PHOSPHATES AND PHOSPHORUS.

PHOSPHATE DEPOSITS IN WESTERN UNITED STATES.

By F. B. WEEKS and W. F. FERRIER.

INTRODUCTION.

The present paper has been prepared as the result of ten days' field work by Mr. Weeks in October, 1906, and of previous reconnaissance surveys by Mr. Ferrier made to determine the distribution of the phosphate series, and of observations made by him in establishing and developing the mining operations at Montpelier, Idaho.

It has been thought advisable to bring together in this paper such general information relating to the phosphate deposits in the West as is now available, describing in some detail the localities where these deposits have been most extensively opened up and mined and which may serve as a general type, leaving for another occasion the more minute description of their various local characteristics and points of difference in geologic structure.

The discovery of these beds has opened up a new industry in the West, the future of which is largely dependent on the granting of such rates by the railroads as will enable the manufactured product or raw material to be sold at a profit in Australia, Honolulu, Japan, and the Middle States, the home market on the Pacific coast being at present a somewhat limited one.

GENERAL DESCRIPTION.

Within the last few years it has been found that the upper Carboniferous rocks of the central Cordilleran region include a series of oolitic beds containing a variable percentage of P_2O_5. These beds are known to occur over a considerable area in southeastern Idaho, southwestern Wyoming, and northeastern Utah. Prospecting has been carried on at a number of widely separated localities. The strike of the beds follows the general northwest-southeast trend of the ranges along which they outcrop.

In Idaho the beds outcrop along the Preuss Range, extending from the line of Bannock and Bear Lake counties in a southeasterly direction along its west face. A probable southern extension of these beds near the Idaho-Utah line is found on the mountain slopes east of Bear Lake, where the overlap of upper Mesozoic sediments has been eroded. East of the Preuss Range, in the Sublette Range in Wyoming, are similar beds which follow the southerly trend of this range to Smiths Fork.

The mountains rise 1,500 to 3,000 feet above the intervening valleys and the region is drained by Bear River and its tributaries. The Oregon Short Line Railroad follows the valley of Bear River and affords the only means of transportation to market. At present those beds which can be developed at the least cost and lie nearest the railroad shipping points are being worked. In Utah the phosphate series has been found some distance south of Bear Lake, in the vicinity of Woodruff. The beds also outcrop in Weber Canyon, about 1½ miles below Croydon, and in some of the side canyons. None of these beds are being worked at present. The Union Pacific Railroad, which follows the course of Weber River, will make possible a rapid development in this region.

Beds of good grade, but too thin to be profitably worked, have been observed at other points in these States and also in Nevada. It is highly probable that further exploration will show that these oolitic phosphate beds have a still wider distribution.

Many substances have been mistaken for the phosphate and located, notably some of the fine-grained, loosely bedded, dark-gray ash rocks commonly associated with the lavas of southeastern Idaho and other places. These ash rocks are as a rule much lighter in weight than the phosphate.

The accompanying map (Pl. IV) shows the areas of upper Carboniferous rocks, of which the phosphate series forms a part, and of the overlying and underlying strata of this region; also the location of the deposits of economic value. Others have been reported, but no data are available for this paper.

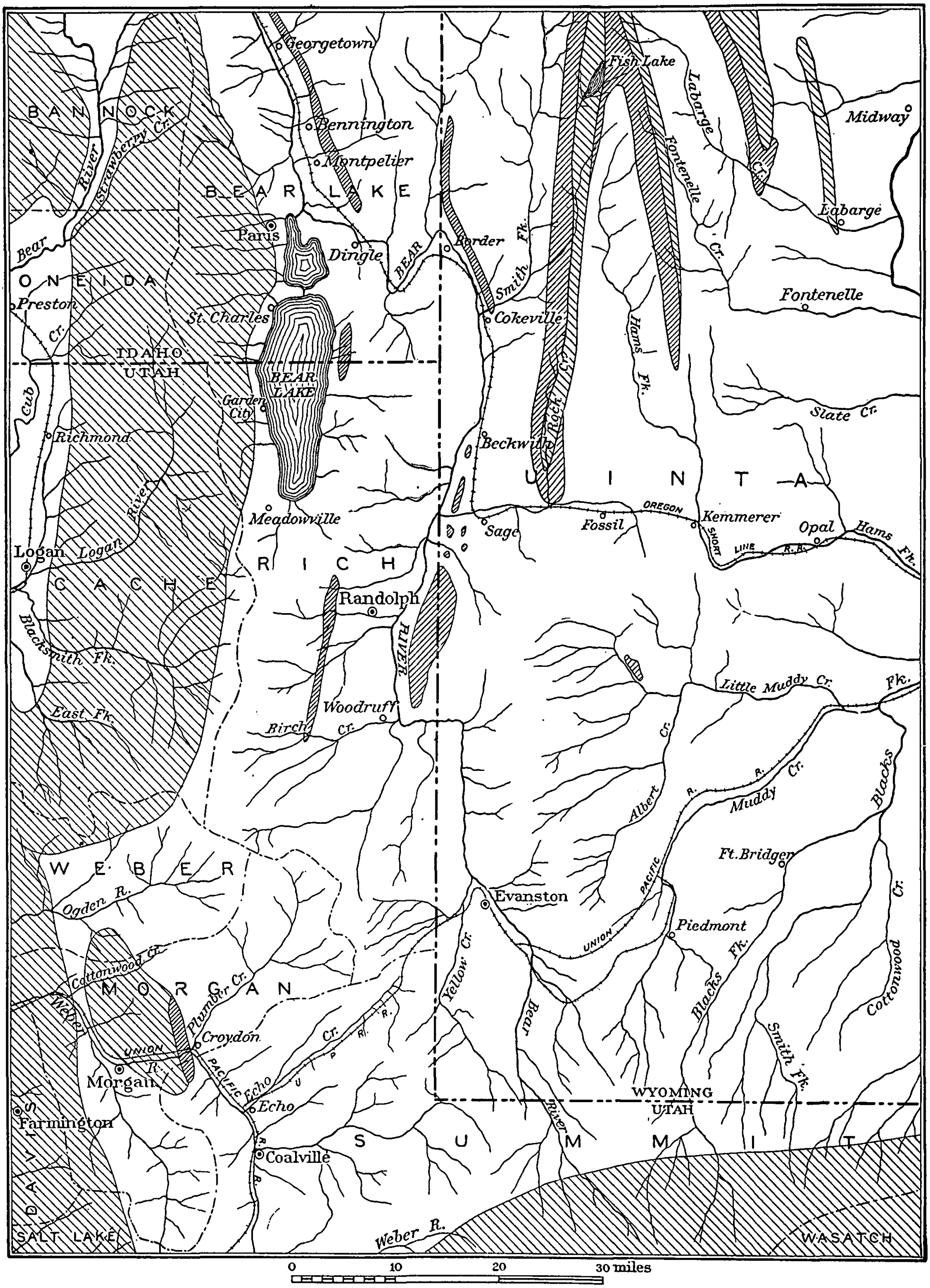
GENERAL GEOLOGY.

The general character and sequence of the sedimentary strata of this region are given in the following section:

Section of Paleozoic strata in southeastern Idaho, southwestern Wyoming, and northeastern Utah.

Carboniferous:
- Mostly light-colored limestones; phosphate beds near base.
- Series of red, white, and green quartzites and sandstones.
- Massive blue and gray limestones.

Devonian:
- Limestone, where present.



0 10 20 30 miles

Pre-Upper Carboniferous | Upper Carboniferous (Phosphate beds near base) | Post-Upper Carboniferous

MAP OF PARTS OF IDAHO, WYOMING, AND UTAH, SHOWING LOCALITIES OF UPPER CARBONIFEROUS ROCKS CONTAINING PHOSPHATE BEDS.

Compiled from field notes and published maps.

Silurian:
  Thin-bedded limestone, where present.
Ordovician:
  White and green quartzites.
  Light-colored, generally thick-bedded limestone.
Cambrian:
  Thin-bedded blue and gray limestone.
  Quartzites, mainly white in some areas, purple in others.

In portions of the area some parts of this section are absent by reason of nondeposition.

Three quartzite series are thus shown to be present in parts of this region. Since the phosphate series occurs a short distance above one of these quartzites, it is important that the prospector be able to recognize its occurrence in the field. This can be done in one of two ways. If a person is familiar with the general characters of the upper Carboniferous fossils, he can readily recognize this part of the section as the limestones, especially those occurring in and overlying the phosphate beds are very fossiliferous and the fossils are well preserved. If this method is not practicable, he can start from a known base and work out for himself the sequence of the various beds. The maps of the Fortieth Parallel Survey and of the Hayden Survey cover parts of the known area and would be useful in selecting a starting point from which to make a detailed section. Owing to the intense folding and compression which the beds have undergone in some localities and their probable repetition by faulting, the latter method may be found difficult to follow.

The whole of this section is known to occur in Weber Canyon and to the north in Utah and Idaho. To the south of the Weber, in the Wasatch Range, the Cambrian limestones, the Ordovician quartzite, and the Silurian and Devonian limestones become thinner and in some places appear to be entirely wanting.

CARBONIFEROUS SYSTEM.

GENERAL DESCRIPTION.

As the phosphate series occurs within the Carboniferous rocks, a more detailed description of these strata will be given. They outcrop over considerable areas in eastern, central, western, and northern Utah, southeastern Idaho, and adjoining portions of Wyoming, and in northern Nevada. Their lithologic characters are very persistent, and the three subdivisions may be recognized in the above-defined area.

The limestones which form the lower division are generally massive and occur in bold and precipitous outcrops. In many places they are coarse grained and weather rough and in dark colors. They are also rather siliceous and contain some cherty layers and masses. This division is 2,000 feet or more in thickness.

At the top of the limestones the beds become sandy and the quartzite series generally begins with an alternation of sandy limestones and sandstone beds, and continues through several hundred feet of sandstone weathering red and yellow. These are succeeded by yellow, white, and gray sandstones and quartzites, the upper half of the series being quartzite, readily recognizable as such.

This quartzite in most places grades into a dark, rather coarse granular limestone—the Upper Coal Measures limestone of the Fortieth Parallel Survey. The upper part of this formation consists of yellow sandstone and sandy limestones which grade into a blue-gray compact limestone just beneath the phosphate beds. In these blue and gray limestones indistinct fossils weather out on the surface, but are difficult of determination. This portion of the section varies considerably in the character of sediments.

PHOSPHATE-BEARING SERIES.

The phosphate series consists of alternating layers of black or brown phosphatic material, shale, and hard blue or gray compact limestones. The limestones are in the main very fossiliferous, containing well-preserved forms of *Rhynchonella*, *Chonetes*, *Omphalotrochus*, and *Productus*, which are apparently the characteristic fossils of this horizon. The shales contain *Lingula* and lamellibranchs.

The phosphate series is in places about 90 feet thick. The beds vary in thickness from a few inches to about 10 feet, but where of this extreme width are in general broken by thin layers of shaly material poorer in P_2O_5. At the base the series begins with limestone, and as a rule 6 to 8 inches of soft brown shale overlies this basal limestone. Above is the main phosphate bed, 5 to 6 feet thick. This is almost entirely oolitic in structure and high in P_2O_5. Several other beds, varying in thickness from a few inches to about 10 feet, separated by 6 inches to 2 feet of limestone or shale, occur in the series. The beds of extreme thickness, as already mentioned, contain seams of shaly material, itself phosphatic, too thin to be separated from the pure oolitic material in mining. All the sections that have been examined show one and some of them two beds which are of commercial value. The other beds are not of sufficient thickness, nor of a grade which will pay to mine at present.

The phosphate series is overlain by a coarse-grained, locally brecciated limestone, for the most part in massive outcrops. Above this limestone is sometimes found 100 feet or more of nearly white limestone, but as a rule it is succeeded by a series of blue and gray limestones containing large spirifers and *Productus*. Next above is a series of red sandstones and shales containing brachiopods and lamellibranchs. Still higher in the section is a considerable thickness of blue, gray, and greenish limestones, which form the upper part of the upper Carboniferous series, and in the Montpelier region there are siliceous limestones and red sandstones containing ammonites and other fossils of lower Triassic age.

GEOLOGIC STRUCTURE.

The geologic structure of the region under discussion is very complex. The strata have been uplifted, sharply folded and faulted, and partially buried beneath the overlap of later sediments. It has been noted, however, that the phosphate series has been very little disturbed or displaced by the movements which have affected the sedimentary section as a whole.

WASATCH RANGE.

In Weber Canyon, where the phosphate series occurs, there is in the underlying Weber quartzite a sharp anticlinal fold that develops into a thrust fault. This structure is not readily detected on account of the heavy wash and the overlap of later sediments.

BEAR LAKE PLATEAU.

The Bear Lake Plateau comprises the region east of Bear Lake and the area to the south represented on the maps of the Fortieth Parallel Survey as Bear River Plateau. It also represents the eastern side of the Wasatch uplift. The sharply compressed fold of the Weber Canyon section appears to extend through this area, as the Carboniferous beds where exposed are in general characterized by steep dips and local variations in strike. A similiar structure is reported east of the north end of Bear Lake.

CRAWFORD MOUNTAINS.

The Crawford Range extends from Bridger Creek in a southwesterly direction, with outliers to the north, including the Beckwith Hills north of Twin Creek. Veatch [a] considers the structure as a broken anticline with a syncline developed on the eastern slope. A fault of considerable displacement follows the eastern side of the range and probably extends to the north in the Sublette Range east of Cokeville.

SUBLETTE RANGE.

The Sublette Range is formed of a sharply compressed series of Weber quartzites and upper Carboniferous beds. On the eastern side of the range a fault of considerable throw occurs, bringing the Bear River Cretaceous beds against the upper Carboniferous. In the northern part of the range the dip flattens and the topography is much less rugged in character.

[a] Veatch, A. C., Prof. Paper U. S. Geol. Survey No. 56, 1907.

PREUSS RANGE.

The Preuss Range extends from Bear Lake northward along the east side of Bear River Valley beyond the limits of the area shown on the map (Pl. IV). Only the southern part of this range was visited. Here the general structure seems to be that of a broken anticline. The western side of the fold is made up of the phosphate series and the higher strata of the "Permo-Carboniferous" and overlying Triassic beds. The eastern side of the fold is probably formed of the same series, though not so well exposed, and of overlying Jurassic shales, thin-bedded limestones, and sandstones, as shown by fossils from two localities.

DESCRIPTION OF VARIOUS LOCALITIES.

In that part of the Wasatch Range which lies east and south of Salt Lake City the phosphate series, so far as it has come under the writers' observation, does not attain the thickness seen at other localities, and the phosphate beds are too thin to be of economic importance.

WEBER CANYON, UTAH.

The Paleozoic section from the Cambrian quartzite to the top of the Carboniferous is exposed in Weber Canyon from Peterson, a station on the Union Pacific Railroad, to Croydon. From the lower tunnel to the upper tunnel between Morgan and Croydon the Weber quartzite is exposed. A short distance above the lower tunnel there is a sharp anticline in this series, somewhat broken. The canyon follows the trend of this anticline for about half a mile, and the red, yellow, and white quartzites form bold escarpments on both sides of the river. The quartzites grade into coarse sandy beds, weathering in rounded cliffs, and into thin-bedded cherty limestones. Near Robinson's ranch the beds are nearly perpendicular, and the fold appears to have become a thrust fault. The phosphate beds, which seem to have been involved in this thrust movement, appear in canyons several miles farther north, but at a considerable distance west of the line of strike of these beds on the south side of the canyon. About one-fourth mile below Robinson's house the phosphate series has been exposed on the south side of the canyon in a number of test pits.

The following section is exposed on the south side of the river:

Section of phosphate series in Weber Canyon, Utah.

1. Blue-gray limestone.
2. Phosphate bed.
3. White and gray limestone with many bands of phosphate varying in thickness.
4. Light-blue and gray limestones, siliceous and cherty; yellow calcareous and siliceous beds; and white limestone.

The detailed structure and sequence of the phosphate series here has not yet been fully worked out. Heavy wash covers the base of the hills, extending a considerable distance up their flanks, to a point where the phosphate beds have been opened not far above the basal limestone.

Some of the beds contain flattened nodules of a white, extremely fetid calcite, many of them of large size. These have also been observed at other localities, in beds above the main phosphate bed.

The dip of the strata in the above section is steep, varying from 45° to 60° to the east, with an average strike of N. 10° W. On the north side of Weber Canyon the beds are closely folded and there appears to be an overthrust by which the outcrop of these rocks bends somewhat to the west.

The phosphate series has been traced for some distance on both sides of the canyon by means of test pits and outcrops, but no extensive developments have been made.

The following is a section in Tunnel Hollow, 1 mile south of the section just given:

Section in Tunnel Hollow.

1. Blue-gray limestone.
2. Phosphate and interbedded limestone.
3. Alternating bands of shale and phosphate.
4. Blue limestone, yellow sandy beds, and gray limestones, containing spirifers, *Productus*, Bryozoa, etc.
5. Red shales and sandstones.

WOODRUFF, UTAH.

The phosphate series at Woodruff, Utah, is largely concealed by heavy wash, and sufficient work has not yet been done to permit the making of a detailed section. The phosphate beds are exposed along Twelvemile, or Woodruff, Creek and Sugar Pine Creek, about 12 miles west of Woodruff. The best bed immediately overlies the basal limestone and averages about 5 feet in thickness. There is a series of smaller beds separated by limestone and shale, as observed at the other localities. The upper limestone, with characteristic large spirifers and *Productus*, is also present. Sandstone and quartzite, standing nearly vertical in places, crown the ridge on the west side of Twelvemile Creek toward the south end of the outcrop and also occur on Sugar Pine Creek. A careful determination of the fossils and comparison with those at Montpelier, Croydon, and other places is being made and the results will be given in a later paper. The strike of the beds varies locally, but a rough average would be about N. 15° E.; the dip is to the west at various angles, ranging from nearly horizontal to 60°.

SAGE, WYO.

The phosphate beds are seen again near Sage, Wyo., a station on the Oregon Short Line Railroad, about 24 miles northeast of Woodruff. The outcrop extends in a southerly direction a few miles to the southwest of the railroad. Some shipments have recently been made from Sage to the Pacific coast and work is now going on.

COKEVILLE, WYO.

The Sublette Range extends along the eastern side of the Bear River valley in this region. A bold escarpment of Carboniferous strata, which has been cut through by Smiths Fork, faces the valley opposite Cokeville, Wyo. The section as exposed on the north side of Smiths Fork is shown in fig. 18.

The quartzite beds are in vertical position with a tendency to overturn to the west. In the lower part of the upper Carboniferous

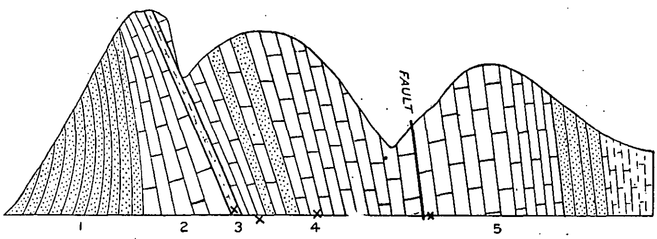


FIG. 18.—Sketch section 2 miles northeast of Cokeville, Wyo., on north side of Smiths Fork. 1, Weber quartzite; 2, upper "Coal Measures" limestone; 3, phosphate beds; 4, "Permo-Carboniferous" limestones and sandstones; 5, Cretaceous (Bear River) limestones and sandstones; X, fossil localities.

series the beds dip 65° E. for some distance, beyond which they stand nearly vertical. A fault occurs by which the Bear River (Cretaceous) is brought against the "Permo-Carboniferous," cutting out the Triassic and Jurassic, which according to Veatch[a] have together an average thickness of 5,500 feet in the region to the east. The strike of the beds follows the general trend of the range.

About 2 miles northeast of Cokeville, on the north side of Smiths Fork, the surface covering has been removed from the phosphate beds, which are exposed for a distance of 400 feet up the slope of the ridge, dipping 65° E. The uppermost layer of the series is a 6-foot bed of phosphate and below this, separated by 3 feet of brown shale and hard, blue limestone, is another bed 4 to 5 feet thick.

Two tunnels have been cut into the main bed, one about 35 feet the other about 50 feet in length. A square box chute with steel bottom has been built along the outcrop, extending down to storage bins near the base of the ridge. The rock is hard and requires considerable blasting. The material is shoveled into wheelbarrows,

[a] Veatch, A. C., Bull. U. S. Geol. Survey No. 285, 1906, p. 334.

taken to the platform at the tunnel mouth, and dumped into the chute, which conducts it by gravity to the storage bins. The phosphate will be dumped into wagons and hauled to the railroad at Cokeville, a distance of about 2½ miles over a level road. The property is controlled by the Union Phosphate Company. At the time of visit (October 12, 1906) three or four men were working in the tunnel and considerable material had accumulated awaiting the arrival of cars. No facilities for rapid handling of the material at the railroad had been provided. Development was progressing as rapidly as possible with the limited number of men employed.

THOMAS FORK, WYOMING.

There is an extensive exposure of the phosphate series low down on the flanks of the Sublette Range on the east side of Thomas Fork, which empties into Bear River at Border, Idaho, a station on the Oregon Short Line Railroad. As at Montpelier, the series is exposed in numerous small draws that cut across the strike, and also in Raymond Canyon, which penetrates the range. Between these points the outcrop is largely concealed by heavy wash. Several peculiar features characterize the series here and its detailed structure and geologic relations have not yet been fully worked out. At the south end of the exposure the beds stand at a high angle, in places almost vertical, and the best phosphate bed appears to be underlain by a hard, gray, exceedingly siliceous rock, apparently a cherty limestone. This has withstood the erosion of the softer strata and outcrops boldly, forming high vertical reefs along the range. Above the main phosphate bed there is the usual succession of limestones, shales, and phosphate. The structure is somewhat complicated owing to the faulting and folding of the strata. At the north end of the exposure, which is about 7 miles long, the beds in most places have a flatter dip, ranging from 45° to 60° W. The general strike at the south end is roughly north and south and at the north end of the exposure swings a little to the west. Some long cuts were made across the strata late in the fall of 1906, in order to expose their sequence, but snow came before the detailed study of the section was completed.

MONTPELIER, IDAHO.

The succession of strata in the range east of Montpelier, Idaho, is, in places, broken by folding and faulting and where this is the case the structure is difficult to follow, since not only does the faulting vary in amount of displacement, but the beds, particularly on the west side of the fold, contain numerous rolls which cause both the strike and dip to vary considerably within rather short distances. The intense compression to which these beds have been subjected has produced in places a very remarkable fracturing by which they appear to be on edge, with a general north-south strike. The dip, however, is to the west at angles of 20° to 30°.

In the canyon of Montpelier Creek the lowest beds exposed are yellow, sandy limestone and sandstone and blue-gray siliceous limestone, which immediately underlie the phosphate series. The overlying limestones generally occur in massive outcrops. A prominent spur of the range extends nearly to the town of Montpelier and is formed of limestones and sandstones of upper Carboniferous and Mesozoic age. The lower portion of the upper Carboniferous series, including the phosphate beds, is exposed on the north side of Montpelier Creek, as shown in the accompanying section (fig. 19).

On the south side of Montpelier Creek the phosphate series is buried beneath the detrital slopes, and the outcrops of the phosphate beds

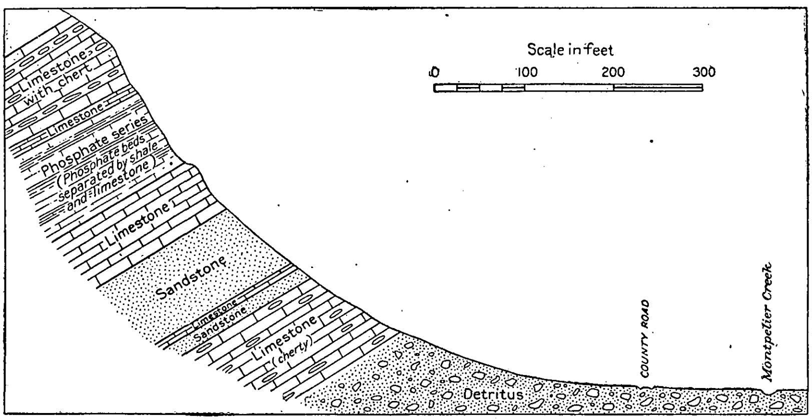


FIG. 19.—Section of Carboniferous strata on north side of Montpelier Creek, Idaho.

are exposed only in the numerous draws which cut across the strike along the range. Between these points the beds are not visible except where exposed by the large amount of development work which has been done, particularly on the Waterloo placer-mining claim. Their presence, however, is indicated by pieces of float and the characteristic darkening of the soil overlying them. Here the beds dip to the west at a low angle—about 20° to 30°. They are remarkably uniform in character over a wide area, rolling slightly, but showing no signs of any very serious disturbance. Erosion has removed the upper beds from a large portion of the ground, leaving extensive areas in which the main phosphate bed is now covered by only a 2-foot band of limestone and a few feet of shale and surface detritus. Here and there the top of the phosphate bed itself forms the surface of the ground and in places the bed has been completely eroded, leaving only the hard underlying cherty limestone. The band of limestone already referred to, which immediately overlies the main phosphate bed, is locally shattered in a remarkable manner without displacement, the phosphate bed beneath being but little affected and both limestone and phosphate retaining their usual dip. The succession of the beds forming the phosphate series, as exposed in the workings of the Waterloo claim, is given in the accompanying typical section (fig 20).

On the south end of the claim and also at the north end in the higher ground the full width of the top phosphate bed, shown as

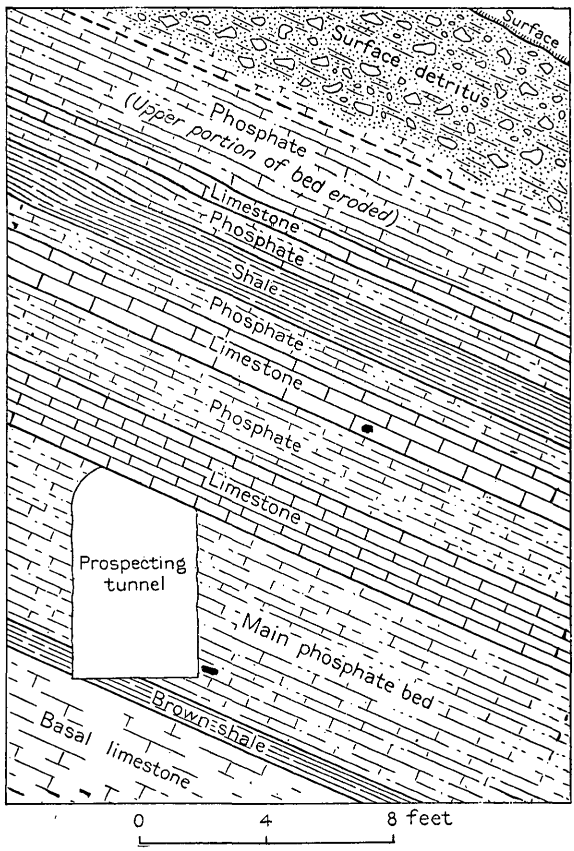


FIG. 20.—Typical section of lower portion of phosphate series, Montpelier, Idaho.

eroded in the section, is seen to be about 10 feet or more. It contains some large lime nodules, black and very hard, also thin layers of brown shale, and is overlain by a succession of alternating beds of limestone, shale, and phosphate, the phosphate being too thin or too low in grade to be profitably worked at present. This part of the series is best seen on the north side of Montpelier Creek, where it passes up into the massive limestones already mentioned. The dips here are in the main somewhat steeper.

From a practical standpoint the limestone immediately overlying the main phosphate bed at Montpelier is of considerable importance, being very uniform in character wherever found and containing abundant specimens of a coiled shell, *Omphalotrochus*, which, so far as observed, seems to be confined to this bed. This limestone or "cap lime," as it is called by the miners, is a valuable landmark in prospecting for the main bed of phosphate. It averages 2 feet in thickness, is dark gray in color, and very hard when freshly exposed, but rapidly weathers brown and finally disintegrates completely. Large blocks of it which have lain on the ground less than two years crumble to pieces when lightly struck with a hammer. In common with most of the other bands, it emits a strong bituminous odor when broken. Analyses show that some of these limestones contain several per cent of P_2O_5. Fossils are much more abundant in some than in others. In development work the position in the series of some of the beds can readily be determined from their fossils, even by one with no knowledge of paleontology. Such characteristic forms as *Omphalotrochus*, *Rhynchonella*, *Chonetes*, and *Productus* are abundant and well preserved. A remarkable specimen showing three large fish teeth in a portion of the jaw was recently discovered in the cap lime. The shales contain *Lingula* and lamellibranchs.

The main phosphate bed is the lowest one in the series at this locality and is just over the basal limestone, which contains much silica, in many places segregated as irregular bands and masses of chert. The phosphate layers are black to brownish in color and finely to coarsely oolitic in structure.

The beds rich in P_2O_5—for example, the main phosphate bed—are almost entirely oolitic, the small black granules being densely packed together with but little matrix material and effervescing but very slightly with HCl. The phosphate has a bituminous odor when freshly broken. As the number of oolitic grains, and therefore the P_2O_5 content, decreases, the beds assume more of the character of oolitic shales or limestones.

Several thousand tons of phosphate from the main bed at Montpelier, the whole of the material 5½ to 6 feet wide between the inclosing limestones being mined and shipped, showed a remarkably uniform content of P_2O_5, the average of a large series of analyses on carload lots giving a total of a little over 32 per cent P_2O_5, equivalent to 70 per cent bone phosphate. As the result of a careful experiment, it was found that a cubic foot of the phosphate in the main bed weighed 150 pounds. This gives 13.3 cubic feet to the ton.

The stratum varies considerably in hardness, the lower 2 feet being very hard and blocky and the upper portion being softer, with a more shaly structure.

In early days the dark shales associated with the phosphate were, owing to their bituminous odor, frequently taken to indicate the presence of oil or coal, and the deposits at Montpelier were filed on as coal lands and considerable work was done in the effort to find that material.

As the dip is low at this place, the beds are worked as an ordinary flat coal seam with pillar and stall. The phosphate is mined by both open-quarry and underground workings. A loading platform is placed at the foot of a gravity tramway running up the slope of the hill, the top of the platform being on a level with the main working tunnel. The phosphate rock is delivered at the platform in ordinary standard ore cars from both quarry and mine and loaded directly into the wagons through a chute. It is then hauled about 4½ miles to the Oregon Short Line Railroad at Montpelier and dumped into the cars through a door in a loading bridge built over the siding. It is now being shipped to the works of the San Francisco Chemical Company at Martinez, Contra Costa County, Cal., and there made into superphosphates to be used as fertilizers.

HOT SPRINGS, IDAHO.

The phosphate series is found at Hot Springs, Idaho, near the north end of Bear Lake on its east side, 14 miles south of Montpelier, forming the continuation of the series seen at the latter place and having the same general characters, but dipping at higher angles to the west. The deposits are extensive.

BENNINGTON AND GEORGETOWN, IDAHO.

To the north along the general line of strike the phosphate series is seen near Bennington, Idaho, about 5 miles from Montpelier, where it is apparently considerably broken and faulted, and again in a steep canyon some miles east of Georgetown, which is 11 miles northwest of Montpelier.

VICINITY OF SWAN LAKES, IDAHO.

About 4 miles east of Manson, a small siding on the Oregon Short Line Railroad, a mile south of the line between Bannock and Bear Lake counties, Idaho, the phosphate series is exposed in a high range of hills. The strata are much faulted and folded, but little development work has yet been done, and the detailed structure is therefore not yet satisfactorily worked out. The series has been traced for several miles along the flanks of the range, which is cut by deep gulches, and also, owing to the folding, is found on the high ground. The general line of strike swings more to the west than at

Montpelier, and the dips are to the west at widely varying angles. There is a bed of phosphate here which corresponds in its general character, thickness, and grade to the main bed at Montpelier and, at several places where it is opened up, dips from 20° to 30° to the west. It is overlain by a band of limestone in which *Omphalotrochus* and *Chonetes* have been recognized. Above this band of limestone there is the usual succession of beds of phosphate, limestone, and shale. In places this phosphate bed is faulted and apparently lies over a massive limestone in which a large *Productus* is found. Work is being undertaken to trace out the sequence and extent of the phosphate beds at this locality.

DEVELOPED PHOSPHATE DEPOSITS OF NORTHERN ARKANSAS.

By A. H. PURDUE.

INTRODUCTION.

The field work for this paper was done in the latter part of August and the first part of September, 1906. Previous to this time (in the latter part of 1903) the writer made a visit to the developed deposits for the purpose of arranging for an exhibit of the phosphate rock and its products at the Louisiana Purchase Exposition. The company operating the mines and the fertilizer plant connected therewith freely assisted in preparing an exhibit and, among other things, shipped to the exposition a solid block of phosphate rock 4 feet wide, 8 feet long, and somewhat more than 4 feet thick. This block of stone attracted the attention of those who were interested in the fertilizers and phosphate deposits of the country and excited special interest in the deposits of Arkansas, an interest that justifies the preparation of the present paper.

The area over which the phosphate deposits of northern Arkansas occur is mentioned in the following reports of previous writers:

OWEN, DAVID DALE. First report of a geological reconnaissance in the northern counties of Arkansas, made during the years 1857 and 1858. 1858.

PENROSE, R. A. F. Manganese; its uses, ores, and deposits: Ann. Rept. Geol. Survey Arkansas for 1890, vol. 1.

HOPKINS, T. C. Marbles and other limestones: Ann. Rept. Geol. Survey Arkansas for 1890, vol. 4.

BRANNER, J. C. (State geologist). The lead and zinc region of northern Arkansas: Ann. Rept. Geol. Survey Arkansas for 1892, vol. 5.

BRANNER, J. C. The phosphate deposits of Arkansas: Trans. Am. Inst. Min. Eng., vol. 26, 1896, pp. 580–598.

BRANNER, J. C., and NEWSOM, J. F. The phosphate rocks of Arkansas: Bull. Arkansas Agr. Exp. Station No. 74, 1902.

ULRICH, E. O., and others. Zinc and lead deposits of northern Arkansas: Prof. Paper U. S. Geol. Survey No. 24, 1904, p. 100.

GEOGRAPHY AND HISTORY OF THE PHOSPHATE BEDS.

Geographic distribution of the beds.—The developed phosphate deposits of Arkansas are on Lafferty Creek, on the western edge of Independence County. The only point at which the beds are now worked is about three-fourths of a mile east of White River and the same distance from the White River branch of the Missouri Pacific Railway. A spur extends from the main line up Lafferty Creek, past the quarry, and on to the old workings, which are about a mile to the northeast, on East Lafferty Creek. Although this is the only locality at which the deposits have been developed, they have a wide east-west extent, reaching from the town of Hickory Valley, 10 miles northeast of Batesville, westward at least as far as the town of St. Joe, in Searcy County, a distance of more than 80 miles in a direct line. This statement must not be taken to mean that phosphate rock outcrops throughout the whole of this distance or that all the deposits found are sufficiently large or of high enough grade to work with profit. It means that a phosphate bed, which is practically horizontal, outcrops in a winding line on the hillsides and in other places between the points mentioned. A phosphatic horizon can be traced westward to the western border of the State, but at no point west of St. Joe have phosphate rocks, in considerable amount, attracted the attention of geologists. Thin beds of phosphatic sandstone are found in the Devonian shales in the western part of Carroll County, on War Eagle Creek. While it is certain that prospecting for workable deposits would be useless throughout most of the distance over which the phosphate rock outcrops, it can confidently be expected that minable deposits other than those now known will be discovered, especially in the eastern part of the field.

Topography of the area.—The area near the developed deposits is much dissected by streams. The main line of drainage is White River, which here stands about 250 feet above sea level. Above the river on both sides are steep-sloping hills or almost perpendicular bluffs. The tributaries of White River flow southward in valleys that lie from 200 to 400 feet below the hills on both sides. Lafferty Creek, on which the developed deposits are located, flows in a valley that is 400 feet deep.

Discovery and history.—The following account of the discovery of the phosphate deposits of northern Arkansas has been furnished the writer by Dr. J. C. Branner, ex-State geologist of Arkansas:

The first mention of the phosphate deposits of Arkansas was made by Owen, who spoke of the bed at St. Joe as a vein of ore containing iron and manganese (?).[a] Owen, however, did not recognize the material as phosphate rock. The next mention was made by Penrose in his manganese report.[b] He also failed to determine the true nature of the rock, and Doctor Wolff, of Harvard, was disposed to think it volcanic tuff. Hopkins noted the beds at several places, and mentions them in his marble report,[c]

[a] Owen, David Dale, First Report of a Geological Reconnaissance of the Northern Counties of Arkansas, made during the Years 1857 and 1858, p. 79.

[b] Penrose, R. A. F., Manganese; its uses, ores and deposits: Ann. Rept. Geol. Survey Arkansas for 1890, vol. 1, pp. 126–127.

[c] Hopkins, T. C., Marbles and other limestones: Ann. Rept. Geol. Survey Arkansas for 1890, vol. 4, pp. 212–213.

but he did not recognize them as phosphate rocks. I saw and made notes of several of the phosphate localities in 1890, but the rocks were not recognized to be phosphate beds until 1895, when I had analyses made here at Stanford University. That same year I went to Arkansas * * * and gathered the bulk of the information that enabled me to publish the paper brought out by the American Institute of Mining Engineers in vol. 26 of their Transactions.

What has been written concerning the phosphate deposits of northern Arkansas as such is to be found in the papers by Professor Branner and by Professors Branner and Newsom.[a] Inasmuch as the present paper deals with only a limited portion of the area over which the phosphates extend, those desiring a wider knowledge of the extent and nature of the beds are referred to these two papers.

GEOLOGY OF THE REGION.

In the area over which the phosphate deposits of northern Arkansas occur nothing but sedimentary rock is exposed at the surface. The ages, relations, and names of the formations in the eastern part of the area are given in the following section:

General section in phosphate region of northern Arkansas.

Carboniferous:
- Boone chert, including St. Joe marble.

Devonian:
- Chattanooga shale and Sylamore sandstone.

Silurian:
- St. Clair limestone.

Ordovician:
- Cason shale.
- Polk Bayou limestone.
- Izard limestone.

The above rocks will be briefly described, for the purpose of assisting those who may desire to prospect for phosphate rock.

Izard limestone.—This limestone, as described by Dr. T. C. Hopkins,[b] "is a smooth, fine-grained, compact, homogeneous, nonfossiliferous, evenly bedded limestone, breaking with a conchoidal fracture, and is mostly of a dark blue color, varying locally to buff, light and dark gray, and almost black."

This limestone occupies the lower part of the valleys in the region of the developed deposits. It constitutes the lower part of Penters Bluff and occurs along Lafferty Creek and its tributaries and at Phelps Spring, a half mile north of Cushman. This limestone varies considerably in thickness. According to Mr. Hopkins, 280 feet[c] at the base of Penters Bluff is Izard limestone, which reaches down to the

[a] Branner, J. C., The phosphate deposits of Arkansas: Trans. Am. Inst. Min. Eng., vol. 26, 1896, pp. 580-598. See also Branner, J. C., and Newsom, J. F., The phosphate rocks of Arkansas: Bull. Arkansas Agr. Exp. Sta. No. 74, 1902.

[b] Ann. Rept. Geol. Survey Arkansas for 1890, vol. 4, p. 109.

[c] This measurement is probably too great, according to Mr. E. O. Ulrich.

water's edge of White River. A mile and a half west of Cushman, on the point of the hill in the northern part of sec. 7, T. 14 N., R. 7 W., the limestone is 110 feet thick. On the south slope of Pumpkin Branch it is 130 feet thick; in the northwestern part of sec. 1, T. 14 N., R. 8 W., it is 210 feet thick. At least 50 feet of it is exposed along the lower part of West Lafferty Creek.

The Polk Bayou limestone.—This limestone immediately overlies the Izard limestone. It is everywhere present in the vicinity of the developed deposits, but is not so widespread over northern Arkansas as the Izard limestone. At Phelps Spring, just north of Cushman, it is 120 feet thick. Both limestones are exposed here, the spring issuing from the Izard. At the cave 1½ miles west of Cushman it is 130 feet thick. One-half mile north of the cave and across the hollow from it, in the northern part of sec. 7, T. 14 N., R. 7 W., it is 75 feet thick.

This limestone occurs in massive beds. In color it varies from a rather light gray at the basal portion to a brown, in some places a chocolate color, at the top. The texture is very coarse, the rock being made up of crinoid stems and other fossil fragments, bound together by crystals of calcite. Much-weathered specimens of this limestone present a spongy resistance to the blows of the hammer, and break up into coarse, sandlike material.

The Cason shale.—Within the area examined by the writer the rocks at the horizon of the Cason shale are of variable nature. It is at this horizon that the phosphate rocks herein considered occur. Usually somewhat more than 4 feet at the top consist of shale, or, in the outer part, of clay derived from the disintegration of the shale. The upper part of the shale is yellow to brown in color; the lower portion, which ranges in thickness from 2 to 14 inches, is green. In some places, as at the phosphate quarry later to be described, the shale contains a thin bed of low-grade iron ore. In other places it is manganiferous. Such samples as were tested were found to be phosphatic, and the rock is probably so everywhere.

The phosphate rocks of the region are associated with this bed of shale. All of the developed deposits here are below it, but in other places there are phosphatic beds above shale, which is presumably the same as this. The phosphate beds vary in character, ranging from those that are brown and sandy and of low grade to those that on fresh surfaces are bluish gray, apparently without sand, and of uniform texture and color. It is the latter that are worked. They will be more fully discussed later in the paper.

Manganese ore is at many places closely associated with the phosphate beds. So common, indeed, is the association of the two that débris of the manganese, which is always plainly perceptible where present, is a good guide in prospecting for phosphate rock.

The St. Clair limestone.—The St. Clair limestone lies above the Cason shale. In the vicinity of the developed deposits it is from 8 to 18 feet thick. It is a compact crystalline limestone, pinkish in color, and is composed largely of small fragments of crinoids and other fossils. The fossil fragments stand out on weathering, producing very rough surfaces. The St. Clair limestone is thought to be the only representative of the Silurian in the region.

The St. Joe marble and Boone chert.—Upon the St. Clair limestone rest rocks of Carboniferous age, known as the St. Joe marble and the Boone chert. The former is the older of the two, and is only locally present in the eastern part of the phosphate region. Where typically developed the St. Joe limestone occurs in layers from a few inches to 2 feet or more in thickness. Elsewhere it is usually a somewhat coarse-textured rock, and is gray at the lower and upper parts, while the middle portion is often red, but the rocks that occupy the stratigraphic position of the St. Joe in the locality under discussion are usually gray to dove-colored, compact, and contain large numbers of calcite seams. These beds may be the representatives of the St. Joe marble, and may therefore belong to an older Carboniferous formation.

The Boone chert is a heavy deposit of limestone, contains a large amount of chert, and is of wide extent over the southern part of the Ozarks. Where the St. Joe is absent in the region under discussion the Boone chert rests on the St. Clair limestone if this is present; if not it rests on the Cason shale, the chert lying immediately over the phosphatic deposits.

THE DEVELOPED DEPOSITS.

Location.—The developed phosphate deposits of northern Arkansas are confined to secs. 14 and 15, T. 14 N., R. 8 W., situated on Lafferty Creek, near the junction of East Lafferty and West Lafferty creeks, about 4 miles a little south of west of the town of Cushman, in Independence County. They are about 12 miles northwest of Batesville, the county seat, and from a half mile to 1½ miles from White River and the White River branch of the Missouri Pacific Railway.

History of the operating company.—The following history was furnished by Mr. F. S. Williams, secretary and manager of the company operating the mines:

In June, 1900, a company was organized under the name of the Arkansas Phosphate Company, for the purpose of developing the phosphate beds along Lafferty Creek, Independence County, Ark. After several months of prospect work it was found that the phosphates exist in sufficient quantities to justify extensive mining operations. A mining and milling plant was erected, several miles of railway spur were laid, and mining was begun. After only a few months of active operation the plant was destroyed by fire, which stopped the work. A much larger plant is now nearing completion at Little Rock, to which the crude products of the mine will be shipped in the future, to be manufactured into various phosphatic and fertilizer products.

Little Rock was selected for the new plant because of its central location and its good railroad facilities. The company in the meantime has had its name legally changed to the Arkansas Fertilizer Company. The new plant will have an annual capacity of 40,000 tons, with a shipping capacity of 15 to 18 cars a day.

The company has mined to this time (October, 1906) about 10,000 tons of crude phosphate, of which about 2,250 tons have been produced within the last four months. The present output of the mine is approximately from 500 to 600 tons a month. The company is now manufacturing fine ground crude phosphate, acid phosphate, and a full line of other fertilizers made from Arkansas phosphates blended with ammoniates, potash, etc.

Description of developed deposits.—The deposits first developed are in a small ravine that enters East Lafferty Creek from the east, in the northern part of sec. 14, T. 14 N., R. 8 W. At this place the phosphate rocks outcrop on the hillsides at an elevation of about 500 feet above sea level, and have a low dip toward the west. The development extends for about half a mile on either side of the road that runs along the bottom of the ravine. The work at this point was done mainly by running adits into the hillside and mining out the rock, though some of the rock was obtained from open quarries.

The phosphate at this place occurs beneath a ledge of St. Clair limestone from 8 to 10 feet thick. The workings had been abandoned for three years when the writer last visited the place, and the exposures were more or less obscured. The bed that was worked here is about 22 inches thick, lying beneath a yellow to brown colored clay from 4 to 5 feet thick. Beneath the phosphate bed is a phosphatic sandstone, the thickness of which was not determined, but it rests upon the Polk Bayou limestone. The two phosphate beds are usually separated by a layer of manganiferous iron ore 1 or 2 inches thick.

Such exposures of the developed phosphate bed as were seen here showed that it had been considerably weathered and its original appearance much changed. The rock observed in the adits was soft and earthy and of a dark brown color, containing numerous small subangular fragments and closely specked by small, white grains. On examination under the magnifier the rock is found to contain large numbers of small, apparently sandy pebbles. Where exposed to the weather it is brown to yellow on fresh surfaces. Many of the old surfaces and joints are colored black with a thin coat of manganese stain. Weathering brings out thin shaly laminæ in some places.

The discovery of heavier deposits on Lafferty Creek, about a mile southwest of the above workings, led to their abandonment and the opening of mines at the new place. These deposits are on the east slope of the hill that lies between Lafferty Creek and White River, near its base. The following section shows the phosphate beds and their geologic relations:

Section containing phosphate beds.

	Ft.	in.
St. Clair limestone.		
Brown to black shale	2	0
Low-grade manganiferous iron ore	0	15
Green to dark clay shale	0	14
High-grade phosphate	4½–6	0
Manganiferous iron ore	0	2
Low-grade phosphate	4	0
Polk Bayou limestone.		

Only the upper phosphate bed is worked, the lower being considered of too low grade. At present the stone is worked by quarrying. The main quarry at the time of the writer's visit was 375 feet long by about 30 feet wide. An additional 150 feet at the north end was stripped, ready for quarrying. South of the main quarry there were two smaller ones, 150 and 225 feet, respectively, from the main quarry, thus making a total distance of 750 feet along which the deposit was opened. Besides the beds had been prospected by sinking shafts 480 feet farther south, at which point the dip of the beds brings the deposit below the creek. The beds outcrop at points north of the main quarry and have been prospected more or less for 1,000 feet along the hillside. The total distance, therefore, along which the beds at this place outcrop and are known to be workable is about 2,200 feet.

East of this point, on the opposite side of the creek, an adit 30 feet long has been run into the hillside. This adit was driven apparently for the purpose of prospecting the upper of the two phosphate beds, which at this place is 3 feet 4 inches thick. Beneath this, as at the main workings, there is a phosphate bed of lower grade, the thickness of which could not be ascertained at the time of the writer's visit, but it is probably about 4 feet.

As above stated, it is only the upper of the two phosphate beds that is now quarried for commercial purposes. This is a compact, homogeneous, light-gray rock with a specific gravity of about 3. At a distance it has the appearance of volcanic tuff. The color is due to small white particles that are thoroughly mixed with dark-gray material. The white particles appear to the unaided eye and under the magnifier as if they might be small fragments of bones. The dark-gray material is made up of particles of varying size, some so small that they can be seen only with the magnifier, others a quarter of an inch in diameter. These particles are more or less angular, some of them strikingly so, making the stone distinctly conglomeratic in appearance. The stone emits an earthy odor. In order to determine whether the gray particles are really fragmentary material or concretions and also to ascertain the nature of the white fragments, a specimen was submitted to Dr. Albert Johannsen, of the United States Geological Survey, for microscopic examination, who reports as follows:

The thin section is made up chiefly of organic remains, perhaps fragments of bone, in a cement of calcite, with very little of an isotropic, deep purplish mineral, having an index very much less than Canada balsam—probably fluorite. The sections show no concretions; the calcite seems to be a filling between the fragments of bone.

A small portion of rock at the outer edge has been leached of lime by surface waters and when freshly quarried is dark colored. This is called by the quarrymen "black phosphate." It contains a considerable amount of water, to which the color is attributable, and is richer in phosphate than the remainder of the bed.

The lower bed is similar to the upper one, though darker in color, more compact, and not conglomeratic, so far as observed. The darker color is due to the smaller amount of the white material and possibly to a larger amount of iron or manganese, or both. It has a greenish tinge, which is suggestive of glauconite. This bed becomes very ferruginous in its upper part and is here, as in the old workings on East Lafferty Creek, separated from the bed above by a thin layer of manganiferous iron ore.

The following analyses of specimens of the rock were made in the laboratory of the United States Geological Survey. Number 1 was a specimen taken from the lower bed; Nos. 14–18 were specimens from the bed now being worked.

Analyses of phosphate rock from Arkansas.

No.	Where taken.	Phosphoric acid (P_2O_5).	Equivalent in calcium phosphate. ($Ca_3(PO_4)_2$).
14	4 inches from top of bed	25.86	56.45
15	Middle of bed	27.24	59.46
16	8 inches from bottom of bed	27.40	59.81
17	"Black phosphate"	32.60	71.06
18	Composite sample	29.18	63.70
1	From lower bed	13.46	29.38

Amount of the phosphate rock.—The aggregate thickness of the two beds at the quarries is from 8½ to 10 feet, but, as already stated, only the upper bed is worked at present. Somewhat more than one-half a mile west of the quarries, on the opposite side of the hill and above the railroad, the phosphate horizon is represented only by a bed of red calcareous shale 6 inches thick, overlain by brown, compact limestone 20 inches thick. Both of these beds are slightly phosphatic.

How far west of the quarries the bed now being worked will hold out is problematical, though it is reasonable to suppose that it will maintain a workable thickness at least halfway through the hill.

Opposite the quarry, on the east side of Lafferty Creek, an adit shows that the upper bed of phosphate is 3 feet 4 inches thick. Only development work can determine how far this thickness is maintained, but the fact that phosphatic débris occurs extensively on the undeveloped southern part of sec. 14, immediately to the east, indicates that this thickness might hold for a considerable distance. As stated above, the rock is about 22 inches thick in the northern part of sec. 14, where it was first worked.

Methods of working.—At the old workings on East Lafferty Creek the phosphate rock was worked by stripping and quarrying and running short adits into the hill on a level with the phosphate beds. At the present workings only the former method has been used thus far. The beds so outcrop as to permit the company to work by this method for some time if they choose to do so; but eventually it will be necessary to run adits into the hillside. Drilling is done by hand, and the rock is hauled in wagons to the opposite side of the creek, where it is loaded on the cars for shipment. Before shipment the "black phosphate" is dried by ricking up the rock and leaving furnaces at the bottom, in which fires are built. Much the greater part of the stone is not weathered and is shipped without drying.

ORIGIN OF THE PHOSPHATES.

The comparatively uniform thickness of the phosphate beds and their occurrence, within the locality considered, always at the same geological horizon, at once determine them as of sedimentary origin. If any further evidence for such origin is necessary, that furnished by the microscopic examination is conclusive. This examination determines the gray, pebblelike material not to be concretions (consequently waterworn material) and the white particles that constitute so large a part of the mass to be organic remains.

Doctors Branner and Newsom think that the beds are probably deep sea (though not abysmal) deposits, and that their phosphatic nature is probably due to "the droppings of fishes and other marine animals and to accumulations of organic matter that settled to the bottom of the quiet waters that covered this part of the world during Silurian and Devonian times."[a] But from the conglomeratic character of the rock brought out by microscopic examination it appears that the deposition of the phosphate beds took place in shallow water, having closely followed the shore line as it advanced landward. This is further shown by the fragmentary character of the organic mate-

[a] The phosphate rocks of Arkansas: Bull. Arkansas Exp. Station No. 74, p. 69.

rial, a character that was probably produced by wave action along shore, which ground up the shells or the bones, as they may have been. It would seem that the droppings of marine animals, as above suggested, might account in part for the phosphatic nature of the beds, but the presence of so large an amount of organic fragments suggests that wave action was probably its chief cause. The exact character of these organic fragments can not yet be stated. Although they appear to be fragments of bones, the probability that they are such is much reduced by the fact that beds are placed (at least tentatively) in the Ordovician, and the probability that they are Ordovician forces one to the conclusion that the fragments are more likely those of the tests of crustacea, which are known to be phosphatic.

AGE OF THE PHOSPHATES.

The phosphates of northern Arkansas have heretofore been considered as of Devonian age, though Professors Branner and Newsom suggest that phosphates of earlier age may occur.[a] The lithologic character of the limestone above the phosphate beds on Lafferty Creek and its tributaries led to the supposition that this is the St. Clair limestone, which is of Silurian age. Fossils collected from this bed and sent to Mr. E. O. Ulrich, of the United States Geological Survey, confirmed this supposition. Fortunately, Mr. Ulrich had already visited the locality himself, which makes his determination of the beds all the more reliable. Two lots of fossils from the limestone above the phosphate beds at two different places were sent to Mr. Ulrich, and in a letter concerning them he says:

> Both lots of fossils are unquestionably indicative of the St. Clair limestone. The species are mostly different in the two lots, but all are of Silurian types known to occur in the St. Clair.
>
> The phosphate along Lafferty Creek occurs, judging from your evidence and my own observations, in the equivalent of the Cason shale, which elsewhere in the vicinity of Batesville contains the manganese. * * * It was only last year that I had an opportunity to satisfy myself that the phosphatic deposits being worked along the east bank of Lafferty Creek were undoubtedly in shale intervening between the Polk Bayou and the St. Clair limestone.

The Cason shale is considered by Mr. Ulrich as of Ordovician age. Certainly the phosphate beds are not younger than Silurian.

PROSPECTING FOR PHOSPHATES.

As the phosphate rocks of northern Arkansas are usually covered by soil where they outcrop on the hillsides, a few suggestions to prospectors in search of these beds may be of advantage. As one passes up the hillsides of the deeper valleys in western Independence County he goes first over a compact, gray to dove colored, brittle

[a] The phosphate rocks of Arkansas: Bull. Arkansas Exp. Station No. 74, pp. 66, 67, 69.

limestone, that breaks easily under the blows of the hammer. This is the Izard limestone. Above this is a coarsely crystalline limestone, light gray at the bottom, but growing darker toward the top, until the upper portion is at some places almost chocolate colored. This is the Polk Bayou limestone. It is at the top of this limestone that the phosphate of the locality occurs. In case the St. Clair limestone is present it will be found above the phosphate; if not, the Boone chert (possibly the St. Joe marble) will be found above it. It is useless to look for phosphate above the base of the Boone chert or below the top of the Polk Bayou limestone. In case the rocks on the hillsides are all hidden, the position of the phosphate beds may be determined approximately by examining the débris of the surface. At many places there are fragments of dull-gray rocks that look like sandstone, but these on being broken are yellow on the fresh surfaces. These are fragments of the phosphate rock. Fragments of manganese ore, which are easily recognized and always conspicuous when present, are good indications of the phosphate horizon, as the two are closely associated. Of course it must be remembered that loose material works its way downhill, so that only the upper limit of the material here described marks the position of the phosphate beds.

SUMMARY AND CONCLUSION.

While it is known that there is a phosphatic horizon of wide extent in northern Arkansas, the deposits have been developed at only one place, viz, on Lafferty Creek, in the western part of Independence County.

The geological formations of the vicinity of the developed deposits from below upward are: The Izard limestone, the Polk Bayou limestone, the Cason shale, the St. Clair limestone, the St. Joe marble, and the Boone chert. The developed deposits occur between the Polk Bayou limestone and the St. Clair marble, consequently at the horizon of the Cason shale, which is thought to be of Ordovician age.

The phosphate rock is of sedimentary origin, and where developed is light-gray, homogeneous, and conglomeratic, the pebbles being the size of peas and smaller.

The beds probably were laid down near shore as the sea advanced landward. Their phosphatic nature is thought to be due mainly to the fragments of organic matter that constitute so large a portion of their mass, though it may be due in part to the droppings of marine animals.

PHOSPHORUS ORE AT MOUNT HOLLY SPRINGS, PA.

By George W. Stose.

INTRODUCTION.

Phosphorus was formerly made solely from bones and organic substances, and it was not until the last decade, when the electric furnace was perfected, that natural phosphates were used to any extent in its manufacture. The extraction of phosphorus from mineral deposits brings the industry within the scope of the Geological Survey's investigations. The mineral from which phosphorus was first obtained was phosphorite, or rock phosphate, an impure fluophosphate of calcium, from which soluble phosphate fertilizer is generally made. Apatite, a fluophosphate or chlorophosphate of calcium, has been used in Europe and Canada to a small extent, but wavellite, or aluminum phosphate, so far as known, has not been heretofore used commercially in the manufacture of phosphorus, as the mineral does not generally occur in minable quantity.

DISCOVERY AND DEVELOPMENT.

At the foot of the northern slope of South Mountain, in the vicinity of Mount Holly Springs, Pa., 20 miles southwest of Harrisburg, a deposit of wavellite occurs in white clay associated with manganese and iron ores. For many years iron mining was a prosperous industry along the foot of the mountain in this region, but owing to competition from the great deposits of the West and South it has ceased to be profitable and the mines have long been idle. The iron is a secondary product, having been leached from the iron-bearing shales and limestones and deposited in the residual sand, gravels, and clays lying on the limestones in the valley. Associated with the iron, in general underlying it or on the side toward the mountain, is a body of clay, in places highly colored and plastic, elsewhere pure white or cream colored, siliceous, and less plastic. The extensive use of pure white clay as a filler for wall paper and for other commercial purposes has created an increasing demand for the clay of this region, and it is extensively mined in the vicinity of Mount Holly Springs and prospected for everywhere along the mountain front. In one of these prospect pits, on the property of T. J. Spangler in the vicinity of Moores Mill, 4 miles west of Mount Holly Springs, peculiar round white nodules, chiefly in aggregates and botryoidal masses, were found in the white clay. The less weathered of these nodules when broken open show a beautiful radiate silky fibrous structure. The mineral proved to be a pure form of wavellite, or aluminum phosphate, a mineral that is rather uncommon in so pure a form and is not known to occur elsewhere in sufficient quantity to be mined. The American Phosphorus Company was organized by Philadelphia capitalists to develop the deposit, and a mill for the extraction of the phosphorus from the ore was built near the mine. T. J. Spangler, superintendent of the mine and owner of the land, is paid a royalty on the ore extracted. The mine was opened in 1900, the first years being devoted to prospecting and experimenting with the reduction of the ore. During 1905 the mine was in active operation and 400 tons of ore were reported to have been extracted and reduced in the company's furnaces.

The mine is operated by open cut. The phosphate is scattered through the white clay and appears to lie between a manganese deposit in reddish clay and the mountain. The open cut after reaching a depth of about 30 feet was stopped because of water. A shaft near by was said to have passed through clay with phosphate ore from a depth of 12 to 52 feet, at which point 16 feet of manganese ore was encountered. When examined in August, 1906, both the shaft and the open cut were filled with water and the workmen were stripping for an enlargement of the pit. A tunnel is to be dug from a ravine below to drain it, so that mining can be continued to greater depth. The deposit is apparently limited in width to 40 or 50 feet, with a depth ranging from a few feet on the valley side, to 50 feet on the mountain side, as indicated by the shaft, and is of undetermined length along the mountain.

The only other deposit of phosphorus ore discovered in this vicinity is on the other side of the ridge in the small valley east of Upper Mill, 1 mile south of Mount Holly Springs. In the clay prospects of J. L. Musser small bean-shaped fragments and nodules of the phosphate are associated with manganese ore, but its quantity and extent had not been determined. Wavellite was also observed by T. C. Hopkins [a] in the white clay deposits of North Valley Hill, on the north side of Chester Valley.

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[a] Ann. Rept. Pennsylvania State College 1889–1900, appendix 3, p. 13.

GEOLOGY.

Cumberland Valley is a broad rolling plain 8 miles wide in the vicinity of Mount Holly Springs, whence it extends eastward to Susquehanna River and southwestward to Potomac River. It is limited abruptly on the southeast by South Mountain, a tract of parallel ridges which, near Mount Holly Springs, have an east-west trend.

The valley is composed largely of closely folded limestone of Cambrian and Ordovician age, younger Ordovician shales (Utica and Eden) overlying the limestone along the northwestern side of the valley. The front ridges of the mountain are made up of Cambrian quartzite and conglomerate with slate and soft sandstone valleys between. The southeastern ridges are of older volcanic rocks, both rhyolitic and basic.

In the vicinity of Mount Holly Springs the general structure is that of an anticlinorium with the southern limb covered by Triassic sediment. The lavas of pre-Cambrian age exposed at the axis are here chiefly rhyolitic and have a marked cleavage or schistosity dipping about 35° S., which obliterates largely the original banding. The basal Cambrian sediments consist of a coarse quartz conglomerate, massive quartzites, and thin slates. These are closely folded and overturned, dipping steeply to the south, although cleavage to the south is so highly developed that the stratification is difficult to determine. In the longitudinal valley of Mountain Creek a narrow belt of overlying limestone is infolded.

Walcott found fragments of *Olenellus* and *Hyolithes communis* in the upper scolithus-bearing sandstone just above Mount Holly Springs. This scolithus bed, which forms the north face of Mount Holly Ridge, resembles in every respect the Antietam sandstone, the uppermost sandstone of the mountain-making series of South Mountain in the vicinity of Chambersburg, and the finding of Georgian (Lower Cambrian) fossils in these beds further confirms this view, because fossils have not been found below this horizon in South Mountain. The limestone near the mountain is covered by wash. The nearest outcrops dip steeply to the south, being probably overturned, but fossils have not been found in them near Mount Holly Springs, so that the exact relations of the limestone to the sandstone of the mountain have not been determined. Walcott concluded[a] that a great fault exists along the west face of the mountain, agreeing in this respect with the earlier views of Lesley and Frazer, as published in the reports of the Second Geological Survey of Pennsylvania.

From recent detailed studies in South Mountain from the Maryland State line northward to the latitude of Chambersburg the writer has proved[b] the absence of a fault of any magnitude along that part of the

[a] Walcott, C. D., Cambrian rocks of Pennsylvania: Bull. U. S. Geol. Survey No. 134, 1896, pp. 24-27.
[b] Jour. Geol., vol. 14, 1906, pp. 201-220.

mountain front. Since the uppermost fossiliferous sandstone of the Cambrian (Antietam) forms the front of the mountain at Mount Holly Springs and there are no data concerning the age or attitude of the limestone immediately adjacent, it is assumed that the relations there are the same as those observed farther south; that is to say, that the sequence is normal or unbroken by a fault of appreciable magnitude.

ORIGIN.

The wavellite and the manganese and iron ores are secondary deposits in the surface gravels, sands, and clays which cover the rock outcrops at the foot of the mountain. These surface deposits are in part residual, in part transported. White sands, next to the mountain, are followed by beds of pure white siliceous clays, and these by colored plastic clays. The sand is derived from sandstones which have been leached of their calcareous cement, and in the quarries the loose sand merges into the unaltered rock. The white clay is a decomposed hydromica slate, transition into which has been described in the reports of the Second Geological Survey of Pennsylvania and by Hopkins.[a] Similar relations were observed in the clay mines by the writer,[b] but the exposures are not so clear and definite as they were when the iron mines were in active operation. The colored plastic clay is apparently derived from impure limestone. Generally these beds are steeply inclined or vertical, like the undecomposed rocks, but in places they have moved down the slope, lie flat, and have become covered over by and mixed with the quartzite débris from the mountain above.

In this heterogeneous mass the mineral deposits occur. Throughout the South Mountain district the iron ore that is associated with the basal part of the limestone is at the horizon of the hydromica slate at the contact with the sandstone, and is usually found in the highly colored clay, the limestone residuum, overlying the white clay derived from the hydromica slate. In many places the ore dips steeply into the hill parallel to the bedding and appears to be interbedded with the rocks.

It seems reasonable to conclude, therefore, that the original deposition of iron was in some way a feature of the change of sedimentation from shore detritus to calcareous silt, probably not as a massive bed of ore but as ferruginous sediments. The solution of the limestone and the decomposition of the other rocks has left the iron and clay residuum, and the iron has been further concentrated in the clay by solution and redeposition.

The wavellite undoubtedly had a similar history, for it is a common constituent of the iron and manganese ores. Analyses show its presence to a greater or less extent in all the iron ores of the region.

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[a] Op. cit., pp. 11-13.

[b] See pp. 323-324 of this bulletin.

The phosphorus in some ores amounts to 0.5 per cent; in others it reaches 1.5 per cent. At Mount Holly Springs the wavellite occurs chiefly in nodular form, with radiate structure, inclosed in the white clay, but it is also found coating pieces of quartzite and manganese ore. The phosphorus was probably associated with the iron in its original occurrence and in the process of redeposition it combined with the alumina, but it is possible that it may have been in part derived from the phosphatic animal remains in the sediments. It is known that trilobites and other fossils with phosphatic skeletons once existed in these beds in considerable abundance. They are still found in the limestones, and their casts are occasionally observed in the sandstones, but the phosphatic material has all been removed from the porous beds by solution, and may have been deposited in the white clay adjacent to the iron and manganese.

MANUFACTURE OF PHOSPHORUS.

The old method of making phosphorus, which has been in use since the beginning of the nineteenth century, is as follows: Bones are roasted and crushed, and the powdered bone ash (calcium phosphate) is treated with sufficient sulphuric acid to convert all or part of the calcium into calcium sulphate and the phosphorus into calcium metaphosphate, or even into phosphoric acid. This is partially evaporated, mixed with powdered charcoal, and reduced in a furnace in a clay retort. Phosphorus vapor and carbon monoxide distill off, and the phosphorus is condensed under water in a yellow, waxy form. Theoretically the reaction would be as follows:

$$2Ca_3(PO_4)_2 + 6H_2SO_4 + 12C = 6CaSO_4 + 12CO + 2H_2 + P_4 + 4H_2O.$$

It is found in practice, however, that the following is more nearly what takes place:

$$3Ca_3(PO_4)_2 + 6H_2SO_4 + 10C = 6CaSO_4 + Ca_3(PO_4)_2 + 10CO + 6H_2O + P_4.$$

In this process much loss results from the destruction of the retorts by the acid and intense heat, and only about one-half of the phosphorus in the charge is recovered. There is also danger of igniting the phosphorus when removing it, and the greatest care is required to prevent the vapor from condensing in the tubes and clogging them. Many improvements and modifications of this process have been patented in recent years. Wöhler early suggested that calcium phosphate, either burnt bones or rock phosphate, be heated with sand and carbon without the sulphuric-acid treatment, and the Wing patent (1891) followed the same general method.

In the Wing process the charge of bone ash or pulverized rock phosphate and silica is moistened and made into balls, and is placed in the cupola in layers, alternating with coke or coal, which furnish incandescent carbon to reduce the phosphoric-acid fumes. The silica releases the phosphoric acid from the phosphate in the form of the anhydride P_2O_5, which is reduced by the incandescent carbon and a reducing flame to phosphorus. The fumes pass off to depositing chambers, kept at a temperature of 500° F., where most of the phosphorus is deposited in the red form and the remainder is caught in a water chamber as yellow phosphorus. The process is made continuous by feeding the charge from the top, dumping the residuum from the grate below, and using two depositing chambers alternately.

With only the ordinary furnace at command this method was found impracticable on account of the high degree of heat required to smelt so refractory a charge. Electricity as a powerful heating agent had been known for some time and was expected to furnish the solution of the problem, but only recently has the invention of the electric furnace made it commercially feasible. It has now been generally introduced throughout Europe and America in the production of phosphorus on a profitable basis.

The Readman patent (1889) is the process which has come into commercial use in most countries. Bone ash or crude phosphoric acid is mixed with powdered coal or charcoal, or, if mineral calcium phosphate is used, it is roasted, crushed, and mixed with charcoal and silica or some basic salt. The mixture is reduced in a continuously operated electric furnace in a reducing atmosphere, by passing the current from carbon electrodes through the mass, which acts as a resistant conductor and is heated to incandescence. The silica combines with the calcium to form calcium-silicate slag. The phosphorus and carbon monoxide distill off as before. Distillation begins at 1,150° C. and requires 1,400° to 1,500° C. to complete the process. The chemical reaction is—

$$2Ca_3(PO_4)_2 + 6SiO_2 + 10C = 6CaSiO_3 + 10CO + P_4.$$

In Harding's patent (1898) pulverized rock phosphate is boiled with sulphuric acid, and the phosphoric acid, free from lime, is filtered out and boiled down to a sirup. This is mixed with granulated carbon heated in a reverberatory furnace, and then smelted in an electric furnace by electric arcs between the electrodes and the mass. A hydrogen atmosphere is obtained by spraying gasoline into the furnace.

In the Gibbs furnace, which was devised especially for the manufacture of phosphorus, instead of the electricity discharging through the mass, it passes through a continuous highly resistant medium, such as a carbon rod, placed above the charge. The rod becomes incandescent, and the roof, which is arched over the grate, reflects the heat as in a reverberatory furnace.

The Readman process was modified by the Irvine patent in 1901. The charge is the same as in the earlier method, although either aluminum or calcium phosphate can be used with the silica or basic salt flux. The two carbon electrodes are suspended vertically from above and are connected below at the start by coal, through which the current passes. After the charge is melted the slag forms on top, and thereafter the current passes through it as the conductor between the electrodes. Fusion is continuous, and the excess of slag is tapped off gradually so as not to expose the ends of the electrodes.

A process patented in 1903 by Duncan takes 77 parts of powdered phosphate, either organic or mineral, and 23 parts of powdered carbon, mixed with tar as a binder. This is dried, and after a preliminary heating, as a matter of economy, in a hydrogen flame, a by-product in the manufacture, it is put into an electric furnace and calcium phosphide is continuously produced. This is put into a chamber submerged in hydrogen, and after adding water it forms phosphorus hydrides. On heating, the hydrides are reduced to phosphorus in pure state, either red or yellow, depending on the degree of heat at which it is allowed to deposit.

In 1902 Parker patented a process in England for the reduction of aluminum phosphate, which is treated with sulphuric acid and then with an alum-forming sulphate, all the alumina being removed by the crystallization of the alum previous to the electric treatment. The residual liquor is mixed with coal and other carbonaceous material and reduced in an electric furnace.

The American Phosphorus Company, through G. C. Landis, its chemist, secured a patent in January, 1907, on certain improvements in its furnace that were designed to prevent the escape of fumes, vapors, and gases, or their absorption by the furnace lining. This is accomplished by an outer lining of nonabsorbent brick and by a sealing device for all openings into the furnace, whereby the projecting flanges of the joints are inclosed in a moat of water. The furnace has an inner lining of carbon bricks that acts as one electrode, and one or more vertical carbon rods are used for the other electrode, which may be adjusted either to furnish a continuous current through the charge or to produce with it an electric arc.

The phosphorus obtained by most commercial processes is a crude form of the white or yellowish waxy variety, containing sand, carbon, clay, and other impurities. These are removed in various ways—by filtering while molten and submerged in water through powdered charcoal or through canvas; by forcing the molten mass through porous pottery by means of steam; or by redistillation in iron retorts. The best method of purification, however, is to treat the crude phosphorus, when molten, with a mixture of potassium dichromate and sulphuric acid, or with sodium hypobromite, some of the impurities being dissolved and others rising to the surface as scum.

Because ordinary white phosphorus is very poisonous and injurious to handle, other forms of the element have been sought. Red amorphous phosphorus, which is not poisonous, is readily prepared by heating the ordinary variety to 250° C. in a closed vessel under pressure or excluded from air and water. It has not the same qualities, however, as the white crystalline variety. A red crystalline form, recently discovered in Germany, is made by heating to boiling a 10 per cent solution of white phosphorus in phosphorus tribromide. This form is not only nonpoisonous but is an efficient substitute for white phosphorus in making matches.

PRODUCTION.

The industry in this country is so young that statistics are difficult to obtain; in fact, general information on the subject is lacking. The world's production of phosphorus has been variously estimated to be from 1,000 to 3,000 tons a year, and until very recently this was almost entirely a foreign industry. The greater part of the world's supply is made in the Albright & Wilson factory, Wednesfield (Oldbury), England, where the Readman process originated. This plant is said to produce 500 tons a year. Other large factories are located at Lyons, France, and at Griesheim and Frankfort, Germany. There is also a plant in Sweden and numerous smaller ones in Russia, six of which, located near Perm, had an output of about 140 tons in 1890.

In the United States the first phosphorus works were built about forty years ago in Philadelphia by Moro Phillips, and this factory has continued in operation until very recently. J. J. Allen's Sons' plant was established in Philadelphia in 1891, and they supplied the Diamond Match Company, the largest match manufacturer in the United States, in competition with imported phosphorus. In 1897 the English firm of Albright & Wilson, under the firm name of the Oldbury Electro-Chemical Company, built at Niagara Falls a 300-horsepower factory of the Readman type, which has since supplied the Diamond Match Company and furnished the major portion of the domestic product. This company has recently made a further improvement in its plant by introducing the Irvine patent furnace, and it is reported that by this method 80 to 90 per cent of the phosphorus is extracted from the raw material, a high-grade phosphate rock. This is similar to the results obtained in the English works, where 86 per cent is recovered. The company has six furnaces of 50 horsepower each, with a daily capacity of 170 pounds of phosphorus, a total of 1,020 pounds a day. The production varies according to the demand.

The General Chemical Company, a small domestic manufacturer and the successor of Mr. Phillips in Philadelphia, recently acquired the Duncan patent. Another company was formerly established at Long Island City, N. Y., where it operated furnaces by electricity from the city supply.

At the census of 1900 three establishments were reported in operation, but at the 1904–5 census only the Oldbury Electro-Chemical Company, of Niagara Falls, reported.

The American Phosphorus Company built its first mill at Moores Mill, near Mount Holly Springs, Pa., in 1902, and the old method of heating by gas was employed. This mill burned down and another was built and put into operation by 1905. Electric furnaces were installed in the new plant and operated during 1905, but the production of electricity by steam was too expensive, and in 1906 the mill was moved to Yorkhaven, Pa., where electricity generated by water power could be had. The process in use by this company is that of G. C. Landis, its chemist, and is kept a secret, as it is claimed that it is a marked improvement on previous methods. As far as could be learned for publication without detriment to the company's interest, the wavellite (aluminum phosphate) and phosphorite (calcium phosphate), which at present is obtained from South Carolina, are roasted, mixed with silica and charcoal, and reduced in a patented electric furnace. The slag is removed every three or four hours, and the phosphorus fumes are condensed under water in the crude yellow waxy form which requires refinement. Eighty-five to 90 per cent of the phosphorus in the ore is said to be extracted. The average production of this plant for the last three years is reported to be 500 pounds a day.

In addition to the domestic production, the United States imports annually 30,000 to 40,000 pounds of phosphorus, on which a duty of 18 cents a pound is paid. The price in the New York market ranges, according to quality, from 45 to 70 cents a pound.

USES.

Phosphorus is used chiefly for making matches, which were first manufactured on a commercial scale in 1833. Parlor matches were invented in 1848 and safety matches in 1855. The white phosphorus is used for ordinary matches and the red amorphous form for safety matches. On account of the injury to health in making and handling the ordinary phosphorus and the danger from fire in using parlor matches, certain European countries have forbidden the manufacture and sale of the white variety, so that amorphous phosphorus and safety matches are coming into general use. The newly discovered crystalline red phosphorus is not only nonpoisonous, but is suitable for ordinary matches.

Phosphorus is sold in the market in round sticks molded through glass tubes and is usually stored under water. Its uses other than for matches are for fuse compositions, rat and insect poison, phosphoric acid, and other compounds used in medicine and the arts. It is also used in the precipitation of precious metals, electrotyping, and in phosphor-bronze.

SURVEY PUBLICATIONS ON PHOSPHATES AND OTHER MINERAL FERTILIZERS.

The following papers relative to phosphates, gypsum (land plaster), and other mineral materials used as fertilizers have been published by the United States Geological Survey or by members of its staff. Further references will be found under the head of "Gypsum" in the list on page 266 of this volume:

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