described. (See index map, fig. 11.)

LOMBARD

Lombard is on Missouri River in Gallatin County, at the intersection of the Chicago, Milwaukee & St. Paul Railway with the Helena branch of the Northern Pacific. Near the station are cliffs of Madison limestone overlain by the Quadrant and higher beds, which are excellently exposed westward to the fault that brings these rocks into contact with the Belt series. A little above the base of the Quadrant are beds of black shale approaching coal in composition, which have been prospected in the search for coal along the railroad near Lombard and at other places.

The Quadrant and Phosphoria formations are between 600 and 700 feet thick and consist of the following parts, described in ascending order. Resting on the nearly even surface of the Madison limestone is 30 feet of ocherous sandy conglomeratic rock with pebbles of Madison limestone. This grades upward into beds of shale, clay, and sandstone, all more or less calcareous and generally of brick-red color, having an aggregate thickness of about 100 feet. The succeeding beds are carbonaceous shale and dark shaly to massive-bedded limestone about 215 feet thick with fossils abundant throughout.

Haynes [9] describes a section near Lombard, about 650 feet thick, consisting of limestone, shale, and quartzite, with a layer of black coaly shale. He refers this section to the Quadrant, but the upper part probably represents the Phosphoria.

The carbonaceous shale and dark limestone are overlain by about 325 feet of gray limestone and sandstone, all more or less dolomitic and becoming increasingly sandy upward, the highest bed being

[9] Haynes, W. P., The Lombard overthrust: Jour. Geology, vol. 24, p. 286, 1916.

quartzitic. These beds contain fragments of fossils too poorly preserved for identification. The resistant quartzite beds at the top form long dip slopes from the summit of the mountain to the northwest base, where they are overlapped by higher beds consisting of nodular chert in thin layers that make up the upper portion of the Phosphoria formation. The base of this chert is the stratigraphic position of one of the principal phosphate beds in other areas, but no phosphate rock of importance is present here, only a few inches of dark cherty quartzite containing scattered specks of phosphatic oolites. The chert beds, about 40 feet thick, are overlain by brownish shaly calcareous sandstone, a part of the Ellis formation.

ELKHORN DISTRICT

Between the Elkhorn mining camp, in Jefferson County, and Radersburg, in Broadwater County, to the southeast, are extensive outcrops of the Phosphoria formation,[10] which were examined in the search for phosphate rock. The route followed led from Townsend, on Missouri River, southwest to the vicinity of Radersburg, thence up Slim Sam Fork of Crow Creek and south to Johnny Gulch, thence west to the vicinity of Elkhorn. A layer of phosphate rock nearly 1 foot thick and containing 56.98 per cent of tricalcium phosphate was found in the exposures nearest Elkhorn. Elsewhere phosphatic quartzite was found in the stratigraphic position usually occupied by the phosphate bed.

The hills southwest from Townsend along the Radersburg road consist of the reddish-brown sandy shale of the Belt series. About 1,000 feet west of the road, which leads nearly south, parallel to the strike, is a hogback of Flathead quartzite, succeeded in turn by the entire Paleozoic series of formations dipping steeply westward and forming high hills, beyond which are meager outcrops of Cretaceous strata mostly covered by a flow of andesitic lava. In most places to the west and southwest the sedimentary rocks are more or less metamorphosed by intrusive dikes and stocks that have favored mineral deposition. Indeed, the region is best known for its metalliferous mines.[11]

The best exposures of the Phosphoria and associated formations in the locality are on the east side of Crow Creek valley, about 3 miles north of Radersburg, and along Johnny Gulch, in sec. 21,

[10] Geologic maps covering portions of this area are given in U. S. Geol. Survey Bull. 470, Geologic relation of ore deposits in the Elkhorn Mountains, Mont., by R. W. Stone, 1911, and U. S. Geol. Survey Prof. Paper 74, Geology and ore deposits of the Butte district, by W. H. Weed, 1912.

[11] Stone, R. W., op. cit. Weed, W. H., Geology and ore deposits of the Elkhorn mining district, Jefferson County, Mont.: U. S. Geol. Survey Twenty-second Ann. Rept., pt. 2, pp. 399–550, 1901.

T. 5 N., R. 1 W. The rocks along Johnny Gulch have been so disturbed by minor faulting that reliable measurements can not be made. The upper quartzite member of the Phosphoria is overlain by about 2 feet of dark cherty quartzite thickly speckled with white oolites and chalky nodules of phosphatic content. A float sample on analysis was found to contain 25.35 per cent of tricalcium phosphate. Five feet higher is impure brownish sandy limestone containing fossils of Jurassic age.

Along the mountain side 1 mile southeast of Elkhorn, in sec. 24, T. 6 N., R. 3 W., the Phosphoria beds dip about 17° E. Near the top of the formation is a thin bed of phosphate rock separated from the overlying impure Jurassic limestone by 5 feet of pink chert and underlain by cross-bedded pink to gray quartzite. The phosphate rock, which ranges from 8 to 12 inches in thickness, is dark brown to nearly black, with the usual gray bloom on the weathered surface. It is made up of small oolites firmly cemented by silica. The specific gravity is noticeably greater than that of ordinary limestone, indicating a rock of a fairly high grade, and the analysis showed 56.98 per cent of tricalcium phosphate. The chert above the phosphate bed contains scattered lumps and granules of phosphorite.

As it passes southward into sec. 36 the phosphate bed ranges in thickness from 1 to 7 inches or locally is absent. The quartzite separating the phosphate rock from the overlying Jurassic calcareous sandstone ranges from a few inches to several feet in thickness and is intermixed with stream-rounded pebbles of chert derived from erosion of the Phosphoria. Scattered outcrops of the Quadrant and Phosphoria form low hills extending across the east side of T. 5 N., R. 3 W., on both sides of Elkhorn Creek and south into the flood plain of Boulder River. The quartzite beds are overlain by dark nodular chert containing a few inches of siliceous phosphate rock. A sample collected in sec. 10 was found on analysis to contain 38.41 per cent of tricalcium phosphate.

BULL MOUNTAIN

Bull Mountain lies west of Boulder River, between Boulder and Whitehall. The area is represented in the geologic map of the Butte district,[12] which shows the greater part of the mountain as of andesitic lava, tuff, and breccia. At the south end is an area of Paleozoic and later rocks, which are considerably metamorphosed. From the Tertiary "lake beds" along the eastern base of the mountain rise beds of agglomerate and lava that dip 30°–60° E. The steep moun-

[12] Weed, W. H., Geology and ore deposits of the Butte district, Mont.: U. S. Geol. Survey Prof. Paper 74, pl. 1, 1912.

tain slopes consist largely of somewhat massive volcanic rock and indurated pyroclastic material.

On the mountain in T. 2 N., R. 3 W., about 5 miles northeast of Whitehall, are exposures of the Quadrant and Phosphoria formations interstratified with a number of sills nearly parallel to the bedding. Toward the south these formations and the overlying Jurassic beds are increasingly metamorphosed. The bedding of the Quadrant quartzite was at one point found to be almost entirely obscured by jointing developed nearly at right angles. Although the exposures are good, no phosphate rock was found.

CANYON OF JEFFERSON RIVER NEAR CARDWELL

Cardwell is on Jefferson River near the mouth of Boulder River. A few miles farther east the broad valley narrows to a sharp canyon only wide enough for the tracks of the two railroad lines between the river and the steep cliffs. Complete exposures of the Quadrant and Phosphoria formations, dipping steeply northwestward, are present on the north side of the valley. At this locality there are several thin beds of phosphate rock, which with the associated strata are described in the following section. Several faults introduce doubt as to the total thickness, but the sequence of the beds is clear.

Section near Cardwell, Mont.

	Ft.	In.
Ellis formation:		
Limestone, sandy, impure, cross-bedded; weathers to rusty color; lower beds contain fossils	36	
Phosphoria formation:		
Quartzite, dark gray, containing a few quartz pebbles and bands of chert and a layer of travel-rounded chert pebbles at top	42	
Chert in thin shaly layers	6	
Phosphatic beds:		
Phosphate rock, cherty, oolitic		6
Chert, shaly	2	
Phosphate rock, siliceous, impure		5
Limestone, cherty		9
Phosphate rock, siliceous, impure		7
Limestone	1	
Shale, blocky, siliceous	11	
Phosphate rock, oolitic		4
Shale, calcareous in upper part	6	
Phosphate rock, shaly		10
Shale and dark limestone	2	6
Phosphate rock, impure, coarsely oolitic; 52.66 per cent of tricalcium phosphate		9
Chert		6
Phosphate rock, siliceous		1

	Ft.	in.
Phosphoria formation—Continued.		
Phosphatic beds—Continued.		
Limestone and chert in thin platy layers, dark gray	6	
Phosphate rock, siliceous, oolitic, weathering gray		3
Sandstone, phosphatic, containing pebbles of quartz	1	4
Sandstone, dark gray, slightly dolomitic and cross-bedded, containing peculiar ropy masses and markings	29	
Quadrant formation:		
Quartzite, alternating with dolomitic limestone and thin chert layers; poorly preserved fossils in lower part	140	
Limestone, dolomitic and arenaceous, containing alternating thin layers of chocolate-brown shale and nodular chert; fossils fairly abundant in limestone but poorly preserved	91	
Shale, brick-red	56	
Conglomerate, with matrix of limestone containing rounded pebbles of chert, limestone, and sandstone	4	
Shale, brick-red, alternating with shaly sandstone, with conglomerate made up of pebbles of Madison limestone resting on uneven surface of Madison limestone	80	

SOUTH BOULDER CREEK

South Boulder Creek has its source in the Tobacco Root Mountains and flows northward, uniting with Jefferson River at the upper end of the canyon. Its lower course is a broad, open valley, with a number of prosperous ranches.

The mountain front about 7 miles up South Boulder Creek at the mouth of the canyon consists of Phosphoria beds dipping about 40° N. To the westward the continuity of the beds is interrupted by a number of faults, and the rocks extend under a cover of extrusive rock of andesitic composition. Samples of phosphate rock were collected in an irrigation trench along the valley in sec. 10, T. 1 S., R. 3 W., and at a point 4½ miles west in sec. 1, T. 1 S., R. 4 W. The region to the southwest along the front of the Tobacco Root Mountains was not examined.

On South Boulder Creek the phosphatic beds are less cherty than to the north in the vicinity of Cardwell. There is carbonaceous shale containing at least three thin layers of phosphate rock, the lowest one, 7 inches thick, resting on sandstone. The exposures appear in a prospect pit dug in the black shale on the west side of the valley. Blocks of the phosphate rock strewn along the hillside have the usual oolitic texture and gray bloom by which they are easily recognized. An analysis of the 7-inch layer shows 53.52 per cent of tricalcium phosphate.

At a locality 4½ miles west the Quadrant and Phosphoria beds appear in inconspicuous outcrops along the border of the Madison National Forest. The phosphate bed is exposed in an old prospect pit, on the dump of which there are numerous large fragments. A sample taken from a 10-inch layer shows 76.71 per cent of tricalcium phosphate. The rock is black, is coarsely oolitic, and has the usual light-blue to gray bloom on weathered surfaces. The bed, which lies in cherty shale of nearly vertical dip, is evidently so much sheared that a reliable measurement can not be made.

LOCALITIES ALONG GALLATIN RIVER

Gallatin River from its source in the northern part of Yellowstone Park northward to the vicinity of Bozeman cuts across a number of isolated structural basins containing outcrops of the Phosphoria and associated formations. The northernmost of these, Spanish Creek Basin, is a down-faulted block surrounded by high granite mountains. To the south is the canyon of the Gallatin, about 11 miles long and terminating abruptly at the Lower Basin in soft Mesozoic rocks. Farther south the valley again shows a canyon-like aspect at several points where it is made up of the more resistant Paleozoic strata. The several areas of Paleozoic rocks are described in the following pages.

SPANISH CREEK BASIN AND SQUAW CREEK

Spanish Creek, which flows into Gallatin River from the west about 18 miles southwest from Bozeman, is followed by a wagon road that crosses the low divide to the northwest, then passes down the valley of Cherry Creek to the lower canyon of Madison River, opposite Norris. About 4 miles up the Gallatin from Spanish Creek is Squaw Creek, a tributary from the east. The general trend of these valleys is parallel to the strike of the narrow belt of Paleozoic rocks, limited on the northeast by a fault of large displacement, beyond which is granite. West of Gallatin River in the vicinity of Spanish Creek Basin and east of the river near the headwaters of Squaw Creek are small areas underlain by Quadrant and Phosphoria rocks, which were examined. A thin bed of impure sandy phosphate was found near the southeast end of the Phosphoria exposures on a branch of Spanish Creek. The rock, consisting of gray oolites of phosphorite of various sizes mixed with quartz grains, has a thickness of about 9½ inches. The lower 3 inches is phosphatic sandstone. A sample analyzed for tricalcium phosphate showed 31.20 per cent. The bed has the usual inclosing strata, shaly chert above and quartzitic sandstone below. The brick-red shales of the lower part of the Quadrant formation exposed along the wagon road are at least 50 feet thick, and some of the layers are ripple marked.

The Quadrant and Phosphoria along Squaw Creek are not well exposed, being mostly covered with a thick growth of timber, and the position of the phosphatic horizon was not found. Farther northeast, beyond Mount Blackmore, is another area of Quadrant and Phosphoria, which was not examined.

LOWER BASIN

South of the mouth of Squaw Creek for about 12 miles the Gallatin flows through a canyon cut in granite. This canyon was traversed in early days by a somewhat hazardous rocky trail, but now it has an excellent wagon and automobile road that leads into Yellowstone National Park. At the upper end of the canyon the valley abruptly widens into the broad, flat Lower Basin, which has been developed on slightly resistant Cretaceous beds capped here and there by small tracts of extrusive rock. The approach to the canyon is bordered by steeply upturned Paleozoic beds that strike nearly northwest and are broken by a fault that extends parallel to the strike for several miles, then changes direction, cutting across the Paleozoic strata and burying them under Cretaceous beds that adjoin the granite.

The Quadrant and Phosphoria formations may be seen on both sides of the river near the mouth of West Fork. They are about 350 feet thick, and the Phosphoria is not believed to contain any phosphate rock. Eight miles to the northwest, near the point along the fault where the Quadrant and Phosphoria abut against the granite, a bed of phosphate rock 14 inches thick was found.

At the mouth of West Fork the Quadrant and Phosphoria are composed of the following beds, described in descending order:

Section of Phosphoria and Quadrant formations at mouth of West Fork of Gallatin River, Mont.

	Ft.	in.
Chert in dark-gray nodules which in cross section show concentric white bands. The nodular chert is overlain by chert in thin layers intermixed with dark sandstone	27	
Sandstone, dark, quartzitic, with thin conglomeratic layer in upper part; contains fish teeth	30	
Chert in thin nodular layers; the horizon of the phosphate rock	21	
Sandstone, quartzitic, gray	120	
Limestone, sandy, dolomitic; poorly preserved fossils abundant	72	
Shale, brick-red, not well exposed	70	
Madison limestone, unmeasured.		

The phosphate bed discovered 8 miles northwest of the mouth of West Fork lies in sec. 8, T. 6 S., R. 3 E., where a stratigraphic section was measured. The exposures of the Quadrant formation are not as complete as those of the higher beds, which are also included in the following section:

Section of Phosphoria formation and associated beds, sec. 8, T. 6 S., R. 3 E., Mont.

	Ft.	in.
Limestone, filled with gastropod shells.		
Shale, dark reddish, with beds of impure sandstone and limestone; no fossils; thickness approximate	525	
Jurassic (Ellis formation):		
Sandstone, calcareous, greenish brown; lower layers filled with fossil fragments	45	
Limestone, gray; crowded with fossils	38	
Limestone, dark gray, impure, seamed with calcite veinlets; many fossils, including *Pentacrinus asteriscus*	43	
Limestone, gray, shaly; abundant fossils	118	
Shale, arenaceous and calcareous, ocherous yellow; no fossils seen	65	
Phosphoria formation:		
Quartzite, dark, with cherty nodules showing concentric bands of white in cross section	56	
Chert with irregular cylindrical columns of sandstone	14	
Quartzite, dark, with irregular columns of gray chert	8	
Chert, dark gray, in thin layers	10	
Phosphate rock, gray, oolitic, lower part friable; 70.31 per cent of tricalcium phosphate	1	2
Cherty nodules		3
Sandstone, phosphatic, cherty in lower part; contains fossil fragments	11	
Quadrant quartzite, gray, with a few layers of dolomitic limestone	208	
Limestone, dolomitic, sandy; contains indistinct fossil remains	86	
Shale, pale red, with sandy limestone conglomerate at base resting on Madison limestone	10	

ABOVE LOWER BASIN

South from Lower Basin along Gallatin River the rocks rise gradually in an irregular dome, bringing the Quadrant and Phosphoria a thousand feet above the valley. Along a line extending from the headwaters of Buck Creek southeastward beyond Eldridge post office are several faults and steep outward dips that carry the Quadrant and Phosphoria beds below the surface except along the river at Eldridge, southward from which the beds again rise well into the hills, exposing also several hundred feet of Madison limestone.

Whatever the conditions that limited the deposition of phosphatic material, it is evident that they were in effect here, for the phosphate bed ranges in thickness from only a few inches on Elkhorn Creek to about 33 inches on Buck Creek, 4 miles to the west. The eastern limit of the bed of a thickness of 1 foot or more can be represented by a line along Gallatin River from the northwest corner of Yellowstone Park down to Lower Basin, then toward Wilson Peak, about 3 miles northwest from the entrance to Gallatin Canyon.

ELKHORN CREEK

On the north side of Elkhorn Creek, 2½ miles from its mouth, a phosphate bed was uncovered by digging in the SE. ¼ sec. 11, T. 8 S., R. 4 E. The bed, only 8 inches thick, is made up of light-gray oolites overlain by sepia-brown shale and underlain by 3 inches of phosphatic limestone resting on gray cherty quartzite.

CINNAMON CREEK

The exposures described below are situated along the hogback 2 miles northwest from the forest ranger station. The phosphate bed, with associated strata, is represented in the following section:

Partial section of Phosphoria and Quadrant formations in the SW. ¼ sec. 17, T. 8 S., R. 4 E., Mont.

	Ft.	In.
Phosphoria formation:		
Quartzite, with cherty layers	38	
Shale, sepia-brown	6	
Phosphate rock, black, oolitic, friable; 57.75 per cent of tricalcium phosphate	1	3
Clay shale, yellowish brown		8
Phosphate rock, black, oolitic at top, brownish and waxy in texture at base; contains fossil fragments; 43.02 per cent of tricalcium phosphate	1	3
Quadrant quartzite:		
Quartzite, calcareous at base, where *Spiriferina* and other fossils were found	19	
Nodules of chert in sandy matrix	20	
Shale	1	3
Quartzite, unmeasured.		

The red beds exposed on the east bank of Gallatin River opposite the mouth of Cinnamon Creek are in the basal portion of the Quadrant formation, which is apparently in part equivalent to a portion of the Brazer limestone of Idaho.[13] In the upper portion of the

[13] The Brazer limestone was named by G. B. Richardson, from Brazer Canyon, in the Crawford Mountains, northeast of Randolph, Utah (Am. Jour. Sci., 4th ser., vol. 36, pp. 407–413, 1913). It lies between the Madison limestone (Mississippian) and the Wells formation (Pennsylvanian) and is from 800 to 1,400 feet thick, consisting of massive limestone with locally more or less chert, shaly layers, and sandstone. Near Laketown a thin bed of phosphate rock occurs in the shaly lower part of this formation. Variations in thickness suggest an unconformity between the Brazer and the overlying Pennsylvanian. Fossils from the Brazer in this area identified by G. H. Girty compose a fauna regarded by him as related to the Moorefield shale of Arkansas, which he considers of basal upper Mississippian (probably St. Louis) age.

earthy reddish-brown red beds is a layer of the blue oolitic claylike material 1 foot thick which was suspected of being phosphatic, but on analysis was found to contain less than 2 per cent of tricalcium phosphate. A phosphate bed at about this horizon has been discovered in the Brazer limestone at a number of places in Utah.[14] Although search was made at numerous places in Montana for a similar bed, this is the only locality where any trace of one has been discovered.

BUCK CREEK

On the north side of Buck Creek, about 2 miles north from the sampling point described above, good natural exposures of the phosphate were found. The deposit consists of a single bed of brownish oolitic friable material 24 inches thick, containing 52.44 per cent of tricalcium phosphate. The weathered fragments are light gray. The bed is separated from the quartzite below by 2½ feet of shale and phosphatic sandstone.

About 3 miles farther up Buck Creek, in section 13, T. 8 S., R. 3 E., the Quadrant beds dip below the valley at a steep angle.

MIDDLE BASIN

South of Eldridge post office is an unsymmetrical upfold which brings the Madison limestone to the surface. The axis of the fold trends roughly north, and the fold is separated from the Buck Creek-Buffalo Horn Creek uplift, to the north, by the low saddle at Eldridge. Up Taylor Fork the Paleozoic beds extend under the Cretaceous with a dip of about 25° W. The beds on the east flank are slightly overturned along the Gallatin a little above the mouth of Sage Creek and are cut by several normal faults parallel to the strike.

An unsuccessful search for good exposures of the Phosphoria formation was made along the top of the bluff on the north side of the river. The position of the upper phosphate bed is everywhere obscured by slide rock, but the bed was discovered by means of float fragments and uncovered at a point in the SE. ¼ sec. 2, T. 9 S., R. 4 E. The layer, only 3 inches thick, consists of white oolites intermixed with lumps of calcareous clay. Above the phosphate is cherty shale.

An unsuccessful search for good outcrops was made about the mouth of Taylor Fork and also up Sage Creek for a distance of about 4 miles.

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[14] Finch, E. H., unpublished manuscript.

YELLOWSTONE NATIONAL PARK

LOCALITIES ALONG WEST BOUNDARY

The areal geology of Yellowstone Park is covered in Folio 30 and in the atlas accompanying Monograph 32 of the Geological Survey.

In the vicinity of Gallatin station and to the south for about 7 miles the rocks most in evidence are the eastward-dipping quartzites of the Quadrant and Phosphoria formation, together with sills, dikes, and flows of porphyrite, which have produced more or less induration of the sandstone and chert. A normal fault extends south along Gallatin Valley, the beds on the west side being dropped possibly 800 feet. To the east and south are flows of rhyolite capped by basic breccias and agglomerates.

Projecting above the rhyolite sheet at a number of places near the wagon road along Grayling Creek, 8 to 12 miles south of Gallatin station, are pre-Cambrian black schist and crystalline limestone that resemble rocks in the Madison Valley believed to be of Algonkian age. A little farther south the road leads down over a sagebrush flat to the broad Madison Valley, a nearly level, timbered, sandy stretch 9 miles wide, which the road crosses to the village of West Yellowstone. The sandy terraces bordering the flood plain of Madison River are possibly 50 feet high and consist mostly of pebbles of dark obsidian, together with gray crystalline fragments of feldspar derived from the weathered rhyolite.

Incomplete exposures of the Phosphoria and associated formations may be seen near the west boundary of Yellowstone National Park on Bacon Rind Creek and Snowslide Creek and in the vicinity of Gallatin station. In each place the beds show the effect of proximity to the intrusive or extrusive rocks, being considerably indurated. The cherty member of the Phosphoria, which consists of thin shaly, wavy layers of chert, is baked into huge blocks 10 feet or so in diameter that roll down the steep slopes into the valleys.

The upper phosphate bed was discovered in sec. 26, T. 9 S., R. 5 E., at a point half a mile north of Gallatin station. The bed is 12 inches thick, has the usual oolitic texture and nearly black color, and weathers to bluish gray. It is separated from quartzite below by 4 inches of phosphatic conglomerate. A sample of the 12-inch layer shows 48.29 per cent of tricalcium phosphate.

QUADRANT MOUNTAIN AND VICINITY

Quadrant Mountain can be reached with a pack outfit from Fort Yellowstone, 8 miles to the east, or from the road along Gallatin

River, about 12 miles to the west. The easiest route is the Fawn Pass Trail, which leads from the mouth of Fan Creek, a tributary of the Gallatin, eastward over Fawn Pass and down Fawn Creek to the point where it bends southward, thence over a low divide and across Snow Pass to Mammoth Hot Springs. Much of the route lies in a densely timbered area, but the trail is kept in good condition because it parallels a telephone line. From Fawn Pass one can go either southward along the mountain top or down the valley to a point opposite "The Pocket," then up the steep slope to the flat grassy top of Quadrant Mountain. The numerous game trails make travel easy with a saddle horse, especially near the mountain top, which is a great treeless pasture where the traveler is almost sure to see hundreds of elk and perhaps a few bear and mountain sheep.

A trip to Quadrant Mountain was made from the Gallatin side for the purpose of studying the Quadrant formation in its type locality. The mass of the mountain, consisting of Madison limestone and sandstones and quartzites of the Quadrant and Phosphoria formations, is capped by about 30 feet of thin-bedded white limestone of Triassic age, with a small mound-shaped remnant of the overlying red sandy shales about 200 feet thick. The precipitous east and south mountain slopes present excellent exposures of the resistant quartzite beds. The same is true of the cirque valleys on the north side of Bannock Peak, whose summit stands at an altitude of about 10,400 feet.

Numerous stratigraphic measurements of the exposures in the vicinity of Quadrant Mountain are given in Monograph 32.[15] The Quadrant formation consists of sandstone and quartzite with embedded limestone having a total thickness of 450 to 500 feet and is overlain by quartzite with rolls and layers of chert which were included by Weed in the Teton formation. These beds, about 100 feet thick, are equivalent to the Phosphoria formation of Idaho, regarded as Permian, and, as would be expected, contain layers of phosphatic material. Above the cherty quartzite is gray to yellowish-gray thin-bedded limestone possibly 60 feet thick. The limestone, as indicated by its lithology and fossil content, is of Triassic age and is equivalent, in part at least, to the Dinwoody formation of western Wyoming and the Woodside formation of Idaho. The overlying red beds are probably related to the similar beds in the Chugwater formation of Wyoming.

"The Pocket" is probably a product of glaciation, being a rounded hanging valley scooped out of the northward-sloping upland, 1,000 feet above the valley of Fawn Creek. At its head is a small blue-

[15] Hague, Arnold, and others, Geology of the Yellowstone National Park: U. S. Geol. Survey Mon. 32, pt. 2, pp. 31–40, 1899.

green lake fed by water from banks of melting snow. At the south end are fair exposures of the Phosphoria and associated formations, and at this point a section was measured and phosphate samples collected.

Section of Phosphoria and associated formations near south end of "The Pocket," Quadrant Mountain, Wyo.

	Ft.	in.
Triassic:		
Limestone, thin bedded, gray, weathers sepia brown; grades up into yellowish sandy shaly beds. *Lingula* shells are plentiful in the limestone	60+	
Phosphoria formation:		
Sandstone, dark gray, with scattered chert nodules	15+	
Chert, in rolls and wavy layers, with irregular sandy layers in upper part	30+	
Sandstone, dark gray, with feathery markings resembling the cauda galli of the Devonian on bedding; scattered siliceous nodules and ropy masses; fish bones plentiful	9	
Phosphatic rock, gray, with green specks	1	2
Sandstone, dark gray, with feathery markings, chert, and fish bones similar to those in the 9-foot bed of sandstone next above	22	
Quartzite, dark gray	16	
Phosphate rock, sandy, resinous, brown on fresh fracture; contains comminuted fragments of *Lingulidiscina;* 43.79 per cent of tricalcium phosphate	3	2
Quartzite, gray, phosphatic in upper part	18	
Quadrant formation:		
Limestone, dolomitic, white, finely crystalline	7	
Sandstone, gray, cross-bedded	16	
Limestone, dolomitic, white, finely crystalline	23	
Sandstone, quartzitic, alternating with sandy dolomitic beds; poorly preserved fossils plentiful near base	200+	

Another section measured on the southeast side of Quadrant Mountain shows a thickness of about 460 feet for the Quadrant formation. The basal bed of the overlying Phosphoria formation is a phosphatic conglomeratic sandstone 1 foot thick, containing well-rounded chert pebbles half an inch in diameter, fragments of fish bones, black phosphate nodules, and broken shells of the brachiopod *Lingulidiscina*. Some of the phosphate nodules are botryoidal excrescences or irregular finger-like masses that extend downward from the base of the quartzite into the underlying calcareous sandstone. The phosphate bed grades upward into dark cherty quartzite. No good exposures of the upper phosphate bed were found here.

The following detailed section of the basal portion of the Quadrant formation was measured on the north face of Bannock Peak, *Section of basal portion of the Quadrant formation on north side of Bannock Peak, Wyo.*

	Feet
Sandstone, gray, dolomitic, alternating with dolomitic sandy limestone	56
Sandstone, yellowish, friable	25
Sandstone, ferruginous, shows purplish spots with small dolomite crystals	10
Sandstone, dolomitic	21
Shale, red, sandy, slightly calcareous	11
Sandstone, yellow and red, conglomeratic, resting on Madison limestone	18

A little northwest from Bannock Peak are excellent exposures of the Phosphoria beds. The lower phosphate bed, which was found and sampled at "The Pocket," on Quadrant Mountain, is insignificant here and appears as phosphatic sandstone. The upper phosphate bed, approximately 40 feet higher, is represented in the following section:

Section of upper phosphate bed and associated strata of the Phosphoria formation near Bannock Peak, Wyo.

	Ft.	in.
Sandstone, dark gray, phosphatic, cherty	10+	
Phosphate rock, gray, sandy, containing large phosphate granules; 40.73 per cent tricalcium phosphate	1	6
Sandstone, slightly phosphatic, cherty	17	
Sandstone, calcareous, shaly, with conglomeratic layers; basal beds of Phosphoria formation	15	

The evidence obtained in the Quadrant Mountain region indicates that the lower phosphate bed is of clastic origin. It consists largely of phosphatized shell fragments and is several feet thick at some places but absent at others. It is of low grade—in fact, it is merely a phosphatic quartz sandstone. The upper bed is lean also and less than 2 feet thick. Search in the red beds in the basal portion of the Quadrant failed to reveal any bed of phosphate such as has been found elsewhere.

MADISON RANGE

Through the greater part of its length the Madison Range is traversed by a longitudinal fault named the Madison fault, along and near which are steeply upturned Paleozoic and Mesozoic rocks. These are bordered on the west by high mountains of crystalline rocks. The two principal areas of Paleozoic beds are at the east side of Madison Valley opposite Ennis and south of the Sphinx, about the headwaters of Taylor Fork of Gallatin River. Farther to the southeast are the Beaver Creek and Cabin Creek areas, bordering Hebgen Reservoir and the Monument Mountain area on the north. These areas are described in turn beginning at the southeast.

MONUMENT MOUNTAIN-CABIN CREEK AREA

GEOGRAPHY

West of Yellowstone Park and north of Hebgen Reservoir is an area that will be considered as a unit because of the almost continuous though crooked outcrop through it of the Phosphoria formation. From Monument Mountain, in sec. 12, T. 10 S., R. 4 E., the outcrop extends westward across the headwaters of Sage Creek, then turns sharply toward the southeast for a distance of 6 or 8 miles, forming a row of hogback peaks nearly 11,000 feet in altitude, which are prominent landmarks, especially when viewed from the north. To the southwest the beds dip into a synclinal basin, from which they rise on the opposite side, 3 to 5 miles south, with a vertical to overturned dip. Thence they crop out westward to Beaver Creek, where they are cut by one of the principal faults of the region.

The area, although not exceedingly rugged, is difficult of access on account of the general thick growth of timber. It is traversed by few trails except those made by herds of elk, its remoteness from settlements and the recent creation of a State game preserve making it a retreat for several kinds of game. The mountainous ridges above an altitude of perhaps 9,500 feet are bounded by steep approaches with rocky talus slopes devoid of timber. Here and there on the summits are small areas of grassy pastures, and the densely timbered tracts are broken in places by grassy glades. The synclinal areas lying between the ridges are topographic basins with minor inequalities of the surface produced by streams cutting through rather soft shaly Mesozoic beds that alternate with a few more resistant sandstone beds. Much of the area drained by Tepee Creek is a dissected plateau with a soil which has been formed by the disintegration of rhyolite and which appears to be exceptionally fertile. This area has been burned over within the present generation, and a new growth of lodgepole pine, perhaps 10 years old, stands so thick that travel through it with a horse is next to impossible.

Grayling Creek, the largest stream joining the Madison from the north in this vicinity, drains a considerable area in the adjacent portion of Yellowstone Park. Within a mile or so of its mouth is considerable bottom land susceptible of irrigation. There is likewise about a square mile of irrigable land about the mouth of Red Creek, whose waters are being utilized at Grayling. Cabin Creek, a stream of slightly larger volume than Red Creek, issues from a narrow rocky canyon a few hundred yards from its point of junction with Madison River. It is bordered by gravel-covered bench land of little or no agricultural value. The same is true of Beaver Creek, a still larger stream fed by numerous tributaries from the highest snow-covered peaks of the Madison Range. A part of the Beaver

Creek drainage basin is well suited for grazing and has been used as a cattle range for several years.

STRATIGRAPHY AND STRUCTURE

The stratigraphy of this area is not greatly different from that of the Indian Creek area, some 15 miles to the northwest, which is described on pages 196–197. The principal difference is the presence of about 450 feet of Triassic red beds just beneath Ellis marine limestone. Those strata thin in wedge shape northward and are absent on Indian Creek. The Madison limestone, about 1,000 feet thick, is overlain by the Quadrant, which exhibits its usual quartzitic character and is in turn overlain by the Phosphoria formation. The post-Phosphoria beds are illustrated by the following measurements made in sec. 29, T. 10 S., R. 4 E.:

Section in sec. 29, T. 10 S., R. 4 E., Mont.

	Feet
Kootenai formation:	
Clay shale, in alternating gray, chocolate-colored, red, and blue tints	50+
Sandstone, cross-bedded, greenish gray	20
Ellis formation:	
Limestone, sandy, and calcareous sandstone that weather rusty brown, oolitic in lower portion; filled with fossils, mostly in fragments; belemnites seen	25
Shale, calcareous, or shaly limestone; contains many pelecypods	90
Limestone, gray	6
Triassic red beds: Shale, brick-red; upper limit not sharp, marked chiefly by a change in color, little change in texture	450

The rugged alpine portion of this area on the west side of Beaver Creek consists of pre-Cambrian crystalline rocks that lie in faulted contact on the east with beds as late as Upper Cretaceous, their relations denoting a displacement of at least 7,000 feet. From the vicinity of Hebgen Reservoir this fault extends northwestward a distance of 40 miles. The slightly overturned attitude of the beds at some points near the contact may indicate overthrusting, although this inference could not be verified at any point by inspection of the contact.

Several faults of minor displacement were found on Monument Mountain. The largest one extends north toward the mouth of Sage Creek, and its downthrow, amounting to a few hundred feet, is on the east side.

In the southwestern part of T. 11 S., R. 4 E., are many minor faults cutting the Quadrant exposures along Kirkwood Creek. These appear to be of a later date than the principal fault extending southwestward through this neighborhood.

PHOSPHATE ROCK

MONUMENT MOUNTAIN

Monument Mountain is one of several peaks of about 10,000 feet altitude at the headwaters of Snowslide, Sage, and Bacon Rind Creeks. Out of the steep slopes have been scooped a number of glacial cirques in which lie small ponds that form the beginnings of several streams. In these places are complete exposures of various parts of the section from the base of the Madison limestone to the top of the quartzite in the Phosphoria, which constitutes the highest mountain-making formation.

The principal phosphate bed was uncovered on the northeast side of Monument Mountain, in sec. 7, T. 10 S., R. 5 E., and found to be 1 foot 3 inches thick. The rock is gray and of oolitic texture and contains considerable argillaceous and ferruginous material. Analysis of a sample shows 58.08 per cent of tricalcium phosphate. Below the phosphate layer is quartzite containing poorly preserved brachiopod shells, and above it is dark quartzitic chert.

MOUNTAIN SHEEP POINT AND VICINITY

Four miles southwest of Monument Mountain, in sec. 34, T. 10 S., R. 4 E., is a peak designated Mountain Sheep Point. Its altitude, 10,600 feet by aneroid determination, is 300 feet less than that of the highest summit along the strike of the rocks, 2 miles to the northwest. The Quadrant and Phosphoria beds at the summit of the mountain dip steeply southward, forming on the north a precipitous cuesta slope which is pitted by several cirque valley heads of streams tributary to Sage Creek. The following section of the lower portion of the Quadrant was measured at Mountain Sheep Point:

Incomplete section of Quadrant formation at Mountain Sheep Point, Mont.

	Feet
Quartzite, gray	100±
Limestone, gray, with shaly buff-weathering layers, alternating with gray quartzite	30
Quartzite, gray	13
Limestone, bluish gray, shaly	20
Quartzite, mottled bluish and gray	10
Limestone, dark gray, green, and red mottled, siliceous	5
Limestone, shaly, reddish	6
Sandstone, fine grained, shaly, brick-red with circular spots of drab as much as 2 inches in diameter	36
Madison limestone, unmeasured.	

Another section of the Phosphoria and underlying strata was measured in sec. 28, west of Mountain Sheep Point. The specimens of *Fusulina* discovered in the upper portion of the Quadrant are believed to constitute the first reported occurrence of this genus in either Montana or Wyoming.

Section in sec. 28, T. 10 S., R. 4 E., Mont.

	Ft.	in.
Phosphoria formation:		
Sandstone, dark gray, with cherty balls that show light and dark concentric bands in cross section; ripple and worm-trail marked; contains fish bones	20	
Sandstone, dark gray, containing irregular gray cherty stringers	21	
Chert, gray, in thin irregular wavy layers	27	
Phosphatic bed:		
Limestone, gray, oolitic, containing fish teeth		4
Phosphorite, black, oolitic, friable	1	1½
Shale		8
(A sample of the three above layers shows 65.48 per cent of tricalcium phosphate.)		
Sandstone, dark gray, phosphatic in upper portion, containing irregular cylindrical columns of lighter-colored sandstone	8	6
Quadrant formation:		
Dolomitic limestone brecciated and mixed with sandstone in upper part	28	
Quartzite, with dolomitic beds at base containing *Fusulina*	30±	

RED CREEK

The foothills about the mouth of Red Creek consist of granitic gneiss and schist capped by the Paleozoic limestone series. To the northwest for several miles the angle of dip is low, but to the northeast the beds stand in a nearly vertical position, forming a sheer wall of limestone that extends northwestward across Red Creek, then bends in an arc west and southwest along Kirkwood Creek. Red Creek has cut a sharp notch through this natural barrier, along which are exposed the Phosphoria and overlying Triassic beds. The sequence is interrupted by faulting nearly parallel to the bedding, but the following measurements were made:

Section on Red Creek, Mont.

	Feet
Triassic:	
Red beds in even shaly layers, calcareous in lower part and differing little in lithology from brownish beds below	150±
Limestone, very impure, ocherous, sandy, crystalline; contains pelecypod shells	33
Limestone, impure, in blocky to shaly layers, bluish gray, weathering brown; contains *Lingula* shells	95
Phosphoria formation: Cherty white and gray beds with quartzite below, unmeasured.	

The steeply northeastward-dipping beds of Red Creek canyon rise again from a sharp syncline about a mile northeast, where the uppermost Madison and Quadrant beds form the usual hogback, the east slope of which is overlapped by the rhyolite sheet that extends over much of Tepee Creek basin.

CABIN CREEK

Cabin Creek, like Red Creek, emerges a few hundred yards above its mouth from a narrow, deep canyon cut through a wall of overturned limestone. At the upper end, where the canyon broadens to a basin on the soft Mesozoic rocks, are good exposures of the Phosphoria beds lying in an overturned attitude, dipping 42° SW. At this point the following measurement of the upper phosphate bed was made.

Section of phosphatic beds of Phosphoria formation in sec. 14, T. 11 S., R. 3E., Mont.

	Ft.	in.
Chert in shaly, wavy layers, unmeasured.		
Phosphorite, black, oolitic, siliceous near top; 61.83 per cent of tricalcium phosphate	1	5
Shale, gray, calcareous		11
Quartzite, cherty, containing at base phosphatic fragments of *Lingulidiscina* and conglomerate which mark the position of the lower phosphate bed and also the base of the Phosphoria formation	18	
Dolomitic cherty gray limestone, unmeasured.		

About a mile and a half northwest of the locality described above the Phosphoria beds terminate at the fault contact and abut against greenish sandstone of Upper Cretaceous age. The point is at the north end of a prominent butte of Madison limestone stained by the red shaly clay at the base of the overturned Quadrant beds. The Phosphoria beds are not well exposed.

Close to the fault contact at the summit of the ridge is an outcrop of the overlying brown shaly Triassic beds, which are of interest for the reason that they contain layers of white gypsum.

LIGHTNING CREEK-INDIAN CREEK AREA

GENERAL FEATURES

The great fault extending along the axis of the Madison Range has caused the concealment of the Paleozoic beds from Beaver Creek northwestward to the vicinity of Lightning Creek, a distance of about 6 miles. From Lightning Creek northwestward to Indian Creek this fault cuts across Paleozoic and pre-Cambrian rocks, and there is an uninterrupted sequence of the sedimentary beds dipping steeply northeast and flattening toward a broad, irregular synclinal basin. The resistant crystalline rocks forming the west front of the range tower 5,000 feet or more above the broad Madison Valley to the west in a series of imposing peaks as much as 11,000 feet in altitude. The less resistant Mesozoic rocks east of them form an extensive plateau 8,000 to 9,000 feet in altitude, which is dissected by streams tributary to Gallatin River. Indian Creek is one of the few streams that have carved their way westward from the plateau across the resistant Paleozoic and pre-Cambrian rocks that form the high portion of the mountain range.

Practically all of the area except the most elevated and rocky portions is covered with timber. The growth is densest along and near the valleys, but on the ridges are small untimbered tracts, some of which are used as summer range by sheep and cattle growers. About 10 years ago lumber camps were operated on Lightning Creek and also to the northeast along Buck Creek. Those areas that have been logged over now form a wilderness of slashing where travel with a saddle horse is next to impossible. The timber, although largely lodgepole pine, also includes considerable Engelmann spruce and fir.

The Phosphoria beds in the Lightning Creek-Indian Creek area dip steeply northeast except locally where they are overturned near the great fault. The bold, gray wall of Madison limestone is flanked by less imposing Quadrant strata, at the base of which are red shales that form a marked contrast to the underlying limestone, noticeable even when seen from a distance of 5 miles. Good exposures of the Phosphoria and higher beds are not plentiful, as much of the surface is covered with driftlike material from the adjacent highlands to the west. The phosphate bed was uncovered on Taylor Fork, at a point 2 miles to the northwest, and on Indian Creek.

TAYLOR FORK

Along Taylor Fork a little above the mouth of Lightning Creek a good exposure of the phosphate bed was made by digging, and the section measured was as follows:

Section on Taylor Fork, in the SW. ¼ sec. 19, T. 9 S., R. 3 E., Mont.

	Ft.	in.
Triassic: Impure siliceous limestone containing wavy *Lingula* shells	70±	
Phosphoria formation:		
Cherty sandstone	85	
Chert in thin wavy layers	27	
Shale, phosphatic	1	6
Phosphate, dark oolitic; 65.31 per cent of tricalcium phosphate	1	7½
Shale, dark, slightly phosphatic	1	6
Phosphate, impure, sandy		9½
Sandstone, unmeasured.		

A good exposure of the phosphate bed farther north, in sec. 11, showed the principal bed to be 2½ feet thick and free from shale except in the upper fourth. The general dip northward from Taylor Fork is about 35°–40° NE. and the strike N. 40°–50° W.

INDIAN CREEK

On the north side of Indian Creek in sec. 20, T. 8 S., R. 2 E., are complete exposures of the strata from the Madison limestone up into the Cretaceous, comprising a thickness of nearly 2,000 feet and thus presenting an unusual opportunity for stratigraphic study. The sequence and character of the beds are shown below.

Section on Indian Creek, Mont.

	Ft.	in.
Cretaceous:		
Limestone, cream-colored; lower portion filled with gastropods	50	
Clay shale, ferruginous, with a few irregular sandy layers and a layer of rusty yellow limestone, lavender on fresh surfaces	400	
Sandstone, quartzitic	38	
Clay, shale, variegated reddish and brown	64	
Sandstone, coarse, with dark chert pebbles	32	
Shale and clay with carbonaceous layers	49	
Sandstone, arkosic, coarse, with undulating base	158	
Shale and shaly sandstone, reddish in lower part	168	
Jurassic:		
Shale, bluish gray to green, with layers of impure limestone	98	
Sandstone, friable, greenish	14	
Limestone, granular, gray; rich in marine fossils	32	
Shale, greenish gray	18	
Limestone, gray	51	
Limestone, gray, shaly; rich in fossils	88	
Shale, gray, calcareous	28	
Triassic (?):		
Shale, ocherous yellow, sandy, gypseous	89	
Shale, sandy, calcareous, gray, grading down into impure sandy limestone	25	
Sandstone, cross-bedded, friable, yellowish	42	
Shale, calcareous, sandy, grading down into impure sandy limestone rich in fossils, including *Lingula*	102	
Phosphoria formation (Permian):		
Quartzite, dark, cherty; traces of fossils	65	
Chert in irregular layers, traversed by vertical sandstone columns	14	
Quartzite, dark, cherty	8	
Chert, dark gray, in thin layers	10	
Phosphate beds:		
Oolite, dark gray		4
Limestone, dark gray		10
Shale		2

	Ft.	in.
Phosphoria formation (Permian)—Continued.		
Phosphate beds—Continued.		
Phosphate rock, black, friable	1	7
Shale		2
Phosphate rock, black, oolitic	1	2
(A sample of the above three layers shows 57.52 per cent of tricalcium phosphate.)		
Shale, black	1	10
Phosphate rock, impure		4
Sandstone, cherty, phosphatic	11	
Quartzite, dark	12	
Shale	3	
Limestone, sandy; traces of phosphatized fossils in upper part; chert pebbles in lower part	6	
Quadrant formation: Quartzite, gray, cross-bedded, unmeasured.		

MOUNTAIN FRONT EAST OF ENNIS

The front of the Madison Range east of Ennis for a distance of about 12 miles is made up of a narrow north-south belt of steeply dipping, considerably faulted Paleozoic strata. The mountain slopes are decidedly rugged and difficult of ascent, being unusually rocky and for the most part timbered, especially on the valley slopes of Cedar, Jack, and other creeks. Beyond the first summits are large areas of less rugged upland with open grassy pastures that are used for sheep grazing. The Forest Service has opened an excellent trail up Cedar Creek, which furnishes access to the mountain top. Another trail leads up Jack Creek and across the divide down a branch of West Fork of Gallatin River. Lone Mountain, along the north slope of which this trail passes, is one of the most beautiful in the Madison Range. Its altitude is about 11,000 feet, and when seen from the east its snowy conical mass resembles a typical Andean volcanic peak.

No good exposures of the phosphate bed were found, but its position at numerous points was determined by the presence of float fragments of the rock. A zone of faulting paralleling the strike of the rocks interrupts their continuity here and there and conceals the Phosphoria formation from Tolman Creek southeast for 8 miles. Between Cedar Creek and Jack Creek the beds are vertical to overturned and have locally a westward dip as low as 30°. There is little evidence as to the thickness of the phosphate bed, but it is apparently more than 1 foot. On Tolman Creek blocks of rich-looking black oolite 4 inches in diameter were found. At the nearest sampling point near Lone Mountain, about 9 miles to the east, a bed 14 inches thick yielded on analysis 70.31 per cent of tricalcium phosphate.

GRAVELLY RANGE

STRATIGRAPHY

West of Madison Valley and south from Virginia City to Centennial Valley is the Gravelly Range, of which Black Butte, a massive volcanic plug of black basaltic rock 10,800 feet in altitude, is the most prominent peak. South and southwest of Black Butte several less prominent ridges reach an altitude of slightly more than 10,000 feet.

The pre-Cambrian rocks exposed in the Gravelly Range are chiefly granitic gneiss with scattered dikes of diabase or peridotite. In addition there are several areas of mica schist, marble, and quartzite. The wooded mountain side opposite Lyon along the second standard parallel is mostly granite, which crops out westward for about 4 miles, and is succeeded by a belt of dark hornblende-mica schist with much magnetite and hematite.

Farther west along the second standard parallel for a distance of 5 miles is the sequence of Paleozoic limestones, dipping gently westward, and overlain by the Quadrant quartzite. This is in turn overlain by the Phosphoria formation, which is capped by the Triassic shaly limestone and younger Triassic red beds that appear around the base of Black Butte.

The Madison limestone, probably 1,000 feet thick, forms numerous rounded summits more than 10,000 feet in altitude east of the crest of the range. Here and there the gray limestone is capped by more or less rugged peaks of dark volcanic rock. Other high peaks formed by the resistant overlying Quadrant beds appear a few miles west of the belt of Madison limestone.

No complete measurement of the Quadrant formation was made in the Gravelly Range, but it is evident that the formation is much thinner there than in the Snowcrest Range, to the west—probably no more than 350 feet thick. The usual red shaly member is present at the base, and the overlying beds consist chiefly of quartzitic sandstone with a less amount of limestone. The best exposures observed are near the head of Ruby Creek, at the north side of T. 10 S., R. 2 W. The following section, measured on the north side of the high point in sec. 3, shows all but the basal part of the Quadrant and the overlying Phosphoria and Triassic beds.

Section of Quadrant and overlying beds near the head of Ruby Creek, in sec. 3, T. 10 S., R. 2 W., Mont.

	Feet
Triassic: Shale, or shaly thin-bedded limestone, brown to yellowish on weathered surface; fossiliferous	95
Phosphoria formation:	
Sandstone, calcareous, with scattered chert masses and small cubes of pyrite; weathers into irregular layers, some of which contain abundant small fossils	17

Phosphoria formation—Continued.	Feet
Quartzite, dark, cherty in lower portion; indistinct fossil fragments abundant in upper 5 feet. Extending across the bedding are peculiar distorted rods or cylinders of sandstone of lighter gray than the inclosing quartzite; some of these rods are cherty and break from the cliff in sections 1 foot long	50±
Chert, upper part nearly porcelain-white, with peculiar rough, jagged surface	36
Quartzite, dark gray, mottled with irregular chert bands	4
Chert, in thin wavy layers, dark gray, weathering brownish	45
Shale, black, underlain by about 2 feet of friable black oolitic phosphate rock, which rests on a thin bed of faint-red clay shale. No good exposures found	21
Quartzite or siliceous limestone, cherty, with phosphatic fossil fragments in upper part	9
Quartzite, with many phosphatic shells of *Lingulidiscina* and also fish bones	2
Limestone, fine textured, gray	12
Limestone, impure, gray, mixed with chert and irregular included lenses of fossiliferous sandstone	17
Quartzite and nodular chert with irregular bands of fine-textured dark-gray limestone. The chert nodules in cross section show concentric bands of white and dark gray	10
Conglomerate of phosphate nodules, greenish; many fossils	¾
Chert, shaly, dark gray, weathering to rusty brown, grading down into phosphatic chert conglomerate	4
Quadrant formation:	
Limestone, impure, fine textured, gray, cherty near top	17
Sandstone, gray, with irregular flowlike inclusions of limestone	7
Limestone, fine textured, argillaceous, white	15
Sandstone, dolomitic, brownish gray	17
Limestone, crystalline	3
Quartzite, unmeasured.	

At this point, as at other points in the region, the best opportunity for observing the rocks is found on the north exposures, where the snow remains longest, retarding vegetation, and the frost action loosens a great quantity of rock that slides down the steep slopes and forms accumulations of talus at the base. As a rule only the more resistant hard rocks are clearly exposed; shaly beds give gently sloping shelves more or less buried under the products of weathering.

The section given above represents the general sequence of the Phosphoria beds. There is the lower phosphatic layer, lean and more or less conglomeratic at the base, and over this about 55 feet of quartzitic sandstone interbedded with smooth-textured argillaceous gray limestone, upon which rests the upper phosphatic member consisting of shaly beds about 20 feet thick that contain several layers of phosphate rock. Over this is about 45 feet of brownish chert in thin wavy layers, which is in turn overlain by about 100 feet of dark-gray quartzite with much chert in layers and irregular ropy masses.

Along the crest of the mountains, particularly in the northern portion, are scattered patches of coarse gravel, which probably suggested the name Gravelly Range. This material, which consists of a motley aggregation of the country rock, was mapped by Peale as glacial drift. Some of it is reported to be gold bearing and was prospected many years ago.

STRUCTURE

Structurally the Gravelly Range forms the west flank of a great anticline, the axis of which extends the length of Madison Valley in a direction a little east of south. The east mountain front is made up of Algonkian and Archean rocks overlain by Paleozoic beds dipping gently westward into the synclinal valley of Ruby River. The precise structural relations of the Gravelly Range to the mountains south of Centennial Valley are not certain, because of the extensive cover of extrusive rocks, but it is evident that the anticlinal axis of Madison Valley bends from south to southeast, extending across the head of Centennial Valley through Henry Lake.

There are no faults of great magnitude in the Gravelly Range. One of the largest, an overthrust from the northwest, extends southwestward through T. 10 S., R. 2 W., and the displacement is probably a little less than 1,000 feet. Other faults, apparently subsequent to the overthrust, were noticed along the top of the mountain from the second standard parallel north for about 10 miles. They trend northward, and the east side is dropped 300 to 600 feet. Only a few of these have been mapped, and there are others farther north which were not traced.

PHOSPHATE ROCK

Neither the lower nor the upper phosphate beds are of much prospective value, as will be seen from the following representative section measured along the west side of Ruby Creek:

Measurement of phosphate and associated beds near south edge of sec. 4, T. 10 S., R. 2 W., Mont.

	Ft.	in.
Chert, brown, in thin wavy layers.		
Shale grading up into shaly chert; lower part weathers to chocolate-brown in concentric bands	6	
Upper phosphatic beds:		
Phosphate rock, gray, oolitic, mottled in upper portion; 63.98 per cent of tricalcium phosphate	1	3

	Ft.	in.
Upper phosphatic beds—Continued.		
Shale, calcareous		6
Phosphate rock, black, oolitic, friable, shaly near top; 56.09 per cent of tricalcium phosphate	1	
Clay shale		8
Shale, carbonaceous phosphatic	2	4
Limestone, shaly		5
Shale, bony, black, phosphatic		10
Phosphate rock, oolitic		4
Limestone, dark, phosphatic		8
Chert and cherty quartzite with speckled appearance caused by scattered phosphatic granules and fossil fragments	71	
Lower phosphatic beds:		
Siliceous gray phosphate rock, low grade	2	
Chert	4	
Phosphate rock, greenish gray, granular; 56.52 per cent of tricalcium phosphate	1	
Limestone, gray, chalky, unmeasured.		

Exposures that would permit measurements of the upper phosphatic beds were not found at any other point in the Gravelly Range. All measurements in adjoining areas to the east, south, and west, however, give results only slightly different and force the conclusion that no more valuable area of the upper phosphate beds is to be found. The rock is so easily disintegrated that at many places along the outcrop no trace of it can be found, but careful examination of the dark soil produced by it will usually reveal the black oolites. The slight crushing resistance of the principal phosphate bed and its intercalation with clay shale give rise to slumping, which must be taken into consideration in digging prospect trenches. A layer actually 2 feet or more thick may appear to be only a few inches near the surface.

The phosphatic layers at the lower horizon in the Gravelly Range are even less important than the upper, being as a rule less than 2 feet thick and generally showing a low content of tricalcium phosphate. Toward the south end of the range the exposures are so poor that no opportunity was found for measurement. Float fragments, noticed at a number of places, indicated the persistence of the lower bed, and a thickness somewhat greater than that on Ruby Creek may be hoped for southward, for the reason that the bed is prominently developed farther south just across Centennial Valley.

WARM SPRING CREEK CANYON

Along Warm Spring Creek about a mile from its mouth are good exposures of the Phosphoria formation. The sequence of the beds is shown by the following section:

Section of Phosphoria formation in Warm Spring Creek canyon, sec. 32, T. 9 S., R. 3 W., Mont.

	Ft.	in.
Triassic: Limestone, brownish gray, arenaceous, impure, in thin platy layers; unmeasured.		
Phosphoria formation:		
Sandstone, dark, quartzitic; traces of fossils	50	2½
Chert in thin dark layers, stained rusty brown	40	
Shale, cherty in upper part, brownish gray	17	
Phosphatic beds:		
Phosphorite, black, oolitic		7
Shale		4
Phosphorite, finely oolitic, friable; 62.71 per cent of tricalcium phosphate	1	8
Clay		5
Shale, black, almost coal in composition; contains 15.29 per cent of tricalcium phosphate and 3 gallons of petroleum to the ton	1	8
Shale, rusty brown		10
Shale, with phosphatic oolites		1½
Shale, brown		5
Phosphorite, black, massive, nonoolitic; weathers to bluish-white "bloom"		8
Phosphorite, coarse textured; fossil fragments; large quartz pebbles at base; 21.81 per cent of tricalcium phosphate	1	2
Sandstone, dark gray, phosphatic	4	
Sandstone, ocherous, shaly	9	
Chert, in thin layers	3	
Limestone, massive, siliceous, dolomitic, gray; pelecypods, gastropods, etc., extremely abundant in lower part	24	
Quartzite, dark colored, with irregular cherty bands	7	
Phosphorite, quartzitic, with gray bloom on weathered surface; scattered fossil fragments; 54.84 per cent of tricalcium phosphate	2	2

RUBY RIVER CANYON

Good exposures of most of the Phosphoria formation may be seen on the north side of the Ruby River canyon, but minor faults are so numerous that accurate measurements can not be made. The phosphate bed was exposed by digging, and its approximate thickness, together with that of the rocks above and below, is shown by the following section:

Section of Phosphoria formation on north side of Ruby River canyon, sec. 18, T. 9 S., R. 3 W., Mont.

	Ft.	in.
Chert, brown, in thin layers; unmeasured.		
Shale, sandy, brown, cherty in upper part	7	
Shale, carbonaceous, slightly phosphatic in lower part	9	
Clay shale		9

	Ft.	in.
Phosphatic beds:		
Phosphorite, shaly, oolitic		5½
Chert, black		2½
Phosphorite, siliceous		3
Limestone, argillaceous	1	4
Phosphorite, black, oolitic, middle portion calcareous; 43.50 per cent of tricalcium phosphate	2	8
Quartzite, dark, with irregular cherty bodies	9	
Chert, dark, shaly	2	
Limestone, gray, dolomitic	9	
Shale, ocherous, yellow	1	
Limestone, gray, dolomitic, with irregular sandy layers and chert balls; fossils in lower portion	43	
Shale, yellowish brown, sandy	1	
Limestone, argillaceous	5	
Sandstone, friable, shaly, yellowish to pink; thin layer of limestone near middle	20	
Quartzite, dark, with irregular layers of gray chert	28	
Sandstone, shaly, brown	4	
Chert, dark, shaly	4	
Phosphate rock, siliceous		9
Limestone, fine textured, dolomitic, dark gray	11	
Sandstone, friable, grayish, unmeasured.		

SNOWCREST RANGE

STRATIGRAPHY

The Quadrant outcrop was followed southward from the Ruby River canyon for a distance of about 8 miles. The quartzitic beds form the mountain top for the greater part of the distance and litter the slopes with great quantities of angular boulders. A little beneath the crest on the east slope the beds are vertical to overturned, but they arch over the mountain top and dip westward at a gentle angle to a fault which brings them against pre-Cambrian rocks. Excellent exposures of all but the upper part of the Quadrant formation were found in sec. 26, T. 10 S., R. 4 W., and the measurements are given below. The unusual thickness is noteworthy, being nearly 1,000 feet.

Section of Quadrant formation in Snowcrest Range, sec. 26, T. 10 S., R. 4 W., Mont.

	Feet
Limestone, dolomitic, with gray sandy layers; approximate thickness	80
Sandstone, quartzitic, gray	138
Shale, calcareous, mottled gray and brown	5
Sandstone, quartzitic	36
Shale, calcareous, mottled gray and brown	5
Sandstone, quartzitic	25
Limestone, cherty, dolomitic, with thin sandy layers	29
Sandstone, quartzitic, gray	40
Shale, black	2

	Feet
Sandstone, quartzitic, gray, with dolomitic layers and thin layers of fine-textured dark-gray limestone	205
Limestone, dark gray; few fossils; several quartzitic layers	55
Quartzite, pinkish	30
Limestone, dark colored, shaly, with some massive layers, containing black to brown chert nodules; fossils extremely abundant in shaly layers and indicate upper Mississippian age	253
Rocks poorly exposed	50
Sandstone, conglomeratic at base; regarded as basal member of Quadrant formation; approximate thickness	20
Covered interval	25
Madison limestone: Limestone, fissile, shaly, dark, rich in fossils, unmeasured.	

PHOSPHATE ROCK

The evidence as to the character of the phosphate beds in the Snowcrest Mountains is given in the preceding descriptions of Warm Spring Creek and Ruby River canyons, in which samples were collected and measurements made. No exposures suitable for sampling were found along the Snowcrest Mountains southward for a distance of 8 miles, to the point where work was discontinued. It is evident that neither the lower nor the upper phosphatic beds are of immediate prospective value. The combined thickness of the richer laminae, including small amounts of shale, is about 2½ feet. The percentage of tricalcium phosphate is low compared with that of beds now considered worth exploiting.

Most of the phosphate rock is so friable that it can readily be crumbled between the fingers, and therefore fragments are not plentiful on talus slopes. Good exposures are rare, and it is usually necessary to dig a shallow trench to find the beds, but their position, only a few feet below the thick chert member, renders their discovery easy.

CENTENNIAL VALLEY

One of the most striking of the broad intermontane valleys lying in the midst of the Rocky Mountains is Centennial Valley, a broad basin nearly as level as a floor, occupied by a small stream that hardly deserves the name river even 50 miles from its source. Downstream for several miles from Lower Red Rock Lake the stream has low banks and is bordered by extensive level marshy lands.

North of Centennial Valley are low foothills, some of which attain an altitude of 8,000 feet, or about 1,500 feet higher than the valley. They consist of arkosic sand, gray to white loosely cemented silt, and thin cappings of lava that slope at various angles. Over the whole is coarse gravel consisting mostly of well-rounded cobblestones of quartzite. The material on the whole resembles the Tertiary "lake beds" described in the Three Forks folio of the Geologic Atlas.

The foothills on the south side of the valley are largely landslide material that has come from the steep north slope of Centennial Range.

Northwest of Lower Red Rock Lake are scattered exposures of westward-dipping beds of greenish-gray Cretaceous sandstone and shale projecting through the mantle of "lake beds" and cappings of lava. East of this belt is an inconspicuous low ridge of Phosphoria chert and Quadrant quartzite that is exposed intermittently from sec. 18, T. 13 S., R. 2 W., northward throughout the Gravelly Range. The exposures near Centennial Valley are poor, furnishing no opportunity for measurements of the Phosphoria formation or sampling of its phosphate beds. The structural relations of these exposures to the same formation along the State line, about 10 miles to the southwest, are in doubt.

REA PASS AND VICINITY

From Rea Pass southeastward into Yellowstone Park lies the great Madison Plateau of rhyolitic lava, apparently made up of overlapping flows of volcanic rock that issued from an ancient volcano, possibly along the high ridge south of Targhee Creek. This rock is a basalt, with crystals of olivine and augite. Locally it is amygdaloidal and contains fillings of calcite. Along the State line this rock rests on Cretaceous strata dipping eastward. One exposure was found in sec. 21, T. 15 N., R. 44 E. About half a mile farther west is a belt of Phosphoria formation, Quadrant quartzite, and Madison limestone striking a little west of north and dipping 30°–60° E. that is cut by minor faults. The poor exposures do not favor prospecting for phosphate rock.

TARGHEE PASS

For a mile south of Targhee Pass the densely timbered mountain slopes consist of volcanic rock, northeast of which is a narrow belt of Jurassic and Cretaceous beds dipping northeast. Along the mountain top between mileposts 717 and 719 is a capping of coarse granitic boulders at an altitude of about 8,100 feet. The relation of these boulders to the flows of volcanic rock is not certain, but it is probable that they extend under the lava.

North of Targhee Pass, for a distance of about 2 miles, the State line follows a hogback of Quadrant quartzitic sandstone varying in dip from south to west. There are no exposures suitable for stratigraphic study of the Phosphoria or prospecting for phosphate rock. The high bare slopes of Bald and Block Mountains, to the northwest, furnish excellent exposures of the lower Paleozoic and Algonkian strata.

CENTENNIAL RANGE

The Centennial Range begins with Sawtelle Mountain, south of Henry Lake, and extends thence westward to Monida, forming the Continental Divide and the Idaho-Montana State line.

WEST OF SAWTELLE MOUNTAIN

Volcanic rock, probably the same as that forming the great black bulk of Sawtelle Mountain, extends southwestward for a distance of several miles, covering the Paleozoic strata to an unknown depth. Evidence of the age of the eruption is furnished by the fact that its materials are apparently missing in the conglomerates that occupy a portion of the erosion basin south of Mount Jefferson, at the head of Red Rock Creek. From the point of emergence of the Paleozoic beds westward to Odell Creek, a distance of 16 miles, there are continuous exposures of the Paleozoic and part of the Mesozoic succession. Some of the local details are described below.

The upper part of the Quadrant formation and the overlying Phosphoria beds were examined at a point 3 miles southwest of Sawtelle Mountain, near milepost 678, along the State line. Beds lower than these are covered by loosely cemented gravel and clay of Tertiary age. The thickness of the upper phosphate bed is only 8 inches. The lower phosphate bed was not discovered.

Section along the Idaho-Montana State line, 3 miles southwest from Sawtelle Mountain

	Ft.	in.
Triassic: Limestone or calcareous shale, weathering grayish-brown; upper beds sandy; many *Lingula* fossils	98	
Phosphoria formation:		
Sandstone, dark, containing irregular masses of ropy chert and peculiar distorted cylinders of gray sandstone standing nearly vertical in dark sandstone	37	
Chert, with sandstone intercalations	25	
Chert in thin layers, weathering brown	24	
Shale, cherty (not measured).		
Shale, carbonaceous; yields on distillation 6 gallons of petroleum to the ton	4	
Phosphate rock, oolitic, gray; contains fish teeth; 57.33 per cent of tricalcium phosphate		8
Clay		6
Sandstone, calcareous, argillaceous, fossiliferous, grading down into dark quartzite, unmeasured.		

The principal branch of Willow Creek that crosses the line between Rs. 41 and 42 E. Boise meridian flows southwestward parallel to a fault. The west side dropped a thousand feet or so, giving a depressed area of slightly resistant Mesozoic beds that were deeply buried under Tertiary lava flows. On the east side are topographically prominent hills of Madison limestone and Quadrant quartzite. About 2 miles to the west the sedimentary rocks again emerge, and from this point westward for 9 miles volcanic rock is little in evidence, occurring mostly near the north and south bases of the mountain slopes.

NEAR MONTANA PRINCIPAL MERIDIAN

Exposures of more than ordinary interest were found along the State line a mile east of the Montana principal meridian. The unusual features here are a thickness of about 4 feet for the lower phosphate bed, the absence of the red shales that are so generally persistent at the base of the Quadrant formation, and the presence of a well-preserved fauna, regarded by G. H. Girty provisionally as Pennsylvanian, in the lower part of the Quadrant formation.

The lower phosphate bed, as usual, is found to consist largely of phosphatic shells, probably mostly of *Lingulidiscina*. The color is light gray with few black specks, and a specimen at first glance resembles fine-grained gray granite. Analysis of a sample from a bed 51 inches thick shows 69.09 per cent of tricalcium phosphate. A collection of float samples from the same vicinity was found to contain 72.28 per cent. Below the phosphate at some places is several feet of conglomerate resting on cream-colored, smooth-textured dolomitic limestone. The base of the conglomerate is the line of division between the Phosphoria and Quadrant formations.

The strata between the lower and upper phosphate beds are about 50 feet thick and consist largely of cherty quartzitic sandstone. A sample from the upper phosphate bed, which is about 14 inches thick, showed on analysis 64.33 per cent of tricalcium phosphate. It is black and oolitic and weathers to a black sandy soil intermixed with dark clay from overlying shale.

Near the point where phosphate samples were collected the following stratigraphic section was measured. The position of the lower phosphate bed is a few feet above the highest strata represented. The saccharoidal texture in the upper beds of the Madison limestone is general, having been observed at numerous places east into Yellowstone Park and north along the Madison and Gallatin mountain ranges.

Section of parts of Quadrant and Madison formations on the Idaho-Montana State line 1 mile east of Montana principal meridian

	Feet
Quadrant formation:	
Sandstone	15±
Sandstone, dolomitic, with thin limestone layers containing traces of fossils	60
Limestone, dolomitic, cream-colored and smooth textured	8

Quadrant formation—Continued.	Feet
Dolomite, saccharoidal texture	18
Limestone, shaly; filled with fossils	4
Limestone, bluish gray, fine textured, mottled with irregular gray dolomitized patches of saccharoidal texture	16
Limestone, dolomitic, finely crystalline, gray	7
Shale, ocherous yellow, locally faint red	6
Sandstone, calcareous, argillaceous	5
Madison limestone:	
Limestone, dolomitic, white, saccharoidal	15
Limestone, shaly	4
Limestone, finely crystalline, gray	5
Limestone, dolomitic, crystalline	4
Limestone, gray, fine textured	5
Limestone, dolomitic, white, saccharoidal	18
Chert, dark brown	4
Limestone, dolomitic, saccharoidal, unmeasured.	

The south slope of the mountain west of the Montana principal meridian furnishes numerous good exposures of beds above the Phosphoria formation. Over it are the Triassic beds, the lower part of which, about 350 feet thick, consists of yellowish-brown sandy shale and impure brownish thin-bedded limestone containing *Lingula*. The beds near the top of this member show beautifully preserved ripple marks. The upper part of the Triassic consists of about 600 feet of brick-red shale closely resembling the Chugwater beds of Wyoming. At the top is pinkish impure limestone containing abundant fossils. Higher beds consist of greenish fossiliferous sandstone, sandy limestone, and calcareous shale of the Ellis formation, overlain by the variegated shales and prominently outcropping sandstone and conglomerate of the Kootenai formation. A little higher in the section, possibly 100 feet higher, are beds of gray limestone filled with fresh-water gastropods.

Near milepost 665.279, at the south side of sec. 3, T. 15 S., R. 1 W. Montana principal meridian, the upper part of the Phosphoria is of unusual interest on account of the absence of chert beds. Typical exposures of beds above the upper phosphate layer show a few feet of shale overlain by 100 feet or so of thin-bedded chert, more or less intermixed with sandstone in the upper part. Such exposures are found within 2 to 4 miles east and west of milepost 665.279, but at that point both the chert and the sandstone are missing, and there is instead 100 feet of slightly calcareous sandy shale of dark color, nearly black in the lower portion. This rests on a bed of black oolitic phosphate 1 foot thick, below which lies a few feet of quartzitic sandstone. The transition from the dark shale of the Phosphoria to the overlying brown Triassic shale is merely a change of color.

ODELL CREEK

The Quadrant and Phosphoria beds appear on Odell Creek about 3 miles north of the State line and dip 30° S. Along the creek and nearly parallel to it is a fault that produces an offset in the outcrop of about half a mile, the west side being shifted to the south. Neither the upper nor the lower phosphate bed was found in this vicinity. Float of the upper bed was found, but none of the lower, and the discontinuous character of the lower bed leads to the suspicion that it may be missing or much thinner here than at the sampling point 8 miles to the east.

O