

# Physical Stratigraphy of the Phosphoria Formation in Northwestern Wyoming

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## CONTRIBUTIONS TO ECONOMIC GEOLOGY

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### PHYSICAL STRATIGRAPHY OF THE PHOSPHORIA FORMATION IN NORTHWESTERN WYOMING

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By Richard P. Sheldon

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#### ABSTRACT

The rocks of the Phosphoria formation in northwestern Wyoming fall into five stratigraphic units, which, from oldest to youngest, are provisionally called the *A*, *B*, *C*, *D*, and *E* units. Units *A*, *C*, and *E* are composed dominantly of chert, carbonate rock, and sandstone, whereas units *B* and *D* are composed dominantly of mudstone, phosphorite, and dark carbonate rock. Units *C* and *D* are continuous over all of northwestern Wyoming, whereas unit *A* grades into unit *B* and unit *E* grades into unit *D* to the southwest. Both units *A* and *B* pinch out to the north. With the possible exception of unit *A*, these units can be recognized in southwestern Montana. Units *B*, *C*, and *D* are equivalent to the phosphatic shale, Rex, and upper shale members of the Phosphoria formation in southeastern Idaho. The formation as a whole exhibits a facies change from dominantly chert, mudstone, and phosphorite in the southwestern part of northwestern Wyoming to dominantly carbonate rock and sandstone in the northeastern part. The facies change with thinning and pinching out of units and the intergradation of units.

The rocks of the formation in the area of the report are cyclically deposited. The rock record of a single ideal cycle consists, from base to top, of carbonate rock, chert, phosphorite, chert, and carbonate rock. Sandstone and glauconite in general are found in the carbonate phase of the cycle, whereas mudstone, pyrite, and organic matter are found in the chert and phosphorite phases of the cycle. An eastward facies transition from phosphorite to chert and chert to carbonate rock is analogous to the upper half of the cycle, which is: phosphorite, chert, and carbonate rock in ascending order. The phosphorite phase of the cycle is represented by units *B* and *D*, whereas the other phases are represented by units *A*, *C*, and *E*. Two complete cycles are found in southwestern Wyoming.

These stratigraphic relations represent two transgressions and regressions of areally zoned environments. The phosphorite phase is the more transgressive; the carbonate rock phase is the more regressive. The physical-chemical environments in which the sediments accumulated probably varied between an environment with a pH of above 7.8 and an Eh of greater than zero for the carbonate rock phase of the cycle, and an environment with a pH of less than 7.8 and an Eh of less than about -0.25 for the phosphorite phase of the cycle. These

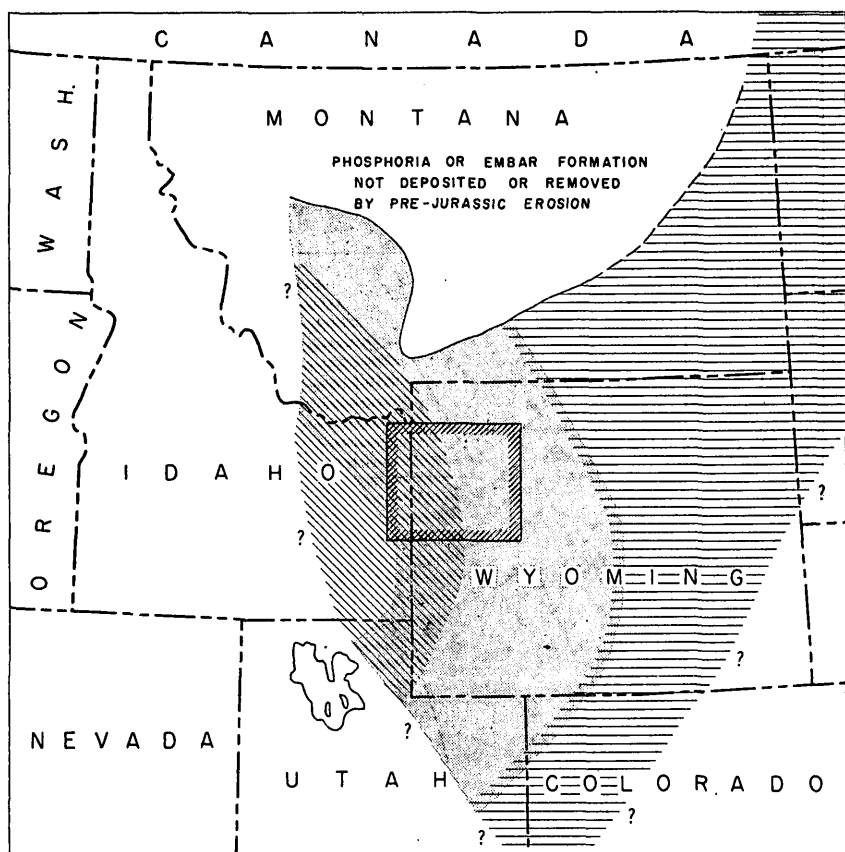
environments probably were effected by an upwelling of cold water on a shelf to the east. The transgressive and regressive migrations of the shelf probably were tectonically controlled.

## INTRODUCTION

The sediments which formed the Phosphoria formation of Permian age and its equivalents were deposited in the Cordilleran miogeosyncline in Idaho and north-central Utah and on the adjoining platform to the east in Wyoming, Montana, and northeastern Utah. These rocks consist of a number of relatively uncommon types such as phosphorite, black shale, bedded chert, evaporites, and red beds as well as more common rocks such as limestone, dolomite, and sandstone. In general, chert, mudstone, and phosphorite were deposited in the miogeosyncline, and carbonate rock and sandstone were deposited on the platform. Farther east a red bed and evaporite facies is developed (McKelvey and others, 1953) (fig. 10).

The manner in which these facies changes are effected has been difficult to determine because Cretaceous and Tertiary orogeny, volcanic activity, and erosion have combined to isolate most of the principal areas where the Phosphoria now crops out in southwestern Montana, central Wyoming, and southeastern Idaho. The northwestern Wyoming area, however, contains a number of closely spaced outcrops of the Phosphoria formation that help to bridge the gap between the other areas. This key area, therefore, was selected for studies designed to provide stratigraphic correlation between the components of the Phosphoria formation in the other areas and to define the nature of the facies changes from one area to another.

The preliminary results of these studies are presented here. In substance, they show that the formation can be divided into five lithologic units, provisionally termed units *A*, *B*, *C*, *D*, and *E*, from base to top; that these units are continuous over most of northwestern Wyoming (pl. 9); and that for the most part they are correlative with the major lithologic units of the formation in adjacent areas. The chief aspects of the facies change both by an eastward thinning or pinching out of chert, mudstone, and phosphorite units, and by gradation of beds of one rock type into beds of another. The most significant gradations are the eastward gradation of phosphorite to chert and chert to carbonate rock. In the area transitional between the chert-mudstone-phosphorite facies and the sandstone-carbonate facies in northwestern Wyoming, the depositional sequence from bottom to top is: carbonate rock and chert; phosphorite and mudstone; chert; carbonate rock and sandstone; phosphorite and mudstone; chert; and, finally, carbonate rock and sandstone. This sequence records two transgressions represented by the phosphorite and mud-



## EXPLANATION

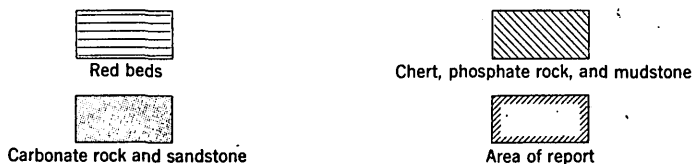


FIGURE 10.—Index map showing location of area of this report and dominant lithologic character of the Phosphoria formation and its correlatives.

stone, and three regressions represented by the carbonate rock, sandstone, and chert.

## FIELD WORK AND METHODS OF STUDY

The investigations on which this report is based were carried out by the U. S. Geological Survey during the summers of 1950, 1951, and 1952. About 20 complete sections of the Phosphoria formation (fig. 11) were measured and described in detail and the phosphatic portions of the formation were sampled and analyzed for  $P_2O_5$  and

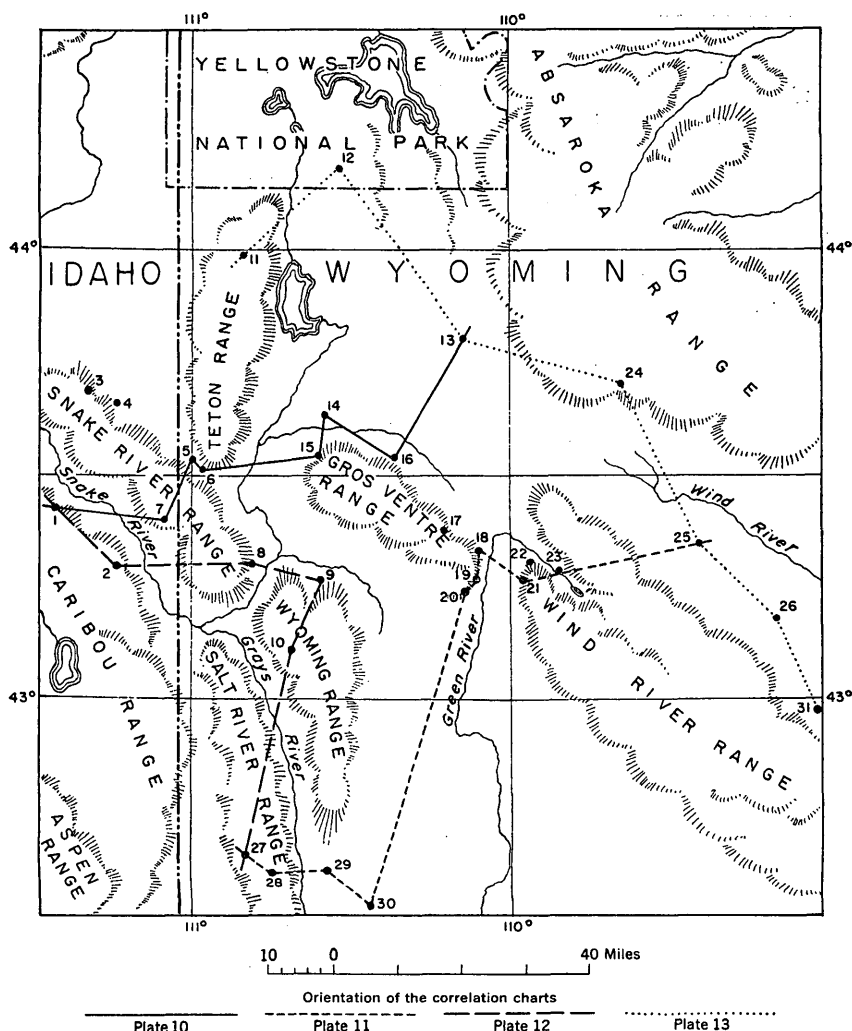


FIGURE 11.—Map showing mountain ranges in northwestern Wyoming and localities where the Phosphoria formation has been sampled and described.

**Localities:**

- |                 |                       |                                |
|-----------------|-----------------------|--------------------------------|
| 1. Fall Creek   | 11. Forellen Peak     | 21. South Fork of Gypsum Creek |
| 2. Bear Creek   | 12. Red Creek         | 22. Sheep Mountain (d)         |
| 3. Trench E (a) | 13. Togwotee Pass     | 23. White Rock (d)             |
| 4. Trench D (a) | 14. Gros Ventre Slide | 24. Burroughs Creek            |
| 5. Hungry Creek | 15. Flat Creek        | 25. Dinwoody Canyon            |
| 6. Teton Pass   | 16. Crystal Creek     | 26. Bull Lake                  |
| 7. Trench H (a) | 17. Darwin Peak (b)   | 27. Cottonwood Creek (e)       |
| 8. Hoback       | 18. Tosi Creek        | 28. Poison Creek               |
| 9. Buck Creek   | 19. Rock Creek (c)    | 29. Middle Piney Lake          |
| 10. Steer Creek | 20. Bartlett Creek    | 30. Lakeridge 1 well           |
|                 |                       | 31. Baldwin Creek (f)          |

**References:**

- |                        |  |   |
|------------------------|--|---|
| (a) Gardner (1944)     | (c) Blackwelder, Eliot, (unpublished manuscript) | (e) Love, J. D., and Smith, L. E., (unpublished manuscript) |
| (b) Blackwelder (1918) | (d) Baker (1946)                                 | (f) King (1947)   |

acid insoluble (Smart and others, 1954; Sheldon and others, 1954; Cheney and others, 1954; Sheldon and others, 1953).

The rock descriptions are based on megascopic examination, supplemented by microscopic examination of most of the beds at Flat Creek and Fall Creek (pl. 9; tables 1, 2) and some beds in the upper half of the core from the General Petroleum Company's 1 well, and also on chemical analyses for phosphate and acid insoluble.

### ACKNOWLEDGMENTS

Many members of the U. S. Geological Survey during the last 15 years have contributed to the growing understanding of the Phosphoria formation. I have tried not to anticipate the conclusions of those currently working with the Phosphoria, but in placing the strata studied for this report in their regional setting I have relied heavily on the work of others. The current studies of V. E. McKelvey, E. R. Cressman, and T. M. Cheney in particular have been used. V. E. McKelvey, in addition, pointed out the problem to me in 1950, and has since generously aided me in its study. K. B. Krauskopf kindly reviewed the manuscript. I would like to acknowledge R. A. Smart, T. M. Cheney, M. A. Warner, R. G. Waring, and H. W. Peirce who, with the author, described and sampled most of the sections studied. Members of the National Park Service in Yellowstone and Grand Teton National Parks, the U. S. Forest Service rangers in the many national forests in the area, and the Shoshone tribe in the Wind River Indian Reservation have all been very cooperative. This work was done partly on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

### STRATIGRAPHY

The Phosphoria formation in northwestern Wyoming consists of three to five lithologic units, provisionally called units *A*, *B*, *C*, *D*, and *E* in ascending order. Unit *A* is composed of chert and carbonate rock; unit *B* of phosphorite, mudstone, and carbonate rock; unit *C* of carbonate rock, chert, and sandstone; unit *D* of phosphorite, mudstone, and carbonate rock; and unit *E* of chert, carbonate rock, and sandstone (pl. 9). The nomenclature of this sequence of rocks has been changed frequently in the past, causing several inconsistencies in the present nomenclature. In order to help in a better understanding of the present system, it is appropriate to review the history of the nomenclature before further defining the units used in this report and describing their areal variations and vertical lithologic sequences.

### REVIEW OF NOMENCLATURE

In Yellowstone Park, Hague, Iddings, and Weed (1899) named a sequence of sandstone, red and green shale, and chert the Teton

formation. They defined the formation as the beds overlying the Quadrant quartzite of Carboniferous age and overlain by the Ellis formation of Jurassic age. They thought that the Teton formation was "Juratrias" in age. The name has since been discarded, because it was subdivided later into other formations, which do not logically form a group.

In 1906 Darton gave the name Embar formation to limestone and shale beds lying above the Pennsylvanian Tensleep sandstone and below the Triassic(?) Chugwater formation in the Owl Creek Mountains, Wyo. These beds were thought to be Pennsylvanian in age. Blackwelder (1911) tentatively extended the name Embar into the Wind River and Gros Ventre Ranges.

In 1907 Boutwell named a sequence of calcareous rocks, which had been included in the Upper Coal Measures by King (1878), the Park City formation,

in recognition of the fact that it is the formation which has yielded the bonanzas that . . . have made the (Park City) district famous . . .

The formation was defined as overlying the Pennsylvanian Weber quartzite and underlying a sequence of red shales which he designated the "Permo-carboniferous" Woodside shale. The Park City formation was thought to be Pennsylvanian in age. Also in 1907 Veatch recognized similar rocks in southwestern Wyoming and extended the name Park City formation to them. Gale and Richards (1910) applied the name Park City to similar rocks in southeastern Idaho, northern Utah, and western Wyoming. They differentiated a lower cherty limestone member, a middle phosphatic shale, and an upper chert and limestone member, which they also recognized at the type section of the Park City in Utah. Blackwelder (1911) extended the name Park City to the north to the Snake River Range, Idaho.

Richards and Mansfield in 1912 reorganized the stratigraphic nomenclature in southeastern Idaho. Faunal evidence suggested that the lower member of the Park City formation was Pennsylvanian in age, whereas the middle and upper members were thought to be Permian(?). Thus they grouped the Weber quartzite and lower Park City member and called the unit the Wells formation of Pennsylvanian age; its type section is in Wells Canyon, Caribou County, Idaho. The rest of the Park City formation was renamed the Phosphoria formation and assigned a Permian(?) age; its type section is in Phosphoria Gulch, Caribou County, Idaho. The Phosphoria formation thus included the middle and upper members of the Park City formation. The middle member, consisting of dark phosphatic shale, was not given a formal name, but the upper member, consisting of chert, limestone, and cherty mudstone, was called the Rex chert member; its type section is at Rex Peak, Rich County, Utah.



From 1911 until 1924 the two names, Park City and Phosphoria, were in competition in Wyoming. Schultz in 1914 used the name Park City in the Salt River and Wyoming ranges, applying it to strata lying above the Weber quartzite and below a sequence of red beds. He thereby included beds at the top which are now placed in the Triassic Dinwoody formation, a time correlative of the Woodside formation of Utah (Newell and Kummel, 1942). Mansfield in 1916 reassigned the lower portion of the beds in the Salt River Range to the Phosphoria formation.

In 1918 Blackwelder split the Embar formation into an upper unit of Triassic age, which he named the Dinwoody formation, and a lower unit of Permian age, which he did not name but which he said was the correlative of the Park City formation. In 1919, Collier called these two units the Embar group, containing the Park City and Dinwoody formations in the Maverick Springs anticline east of the Wind River Mountains. In 1924, however, Condit placed the same beds in the Phosphoria formation, stating that

studies by several workers had proved that the part of the Embar formation beneath the Dinwoody formation corresponds to only the upper or Phosphoria part of the Park City formation of Utah. . . .

The name Phosphoria has been extended eastward to include Permian red beds in central Wyoming (Ketterer and Swirczynski, 1952; Frielinghausen, 1952), but others (Thomas, 1934, 1948, 1949; Tourtelot, 1952) apply the name only to marine tongues in the red bed facies. However, some authors prefer the name Embar formation in central Wyoming and southern Montana where the Phosphoria and Dinwoody formations are dominantly made up of red beds and are separated only with difficulty (Gardner and others, 1945; Pierce, 1948).

Subdivision of the Phosphoria formation into members has hitherto followed local usage. The division into phosphatic shale and Rex members has been used in western Wyoming by Mansfield (1916), Gardner (1944), Rubey<sup>1</sup> and McKelvey.<sup>2</sup> Rubey and McKelvey, in addition, have distinguished an upper shale member overlying the Rex member. In southwestern Montana two to five lithologic units have been distinguished<sup>3</sup> and have been provisionally termed

<sup>1</sup> Rubey, W. W., 1942, Unpublished descriptions of the Phosphoria formation in the Salt River and Wyoming ranges.

<sup>2</sup> McKelvey, V. E., 1946, Stratigraphy of the phosphatic shale member of the Phosphoria formation in western Wyoming, southeastern Idaho, and northern Utah: U. S. Geol. Survey open-file report.

<sup>3</sup> Klepper, M. R., Lowell, W. R., Myers, W. B., Swanson, R. W., and Kennedy, G. C., 1948, Distribution and stratigraphy of the Phosphoria formation in southwestern Montana: Paper read at Northwest Science meeting, Spokane, Wash. in December 1948.

Lowell, W. R., 1949, Geology of the Small Horn Canyon, Dalys Spur, Cedar Creek, and Dell areas, Montana: U. S. Geol. Survey open-file report.

Butler, A. P., and Chesterman, C. W., 1945, Investigation of trace elements in the Phosphoria formation in southwestern Montana, preliminary report: U. S. Geol. Survey Trace Elements Inv. Rept. 5.

by Klepper units *A*, *B*, *C*, *D*, and *E* from base to top respectively. Unit *A* consists of sandstone and cherty carbonate rock, unit *B* of phosphate rock and phosphatic mudstone, unit *C* mainly of carbonate rock, unit *D* of phosphatic mudstone, and unit *E* of chert and sandstone (Cressman, 1955). In the Lander, Wyo. area, King (1947) divided the Phosphoria into lower, middle, and upper units on the basis of resistant limestone beds (pl. 13).

The terminology of the Phosphoria, as it now stands, is unsatisfactory. For one thing, the base of the beds that disconformably overlie the Tensleep sandstone defines the base of the Phosphoria formation in the Wind River Mountains, Wyo. (Condit, 1924), whereas in southeastern Idaho the base of the dark phosphatic shale of the phosphatic shale member defines the base of the formation (Richards and Mansfield, 1912). Thus the formation includes a chert and carbonate rock unit underlying the phosphatic shale in the Wind River Mountains, but excludes this unit in the Wyoming and Snake River ranges, although the unit is continuous over both areas. For another, the Phosphoria formation now includes three distinct facies (fig. 10): (1) a chert-phosphorite-mudstone facies in southeastern Idaho and immediately adjacent areas; (2) a carbonate rock-sandstone facies in western Wyoming; and (3) a red bed-carbonate rock-evaporite facies in central Wyoming.

#### NOMENCLATURE USED IN THIS REPORT

No permanent solution to the problems of stratigraphic nomenclature is attempted in this paper, since a revision of the nomenclature based on a study of a relatively small area would not be warranted. Instead, the provisional nomenclature used by Klepper and others in Montana is extended to this area. Five units—*A*, *B*, *C*, *D*, and *E*, from base to top respectively—are thus distinguished.

#### METHOD OF CORRELATION

The units of the formation in northwestern Wyoming are defined wholly on the basis of their lithologic character. Therefore, the correlation of unit boundaries in general is based on gross lithologic changes such as the break between beds of phosphatic mudstone of unit *B* and the overlying beds of chert of unit *C*. Similarly, within units some correlations are based on the lowermost or uppermost occurrence of a lithologic type. However, certain lithologic sequences are repeated in detail from one section to another. Moreover, certain beds of unique lithologic character, for the most part phosphorites, can be recognized from section to section. Each of these key beds probably represents synchronous deposition, because it seems unlikely that such unique rock sequences or rock types would be repeated in time.

These key beds have been used to help delineate some of the facies relations. The correlation of such beds is indicated on plates 10 to 13 by a special type of line.

### REGIONAL STRATIGRAPHY

The Phosphoria formation varies significantly in thickness and lithologic character in the four states in which it crops out. For this reason stratigraphic correlation has been difficult and the stratigraphic units delimited in various areas have not always incorporated the same rocks nor been called by the same name. Therefore the regional variations of thickness and lithologic character of the Phosphoria formation are described, and the units delimited in this report are correlated with previously described units in adjacent areas.

#### THICKNESS

The thickness of the formation ranges between 200 and 300 feet over most of northwestern Wyoming, but thins to about 150 feet in the northern part of the area and thickens to about 400 feet in the southwestern part (fig. 12). To the southwest, in southeastern Idaho, the formation thickens to more than 500 feet. The thickness of the formation is about the same in northwestern Wyoming as in immediately adjacent parts of Montana (Cressman, 1955), but over the whole of southwestern Montana the formation shows a greater variation in thickness. East of the area of this report the formation thins to the north (Frielinghausen, 1952; Ketterer and Swirczynski, 1952). To the northeast, in the Big Horn Basin, variations in the thickness of the Phosphoria are almost wholly accounted for by relief on the Tensleep surface (Agatson, 1952, 1954). That is, where the Tensleep is thin, the Phosphoria is thick and the combined thickness of the Tensleep and Phosphoria remains fairly constant.

#### LITHOLOGIC DESCRIPTION

In general the lithologic character of the formation varies with the thickness. Where the formation is thick, in southeastern Idaho, it is composed dominantly of chert, mudstone, and phosphorite. Where the formation is thin, in the eastern portion of the area of the report and in Montana, it is composed dominantly of carbonate rock and sandstone. In central Wyoming and central Montana the Phosphoria formation is thin and consists chiefly of red beds (fig. 10).

#### CORRELATION WITH THE PHOSPHORIA OF OTHER AREAS

Unit *A* of this report has not been definitely recognized in other areas. To the southwest the unit grades into the lower beds of unit *B*. Unit *A* in northwestern Wyoming is possibly the stratigraphic equivalent of unit *A* in areas such as the Centennial Range and

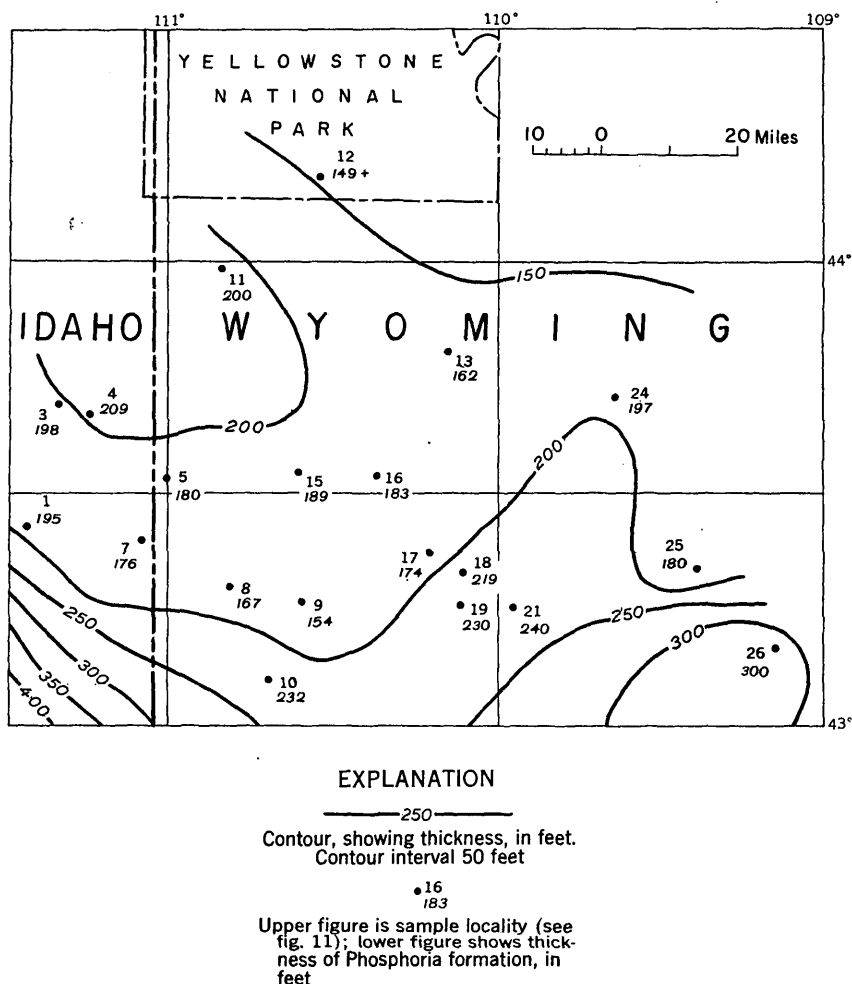


FIGURE 12.—Isopach map of the Phosphoria formation in northwestern Wyoming.

Madison Range, Mont. Beds assigned to unit *A* in the western part of Beaverhead County, Mont. are possibly equivalent to beds included in the upper part of the Wells formation in western Wyoming.

Unit *B* has been designated the phosphatic shale member in the southwestern part of the area of the report (Gardner, 1944) and is correlative with the 200-foot phosphatic shale member in southeastern Idaho (McKelvey, *op. cit.*). The unit probably is the correlative of unit *B* in southwestern Montana (Klepper and others, *op. cit.*; Cressman, 1955).

Unit *C* has been included in the Rex member in the southeastern part of the area of the report (Gardner, 1944). At Brazer Canyon, Utah near the type locality of the Rex, T. M. Cheney (oral communi-

cation 1953) of the U. S. Geological Survey has recognized chert and mudstone beds at the top of the Rex that probably are equivalent to the chert and mudstone of units *D* and *E*. Thus unit *C* is probably equivalent to only the lower massive chert of the Rex member at the type locality. Unit *C* is probably the equivalent of unit *C* in southwestern Montana (Klepper and others, op. cit.; Cressman, 1955).

Unit *D* is probably equivalent to the upper shale member in southeastern Idaho and southwestern Wyoming and was included in the Rex member by Gardner (1944). As stated above, the unit is possibly present at the type section of the Rex chert and is represented by cherty mudstone near the top of the member. Unit *D* is probably equivalent to the unit *D* in southwestern Montana (Klepper and others, op. cit.; Cressman, 1955).

Unit *E*, as has been stated above, is possibly present at the type section of the Rex chert in Utah and is equivalent to the uppermost chert beds of the Rex there. It also is probably the equivalent of unit *E* in southwestern Montana (Klepper and others, op. cit.; Cressman, 1955). Beds of this lithologic type have not been recognized in southeastern Idaho because the chert beds of northwestern Wyoming grade into mudstone in westernmost Wyoming.

In central Wyoming the units of this report cannot be recognized owing to the change to the red bed facies. Three carbonate rock tongues of the carbonate rock facies do extend into the red bed facies, however (Condit, 1917; Thomas, 1934). Thomas (1948) presented the detailed correlation of the units of the red bed facies of the Phosphoria with the carbonate rock facies of the Phosphoria to the west, at the Little Popo Agie River section in the southern Wind River Mountains. The Opeche shale is made up of red beds, which lie at the base of the formation at the same stratigraphic position as the lower part of King's (1947) lower member of the Phosphoria in the southern Wind River Range. The Minnekahta limestone, formerly called the Sybille tongue of the Phosphoria (Thomas, 1934), contains abundant calcite geodes. Thomas (1949) states:

because it carries abundant geodes and because of its stratigraphic position in respect to the unconformity at the base of the Phosphoria, the Minnekahta is tentatively correlated with the geodal limestone just above the lower phosphate zone in the southern Wind River Mountains.

This geodal limestone is the upper part of King's lower member of the Phosphoria. The next stratigraphically higher unit is the Glendo shale of Condra, Reed, and Scherer (1940), a red bed unit that is equivalent to the lower part of King's middle member. The Forelle limestone overlies the Glendo shale of Condra, Reed, and Scherer (1940) and is not lithologically distinctive from other car-

bonate rocks in the Wind River Mountains; however, on the basis of its stratigraphic position it is probably correlative with a 14-foot cherty carbonate rock that is 60 feet above the base of King's middle unit. The unnamed red bed unit above the Forelle limestone is equivalent to the rest of King's middle member. The Ervay tongue marks the top of the Phosphoria and was correlated by Thomas (1934) with the upper limestone member of King at the Little Popo Agie River section, on the basis of both stratigraphic position and similar faunules. A number of species contained in these faunules are restricted to the uppermost beds of the formation. These faunules are also described by C. C. Branson (1930) and includes his *Aulosteges* and *Hustedia* faunules.

King (1947) presented the detailed correlation of the Phosphoria strata from Little Popo Agie River to Baldwin Creek. His Baldwin Creek section is reproduced in figure 12, which shows his member breakdown as well as the Minnekahta, Forelle, and Ervay correlatives. Thomas' and King's correlations, as well as the correlation of the units of this report from Bull Lake to Baldwin Creek, indicate that the Minnekahta limestone lies at the base of unit *C*; the Forelle limestone probably lies about 75 feet above the base of unit *C*; and the Ervay tongue lies at the top of unit *E*.

#### PETROGRAPHIC DESCRIPTION

Before describing the individual units of the formation, it is appropriate to describe the rock types that occur in the formation. Rocks from two localities in the area of the report have been selected for petrographic study; they are the Fall Creek and the Flat Creek sections (fig. 11). The Fall Creek section was selected as a representative of the miogeosynclinal rocks, and the Flat Creek section as a representative of the platform rocks. In addition, some specimens from a few other localities were studied. The petrographic descriptions of the rocks from Flat Creek and Fall Creek are presented in tables 1 and 2 and a description and interpretation of the textures, minerals, and mineral associations of phosphorite, chert, carbonate rock, mudstone, and sandstone are presented below.

#### PHOSPHORITES

Phosphorites of the Phosphoria formation are those rocks composed dominantly of apatite. Altschuler and Cisney (1952) have identified several samples of apatite from the Phosphoria as carbonate fluorapatite. Both anisotropic and isotropic forms of apatite are found; they have similar compositions and structures, but the isotropic form has been called collophane, and the anisotropic form francolite (Fron del, 1943; Deitz, Emery, and Shepard, 1942; and Lowell, 1952).

Phosphorites, perhaps more than any of the other rocks studied,

show wide variations in texture and in the mineral habit and morphology of constituent grains. The types of grains include structureless pellets and nodules, oolites and pisolites, apatite fossil fragments, compound pellets and nodules, phosphate sand, and euhedral apatite crystals. In addition, apatite commonly forms cement. Most phosphorites are composed dominantly of one type of grain, but contain minor, and in many cases prominent, amounts of others. The various types of phosphorite may be described by the use of adjectives depending on the prominent types of grains. Thus, pelletal phosphorite is one composed dominantly of pellets, and pelletal-oolitic phosphorite is one composed dominantly of pellets but with prominent oolites. A phosphorite composed dominantly of fossil remains is termed an organic phosphorite. The most common phosphorites—pelletal and nodular phosphorite, oolitic and pisolitic phosphorite, and organic phosphorite—are described below.

#### PELLETAL AND NODULAR PHOSPHORITES

Phosphorites that are composed dominantly of structureless grains of collophane and francolite less than 2 mm in diameter are termed pelletal phosphorite; if the constituent grains are larger than 2 mm in diameter, the rock is termed a nodular phosphorite. These grains range in color from brownish black to almost white. Pellets and nodules are generally spherical to oblate ellipsoidal in shape, but some have irregular shapes. Their shapes are made more irregular by compaction, solution, and accretion. The larger grains are, in general, better rounded than the smaller. Most pellets are composed of collophane, but francolite pellets are not uncommon. The francolite is a microcrystalline aggregate of grains oriented at random. Many pellets and nodules contain nuclei and inclusions of nonphosphatic material, generally detrital grains of quartz and muscovite and crystals of fluorite, dolomite, and calcite. Judging from the study of the Flat Creek and Fall Creek thin sections, these grains generally have unimodal size distributions and are fairly well "sorted"; however, some phosphorites have a bimodal distribution because the diagenetic solution and redeposition of apatite increases the size of larger pellets at the expense of smaller ones. This bimodal distribution is emphasized if compound grains are counted rather than the smaller pellets within the compound grains.

Pelletal or nodular phosphorite is, in general, a light to dark-colored, soft to medium-hard, thin-bedded rock commonly interbedded with mudstone and carbonate rock, and commonly stratified by alternating laminae of phosphorite containing various proportions of clastic material, carbonate, and carbonaceous matter. Most pelletal phosphorites contain minor amounts of silt and clay, but some of the richest

are associated with minor amounts of very fine to fine sand. In these slightly sandy phosphorites, the sand is generally well sorted and occurs in the matrix of the rock. Inclusions of detritus in the apatite grains are finer in size, ranging down to fine quartz and muscovite silt. Pelletal phosphorites commonly contain dolomite as a microcrystalline matrix. Fluorite occurs as void fillings.

Dark-colored pellets and organic fragments are not commonly associated. Dark pelletal phosphorites, in fact, are fairly free of admixtures of all other types of grains, except compound pellets and nodules.

#### OOLITIC AND PISOLITIC PHOSPHORITES

Oolitic phosphorite is composed dominantly of francolite or collophane grains that exhibit concentric structure and are less than 2 mm in diameter. If the constituent grains are similar but are larger than 2 mm in diameter, the rock is termed a pisolitic phosphorite. The size, shape, and roundness characteristics of these grains are similar to those of pellets and nodules. Nuclei of quartz and phosphatic fossile fragments are more common in oolites and pisolites than in pellets and nodules. The concentric structure of oolites and pisolites is shown both by alternating rings of francolite and collophane and by alternating rings of differing color. In general francolite rings, if present in a grain, are of lighter color than collophane and contain fewer inclusions of foreign material. Francolite rings are made up of fibers of francolite with the *c* crystallographic axis coincident with the long dimension of the fiber and oriented perpendicular to the circumference of the ring. The inner rings of oolites conform with irregularities of nuclei. The number of rings in oolites and pisolites ranges from 2 to about 10. The color contrast between rings varies widely so that there is a continuous series from dark pellets to oolites with mostly dark rings to oolites with mostly light rings to light pellets.

Oolitic phosphorites are commonly medium-dark, medium-hard to hard, thin- to thick-bedded rocks, commonly interbedded with pelletal phosphorites, mudstone, and carbonate rock. Most are generally only crudely laminated if at all. They generally contain minor amounts of very fine to fine sand in the matrix of the rock, and minor amounts of bioclastic apatite grains; only a few contain silt and clay. They are commonly cemented with coarse-grained calcite and have a poikiloblastic texture or are cemented with apatite. Some oolitic phosphorites contain fibrous glauconite in the matrix of the rock.

#### ORGANIC PHOSPHORITES

Organic phosphorite is composed dominantly of apatite fossil fragments. The fragments found in this study include brachiopod shells, fish scales, fish teeth, bone, bryozoans, echinoid spines, casts



of the axial canals of sponge spicules, internal casts of gastropod shells, and internal casts of the holes in bryozoans. These may be divided into three groups depending on whether the fragment is a cast or original fossil and, if it is the original fossil, whether or not it was phosphatic originally. The phosphatic brachiopod shells and fish scales, teeth, and bone were probably originally phosphatic, whereas the bryozoans and echinoid spines were originally calcium carbonate. The brachiopod shells, fish teeth, and bone are now composed of francolite, whereas the other types are usually collophane. Fossil fragments range in shape from angular to well-rounded grains and in size from much larger than the quartz detritus to slightly smaller.

Organic phosphorites are generally medium-dark to light-colored, medium hard to hard, thin-bedded rocks showing sharp and irregular contacts with the beds below. They are commonly interbedded with chert, oolitic phosphate, and sandstone, but they show little lamination in thin section. The bioclastic fragments, if elongate or tabular, are usually oriented with the long axis parallel to the bedding. They generally contain minor amounts of very fine to fine sand. Glauconite is not uncommon in the matrix as grains. Most organic phosphorites contain at least minor amounts of oolites.

#### MISCELLANEOUS APATITE GRAINS

Grains of apatite consisting of an aggregate of smaller oolites or pellets cemented by apatite are termed compound pellets if less than 2 mm in diameter, and a compound nodule if larger. Such nodules and pellets are common in the phosphorites. The cement can be either francolite or collophane and generally is lighter in color than the cemented apatite grains. Compound grains range from spherical to irregular.

Many, if not most, of the sandstones in the Phosphoria contain grains of apatite which are slightly smaller than the quartz grains and are generally better rounded. It seems likely that they were transported and deposited with the quartz grains and thus are best classed as apatite sand grains, regardless of whether they are oolites, pellets, or fossil fragments.

Minute euhedral apatite tablets are found in some of the chert beds of the Phosphoria. They are generally disseminated throughout the rock but are somewhat concentrated in the phosphatic casts of axial canals of sponge spicules. These crystals are minor in occurrence and have not been found to make up more than 1 percent of the rock.

#### CHERT

Chert in the Phosphoria is composed of three different lithologic types: dark bedded chert, light-colored nodular and concretionary chert, and a chert made up of tubular concretions, 0.5-1.5 feet long

and several inches in diameter. These tubular concretions are usually oriented parallel with one another and at an oblique angle to the bedding. They commonly are composed of conical, concentric layers. They occur in matrices of sandstone and carbonate rock, but in places make up all of individual beds. Petrographically, no distinct differences can be seen between bedded, nodular, and tubular chert. However, all gradations may be found between chert fairly rich in carbonaceous matter, which outlines relict sponge spicules, and white chert recrystallized to spherulites (a roughly spherical structure of radially arranged fibers) up to 0.25 mm in diameter, which contains no carbonaceous matter and no relict sponge spicules. In general, the more coarsely crystalline cherts are lighter colored, which is caused mostly by the smaller amount of carbonaceous matter and in part by the coarser grain size. Some of the relict sponge spicules are shown by slightly more coarsely crystalline chalcedony than the matrix chalcedony. The extent to which cherts are formed of sponge spicules is unknown. E. R. Cressman (oral communication, 1954) has found that much of the chert in the Phosphoria in Montana is composed of sponge spicules. In Wyoming, many of the cherts studied contain prominent spicules and many of those that do not contain spicules have been recrystallized, judging from the abundance of spherulites and coarse crystalloblastic texture.

Some of the cherts show a globular texture similar to that of the spherulitic opal reported by Bramlette (1946) from the Monterey formation.

Many of the spherulites and circular sections of sponge spicules in chert under crossed nicols resemble negative uniaxial crosses; whereas others, especially the larger spherulites, show positive crosses, as would be expected if the quartz grew with the *c* crystallographic axis of the quartz fibers oriented radially from a nucleus.

Quartz silt and sand and accessory detrital grains are found in most cherts. In general, the cherts that contain larger spicules contain coarser detrital quartz, which shows that the spicules were sorted before deposition. Many of the quartz grains show spongy overgrowths. Dolomite rhombs are generally scattered throughout chert and make up a prominent part of some of them. Both glauconite and euhedral pyrite cubes occur in cherts but were not found together. Apatite in chert generally consists of fossil fragments, well-rounded sand grains, phosphatic casts of axial canals of sponge spicules, or euhedral apatite tablets.

#### CARBONATE ROCK

The carbonate rock of the Phosphoria formation in the area of the report comprises a wide range of lithologic types. The two most com-

mon types are medium-hard, dark-colored, thin-bedded dolomite and hard, medium-gray to light-colored, massive limestone.

The dark dolomites are commonly interbedded with pelletal and oolitic phosphorite, siltstone, and claystone. They are generally homogeneous, but some are stratified by alternating laminae containing various amounts of sand and silt. They are composed of cryptocrystalline to finely crystalline dolomite crystals, which range from anhedral grains to euhedral rhombs. Commonly, porphyroblastic rhombs of dolomite, consisting of a core of dolomite with many inclusions of carbonaceous matter and rims of clear dolomite, occur in a matrix of microcrystalline dolomite. Euhedral pyrite cubes are common, and the dolomite generally contains important quantities of carbonaceous matter both as inclusions and as crusts around dolomite grains. Apatite pellets are common in dark dolomites.

The light-colored limestones generally are interbedded with sandstone and chert and have a heterogeneous texture due to scattered fossil fragments. They are generally composed of finely to medium crystalline anhedral calcite grains which give the rock a mosaic texture. They generally contain very fine to medium, etched quartz sand grains, apatite fossil fragments, and grains of glauconite.

#### MUDSTONE

Mudstone in the Phosphoria in the area of the report is generally soft to medium-hard, dark- to medium-gray, and fissile to thin-bedded rock composed of quartz and clay detritus. The grains range from silt-sized to clay-sized particles. Quartz silt is universally associated with flakes of muscovite in about a 20-to-1 ratio. Carbonaceous matter and pyrite are prominent in some mudstones and occur in minor amounts in most. Collophane pellets are commonly in laminae in mudstone.

#### SANDSTONE

Sandstone in the Phosphoria is generally a medium-hard to hard, medium- to light-gray, thin- to thick-bedded and commonly cross-bedded rock. The sandstones show a wide range of sorting. Well-sorted sandstones are composed of medium well rounded quartz grains and minor amounts of accessory detrital grains such as feldspar, tourmaline, glauconite, and chert, and varying amounts of apatite grains. They commonly are cemented by calcite or dolomite. The poorly sorted sandstones from Fall Creek and Flat Creek contain large quantities of chert, phosphorite, and carbonate rock grains, admixed with quartz grains. The matrix of poorly sorted sandstones is commonly dolomite or silty clay. The larger grains are better rounded than smaller quartz grains.

## CONCLUSIONS

Several generalizations, which shed some light on the sedimentation and diagenesis of the rocks of the formation, can be made as the result of this study.

## SEDIMENTATION

Laminations that reflect compositional and textural differences are quite common in rocks containing various amounts of argillaceous material. They are several millimeters thick and are found in mudstone, argillaceous pelletal phosphorite, some argillaceous oolitic phosphorite, argillaceous dolomite rich in carbonaceous matter, and argillaceous chert. On the other hand, sandstone, some sandy oolitic phosphorite, sandy organic phosphorite, light-colored sandy carbonate rock, and sandy chert generally do not show such lamination.

The laminated rocks, most common in the geosynclinal assemblage, were deposited under a current action quiet enough not to mix up bottom sediment and destroy the lamination. Platform rocks, on the other hand, tend to be massive and cross bedded and were deposited under somewhat turbulent current action.

The field observations that sandstone is associated with light-colored carbonate rock and some chert, and that mudstone is associated with some chert, phosphorite, and dark-colored carbonate rock, are substantiated by petrographic study. This association is manifested by both interbedding and admixture. An important exception to this is the occurrence of very fine to fine sand in the matrix of otherwise pure phosphorite. E. R. Cressman, who studied the Phosphoria in Montana, and the author separately came to the conclusion that this association was probably due to the winnowing out of mud from phosphatic sediments. The original presence of this mud is indicated by silt and clay inclusions in apatite grains. A very small percentage of the mud originally consisted of sand grains too large to be winnowed out by currents and, thereby, left intermixed with the apatite grains. The concentration of apatite to form phosphorites is therefore probably mainly due to three causes: (1) a small supply of clastic material (Kazakov, 1937), (2) the winnowing out of what fine-grained clastic material might have been deposited with the apatite, and (3) a physical-chemical environment in which apatite is stable and other major chemical rock constituents are not (W. W. Rubey, oral communication).

Cressman (oral communication) has concluded that the concentration of sponge spicules to form chert is also probably due in part to the winnowing out of fine-grained clastic material from a sediment containing larger sponge spicules.

The stratigraphic position of poorly sorted sandstones gives a clue to its possible sedimentation. They most commonly lie between

chert zones and light-colored carbonate rock and well-sorted sandstone zones. If, as is discussed later, the chert is deposited in deeper water than the carbonate rock, the poorly sorted sand is the first sandstone to be deposited in a shelving basin or the last to be deposited in a deepening basin. The sand probably was dumped into the deeper water by abnormal currents and not winnowed sufficiently to yield well-sorted sand.

#### DIAGENESIS

The sediments of the Phosphoria have been appreciably affected during diagenesis. Solution, deposition, and recrystallization have been particularly important.

The diagenetic solution of collophane is shown by stylolites and by the interfering relations between pellets and oolites. It is evident that much of the silica has also moved during diagenesis. Solution has occurred as shown by stylolites in chert and the replacement of chert by carbonate.

The diagenetic deposition of phosphate is shown by several features. Phosphate is deposited around pellets, in some cases, which causes the development of a mosaic texture. Apatite is also deposited as a simple cement in many rocks, and in one limestone collophane was deposited in a vug. Several generations of phosphatic cement can be recognized in some rocks, owing to color variation or collophane-francolite differences. The cement is generally lighter in color than the cemented apatite grains. The diagenetic deposition of apatite is further shown by a siltstone from Fall Creek. The siltstone contains many muscovite flakes oriented parallel to the bedding. Spherical nodules of phosphatic siltstone up to 5 mm in diameter are scattered throughout the rock and differ from the surrounding rock only by the presence of collophane cement. Flakes of mica within the nodules are also oriented parallel to the bedding. Thus the formation of nodules did not disturb the mica flakes and must have occurred after sedimentation and compaction.

Deposition of silica is shown by the overgrowths of quartz on quartz detritus and the silicification of fossils. Chert nodules are generally found in light-colored limestone and differ little from the rest of the rock except for the replacement of microcrystalline matrix calcite with chert and the presence of relict sponge spicules. Apparently sponge spicules were deposited throughout these rocks and the silica subsequently dissolved and was redeposited to form nodules or, less commonly, euhedral quartz crystals.

There is abundant evidence for the diagenetic recrystallization of light-colored chert, carbonate rock, and phosphorite. Porphyroblastic textures are common in dolomite and chert.

Diagenetic recrystallization of apatite to form euhedral or micro-

crystalline apatite is an important process in the formation of phosphorites. Lowell (1952) has suggested that the francolite rings in oolites are formed by recrystallization of collophane. The francolite rings are generally lighter in color than collophane rings, suggesting that a ring containing little carbonaceous matter might recrystallize more easily than one containing much carbonaceous matter. Sander (1951, p. 115-119) described laminated dolomite, rich in carbonaceous matter, from the Hauptdolomite in the Marienberg Alps. The lamination is due primarily to the variation in carbonaceous matter, and the laminae richer in carbonaceous matter are finer grained. Sander ascribed this possibly to the cessation of grain growth due to the bituminous intergranular films. Work on metamorphic rocks has shown that the fine grain size of some phyllites and schist associated with coarser-grained schists is correlative with finely divided carbonaceous material or graphite (Eskola, 1927, 1935; Gevers, 1937). It seems likely that the enlargement of crystalloblasts in some of the sediments of the Phosphoria has been impeded by films of carbonaceous matter. Thus, original sediments that were similar, but contained different amounts of carbonaceous matter, have given rise to rocks which texturally are quite dissimilar.

## DESCRIPTION AND AREAL VARIATION OF STRATIGRAPHIC UNITS

### UNIT A

Unit A, the lowermost unit of the Phosphoria formation in northwestern Wyoming, is composed of variable proportions of carbonate rock, chert, and sandstone. In the southwestern part of the area the unit grades into calcareous and slightly phosphatic mudstone. To the north the unit pinches out. Its thickness in the area ranges from a few inches to 60 feet; the maximum thickness occurs in the southeastern part of the area.

In the eastern part of the area beds of unit A lie disconformably on the Tensleep sandstone. The pre-Phosphoria erosion surface is widespread in central Wyoming<sup>4</sup> (pls. 9-11, 13). Five feet of local relief on this erosion surface was measured at Bull Lake (Branson, 1939). The erosion surface becomes less prominent toward the west. At the Flat Creek and Gros Ventre localities a lenticular conglomerate of chert pebbles several inches thick (too thin to be shown on plate 10) lies on an erosion surface which has a few inches of relief. To the west and south of Flat Creek no erosion surface has been noted. The base of unit A there is placed at the lithologic break between beds of chert and carbonate rock and beds of sandstone and sandy carbonate rock.

<sup>4</sup> Thomas, H. D., talk given at the seventh annual field conference of the Wyoming Geological Association, 1952.

The top of unit *A* is best defined as the base of unit *B*, discussed below.

In the southwestern part of the area, at Fall Creek and Bear Creek (pl. 12), beds of calcareous mudstone at the base of the formation probably are equivalent to unit *A*. The sandy cherty carbonate rock below constitutes the upper member of the Wells formation and is underlain by the middle sandstone member of the Wells formation. At Middle Piney Lake (pl. 11) and at Steer Creek (pl. 12), unit *A* of the Phosphoria formation lies directly on the sandstone member of the Wells formation; thus the upper unit of the Wells probably pinches out eastward and does not grade into unit *A*. Stated another way, beds of unit *A* seem to grade westward into and be equivalent to mudstones at the base of unit *B* and to have no correlatives in the Wells formation.

Unit *A* seems to grade from chert to carbonate rock between Middle Piney Lake and the General Petroleum Company's Lakeridge 1 well and farther to the east is composed dominantly of carbonate rock. Thus, unit *A* and equivalent strata at the base of unit *B* show a calcareous mudstone facies in the western part of the area, a chert or cherty carbonate rock facies in the central part, and a sandy carbonate rock facies in the eastern part.

#### UNIT *B*

Unit *B* overlies unit *A* in the central portion of the area, but in both the north and southwest it is the lowermost unit of the Phosphoria formation. The unit thins from about 60 feet in the southwest portion of the area to a few inches on the northeast flank of the Wind River Range, and pinches out entirely northeastward (fig. 13).

In the southwest part of the area dark mudstone beds, which grade eastward into unit *A*, mark the base of unit *B*. In the central portion the lower contact of unit *B* is placed below a widespread basal medium dark oolitic and nodular phosphorite. Northeastward this bed grades into phosphatic sandstone which rests directly on the Tensleep sandstone. This basal phosphatic bed is unique in lithologic character and it has been used as a key bed in the regional correlation.

In the western part of the area an organic phosphorite marks the top of unit *B* (pl. 12); it consists of white tablets of phosphatic fish scales and brachiopod shell fragments in a dark phosphatic matrix. Farther east—at Flat Creek, for example—the upper beds of unit *B* grade into chert; the top of unit *B* there is placed on the gross lithologic break between mudstone and chert. Still farther to the east the top of unit *B* is placed at the top of the phosphatic sandstone, which constitutes all of unit *B* in that area.

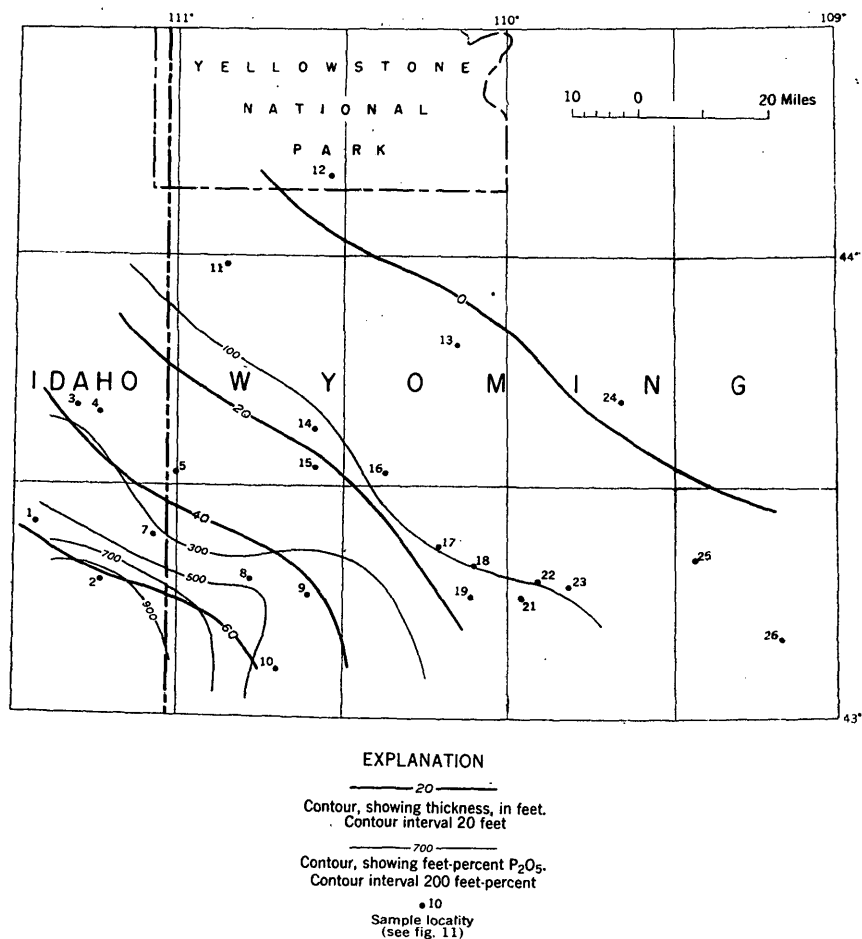


FIGURE 13.—Isopach map of unit *B* of the Phosphoria formation in northwestern Wyoming, showing areal variation in foot-percent  $P_2O_5$ .

Unit *B* is composed mainly of clay and quartz silt. The relative sand content increases northward and eastward, and in the Wind River Mountains it makes up nearly all the clastic portion of the rocks.

The phosphate content of unit *B* changes over the area. The total phosphate content decreases from 900 feet-percent of  $P_2O_5$  in the southwestern part of the area to zero feet-percent in the northeastern part (fig. 13). A petrographic change in the phosphorite accompanies this decrease in phosphate content. In the southwestern part of the area, the phosphatic material is dominantly pelletal; in the central part, oolitic and nodular; and in the eastern part, organic. Organic phosphorite shows greater variations in thickness over the area than the other types. For example, at Bear Creek (pl. 12), 12 feet of organic



phosphorite lies at the top of unit *B*. Fourteen miles to the northwest at Fall Creek and ten miles to the northeast at trench *H* this bed is only about two feet thick.

The vertical distribution of phosphorite in unit *B* also changes over the area. In the eastern part, a bed of sandy phosphorite comprises the entire unit; in the central part, phosphorite occurs only at the base of the unit and is overlain by mudstone; in the southwestern part, beds of phosphorite are intercalated with mudstone beds throughout the unit, and, where this is the case, the petrographic types of phosphorite have a roughly symmetrical distribution. Pelletal phosphorite, which usually makes up the major part of the phosphorite of the unit, occurs in the central part of the unit. Above and below are beds of oolitic phosphorite, and at the top and bottom of the unit usually are organic and nodular phosphorite. Thus, the four types of phosphorite show the same vertical sequence that occurs laterally. V. E. McKelvey (oral communication, 1950) first noticed this type of symmetry in the phosphatic shale member, the correlative of unit *B* in southeastern Idaho.

In the southeastern part of the area carbonaceous material is a prominent constituent of unit *B*. Although very few chemical analyses have been made, the value <sup>5</sup> or darkness of the rock may serve as a rough index of the abundance of carbonaceous matter in the absence of better data (Patnode, 1941). Eastward the unit is lighter in color and may therefore be assumed to be less carbonaceous.

Iron minerals in unit *B* consist of disseminated pyrite in the southwestern part of the area, nodular pyrite in the central part, and glauconite in the eastern part. If, as seems likely (Thomas, 1934; Tourtelot, 1952), the lower portion of the Phosphoria formation grades into red beds east of the area, hematite would represent the easternmost facies of the iron minerals.

In the southwestern part of the area, at Fall Creek and Bear Creek, beds of dark carbonate rock are intercalated with mudstone and phosphorite beds. At Hoback and Buck Creek, carbonate concretions several feet in diameter are found at the same horizon. Further to the east, in the Gros Ventre Range, little carbonate rock is present in unit *B*.

#### UNIT C

Unit *C* overlies unit *B* and is present over all of the area of the report. The unit thickens from less than 75 feet in the north to 150 feet in the southwestern part of the area and to 125 feet in the southeastern part (fig. 14). The unit is composed of various amounts of interbedded chert, carbonate rock, and sandstone, as well as a

<sup>5</sup> Value, chroma, and hue components of color are those used in the Munsell color chart.

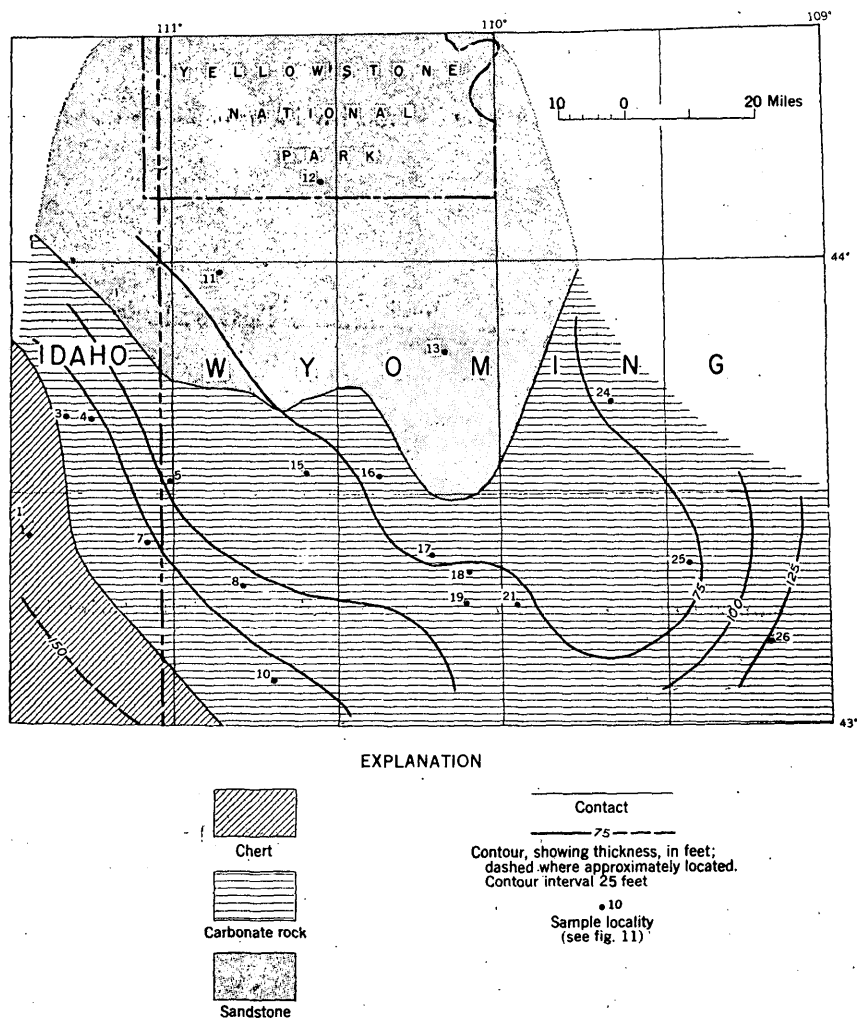


FIGURE 14.—Isopach map of unit *C* of the Phosphoria formation in northwestern Wyoming, showing areal variation in dominant rock types. The dominant lithologic character of unit *C* at each locality was computed by totaling the feet-percent of each component; i. e. the thickness of each bed was multiplied by the estimated percentage of each component in the bed. Isopach maps were then constructed for each component and superimposed to give the dominant lithologic character throughout the field.

few thin intercalated beds of phosphorite and mudstone. In the north, where the unit is less than 75 feet thick, it is composed dominantly of sandstone. In the southwest, where it is thickest, it is composed dominantly of chert. In the rest of the area it is composed dominantly of carbonate rock (fig. 14).

The lower contact of unit *C*, as was discussed above, is placed at the lithologic break between mudstone of unit *B* and chert of unit *C*. In the southwestern part of the area, the base is marked by a

key bed of organic phosphorite at the top of unit *B*. The upper contact of unit *C* is best defined by the lowermost bed of unit *D*, which is discussed later.

The proportion of clastic material in unit *C* increases northward (fig. 15). Corresponding to this change, the proportion of sand in the clastic fraction also increases northward (fig. 15). The total amount of chert in the unit decreases from about 6,000 feet-percent in the southwest to about 1,000 feet-percent in the northeast (fig. 16). The total amount of carbonate rock decreases northward from about 7,000 feet-percent to about 1,000 feet-percent and southwestward to about 3,800 feet-percent (fig. 17).

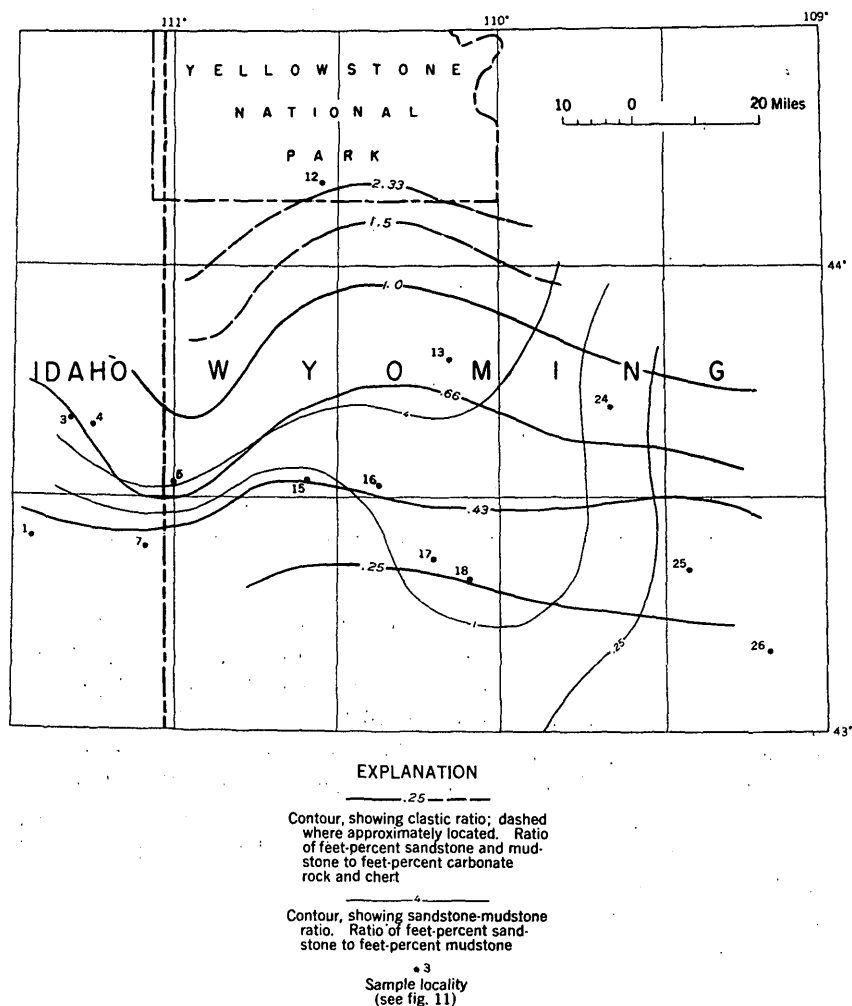


FIGURE 15.—Clastic ratios and sandstone-mudstone ratios of unit *C* of the Phosphoria formation in northwestern Wyoming.

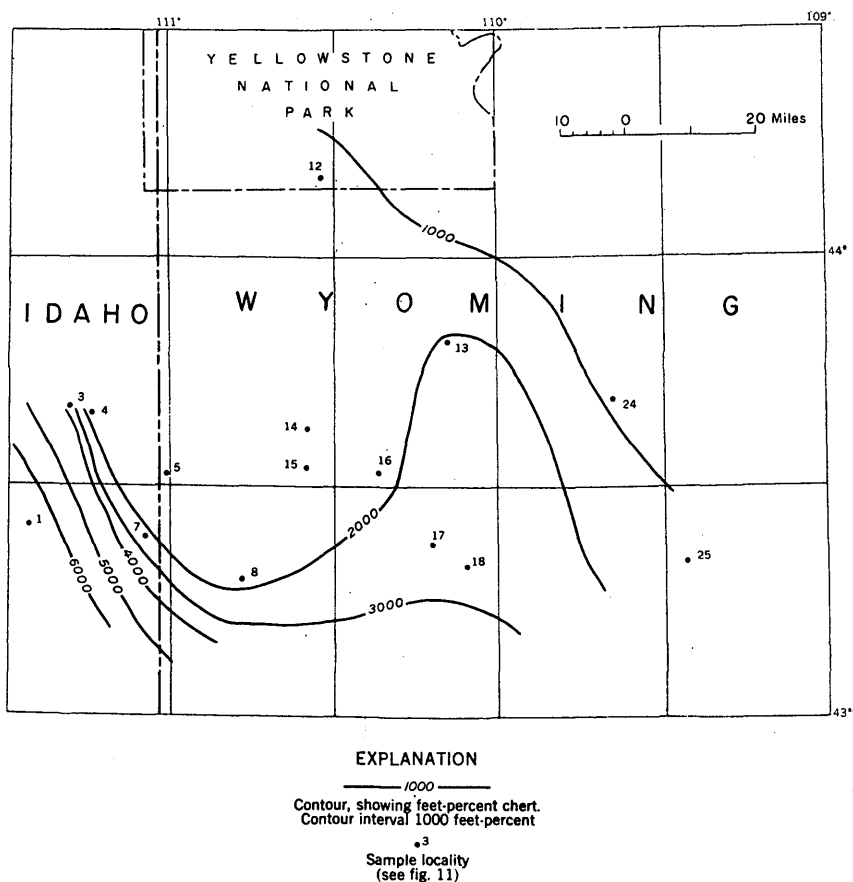


FIGURE 16.—Areal variation in feet-percent chert in unit *C* of the Phosphoria formation in northwestern Wyoming.

These variations are caused both by interfingering and intergradation of rock types and by thinning of individual beds. Chert beds at the base and at the top of unit *C* at Fall Creek, in the southeastern part of the area, interfinger with the beds of sandstone in the northeast (pl. 10). Similarly, chert at the base of the unit at Lakeridge 1 well interfingers with beds of sandstone at Tosi Creek in the northeast (pl. 11). Unit *C* at Red Creek in the northeastern part of the area is dominantly made up of sandstone and chert (pl. 13). These beds of sandstone grade into carbonate rock in the southeast at Burroughs Creek (pl. 13).

The chert of unit *C* is composed of three different lithologic types, which may be found at most localities. However, the proportions among these types of chert vary over the area. In the southwest, the most common type is dark bedded chert. In the east and north,

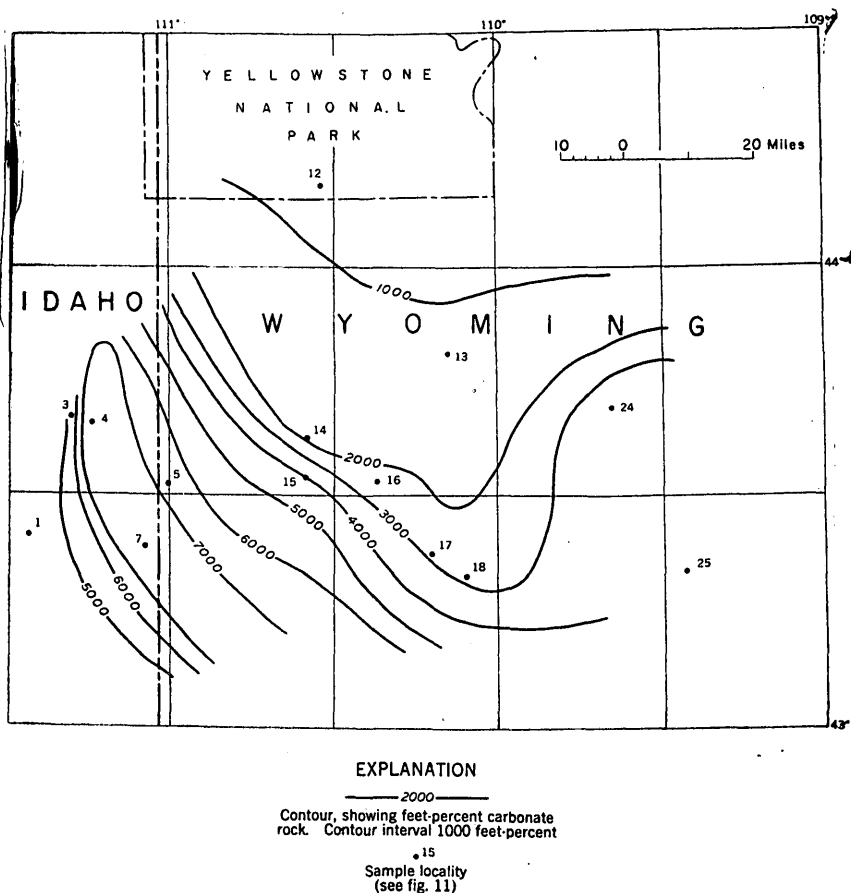


FIGURE 17.—Areal variation in feet-percent carbonate rock in unit *C* of the Phosphoria formation in north-western Wyoming.

light-colored, nodular, and concretionary chert is more common. At the easternmost and northernmost trenches, the chert is dominantly made up of tubular concretions.

The carbonate rock of unit *C* is fairly constant lithologically over the area. It is generally light-colored fine- to medium-grained crystalline limestone. In the southwest, however, the carbonate rock in the unit is darker in color. Brachiopods and bryozoa are common in many of these beds.

The sandstone of unit *C* is also fairly constant lithologically over the area. At Flat Creek the lowermost sand of the unit is poorly sorted, whereas the stratigraphically higher sandstones in the unit are well sorted. The sandstones contain minor quantities of organic and light-colored pelletal apatite grains, and several thin beds of sandy organic phosphorite are intercalated in the unit.

The core of General Petroleum's Lakeridge 1 well contains a bed of anhydritic dolomite about 6 feet thick near the center of unit *C*. The anhydritic dolomite overlies a sandy carbonate rock. About 25 feet of core immediately above the bed is missing, and the next known bed above is a calcareous sandstone. At the surface exposure of the Phosphoria at Middle Piney Lake, nine miles to the west of Lakeridge 1 well, a 2-foot covered zone below a porous carbonate rock unit possibly represents this anhydritic bed.

The sequence of rocks in unit *C* suggests a symmetry about the center of unit *C*. At Fall Creek (pl. 10), beds of chert occur at both the bottom and top of the unit, separated by beds of carbonate rock. Similarly at Cottonwood Creek, unit *C* is made up from base to top of a chert zone, a carbonate rock zone, and an interbedded chert and sandstone zone. In the eastern part of the area, the upper chert zone is not present at all localities although the lower two zones are recognized everywhere.

Vertical sequence of the petrologic types of chert also suggests a symmetry about the center of the unit. In general, dark-bedded chert occurs at the bottom of unit *C* and is overlain by light-colored nodular chert. Tubular chert bodies occur above this and usually are found in a carbonate rock matrix within the carbonate rock zone. In the southwestern part of the area, the upper chert zone, where it is developed, is composed of dark bedded chert. In the central and eastern part of the area, dark bedded chert is not found in unit *C*.

#### UNIT *D*

Unit *D* overlies unit *C* in the area of the report; it is composed of black mudstone and a few intercalated beds of phosphorite and dolomite. The unit thickens from a few feet in the southwestern part of the area to a maximum of 60 feet in the Wind River Range. Northwest of the Wind River Range the unit thins and pinches out (fig. 18).

The base of unit *D* over the whole area is marked by a widespread dark nodular phosphorite that generally contains small amounts of phosphatic fossil remains, such as sharks' teeth and fish scales. At many localities this bed is underlain either by carbonate rock or by sandstone containing fragments of light-colored phosphatic fossils, and it is generally overlain by black fissile mudstone.

In the southwestern part of the area, the top of unit *D* marks the top of the formation. The boundary is placed at the sharp break between the uppermost dark beds of unit *D* and the lowermost beds of buff to tan thin-bedded calcareous siltstone of the Dinwoody formation. Eastward and northeastward the upper beds of mudstone of unit *D* grade into beds of chert (pls. 10, 11) which make up unit *E*;

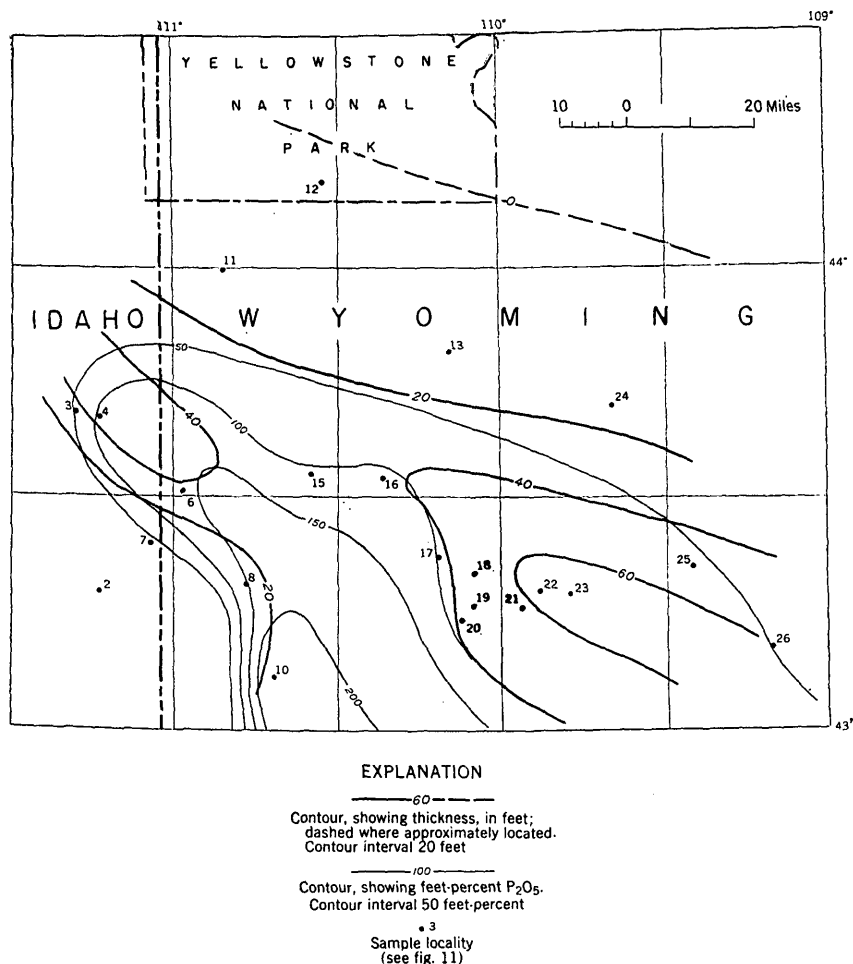


FIGURE 18.—Isopach map of unit *D* of the Phosphoria formation in northwestern Wyoming, showing areal variation in feet-percent  $P_2O_5$ .

where this is the case, the upper contact of unit *D* is placed at the boundary between the dark mudstone of unit *D* and the chert of unit *E*. At most places this contact is gradational; thin beds of chert appear in the upper part of unit *D*, and the interbeds of mudstone disappear in the lower part of unit *E*. Farther to the northeast, the black fissile mudstone that overlies the basal phosphorite grades into chert. Where this is the case the phosphorite wholly composes unit *D* and the upper boundary is sharp.

Unit *D* is composed dominantly of fissile black mudstone made up of clay and quartz silt. Several thin beds of hard dark microcrystalline dolomite are intercalated in the unit and apparently are fairly widespread.

In the southwestern part of the area, thin beds of phosphorite are intercalated throughout the unit. In the northeast, however, phosphorite occurs only at the base, though several phosphatic mudstones occur higher in the unit. The phosphorite changes in character over the area. Pelletal phosphorite is dominant in most of the southwestern part, whereas in the extreme southwest, where the unit is thin, nodular phosphorite is dominant. Nodular phosphorite is also dominant in the eastern and northeastern part of the area.

A systematic vertical distribution of the phosphorite occurs within unit *D* and a part of unit *C*. The uppermost beds of unit *C* are composed of sandstone or carbonate rock containing organic phosphate grains. The lowermost bed in unit *D* is nodular phosphorite. Pelletal phosphatic mudstone beds occur within unit *D*.

Organic material and pyrite are abundant in the southwestern part of the area and decrease eastward. On the east flank of the Wind River Mountains, the mudstones of unit *D* are greenish, possibly owing to the presence of glauconite and the scarcity of organic matter.

#### UNIT *E*

Unit *E* forms the uppermost part of the Phosphoria formation in the central and eastern part of the area but is absent in the southwestern part. It is composed dominantly of chert, carbonate rock, and sandstone. The unit has a maximum thickness of about 100 feet in the Gros Ventre and Teton Ranges and thins northeastward to less than 50 feet (fig. 19). Toward the southwest, the unit thins; its lower chert beds grade into mudstone and are included in unit *D*.

The base of the unit, discussed above, is placed at the boundary between mudstone below and chert above. Where unit *E* is present, its upper contact is also the upper contact of the formation. The contact is placed at the break between the gray chert, light-colored carbonate rock, or sandstone of unit *E* (fig. 20) and the basal, buff to tan thin-bedded calcareous siltstone of the Dinwoody formation. In western Wyoming, Newell and Kummel (1942) have divided the Dinwoody into three units which, from base to top, are: the basal siltstone, the *Lingula* zone, and the *Claraia* zone. They postulate overlap of the upper beds over the lower to the east and suggest, therefore, that the Dinwoody unconformably overlies the Phosphoria in the eastern part of the area. There is no stratigraphic evidence for an erosion surface at the top of the Phosphoria in the area of this report. The lithologic character of the uppermost beds of the Phosphoria formation varies over the area. In the north, the uppermost bed is sandstone, which grades southeastward into carbonate rock. The carbonate rock and the lower beds of sandstone grade westward into chert, and the chert



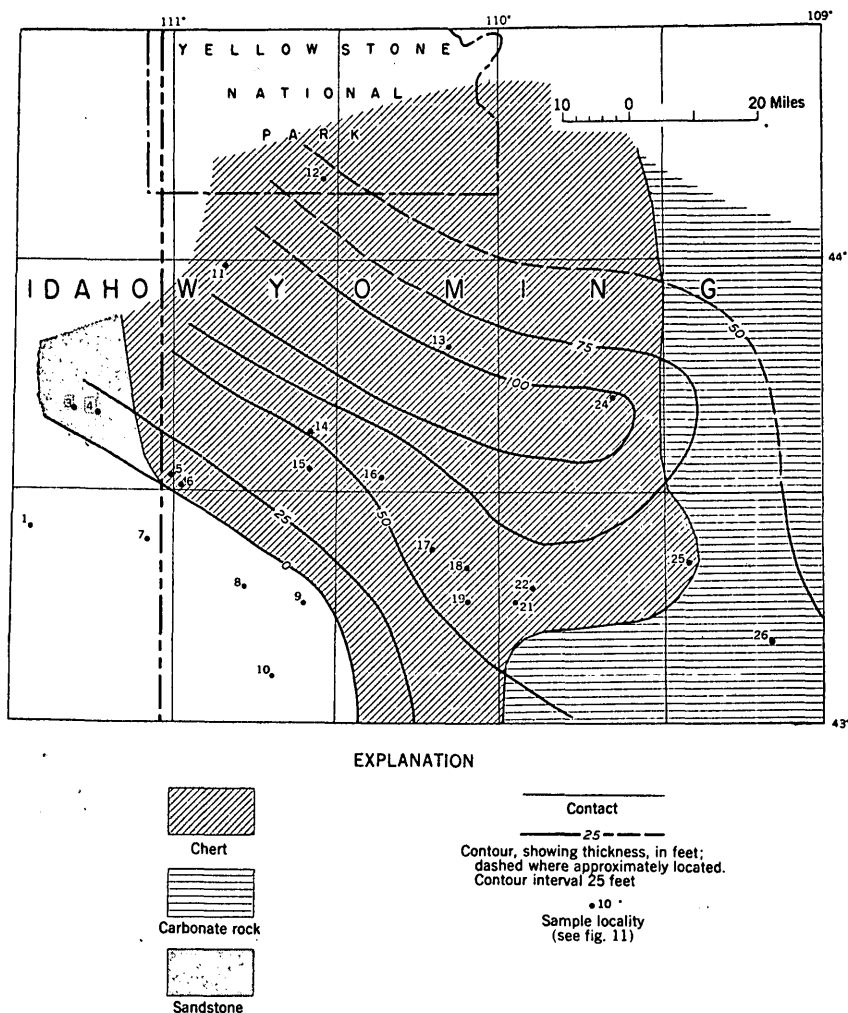


FIGURE 19.—Isopach map of unit *E* of the Phosphoria formation in northwestern Wyoming, showing areal variation in dominant rock types.

grades westward into phosphatic mudstone of unit *D* (fig. 20). As discussed more fully later, the lithologic variation in the uppermost bed of the formation is probably due to facies change rather than erosional truncation.

Unit *E* is composed dominantly of chert over most of the area. The total amount of chert in unit *E* increases from none in the southwest to about 4,500 feet-percent in the northern part of the area, and to about 1,800 feet-percent of chert in the southeastern part (fig. 21). The chert beds occur at the base of the unit; except in the Wyoming Range, they are overlain by beds composed dominantly of sandstone in the north and carbonate rock in the southeast (fig. 20). In the eastern

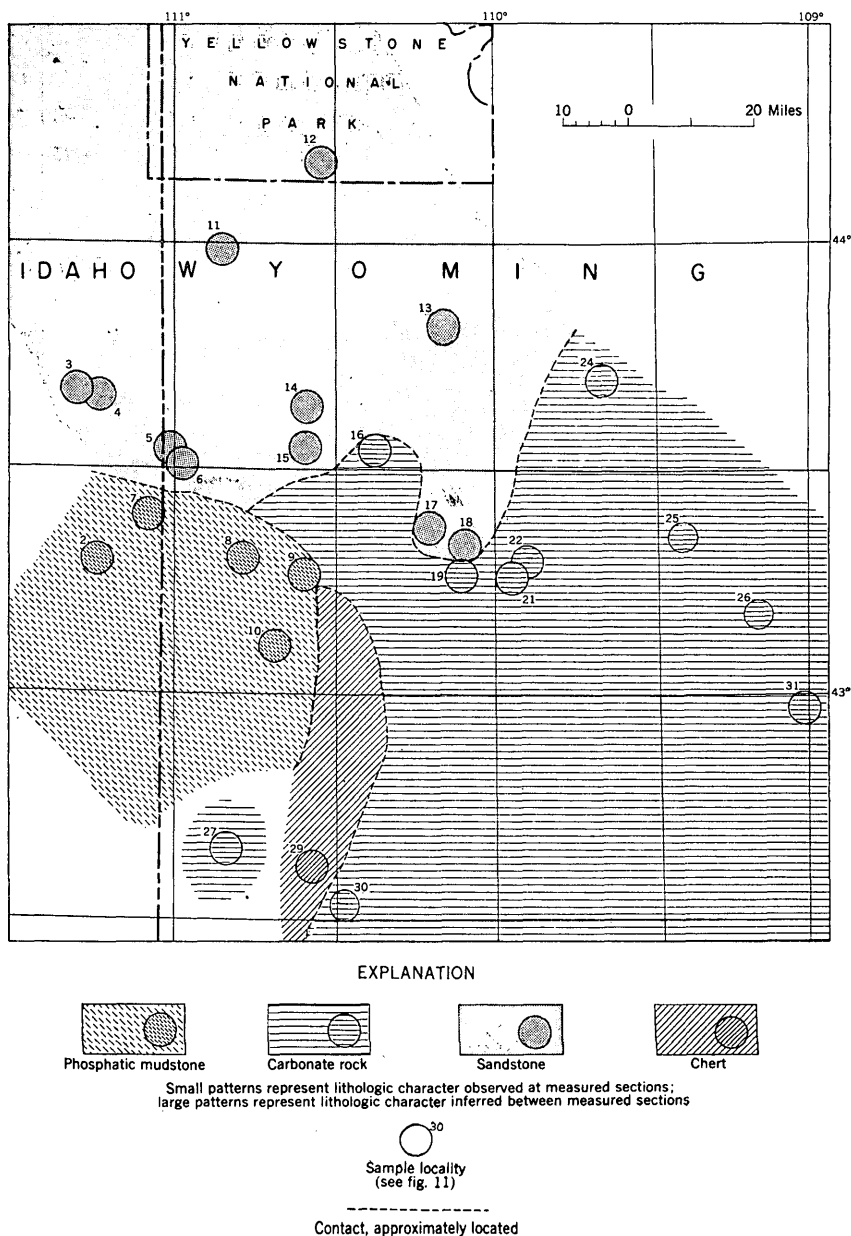


FIGURE 20.—Dominant lithologic character of the uppermost bed of the Phosphoria formation in northwestern Wyoming.

part of the area, the unit is composed dominantly of carbonate rock. The total amount of carbonate rock increases eastward from none in the west to 4,500 feet-percent carbonate rock in the east (fig. 22). The proportion of clastic material in the unit increases northwestward,

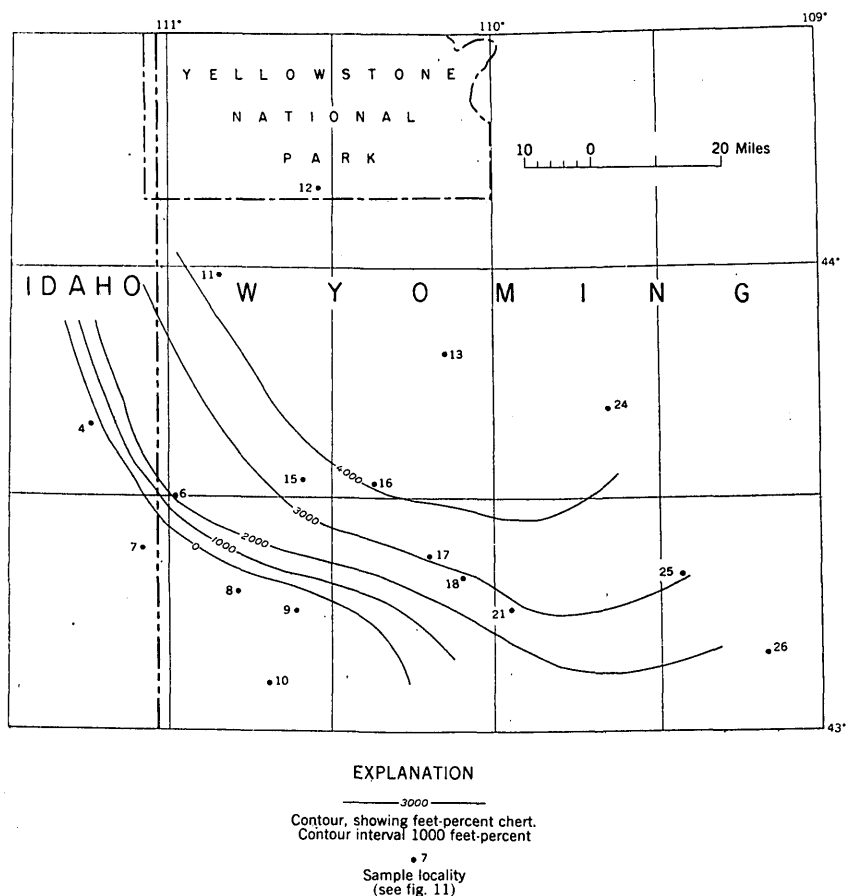


FIGURE 21.—Areal variation in feet-percent chert in unit *E* of the Phosphoria formation in northwestern Wyoming.

and the proportion of sand in the clastic fraction increases northward correspondingly (fig. 23). At the extreme west (fig. 19) unit *E* is composed of a thin bed of sandstone, which is correlative with the uppermost beds of sandstone at the top of the unit to the east. This sandstone offlaps the rest of unit *E*.

The chert of unit *E* is composed of three different lithologic types, which are identical to those contained in unit *C*. The proportions between these types of chert vary over the area. The southwestern edge of unit *E* contains only bedded chert. Tubular chert overlies the bedded chert in the northeast and is dominant in the central part of the area. Concretionary and nodular chert is present in unit *E* but is dominant nowhere. The carbonate rock and sandstone of unit *E* are similar to those of unit *C*.

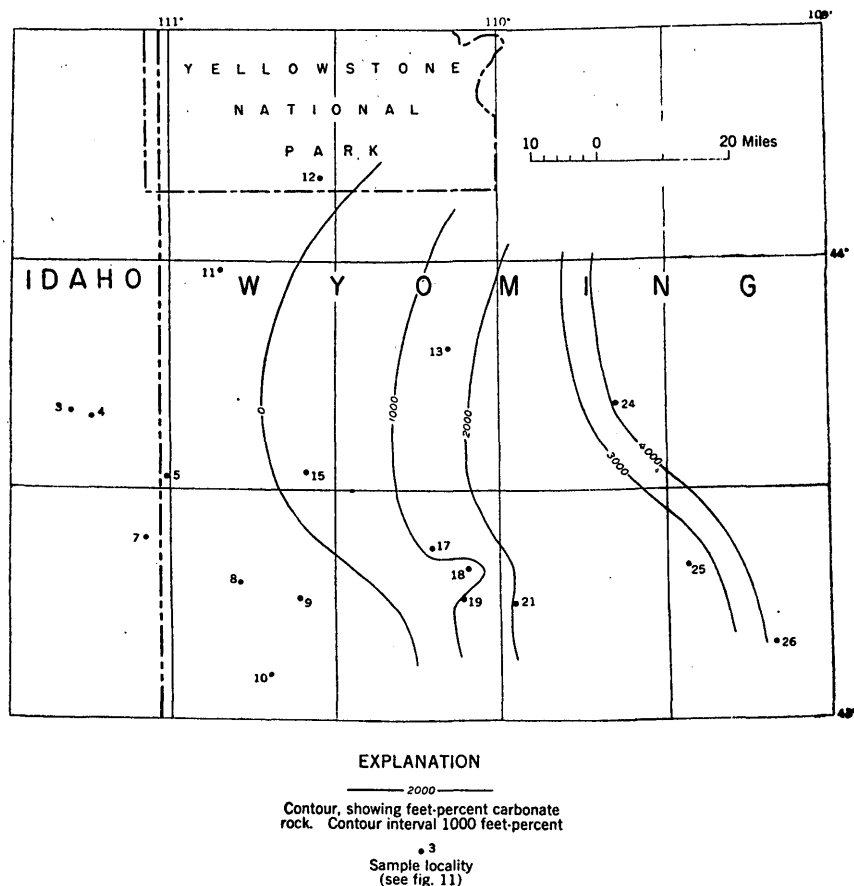


FIGURE 22.—Areal variation in feet-percent carbonate rock in unit *E* of the Phosphoria formation in northwestern Wyoming.

The sequence of rocks in unit *E* is also similar to that in unit *C*, except that no chert zone occurs at the top of the unit. The carbonate rock and sandstone, where present, overlie the chert, the lowermost bed of sandstone being more poorly sorted than the overlying sandstone beds at Flat Creek. The sequence of types of chert is also similar to that in unit *C*.

#### SUMMARY OF STRATIGRAPHIC RELATIONS

The rocks of the Phosphoria formation may be grouped into rock suites whose members show persistent associations. Kazakov (1937) observed that bedded pelletal phosphorite and dark carbonate rock are commonly associated; that nodular phosphorite, sandstone, and glauconite are associated; and that the bedded phosphorite suite commonly grades landward into the nodular phosphorite suite. Mc-

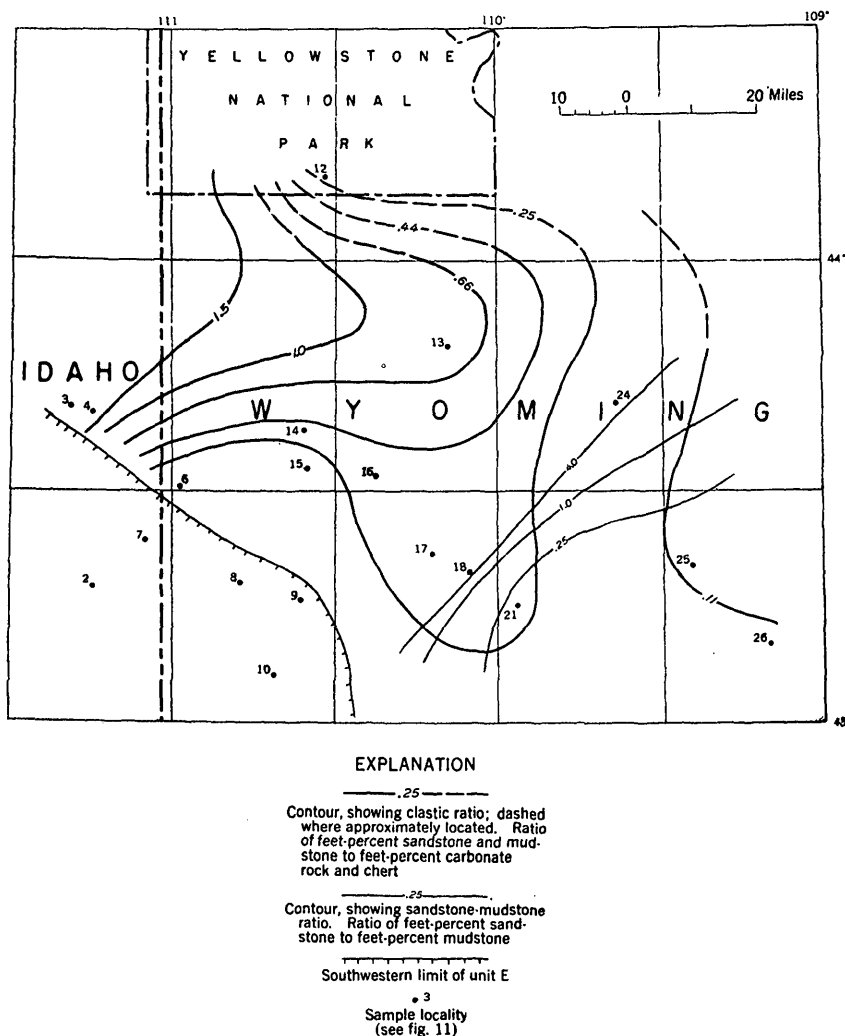


FIGURE 23.—Clastic ratios and sandstone-mudstone ratios of unit *E* of the Phosphoria formation in northwestern Wyoming.

Kelvey (McKelvey and others, 1953) noted that bedded chert and carbonaceous mudstone were other members of the bedded phosphorite suite, and that in the Phosphoria formation the nodular phosphorite suite graded landward into a red bed suite whose members include red beds, carbonate rock, and anhydrite.

In northwestern Wyoming these three rock suites are synchronous lateral equivalents, and where they interfinger an ordered depositional sequence is observed that is analogous to the detailed lateral sequence. These relations are discussed below.

## CYCLICAL ROCK SEQUENCES

The rocks of the formation tend to be symmetrically arranged about the middle of each carbonate rock and chert member. Beginning in the middle of a carbonate rock and chert unit in an idealized section, the upward sequence of chemical and biolithic sediments is: carbonate rock, tubular chert, nodular and concretionary chert, bedded chert, organic phosphorite, oolitic and nodular phosphorite, pelletal phosphorite, oolitic and nodular phosphorite, organic phosphorite, bedded chert, nodular and concretionary chert, tubular chert, and, finally, carbonate rock. Anhydrite, where present, is found in the carbonate phase of the cycle. An idealized cycle is shown on fig. 24.

No such perfect cycles are found, however. The chert and carbonate phases of the cycle usually overlap and organic phosphorite is interbedded with bedded chert at many places. Generally, one or more of the phases are not present, especially the phases between the lower carbonate rock and the lower organic phosphorite. In addition, carbonate rock occurs in many places in the phosphorite phase of the cycle. However, most of this carbonate rock is dark, sparingly fossiliferous dolomite or dolomitic limestone and is not comparable to the light-colored fossiliferous carbonate rock of the carbonate phase of the cycle. Anhydrite has been found in the area of the report only in the core from Lakeridge 1 well, though it probably has been leached away by weathering from several other surface exposures near by.

The clastic rocks are systematically associated with this chemical and biolithic cycle. Sandstone is found in the bedded chert to carbonate rock to bedded chert portion of the cycle, whereas mudstone is found in the bedded chert to pelletal phosphorite to bedded chert portion of the cycle.

The iron minerals, which occur in the Phosphoria in only minor amounts, also appear to fit systematically into the cycle. Pyrite occurs in the bedded chert to pelletal phosphorite to bedded chert portion of the cycle. Glauconite occurs in the concretionary and nodular chert to carbonate rock portion of the cycle, and iron oxide probably occurs in the anhydrite phase of the cycle. Organic matter, as would be expected, is associated with the pyrite in the bedded chert to pelletal phosphorite to bedded chert portion of the cycle.

In the central part of the area, there are two full cycles: the lower, beginning at the base of unit *A* and ending at the carbonate rock zone of unit *C*, and the upper, beginning at the carbonate rock zone of unit *C* and ending at the carbonate rock zone of unit *E*. In the southwest, the upper cycle reaches only the nodular phosphorite stage in unit *D*. Eastward these cycles progressively lose their central portions; thus, in central Wyoming only carbonate rock and anhy-

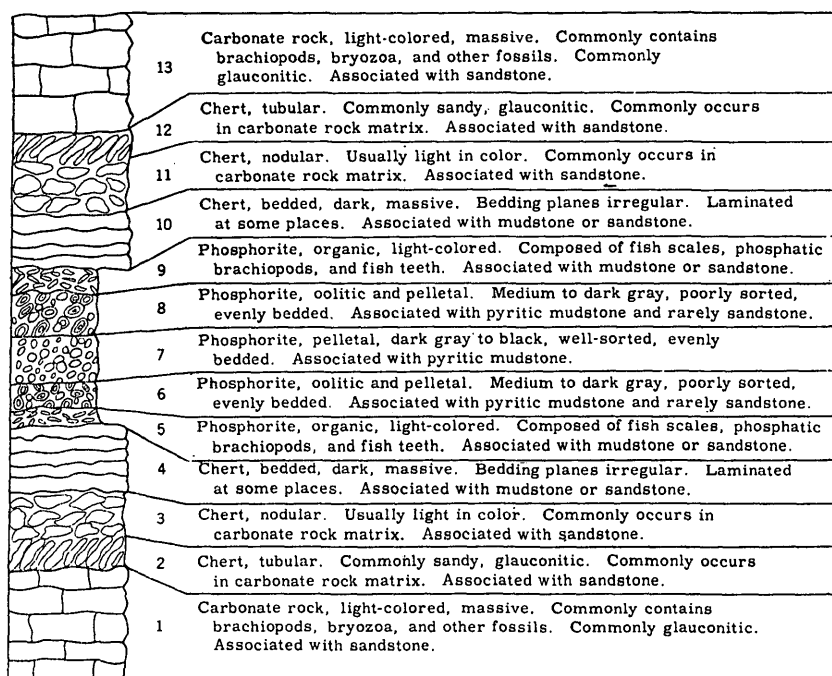


FIGURE 24.—Idealized depositional cycle of chemical sediments of the Phosphoria formation in northwestern Wyoming.

drite are present. Southwestward the outer portions of the cycles are progressively lost; thus, southwest of the area, in southeastern Idaho, only phosphorites and bedded chert are present.

#### LATERAL RELATIONS

The variations in thickness and lithologic character of the rocks of each unit have been discussed. It was further shown that the units make up portions of a cyclic depositional sequence. The units which constitute the same portions of the cycles of deposition are areally compared here, and also the thickness relations between units making up one cycle. To aid in reconstructing the probable environments of deposition, it is important to establish whether or not adjacent phases of the vertical cycle grade into each other laterally. Thus the facies relations discussed previously in the treatment of individual units are summarized below and compared with the vertical cyclic rock sequence.

#### COMPARISON OF UNITS B AND D

Units *B* and *D* make up the portion of the depositional cycle from organic phosphorite to pelletal phosphorite to organic phosphorite.

The variation in thickness and feet-percent  $P_2O_5$  of units *B* and *D* are shown in figures 13 and 18 respectively. Both units *B* and *D*

pinch out northeastward, but unit *D* extends the farther. Unit *B* thickens progressively southwestward, but unit *D* thickens and then thins southwestward. Southwest of the area, unit *D* probably thickens again.

In the southwestern part of the area, unit *B* and unit *D* have about equal amounts of phosphate rock in both the upper and lower parts of the respective units. In the east, however, the upper parts of units *B* and *D* consist of only weakly phosphatic to nonphosphatic mudstone; phosphate rock occurs at the base of the unit. In the extreme northeastern part of the area, both units consist wholly of phosphate rock or phosphatic sandstone. In the phosphate rock of both units, coarse-grained oolites and nodules increase in abundance from the southwest to the northeast. However, where unit *D* is thin in the extreme southwest, nodular phosphorite is dominant. To the east organic phosphate rock assumes prominence in both members and accompanying this lithologic change is an increase in variation of the thickness of individual beds of phosphate rock; that is, they become lenticular.

Finally, both shale units contain dark fine-grained dolomite beds that are megascopically indistinguishable from mudstone. They are quite different from the light-colored, massive, medium to coarsely crystalline fossiliferous carbonate rocks that are prominent in units *C* and *E*.

Thus, in general, the two units show similar areal lithologic variations. In addition, both units thin eastward. Unit *D* also thins southwestward, whereas unit *B* progressively thickens southwestward.

#### COMPARISON OF UNITS *C* AND *E*

The chert and carbonate rock portions of the cycles are composed of units *C* and *E*. Figures 14 and 19 show the variations in thickness and dominant lithologic character of the two units, and figures 15 and 23 show the areal variation of their clastic ratios and mudstone-sandstone ratios.

Unit *C* thins northeastward with a corresponding dominant lithologic change from chert to carbonate rock to sandstone. Unit *E*, on the other hand, is absent in the southwest, lenses in, and then thins to the northeast. Lithologic changes in unit *E* are not as systematically associated with these thickness changes as they are in unit *C*. Similarly to unit *C*, however, unit *E* changes eastward from dominantly chert to dominantly carbonate rock, though for unit *E* this change occurs farther east. A comparison of figures 15 and 23 indicates that the ratio of sandstone to mudstone increases northward in both units. Therefore, the source of clastic sediment was probably at the north and northwest.



Thus, except in thickness, units *C* and *E* show somewhat similar depositional patterns; that is, an increase of clastics to the north and northwest and a dominant lithologic change from chert to carbonate rock to the east. A discrepancy in this generalization is that the uppermost sandstone of unit *E* offlaps the chert of unit *E*; that is, it extends farther west than the chert. In the western part of the area it composes the entire unit.

#### COMPARISON OF UNITS *B* AND *C* WITH UNITS *D* AND *E*

In order to analyze the areal thickness variations of single cycles of deposition it would be desirable to include the rocks from one carbonate rock phase to the next carbonate rock phase of the cycle. However, because the contacts can be placed more easily at unit boundaries, the units selected for thickness analysis have been the stratigraphic units *B* and *C*, to represent the lower cycle, and units *D* and *E*, the upper. Thus, the phases analyzed are actually those from one organic phosphorite to the next organic phosphorite. Since the lower chert phases are generally thin or absent, this approximately corresponds in thickness to the rocks encompassed by the carbonate phases of the cycle.

The areal variation of the combined thicknesses of units *B* and *C* are shown on figure 25. The thickness of the combined units increases southwestward in the same manner as the individual units. The thickness variations of the combined units, however, are less irregular than of individual units.

The areal variation of the upper cycle is shown on figure 26. The cycle is an elongate lens trending northwest with a maximum thickness in the southeastern part of the area. It thins to the northeast and southwest. Units *D* and *E* individually show similar thickness variations (figs. 18 and 19). The variation of the combined thicknesses is somewhat less irregular than the individual thicknesses.

The thickness variations of the lower cycle (approximately the combined thicknesses of units *B* and *C*), however, are different from those of the upper cycle (approximately the combined thicknesses of units *D* and *E*). Therefore, the factors which governed the variations in thickness of units *B* and *C* were similar and the factors which governed the variations in thickness of units *D* and *E* were similar too, but these factors changed between cycles.

#### FACIES

The facies changes within and between the units have been discussed above and are summarized here. The phosphatic beds of unit *B* cannot be correlated individually over the whole area of the report, but they are dominantly pelletal in the southwestern part of the area, dominantly oolitic and nodular in the central part, and domi-

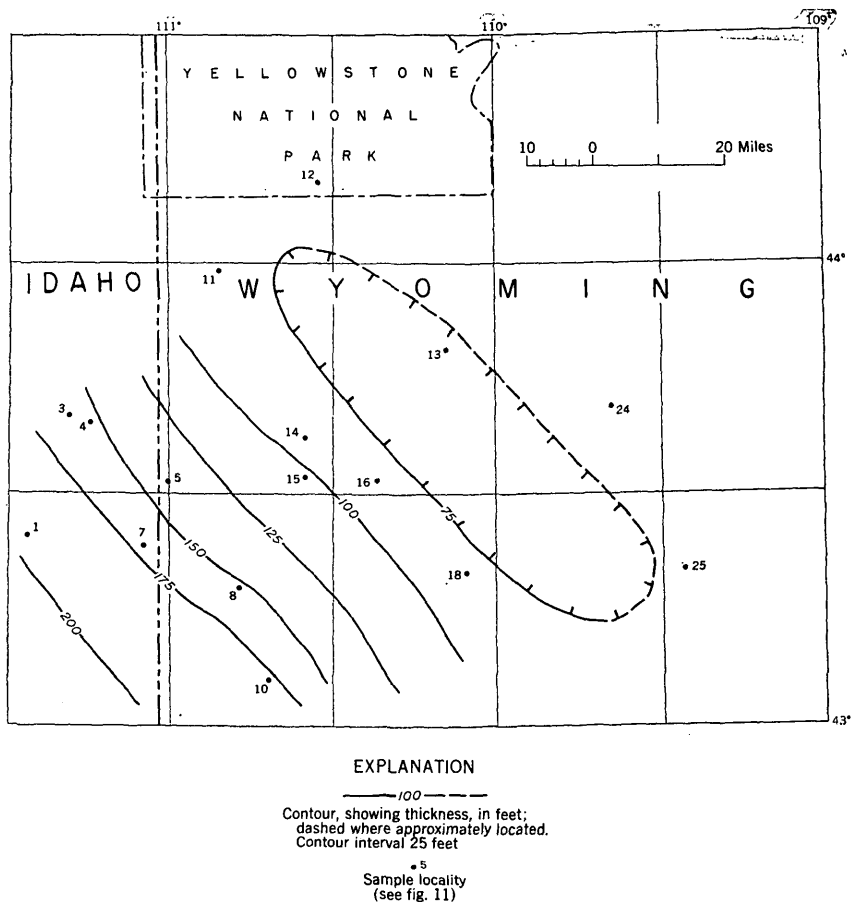


FIGURE 25.—Isopach map of units *B* and *C* of the Phosphoria formation in northwestern Wyoming.

nantly organic in the eastern part. The same phosphorite facies are present in unit *D* although, in the extreme southwest of the area, unit *D* is only a few feet thick and only nodular phosphorite is present. There is little evidence to suggest whether this facies relation is the result of interfingering or of gradation. The basal nodular and oolitic bed of unit *B* in the central portion of the area, however, probably does grade into organic phosphorite to the east. Also, petrographic investigations show that mixed phosphorite types occur.

At the base of the formation in the southwestern part of the area, the lower beds of unit *B* are composed of calcareous mudstone, which is slightly phosphatic, and several thin interbeds of phosphorite. Eastward these grade into chert and carbonate rock of unit *A*. The upper mudstone and phosphorite beds of unit *B* grade from the southwest to the northeast into chert of unit *C*. The organic phosphorite

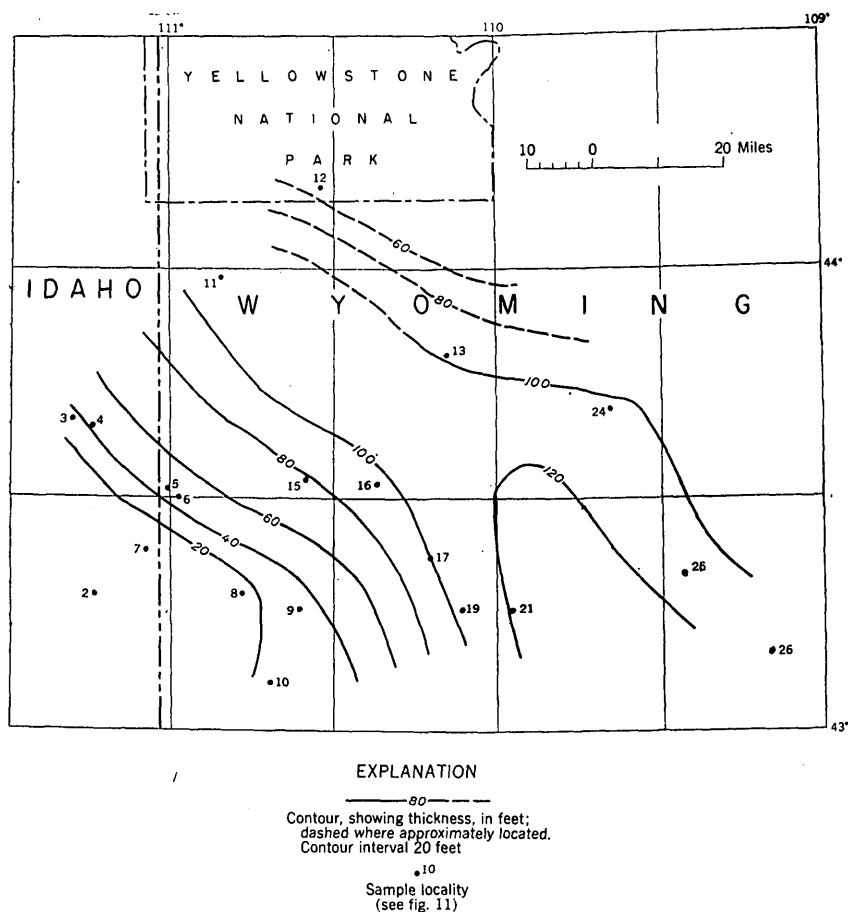


FIGURE 26.—Isopach map of units *D* and *E* of the Phosphoria formation in northwestern Wyoming.

at the top of the formation in the southwestern part of the area grades into chert to the east. The upper beds of unit *D* similarly grade from the southwest to the northeast into chert of unit *E*. Thin organic phosphorite beds and chert beds are commonly interbedded at many localities and in many cherty parts of the section. Mixtures of phosphorite and chert are not rare. Thus some of the phosphorite grades eastward into chert. Organic phosphorite also probably grades into sandstone and limestone. Where the chert phases of the cycle are thin or absent, mixed rocks of organic phosphorite and either sandstone or carbonate rock are usually found at the top of the carbonate rock zones.

The lithologic types of chert probably grade into each other laterally. Although no individual chert bed can be demonstrated to change facies, chert zones change laterally in dominant lithologic type.

For example, the chert of unit *C* in the southwest is dominantly bedded chert; to the northeast it is dominantly nodular chert; still farther northeast it is dominantly tubular chert.

The facies change from chert to limestone may be postulated on the same grounds as were the facies changes of the chert; that is, some tubular chert zones are represented in the east by carbonate rock zones. Also, many tubular chert bodies are embedded in a carbonate rock matrix. Finally, the lateral relations between anhydrite and carbonate rock are not known, mainly because anhydrite has been found in the area of the report only in the core from Lake-ridge 1 well.

Thus, the facies of the Phosphoria are analogous to the rock phases of the cycle of deposition. The eastward facies change of pelletal phosphorite to nodular and oolitic phosphorite is analogous to the passage from the pelletal phosphorite phase to the nodular and oolitic phosphorite phase; the eastward facies change from nodular and oolitic phosphorite to organic phosphorite is analogous to the passage from the nodular phosphorite phase to the organic phosphorite phase; and so forth to the tubular chert and carbonate rock facies and phases.

#### GENETIC SIGNIFICANCE OF STRATIGRAPHIC RELATIONS

The rocks of the Phosphoria are systematically arranged both vertically and laterally. Moreover, some of them are uncommon types. Thus, the combination of factors which controlled the deposition of the sediments was somewhat uncommon and changed in a systematic manner in both space and time. It is not within the scope of this paper to discuss all the factors which appear to be significant to the genesis of the rocks of the formation, but this study has cast some light on several of these factors. These include the paleogeographic setting of the formation in the area of the report and adjacent regions, the depositional environments of the sediments, and the tectonic movements which were active during the deposition of the sediments and which caused transgressive and regressive relations.

#### PALEOGEOGRAPHY

The lithologic character and thickness of the rocks of the Phosphoria formation in the area of the report supply several clues to the Permian paleogeography. McKelvey (McKelvey and others, 1953) suggested that the depth of water probably increased to the west, because carbonaceous matter in the Phosphoria increases from Wyoming to Idaho; clastic material in the Phosphoria decreases in grain size in the same direction; and, whereas crossbedding of the sandstone is not uncommon in Wyoming, the rocks in southeastern Idaho show no crossbedding but commonly show lamination. In the area of the

report the formation ranges in thickness from 150 to 400 feet. These variations are fairly uniform. Thus, according to McKelvey, the rate of deposition and, thereby, the rate of supply of sediment were probably fairly slow and uniform, especially because much of the sea floor in the area of the report probably was below wave base. This indicates that the relief on the sea floor and nearby land areas was probably gentle. In central Wyoming, beds of anhydrite indicate that restricted shallow basins were present on the eastern margin of the sea during some of the Phosphoria time.

The source of much of the sand in the formation was probably at the north; thus a low land mass probably was located in central Montana. East of the area, the transition into red beds marks an increase in the amount of clastic material in the formation (Ketterer and Swirczynski, 1952; Frielinghausen, 1952); it seems possible, therefore, that some of the clastic material in the formation was derived from the east. The red bed facies of the formation is fairly widespread at the east (Thomas, 1934) and the source of this clastic material probably was many miles east of the area of this report.

In summary, the Phosphoria sea was probably fairly deep in southeastern Idaho and shallowed gently eastward; in central Wyoming it terminated at times in shallow restricted basins. In central Montana a low land mass supplied some of the coarser clastic material deposited in the sea, and many miles east of the open ocean another low land mass supplied some finer grained clastic material. The total supply of clastic material was, however, small.

#### PHYSICAL CHEMISTRY OF ENVIRONMENTS OF DEPOSITION

Previous investigations of the geochemistry of phosphorite, carbonate rock, the iron-bearing rocks, and evaporites indicate that the temperature, acidity, redox potential, and salinity of the ocean water mainly control the type of sediment that is deposited (Halla, 1935; Cooper, 1937; Kazakov, 1937, 1938; Dietz, Emery, and Shepard, 1942; Blumer, 1950; Castaño and Garrels, 1950; Kazakov, 1950; Kazakov and Sokolova, 1950; Krumbein and Garrels, 1952; Huber and Garrels, 1953; Mann, 1953; Murray and Gravenor, 1953; James, 1954). The depositional environments of the rocks of the Phosphoria that may be deduced from these studies suggest progressive changes of acidity, redox potential, and salinity corresponding to the vertical and lateral rock changes. The physical chemistry of the deposition of phosphorite, calcium carbonate, the iron minerals, silica, anhydrite, and organic matter is briefly summarized below.

Kazakov (1937) synthesized physical-chemical, oceanographic, and geologic data in advancing an explanation of the origin of phosphorites.

He concluded that phosphorites are precipitated chemically where cold phosphorus- and carbon dioxide-rich waters are warmed as they well up over a shelf, in a manner illustrated by the present oceanographic conditions off the coast of California. Phosphate cannot precipitate, he said, in the zone of photosynthesis, because it is vigorously consumed by phytoplankton. Neither can it precipitate in the deep regions of the sea, below about 200 meters, because of the high  $\text{CO}_2$  content and resulting low pH. He further reasoned that calcium carbonate was precipitated under like conditions but at slightly lower pH and thereby earlier than phosphorite. McKelvey (McKelvey and others, 1953) adopted the Kazakov hypothesis to explain the rocks of the Phosphoria formation, but they concluded that phosphorites can form at depths exceeding 200 meters and probably down to the depth of 1,000 meters, as is evident from the distribution of phosphorites in the present sea floor, and that

The paragenetic relationships of the phosphorite facies of the Phosphoria indicate that the waters ascending the shelf of the Phosphoria sea became saturated first with carbonate-fluorapatite and then with calcium carbonate, rather than the reverse as Kazakov thought.

Krumbein and Garrels (1952) state that if calcite and phosphorite coprecipitate the ratio is very high in favor of calcite; but if the pH is below about 7.8, the activity product of calcite will not be reached, whereas that of phosphorite will, and a phosphorite-rich sediment will be formed. They also point out that the precipitation of phosphorite is independent of the redox potential of the environment.

In summarizing much of the previous work on the precipitation of calcium carbonate, Krumbein and Garrels conclude that both calcium and the carbonate ion are independent of the Eh of the solution and that the precipitation of calcium carbonate in sea water is primarily controlled by the pH of the system, the most favorable conditions being above a pH of about 7.8.

The mineralogy of the iron in sediments depends on both the acidity and redox potential of the system (Castaño and Garrels, 1950; Krumbein and Garrels, 1952). These studies show that at a pH of about 7.8 pyrite is stable if the redox potential of the environment is below about  $-0.25$  Eh; siderite, if it is below about  $-0.05$  volts; and hematite, if it is above about  $-0.05$  volts. A decrease of pH tends to raise these Eh stability ranges somewhat, the pyrite-siderite boundary less than the siderite-hematite boundary. The quantity of iron mineral in the sediment, on the other hand, does not depend on the acidity or redox potential of the system, but primarily on the concentrations and continuing supply of the various ions. The physical-chemical environment in which glauconite is formed is

not known, though it is placed by Krumbein and Garrels in both the siderite and hematite fields. On the basis of associated minerals, James (1954) deduced that greenalite (an iron silicate similar to glauconite) as well as other iron silicates of the pre-Cambrian iron-bearing formation were deposited in mildly reducing to mildly oxidizing conditions.

The physical-chemical environment favorable for the deposition of silica is little known at the present time, although speculations as to the controls of precipitation are many. An excellent review of these hypotheses is given by Bramlette (1946, p. 41). The relative effect of the acidity of sea water, if any, on the precipitation of silica is debatable.

The precipitation of anhydrite occurs when the activity product of calcium ion and sulfate ion is exceeded, owing to the evaporation of sea water. The state of oxidation or reduction of sulfur depends on the redox potential of the system, but under normal saline conditions the sulfur is in the form of sulfate ion. Thus the main control of the precipitation of anhydrite is the salinity of the sea water.

Organic matter in general controls the lower limit of the redox potential and the poise or reducing capacity of the system. If the redox potential of the system is greater than zero, organic matter will be oxidized. Thus organic matter is stable at Eh less than zero (Krumbein and Garrels, 1952).

The preservation of sediments that are formed from the hard parts of organisms would also be controlled by the physical-chemical environment; that is, if the water in which the biogenic mineral is deposited is not saturated with that mineral, it will be unstable and will tend to dissolve (McKelvey, 1946; Krumbein and Garrels, 1952).

The minerals deposited under similar Eh and pH fields have been summarized by Krumbein and Garrels (1952) and presented in graphic form, which is reproduced in figure 27 by permission of the University of Chicago Press. Essentially seven fields are delineated by the boundaries:  $\text{pH}=7.0$ , the neutral fence;  $\text{pH}=7.8$ , the limestone fence;  $\text{Eh}=0$ , the organic matter fence; the boundary between the hematite and siderite stability fields, the oxide-carbonate fence; and the boundary between the siderite and pyrite stability fields, the sulfate-sulfide fence. These stability fields have been set up on theoretical grounds and in part verified by experiment (Huber and Garrels, 1953). Krumbein and Garrels point out that if a rock contains primary sedimentary minerals which fall into these fields, and if equilibrium conditions prevailed at the time of deposition, approximate limits of original pH and Eh environments may be deduced.





retrogressed. The light-colored carbonate rocks contain no organic matter and therefore probably were deposited at an Eh greater than zero and a pH greater than 7.8. Tubular chert is generally light in color and is commonly associated with light-colored carbonate rock and glauconite; it probably was deposited under similar conditions. The dark-bedded chert, on the other hand, is associated less commonly with light-colored carbonate rock and, therefore, probably was deposited at a pH lower than 7.8. Organic phosphorite commonly is associated with glauconite and generally is calcareous; therefore, it probably was deposited at a pH near 7.8. The pelletal and nodular phosphorites are generally fairly free from carbonate rock and are rich in organic matter and pyrite. They probably were deposited, therefore, at an Eh less than about  $-0.25$  volts and a pH less than 7.8. The half cycle of deposition from light-colored carbonate rock to carbonaceous pelletal phosphorite probably represents a progression of pH from about 8.4 to about 7.5 and of Eh from about 0.1 to about  $-0.3$  volts.

Similarly, the facies of the formation indicate that the pH of the sea water progressively rose to the east, probably as the result of the loss of  $\text{CO}_2$ , and that the Eh progressively rose to the east, owing to greater aeration of the bottom and perhaps increased benthonic scavenger fauna. The presence of anhydrite as the easternmost facies indicates that shallow restricted basins, combined with rapid evaporation, allowed the salinity to become greater than 200 parts per thousand. The red beds contain the ferric iron oxides and thus probably were deposited at an Eh greater than about  $-0.05$  volts. This reflects dissolved oxygen in the seawater.

Silica was apparently deposited in a physical-chemical environment intermediate to the environments of phosphorite and light-colored carbonate rock. This would be in and near the center stability field. Thus, if the precipitation of silica is controlled by the acidity of the environment, this study shows that the optimum pH value is probably a little less than 7.8.

The detailed sequence of rocks of the formation does not fit so simple a picture as outlined above, but it seems likely that the change of environments, while fluctuating, showed this progressive trend (fig. 27). Furthermore, rocks which do not lie in adjacent environmental fields sometimes are vertically adjacent. This may seem anomalous, for if the main control were pH and Eh, intermediate type rocks representing intermediate values of pH and Eh should be found. However, the passage from one environment to another could be rapid enough so that little or no sediment had time to form.

As suggested by Kazakov and amplified by McKelvey, it seems likely that the areal zoning of environments probably was due to the

upwelling of cold bottom currents, rich in dissolved material, over a platform. The subsequent increase in temperature and decrease in pressure would cause a loss of  $\text{CO}_2$  and, thereby, a rise in pH. Life would flourish in this nutrient-rich water and result in a large supply of organic matter in the bottom sediment. In water below wave base, the organic matter would be plentiful and the oxygen content low, and thus the Eh would be low. In shallower waters above wave base, the oxygen content would be high enough to oxidize the organic matter and yield high Eh values. Benthonic scavengers could live in the oxygenated water and help in the destruction of organic matter.

#### TRANSGRESSION AND REGRESSION

The sediments of the Phosphoria formation in the area of the report are all marine, and inasmuch as no prominent erosion surfaces within the Phosphoria have been found, it is probable that the area was covered by the sea for all of Phosphoria time. Thus no transgression or regression of the shore line of the sea occurred in the area while the sediments of the Phosphoria were being deposited. It appears likely, however, that the depositional environments, which were areally zoned as described above, transgressed eastward twice, followed in each case by regression, which thus completed the two cycles of deposition.

The horizons of maximum transgression and maximum regression in a very general way define time horizons (Lowman, 1949). Four such horizons can be placed within the formation at about the centers of units *B*, *C*, and *D*, and at the top of the formation. The validity of these horizons as time lines ultimately rests on the interpretation that the key beds indicated on plates 11 to 13 are time horizons. The facies relations are based on this assumption and the transgressive and regressive relations are based on the facies relations.

During the first period of the deposition of Phosphoria sediments in the area of this report, phosphorite and mudstone were deposited in the southwestern part of the area, while chert and carbonate rock were deposited in the central and sandstone in the eastern parts. The northeastern part of the area was above sea level.

The first transgression emplaced the phosphorite environment farther eastward to the central part of the area; during this period thick beds of phosphorite were deposited in southeastern Idaho. These thinned to the northeastward and graded into sandstone in the eastern and northern part of the area. The whole area of the report was receiving sediment during this period.

The first regression occurred in two pulsations, the first of which displaced the phosphorite environment to the southwestern part of the area and emplaced a chert environment over the central and east-

ern part, while sandstone was deposited in the north. A second regressive pulsation emplaced a carbonate environment over most of the area.

The second transgression apparently occurred in two pulsations also. The carbonate environment was displaced slightly northeastward, allowing a chert environment to be emplaced in the southwest. The second pulsation was rapid and emplaced a phosphorite environment over the whole area of the report.

The second regression was slow and even. The phosphorite environment was gradually displaced westward, allowing the progressive emplacement of a chert environment, followed by a carbonate environment. Near the close of this regression a phosphorite environment existed in the southwestern, a chert environment in the south-central, and a carbonate environment in the southeastern parts of the area, and sand was being deposited in the north (fig. 20). At the very close of Phosphoria time sandstone was deposited over the northern part of the area, offlapping the phosphorite and chert deposits.

Superimposed on these two transgressions and regressions were a great number of minor changes of environment, which account for the intricate interbedding of the rocks of the formation. These changes included fluctuations of the physical-chemical environment and variations in the supply and deposition of clastic material.

#### GEOTECTONICS

##### TECTONIC CONTROL OF TRANSGRESSION AND REGRESSION

The transgressions and regressions of the Phosphoria sea could have been caused by eustatic changes of sea level or tectonic movements. For three reasons tectonic control is more plausible. First, the transgressions and regressions occurred in the transition zone between the two tectonic elements, the Cordilleran miogeosyncline and the bordering craton on the east. Second, the isopach maps of the lower and upper cycles (figs. 25, 26) indicate that the basin in which the lower cycle was deposited had a different configuration than the one in which the upper cycle was deposited. The major difference is that the basin of the lower cycle deepened progressively westward, whereas the basin of the upper cycle deepened westward, shallowed, and deepened again. This change of thickness variation of the two cycles is most easily explained by areal variation of tectonic movements. Finally, the Forelle limestone and Ervay tongue, which extend into the red bed facies of the formation, are probably correlative with the carbonate rock zones of the formation in the area under discussion (Thomas, 1934), and thus the middle and upper periods of maximum transgression east of the area probably correspond to the middle and upper periods of maximum regression in the area of the report. If

this is the case, eustatic changes of sea level alone cannot have caused the transgressive and regressive relations, and tectonic control was probably most important. These tectonic movements probably affected a large area of the Permian platform, because the inter-tonguing of rocks deposited in different depth environments occurs not only in Wyoming and Idaho, but also in Montana (Cressman, 1954) and probably in Utah (Cheney, T. M., oral communication).

#### NATURE OF TECTONIC MOVEMENTS

If, as seems to be the case, the major cause of transgression and regression was tectonic movement, something of the nature of these movements can be deduced from the stratigraphic record. Because the transgressions were more rapid than the regressions, the downward movements were more rapid than the upward movements. Because the transgressions and regressions appear to have occurred in pulsations, the tectonic movements probably were pulsating also.

#### TECTONIC PROVINCES

McKelvey (McKelvey and others, 1953) has pointed out the coincidence of the phosphorite-mudstone-chert facies of the formation with the Cordilleran miogeosyncline and the sandstone-carbonate rock facies with the shelf and has discussed the genetic implications. The studies reported here further indicate that the shelf consists of two geotectonic provinces, the stable shelf and the unstable shelf.

The transition zone between the phosphorite-mudstone-chert facies—essentially deep water facies—and the sandstone-carbonate facies—essentially shallow water facies—is wide; moreover, tongues of the deep water facies extend nearly to the red bed facies, and one evaporite tongue extends into western Wyoming in unit *C*. Thus, the formation in western Wyoming is markedly heterogeneous and records unstable tectonic conditions. The red bed facies in central Wyoming, on the other hand, records fairly continuous shallow water deposition, although the sediment deposited ranged from carbonate rock to anhydrite to red beds. The area over which these sediments were deposited was, therefore, more stable than the area to the west and may be called the stable shelf.

#### CONCLUSIONS

The sediments of the Phosphoria formation were deposited in a basin in northwestern Wyoming which shelved gently eastward and northward. Detritus was derived from a low land area in southwestern Montana and from another low land area many miles to the east of northwestern Wyoming.

Cold sea water, rich in phosphorus and  $\text{CO}_2$  welled up over the shelf areas with a consequent change in the physical-chemical char-

acter of the water, the most important changes being a landward increase in alkalinity and redox potential. The type of sediment reflected the change in physical-chemical environment: the pelletal, oolitic, and nodular phosphorite was deposited under conditions of low pH and Eh values; chert, of intermediate values; and carbonate rock, of high values. Of the minor constituents of the sediments, organic matter and pyrite are associated with the phosphorite and some of the chert; glauconite, with the rest of the chert and some of the carbonate rock; and hematite, with the carbonate rock in the red bed facies in northwestern Wyoming. Sand was deposited with the carbonate rock and some of the chert, and mud was deposited with the rest of the chert and the phosphorite.

Owing to tectonic movements, these environments transgressed and regressed twice across northwestern Wyoming, producing an interfingering of the different rock types. The vertical sequence of rocks is cyclic because of the alternation of environments.

The tectonic movements, as recorded by the rocks, were pulsatory: the downward movement rapid and the upward movement slow. Northwestern Wyoming, where the pulsatory movements were active, was the unstable shelf. At the east, in central Wyoming, lay the stable shelf, where tectonic movements were minor. At the west, in Idaho, lay the miogeosyncline, which in Permian time was a negative area, relatively unaffected by the upward tectonic movements.

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho*

[The Phosphoria formation measured and sampled in a bulldozer trench and at natural exposures on the north side of Fall Creek near Swan Valley, SW¼ sec. 18, T. 1 N., R. 43 E., Bonneville County, Idaho, on the southwest limb of an anticline trending northwest. The beds strike N. 40° W. and dip 45° SW. Section measured and sampled by R. P. Sheldon, F. D. Frieske, T. M. Cheney, and R. G. Waring in September 1950. Petrographic descriptions made by R. P. Sheldon. Color terms and numerical designations are from the Munsell color chart. Size terms are from the Wentworth size system. In the bed numbers, the first number indicates the locality (fig. 11); the letter indicates the unit or member that contains the bed; and the second number indicates the bed, in ascending order from the base of the unit. Percentages of constituents are visual estimates, except where the beds are analyzed for  $P_2O_5$  and acid insoluble constituents. These data are published in Smart, R. A., and others, 1954]

No. of bed	Description	Thickness (feet)
Rex Member of the Phosphoria formation (top not exposed, but only a few feet not described):		
1R15-----	Chert, sandy, hard, medium-gray (N 5/0), massive. Consists of 75 percent chalcedony: 60 percent as indistinct structureless spheres, and 20 percent as sponge spicules; 20 percent detrital quartz: very fine to fine, subangular sand; 1 percent apatite: clear euhedral tablets up to $\frac{1}{64}$ mm in diameter; 1 percent dolomite: euhedral rhombs up to $\frac{1}{8}$ mm in diameter; less than 1 percent collophane: grains up to $\frac{1}{4}$ mm in diameter, probably replacement of bioclasts; less than 1 percent pyrite: euhedral; and traces of detrital grains of	26.5

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	muscovite, tourmaline, and sphene. Stratification of rock is shown by laminae containing various amounts of sand. Stylolites occur in chert. Apatite, collophane, dolomite, and pyrite are disseminated throughout rock.	
1R14-----	Limestone, siliceous, hard, medium-gray ( <i>N</i> 5/0), massive. Rock closely resembles bed 1R13h, except that euhedral quartz crystals up to $\frac{1}{2}$ mm wide and $\frac{1}{4}$ mm long make up about 20 percent of the rock. They are evenly scattered through the rock and are unoriented. A few beds of dolomitic chert occur in the unit and are described as follows: Chert, dolomitic, hard, light brownish-gray (10YR 5/1). Consists of 80 percent chalcedony: 60 percent as microcrystalline matrix, 15 percent as sponge spicules, and 5 percent as replaced bioclasts including echinoid spines(?); 20 percent dolomite: euhedral rhombs up to $\frac{1}{4}$ mm in diameter; and 1 percent detrital quartz: very fine, sub-angular, well-sorted sand. Many rhomb-shaped molds occur in rock; rock is veined with calcite.	22.0
1R13-----	<p>Chert, dolomitic, and cherty limestone, hard, dark-gray (<i>N</i> 4/0), massive. Tubular chert concretions make up a large part of unit. Five rock specimens in unit were examined petrographically and are described as follows:</p> <p>h.—41.0 feet above base. Top of unit. Limestone, contains chert concretions, hard, yellowish-gray (10YR 7/1), massive. Consists of 95 percent calcite: 50 percent as coarsely crystalline echinoid spines(?), bryozoan fragments, and shell fragments, and 45 percent as microcrystalline matrix; 3 percent detrital quartz: fine, etched, well-sorted sand; and 1 percent collophane: brown, as replacement of fossils, casts of holes in fossils, and fine, subrounded pellets. Chert concretions are identical to rest of rock except that microcrystalline calcite cement is replaced with microcrystalline chalcedony.</p> <p>g.—36.0 feet above base. Carbonate rock, cherty, sandy, hard, dark-gray (<i>N</i> 4/0), massive. Consists of 60 percent carbonate: anhedral irregular grains up to <math>\frac{1}{2}</math> mm in diameter; 20 percent chalcedony: microcrystalline matrix; and 20 percent detrital quartz: very fine, angular, well-sorted sand. Stratification of rock is shown by a coarse lamination due to color differences. Carbonate is more coarsely crystalline in light to colored laminae.</p> <p>e.—25.0 feet above base. Chert, sandy, dolomitic, hard, dark-gray (<i>N</i> 4/0), laminated, massive. Consists of 60 percent chalcedony: 55 percent as cryptocrystal-</p>	41.0

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued.*

No. of bed	Description	Thickness (feet)
	line chert and 5 percent as microcrystalline sponge spicules; 20 percent detrital quartz: very fine, angular, well-sorted sand; and 20 percent dolomite: euhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter. Rock is stratified by laminae containing various proportions of the above components as well as various amounts of organic matter. Rock contains lens-shaped single-crystal calcite bodies which may be fossil shell fragments. The tubular concretions are texturally much the same as the rest of the rock except there is more chert, sponge spicules are more obvious, and more organic matter is present, especially in axial canals of sponge spicules. Stratification of the concretions is shown by orientation of sponge spicules and is parallel to the bedding.	
	c.—15.1 feet above base. Chert, carbonatic, hard, dark-gray ( <i>N</i> 4/0), laminated, massive. Consists of 50 percent chalcedony: 45 percent as microcrystalline to nearly cryptocrystalline matrix, and 5 percent as sponge spicules; 45 percent carbonate: 5 percent as euhedral rhombs up to $\frac{1}{16}$ mm in diameter, and 40 percent as irregular-shaped aggregates of anhedral grains; and 5 percent detrital quartz: very fine, sub-angular, well-sorted sand. Stratification of rock is shown by chert and carbonate laminae. Carbonate euhedra occur in chert laminae. Sponge spicules occur in carbonate rock laminae. Boundary between laminae is gradational. Sand occurs as lenses parallel to lamination. Rock is veined with calcite.	
	b.—10.0 feet above base. Chert, dolomitic, hard, dark-gray ( <i>N</i> 4/0), laminated, massive. Consists of 60 percent chalcedony: 40 percent as microcrystalline to nearly cryptocrystalline matrix, and 20 percent as sponge spicules; 30 percent dolomite: euhedral grains up to $\frac{1}{8}$ mm in diameter; 10 percent detrital quartz: very fine, angular, well-sorted sand; and traces of detrital grains of plagioclase, sphene, and muscovite. Stratification of rock is shown by thin laminae of sandstone; otherwise texture is very homogeneous.	
1R12-----	Phosphorite, argillaceous, medium to coarsely pelletal, and nodular, medium-hard, dark-gray ( <i>N</i> 2/0), thin-bedded. Nodules consist of phosphatic fossils.	0. 2
1R11-----	Siltstone, carbonatic, sandy, hard, pale-brown (10YR 6/2), thin-bedded. Consists of 60 percent detrital quartz: 35 percent as coarse, angular silt and 25 percent as fine, medium well rounded sand; 20 percent carbonate: euhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter; 10 percent collophane: nodules full of silt inclusions up to 8 mm in diameter, replaced	1. 4

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	bryozoa, fine, well-rounded pellets, francolite brachiopod(?) shells, and a tooth of francolite 4 mm long; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; and traces of detrital grains of chert, sphene, and tourmaline. Rock is stratified as shown by orientation parallel to the bedding of sand lenses, elongate collophane bioclasts, and muscovite flakes.	
1R10-----	Limestone, phosphatic, sandy, hard, medium-gray (N 5/0), massive. Consists of 60 percent calcite: 30 percent as bryozoa, echinoid spines(?), and shell fragments, and 30 percent as microcrystalline matrix; 20 percent collophane: 10 percent as structureless forms, possibly shell fragments up to $\frac{1}{2}$ mm long, and 10 percent as cement and casts of holes in bryozoa; 20 percent detrital quartz: fine, medium well rounded sand; and traces of detrital grains of chert, sphene, and tourmaline. Quartz sand grains are scattered through the matrix of fine-grained calcite and collophane.	1. 9
1R9-----	Dolomite, hard, medium-gray (N 5/0), massive. Consists of 80 percent dolomite: clear, euhedral to subhedral crystals up to $\frac{1}{16}$ mm in diameter showing overgrowths; 10 percent detrital quartz: fine, angular, medium well sorted sand; less than 1 percent chalcedony: sponge spicules; and 10 percent collophane: poorly sorted, fine, angular nodules. Larger collophane grains contain more quartz silt and sand. Rare francolite brachiopod shell fragments and collophane echinoid spines(?) are scattered throughout rock. Stratification of rock is shown by orientation parallel to the bedding of fossil fragments, lenses of quartz sand, and lenses of darker carbonate.	5. 2
1R8-----	Sandstone, cherty, contains chert nodules, hard, medium-gray (N 5/0), thick-bedded. Consists of 50 percent detrital quartz: fine, medium well rounded sand; 35 percent chalcedony: 30 percent as microcrystalline matrix, and 5 percent as microcrystalline sponge spicules which are as long as $\frac{1}{2}$ mm and $\frac{1}{8}$ mm wide; 10 percent dolomite: 5 percent is in euhedral rhombs up to $\frac{1}{4}$ mm in diameter, and 5 percent as coarsely crystalline cement; 5 percent collophane: 2 percent as fine, well-rounded sand and 3 percent as replaced bryozoa and casts of sponge spicule axial canals, which are in part recrystallized to clear, euhedral apatite tablets; and traces of detrital grains of tourmaline. Stratification of rock is shown by laminae containing various amounts of sand and chert. Mixed quartz and carbonate veins cut rock. Carbonate cement gives poikiloblastic texture. Chert nodules consist of do-	6. 4



TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	lomitic chert that is petrographically similar to bed 1R1.	
1R7-----	Chert, dolomitic, hard, dark-gray ( <i>N</i> 4/0), thick-bedded.	4. 2
1R6-----	Phosphorite, hard, brownish-gray (10 YR 3/1), massive. Consists of 65 percent collophane: 40 percent as echinoid spines(?), bone fragments, and brachiopod shell fragments, and 25 percent as fine, well-rounded pellets and compound nodules composed of pellets up to 6 mm in diameter cemented by francolite; 10 percent detrital quartz: fine, well-rounded, medium well sorted sand; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; and 25 percent organic matter, opaque. Rock is crudely laminated with alternating laminae of organic apatite, pelletal apatite, and silt rich in organic matter. Quartz sand grains are concentrated in matrix. Stylolites are common throughout rock and have altered original shapes of many grains.	0. 4
1R5-----	Dolomite, sandy, phosphatic, finely to coarsely pelletal, hard, light brownish gray (10 YR 6/1), massive.	1. 8
1R4-----	Dolomite, silty, hard, medium-gray ( <i>N</i> 6/0). Contains glauconite.	2. 7
1R3-----	Chert, dolomitic, hard, dark-gray ( <i>N</i> 4/0), thick-bedded. Rock is petrographically similar to bed 1R1.	7. 4
1R2-----	Chert, dolomitic, hard, medium-gray ( <i>N</i> 6/0), thick-bedded. Consists of 50 percent chalcedony: clear microcrystalline matrix that contains a few relict sponge spicules; 50 percent dolomite: euhedral rhombs up to $\frac{1}{16}$ mm in diameter; less than 1 percent detrital quartz: coarse, angular silt; and less than 1 percent collophane: pellets and casts of axial canals of sponge spicules. Rock is homogeneous with dolomite rhombs scattered evenly throughout rock. The rock is texturally similar to bed 1R1 but contains less organic matter and fewer and less distinct sponge spicules.	2. 4
1R1-----	Chert, dolomitic, hard, dark-gray ( <i>N</i> 4/0), thick-bedded. Consists of 50 percent chalcedony: sponge spicules up to $\frac{1}{2}$ mm long and $\frac{1}{8}$ mm wide; 10 percent detrital quartz: coarse, angular silt; 40 percent dolomite: euhedral rhombs up to $\frac{1}{16}$ mm in diameter that have rims of clear dolomite and cores of dolomite containing many inclusions; and less than 1 percent muscovite. Organic matter occurs in chalcedony cement. Axial canals of sponge spicules are made up of darker silica than the spicules; circular spicule sections resemble negative uniaxial crosses under crossed nicols; chalcedony cement is microcrystalline. Rock is homogeneous, but traversed by veins of calcite and silica. Stratification is shown by lens-shaped areas of organic	18. 0

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	matter, muscovite, and sponge spicules oriented parallel to the bedding.	
Phosphatic shale member of the Phosphoria formation:		
1P33-----	Dolomite, hard, light brownish gray (10YR 5/1), thin-bedded. Slightly oolitic in lower 0.2 feet.	1. 0
1P32b-----	Phosphorite, sandy, hard, dark-gray (N 3/0), thick-bedded. Thin section composed of three contorted laminae. The lowest lamina is composed of 85 percent collophane: dark brown, medium, poorly formed pellets commonly with quartz and chert nuclei; 15 percent detrital quartz: very fine, angular sand; and less than 1 percent unoriented muscovite. Middle lamina is composed of 85 percent collophane: light-brown, medium, well-rounded, spherical oolites, which commonly have nuclei of quartz and chert; and 15 percent detrital quartz: very fine, angular sand. Oolites are cemented by francolite; phosphatized sponge spicules are common. Rock has a submosaic texture. The upper lamina is composed of 60 percent francolite: medium, well-rounded oolites and brachiopod fragments, cemented in part by francolite; less than 1 percent apatite: clear euhedral to subhedral crystals; less than 1 percent chalcedony: coarsely crystalline, replacements of fossils and cement; and 40 percent detrital quartz: medium sand. Quartz sand occurs mostly in the matrix. The contacts between these laminae are sharp and irregular. Fossil fragments in the upper lamina are oriented roughly parallel to the contact. The rock shows apparently contemporaneous slump structures. Stylolites occur in the lower two laminae parallel to the bedding.	0. 5
1P32a-----	Phosphorite, argillaceous, finely to medium coarsely pelletal, medium-hard, dark-gray (N 3/0), thin-bedded.	0. 5
1P31c-----	Phosphorite, hard, dark-gray (N 4/0, thick-bedded. Consists of 90 percent collophane: fine to very coarse, ellipsoidal oolites which interfere with one another and many of which have a nucleus of quartz or francolite fossil fragments, compound pellets cemented by francolite, and francolite fossil fragments and structureless nodules up to 3 mm in diameter; 10 percent detrital quartz: coarse, angular, medium well sorted silt included in collophane and as matrix. The matrix quartz is better sorted and a little larger in grain size. Rock has a heterogeneous texture due to scattered large grains of collophane and francolite. Matrix has a submosaic texture.	

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1P31b-----	Phosphorite, calcareous, hard, dark-gray ( <i>N</i> 4/0), thick-bedded. Consists of 70 percent collophane and francolite: a mixture of coarse francolite fossil fragments, oolites, and collophane pellets in about equal proportions, and collophane cement; 30 percent calcite: coarsely crystalline, replaces collophane and francolite; and 2 percent detrital quartz: coarse, angular silt. Contact between beds P31b and P31a is sharp, irregular, and in some places overhanging. Tabular fossil fragments in 31b lie parallel to this surface. Angular pebbles of bed 31a occur in bed 31b. The rock shows apparently contemporaneous slump structure.	0. 4
1P31a-----	Phosphorite, sandy, hard, dark-gray ( <i>N</i> 4/0), thick-bedded. Consists of 65 percent collophane: brown, subpelletal to structureless matrix with some fine, well-rounded pellets and some nodules up to 8 mm in diameter; 30 percent detrital quartz: very fine, angular sand; and 5 percent muscovite: flakes up to 3/32 mm in diameter. Muscovite flakes show no apparent orientation. Rock is homogeneous.	0. 4
1P30-----	Dolomite, silty, medium-hard, pale-brown (10YR 5/2), thin-bedded. Consists of 70 percent dolomite: subhedral grains up to 1/16 mm in diameter; 30 percent detrital quartz: very fine, angular, irregular-shaped silt; and traces of detrital flakes of muscovite. Rock has a homogeneous porphyroblastic texture. Chert and calcite veins cut the rock.	0. 6
1P29-----	Phosphorite, argillaceous, very finely to very coarsely pelletal, medium-hard, dark-gray ( <i>N</i> 3/0), thin-bedded.	0. 4
1P28-----	Mudstone, dolomitic, medium-hard, light brownish gray (10YR 5/1), spheroidally weathered.	0. 7
1P27b-----	Phosphorite, soft, crumbly, brownish-gray (10YR 3/1), thin-bedded. Consists of 95 percent cellophane: medium to coarse, well-rounded, spherical pellets whose boundaries are irregular; 2 percent calcite: coarsely crystalline cement having poikiloblastic texture; and less than 1 percent detrital quartz: coarse, angular silt. Rock is homogeneous except for patches of calcite cement. Quartz silt is wholly included in collophane pellets.	0. 5
1P27a-----	Phosphorite, argillaceous, finely pelletal, soft, brownish-gray (10YR 3/1), thin-bedded.	0. 9
1P26-----	Mudstone, medium-hard, brownish-gray (10YR 4/1), thin-bedded, spheroidally weathered.	1. 3

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1P25-----	Dolomite, silty, medium-hard, light brownish gray (10YR 5/2), massive. Rock is similar petrographically to bed 1P22. Contains a silty dolomite concretion 1 foot long.	1. 1
1P24-----	Mudstone, dolomitic, soft, brownish-black (10YR 2/1), thin-bedded.	0. 6
1P23-----	Mudstone, soft, brownish-gray (10YR 3/1), thin-bedded.	2. 1
1P22-----	Dolomite, medium-hard, light brownish gray (10YR 5/1), thin-bedded. Consists of 70 percent dolomite: euhedral to subhedral grains up to $\frac{1}{8}$ mm in diameter in a matrix of granular dolomite whose grains are up to $\frac{1}{4}$ mm in diameter; 30 percent detrital quartz: coarse, angular silt; and less than 1 percent muscovite. Organic matter occurs in matrix. Rock has homogeneous porphyroblastic texture. Quartz is scattered evenly throughout rock.	2. 8
1P21-----	Dolomite, silty, medium-hard, brownish-gray (10YR 4/2), thin-bedded. Consists of 70 percent dolomite: euhedral to subhedral grains up to $\frac{1}{8}$ mm in diameter; 30 percent detrital quartz: very fine, angular, well-sorted sand; and less than 2 percent muscovite: flakes up to $\frac{1}{8}$ mm in diameter. Rock has homogeneous texture.	2. 2
1P20-----	Mudstone, phosphatic, dolomitic, soft, brownish-black (10YR 2/1).	1. 2
1P19-----	Dolomite, medium-hard, brownish-gray (10YR 3/1), thick-bedded. Consists of 90 percent dolomite: euhedral to subhedral grains up to $\frac{1}{8}$ mm in diameter; 5 percent detrital quartz: coarse, angular, well-sorted silt; and 5 percent collophane: dark-brown, medium, angular, elongate pellets. Rock is stratified by laminae of ellipsoidal collophane pellets, lenticular areas of organic matter, and laminae containing various amounts of quartz and muscovite silt. Irregular boundaries of collophane pellets caused by protrusion of quartz or carbonate grains. Pellets are elongate parallel to bedding.	0. 9
1P18-----	Mudstone, phosphatic, dolomitic, soft, brownish-gray, (10YR 4/1), fissile.	0. 4
1P17-----	Dolomite, medium-hard, brownish-gray (10YR 4/1). Rock is petrographically similar to bed 1P14c.	0. 9
1P16b-----	Dolomite, argillaceous, soft, brownish-gray (10YR 4/1), fissile.	0. 4
1P16a-----	Phosphorite, argillaceous, coarsely pelletal, soft, black (N 2/0).	1. 0
1P15b-----	Phosphorite, calcareous, finely to medium coarsely pelletal, soft, dark-gray (N 3/0), fissile.	0. 8
1P15a-----	Phosphorite, finely to medium coarsely pelletal, soft, dusky-brown (10YR 2/2), fissile.	0. 8

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1P14c-----	Dolomite, medium-hard, light brownish gray (10YR 5/1), thin-bedded. Consists of 80 percent dolomite: anhedral to euhedral crystals up to $\frac{1}{16}$ mm in diameter; 10 percent detrital quartz: coarse, angular, well-sorted silt; traces of detrital grains of plagioclase and orthoclase; 10 percent collophane: very fine to medium, well-rounded pellets containing quartz and carbonate nuclei. Collophane also occurs as cement in nodules. Organic matter occurs in matrix. Rock shows a crude lamination due to variation in abundance of pellets. Pellets in individual laminae are well sorted.	1. 9
1P14b-----	Mudstone, dolomitic, medium-hard, grayish-brown (10YR 4/2), thin-bedded.	0. 2
1P14a-----	Dolomite, medium-hard, light brownish gray (10YR 6/1), thin-bedded.	1. 2
1P13b-----	Mudstone, dolomitic, phosphatic, soft, brownish-gray (10YR 3/1).	0. 3
1P13a-----	Dolomite, silty, soft, brownish-gray (10YR 3/1), thick-bedded. Consists of 65 percent dolomite: subhedral to euhedral crystals up to $\frac{1}{16}$ mm in diameter that contain many minute inclusions of organic matter; 15 percent detrital quartz: coarse, angular silt; 5 percent collophane: brown, spherical pellets that contain many inclusions of organic matter; 15 percent pyrite: anhedral grains up to $\frac{1}{16}$ mm in diameter; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Rock has homogeneous granular texture.	0. 6
1P12-----	Interbedded phosphorite, argillaceous, 20 percent, medium coarsely pelletal, soft, brownish-black (10YR 2/1), thin-bedded; and argillaceous dolomite, 80 percent, soft, brownish-black (10YR 2/1), thin-bedded.	2. 4
1P11-----	Interbedded phosphorite, argillaceous, medium coarsely pelletal, soft, brownish-black (10YR 2/1), thin-bedded; and: dolomitic mudstone, soft, brownish-black (10YR 2/1), thin-bedded.	2. 6
1P10b-----	Phosphorite, argillaceous, coarsely to very coarsely pelletal and finely nodular, soft, crumbly, brownish-black (10YR 2/1). Unit contains a few mudstone partings which make up less than 2 percent of the unit.	1. 9
1P10a-----	Mudstone, phosphatic, medium coarsely pelletal, soft, brownish-black (10YR 2/1), fissile.	0. 2
1P9-----	Dolomite, medium-hard, dark-gray (N 3/0), thin-bedded. Consists of 90 percent dolomite: colorless, anhedral crystals from $\frac{1}{64}$ to $\frac{1}{8}$ mm in diameter; minor pyrite: anhedral, opaque grains partly altered to hematite; and organic matter, occurring as cement. Rock has a homogeneous granular texture.	1. 7

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1P8b-----	Dolomite, phosphatic, and dolomitic phosphorite, inter-laminated, soft, brownish-gray (10YR 3/1), thin-bedded. Consists of 60 percent dolomite: subhedral to euhedral rhombs up to $\frac{1}{32}$ mm in diameter; 30 percent collophane: dark-brown, fine to medium, well-rounded, ellipsoidal pellets, showing rims of light-brown collophane about $\frac{1}{128}$ mm thick; 10 percent illite: slight mass-extinction effect; and less than 1 percent detrital quartz: coarse, medium well sorted, angular silt, some grains up to $\frac{1}{8}$ mm in diameter. Unit contains a few compound nodules up to 3 mm in diameter. Rock is stratified by alternating laminae containing various amounts of collophane pellets. Contacts between laminae are indistinct.	0. 2
1P8a-----	Phosphorite, finely to very coarsely pelletal, soft, brownish-black (10YR 2/1), thick-bedded.	0. 5
1P7-----	Dolomite, silty, medium-hard, grayish-brown (2.5YR 3/2), thin-bedded, contains fluorite near base of unit. Consists of 50 percent dolomite: subhedral to euhedral grains up to $\frac{1}{8}$ mm in diameter but most less than $\frac{1}{16}$ mm in diameter; 30 percent detrital quartz: coarse, angular, medium well sorted silt; 20 percent collophane: coarse, ellipsoidal, well-sorted, medium well rounded pellets, containing a few inclusions of carbonate and quartz silt; and less than 1 percent muscovite: flakes up to $\frac{1}{8}$ mm in diameter. Rock is stratified by alternating laminae of silty dolomite and phosphatic silty dolomite. Ellipsoidal collophane pellets are oriented parallel to bedding. Quartz silt is somewhat concentrated in phosphatic laminae. Muscovite flakes are parallel to bedding. Nonphosphatic laminae are darker.	1. 0
1P6-----	Phosphorite, calcareous, medium to very coarsely pelletal, soft, brownish-black (10YR 2/1).	0. 9
1P5c-----	Phosphorite, calcareous, coarsely pelletal to finely nodular, soft, crumbly, brownish-black (10YR 2/1).	1. 2
1P5b-----	Mudstone, phosphatic, very finely pelletal, soft, brownish-black (10YR 2/1), fissile.	0. 2
1P5a-----	Phosphorite, soft, crumbly, black (N 2/0), thin-bedded. Consists of 75 percent collophane and francolite: fine to very coarse, well-rounded, spherical oolites; 1 percent francolite: fossil fragments; less than 1 percent fluorite: purple and colorless euhedral and anhedral crystals; 20 percent calcite: poikiloblastic cement; 5 percent detrital quartz: medium-fine, angular, medium well sorted sand; and traces of detrital grains of feldspar and sphene. About 5 percent of the apatite grains show no concentric structure, and about 30 percent have nuclei of quartz grains, calcite, or fluorite; con-	1. 0

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	centric structure is due to rings of dark- and light-colored collophane as well as francolite; both collophane and francolite form cement; francolite forms compound nodules. Basal 0.2 foot of unit contains pisolites up to 4 mm in diameter. Some oolites are truncated or interfered with by other oolites, giving a submosaic texture. Rock shows a crude lamination due to variations of collophane and calcite cement and laminae of sandstone.	
1P4-----	Mudstone, dolomitic, soft, brownish- gray (10YR 4/1), thin-bedded. Spheroidally weathered. Contains a few phosphatic nodules 0.05 foot above base of unit.	1. 2
1P3-----	Phosphorite, soft, crumbly, black (N 2/0), thick-bedded. Consists of 80 percent collophane: very fine to coarse, poorly sorted and bimodally distributed, rounded, spherical pellets; 5 percent detrital quartz: very fine to fine, subrounded sand; and less than 1 percent fluorite: purple, anhedral, microcrystalline. About 5 percent of the pellets, including mostly the larger grains, show crude concentric structure; pellets interfere with one another, which gives a submosaic texture; some of the larger pellets are compound. Quartz grains occur as inclusions in pellets and are finer grained than quartz grains in matrix. Fluorite occurs as cavity fillings between pellets.	0. 9
1P2-----	Siltstone, soft, black (N 2/0), fissile. Consists of 80 percent detrital quartz: medium to coarse, angular, well-sorted silt; 5 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; and 10 percent collophane: dark brown, occurs as cement in spherical areas up to 4 mm in diameter and scattered, irregular-shaped patches. Rock is homogeneous except for phosphatic siltstone nodules. Muscovite is oriented parallel to bedding throughout rock as well as within nodules. Boundaries between nodules and rest of rock are gradational.	0. 7
1P1b-----	Dolomite, medium-hard, brownish-black (10YR 2/1), thick-bedded. Consists of 90 percent dolomite: euhedral rhombs to anhedral grains up to $\frac{1}{32}$ mm in diameter, some grains showing overgrowths; 5 percent detrital quartz: medium, angular silt; and less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Rock is stratified by interbedded laminae composed of dark, fine-grained dolomite and light, coarse-grained dolomite. Muscovite flakes are oriented parallel to bedding.	7. 6
1P1a-----	Dolomite, phosphatic, soft, grayish-brown (7.5YR 4/2), indeterminate bedding. Consists of 60 percent dolomite: anhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter and microcrystalline dolomite less than $\frac{1}{64}$ mm in diameter; 5 percent detrital quartz: medium	2. 0

TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
	to coarse, angular silt; 5 percent francolite: medium to coarse pellets; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; less than 1 percent feldspar: medium to coarse silt; and organic matter, dark-brown. Overgrowths of dolomite occur on larger dolomite grains. Stratification of rock is shown by laminae containing various amounts of organic matter. Francolite grains are evenly distributed throughout rock.	
Wells formation (upper part only):		
1W25 and 1W24	Chert, sandy; and sandy, cherty carbonate rock, hard, medium-gray ( <i>N</i> 5/0), thin-bedded. Bed is composed of interbedded lenses of chert and carbonate rock. The carbonate rock has replaced chert. The chert consists of 65 percent chalcedony: 50 percent as brownish sponge spicules, in rods up to $\frac{1}{4}$ mm long with a 1:4 ratio of width to length, and 20 percent as spherulitic microcrystalline chert matrix in crystals up to $\frac{1}{64}$ mm in diameter; 30 percent detrital quartz: medium, subrounded, well-sorted sand, with quartz overgrowths and some rutilated grains; 5 percent collophane: fine, well-sorted sand, most grains elongate with 1:3 ratio of width to length, partially recrystallized to clear, colorless apatite euhedra up to $\frac{1}{64}$ mm in diameter; and 2 percent carbonate, mostly dolomite, but in part calcite: rounded grains up to $\frac{1}{8}$ mm in diameter. Apatite euhedra are scattered through chert sponge spicules. Rock is homogeneous. In general, quartz grains are slightly larger than collophane grains. Collophane grains are oriented parallel to bedding. The sandy, cherty carbonate rock is similar to the sandy chert, except that microcrystalline chalcedony has been replaced by carbonate whereas coarse-grained quartz of spherulites and sand grains has not.	2.2
1W23.....	Dolomite, sandy, hard, light brownish gray (10YR 6/1), massive. Consists of 75 percent dolomite: euhedral rhombs and rounded grains, both up to $\frac{1}{8}$ mm in diameter, and possible dolomitized fossils composed of euhedral to subhedral rhombs less than $\frac{1}{64}$ mm in diameter; 20 percent detrital quartz: fine, etched, well-sorted sand; less than 5 percent collophane and francolite: very fine, subrounded, tabular sand; traces of detrital grains of chert and sphene; and traces of hematite grains, possibly pseudomorphous after pyrite. Except for dolomitized fossils, rock is homogeneous. Some apatite grains are rimmed with dolomite and tabular grains are roughly oriented parallel to bedding.	5.8



TABLE 1.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1W22-----	Dolomite, medium-hard, brownish-gray (10YR 4/1), thin-bedded. Contains black (N 1/0) chert lenses, which make up about 30 percent of the unit. Although a few lenses are isolated, most of the chert lenses occur at definite horizons and are closely spaced, which gives the appearance of bedded chert. Dolomite consists of 95 percent dolomite: euhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter, but many euhedral rhombs less than $\frac{1}{4}$ mm in diameter; 5 percent detrital quartz: coarse, angular, well-sorted silt; less than 1 percent muscovite; and less than 1 percent hematite: pseudomorphous after pyrite. Rock is homogeneous. Muscovite is oriented parallel to bedding. Hematite is scattered throughout rock.	11. 0
1W21-----	Dolomite, sandy, soft, porous, yellowish-gray (10YR 8/1), massive. Contains thin zones of concretionary chert which coalesce to form thin beds of chert near top of unit. Chert makes up less than 5 percent of the unit. Sandy dolomite consists of 60 percent dolomite: euhedral rhombs up to $\frac{1}{8}$ mm in diameter in microcrystalline dolomite matrix; and 40 percent detrital quartz: very fine, angular, etched, well-sorted sand. Rock is very roughly stratified with laminae that contain slight variations in amount of quartz sand.	9. 8
1W20b----	Mudstone, soft, yellowish-gray (2.5YR 8/2), fissile. Consists of 60 percent detrital quartz: coarse silt to very fine sand, subrounded to angular; 30 percent illite: shows mass extinction parallel to bedding; 10 percent chalcedony: microcrystalline; less than 1 percent hematite: pseudomorphous after pyrite; and traces of detrital grains of tourmaline and microcline. Stratification of rock is shown by alternating laminae of cherty siltstone and claystone. Chert occurs as cement. Hematite pseudomorphs are scattered throughout rock.	0. 9
1W20a----	Dolomite, calcareous, soft, yellowish-white (2.5YR 9/2), thick-bedded.	0. 3
1W19-----	Dolomite, argillaceous, soft, yellowish-gray (2.5YR 7/2), massive. Consists of 50 percent dolomite: 30 percent as rounded grains up to $\frac{1}{8}$ mm in diameter and 20 percent as microcrystalline matrix; 20 percent detrital quartz: 15 percent as coarse, angular, etched silt and 5 percent as very fine, subrounded sand; 5 percent collophane: very fine, angular, light-brown sand; 15 percent illite: brown, gives mass extinction effect; 5 percent hematite: pseudomorphous after pyrite and disseminated throughout rock; and traces of detrital grains of muscovite and chert. Rock is crudely stratified with lenses of clayey dolomite and silty dolomite.	5. 5

TABLE 1.—*Stratigraphic and petrographic description of the strata of the phosphoria formation at Fall Creek, Idaho—Continued*

No. of bed	Description	Thickness (feet)
1W18-----	Dolomite, silty, sandy, medium-hard, yellowish-gray (2.5YR 8/2), thin-bedded, contains calcite geodes 3.5 feet from base. Consists of 30 percent detrital quartz: 15 percent as coarse, angular silt and 15 percent as very fine, subangular sand; 65 percent dolomite, 20 percent as euhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter and 45 percent as microcrystalline matrix; 5 percent hematite: euhedral cubes pseudomorphous after pyrite disseminated throughout rock; and traces of detrital grains of orthoclase, plagioclase, muscovite, tourmaline, and sphene. Rock is stratified by alternating laminae composed of various proportions of dolomite, silt, and sand.	5.0
1W17-----	Siltstone, dolomitic, medium-hard, yellowish-gray (2.5YR 7/2), thick-bedded. Consists of 80 percent detrital quartz: 75 percent as coarse, angular silt and 5 percent as very fine, medium well rounded sand; 20 percent dolomite: euhedral to subhedral rhombs up to $\frac{1}{8}$ mm in diameter in an anhedral, microcrystalline matrix; less than 1 percent muscovite; less than 1 percent hematite: pseudomorphous after pyrite; and traces of detrital grains of microcline, chert, sphene, and tourmaline. Rock is crudely stratified with several irregular lenses of very fine sand in very coarse silt. Hematite occurs in lenses parallel to bedding but is also disseminated throughout rock. Muscovite flakes are oriented roughly parallel to bedding.	18.0
1W16-----	Sandstone, medium-hard, pale-brown (2.5YR 5/2), thick-bedded, in fault contact with unit below. Consists of 90 percent detrital quartz: medium to fine, well-rounded sand; less than 1 percent hematite: euhedral to subhedral crystals pseudomorphous after pyrite; less than 1 percent chalcedony: clear, microcrystalline cement; and traces of detrital grains of plagioclase, orthoclase, tourmaline, and sphene. Calcite, dolomite, and illite were identified by X-ray but not found petrographically; they probably occur as cryptocrystalline cement. Some quartz grains are strained; others include crystallites which are in linear arrangement. Rock is stratified by laminae of medium and fine quartz sand.	14.0

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming*

Phosphoria formation measured and sampled at natural exposure near Flat Creek, 2.9 miles east of Teton National Forest boundary, sec. 6, T. 41 N., R. 114 W., Teton County, Wyo. Beds dip gently north. Beds measured and sampled by H. W. Peirce, R. G. Waring, R. A. Smart, and M. A. Warner in August 1950. Petrographic descriptions made by R. P. Sheldon. Color terms and numerical designations are from the Munsell color chart. Size terms are from the Wentworth size system. In the bed numbers, the first number indicates the locality (fig. 3); the letter indicates the unit or member that contains the bed, in ascending order from the base of the unit. The percentages of constituents are visual estimates, except where the beds are analyzed for  $P_2O_5$  and acid-soluble constituents. Analyses for  $P_2O_5$  and acid insoluble constituents are published in Sheldon and others, 1953]

No. of bed	Description	Thickness (feet)
Unit <i>E</i> of the Phosphoria formation (overlain by Dinwoody formation):		
15E8-----	Sandstone, dolomitic, cross-bedded, hard, very pale brown (10YR 7/2), thin-bedded. Consists of 80 percent detrital quartz: medium, subangular, etched, well-sorted sand; 20 percent dolomite: subhedral to anhedral grains up to $\frac{1}{4}$ mm in diameter; less than 1 percent collophane: medium, well-rounded pellets; and traces of detrital grains of glauconite and chert. Many quartz sand grains show overgrowths. Dolomite occurs as cement.	10.2
15E7-----	Sandstone, phosphatic, hard, dark-gray (N 4/0), thick-bedded. Consists of 65 percent detrital quartz: very fine to medium, angular to well-rounded, poorly sorted sand; 20 percent collophane and francolite; very fine pellets and fragments up to 8 mm in diameter which are made up of fossil fragments, pelletal phosphorite fragments and collophane pellets; 5 percent illite; cryptocrystalline cement; 10 percent calcite: microcrystalline cement and rare rock fragments; less than 1 percent glauconite: fine to medium, rounded sand; and traces of detrital grains of chert, muscovite and sphene. Stratification of rock shown by several lenses of fine sand.	0.3
15E6-----	Sandstone, very fine grained, hard, dark-gray (N 4/0), thick-bedded.	0.7
15E5-----	Chert, sandy, silty; silt coarse, sand very fine, hard, dark-gray (N 4/0), massive.	1.2
15E4-----	Chert, made up of tubular concretions, hard, brecciated, pale-brown (2.5YR 5/2). Consists of 80 percent chalcedony: microcrystalline grains up to $\frac{1}{4}$ mm in diameter and a few relict sponge spicules; 10 percent dolomite: euhedral rhombs up to $\frac{1}{2}$ mm in diameter; 10 percent detrital quartz: very fine, angular sand; and less than 1 percent collophane: very fine, angular sand. Rock is veined with calcite and chalcedony. Stylolites filled by a thin seam of organic matter occur in the chert. Quartz, glauconite, and collophane are evenly distributed throughout the rock.	26.3

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
15E3-----	Chert, hard, brecciated, medium-gray, (N 5/0), thick-bedded. Consists of 95 percent chalcedony: sponge spicules and microcrystalline grains up to $\frac{1}{4}$ mm in diameter; 2 percent detrital quartz: very fine, angular sand; 3 percent dolomite: euhedral rhombs up to $\frac{1}{16}$ mm in diameter; less than 1 percent glauconite: very fine, well-rounded sand. Sponge spicules are oriented parallel to bedding. Stratification of rock is shown by lenses of dark-colored chert.	4. 3
15E2-----	Dolomite, hard, pale-brown (10YR 5/2), thick-bedded.	0. 7
15E1-----	Chert, hard, medium-gray (N 5/0), thin-bedded, similar megascopically to 15E3. Phosphatic in lower 0.2 foot of unit.	0. 5
Unit D of the Phosphoria formation:		
15D16----	Mudstone, hard, light brownish gray (10YR 6/1), fissile.	1. 6
15D15-----	Claystone, contains elongate chalcedony grains up to $\frac{1}{8}$ mm in length and similar grains of dolomite which probably have replaced chert; otherwise unit is petrographically similar to 15D9.	2. 3
15D14-----	Claystone, contains elongate chalcedony sponge spicules(?) up to $\frac{1}{8}$ mm in length; otherwise unit is petrographically similar to 15D9.	3. 8
15D13-----	Claystone, medium hard, black (N 1/0), fissile.	2. 4
15D12-----	Dolomite, clayey, hard, light brownish gray (10YR 5/1), thick-bedded. Consists of 70 percent dolomite: euhedral to subhedral rhombs up to $\frac{1}{4}$ mm in diameter; 30 percent clay: dark-brown matrix between dolomite rhombs; and less than 1 percent detrital quartz: fine, angular silt. Rock is homogeneous.	0. 7
15D11-----	Claystone, petrographically similar to 15D9.	3. 1
15D10-----	Dolomite, clayey, hard, brownish-gray (10YR 3/1), massive. Consists of 60 percent dolomite: euhedral to subhedral rhombs up to $\frac{1}{4}$ mm in diameter; 40 percent illite; less than 1 percent detrital quartz: fine, angular silt; and less than 1 percent muscovite: flakes up to $\frac{1}{4}$ mm in diameter. Rock is homogeneous.	2. 3
15D9-----	Claystone, medium-hard, brownish-black (N 2/1), fissile. Consists of 80 percent illite; 10 percent detrital quartz: fine, angular silt; 5 percent muscovite; and 5 percent organic matter. Rock is homogeneous.	2. 8
15D8-----	Claystone, silty, petrographically similar to 15D7.	3. 5
15D7-----	Claystone, silty, medium-hard, dark-gray (N 4/0), indeterminate bedding. Similar petrographically to 15D6a except that more organic matter is present in 15D7.	4. 2
15D6b----	Mudstone, soft, light-brown (10YR 5/4).	0. 6

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
15D6a-----	Claystone, silty, medium-hard, dark-gray ( <i>N</i> 4/0), thin-bedded. Consists of 60 percent illite: microcrystalline, shows mass extinction; 30 percent detrital quartz: medium to coarse, angular silt; 5 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; and 3 percent collophane: shown by analysis but not recognized in thin section. Rock is homogeneous. Muscovite and illite are oriented parallel to bedding.	1. 4
15D5-----	Phosphorite, medium-hard, dark-gray ( <i>N</i> 3/0), thick-bedded. Consists of 75 percent collophane, 45 percent as fine, well-rounded, well-sorted pellets, and 30 percent as irregular nodules up to 20 mm in diameter; 5 percent francolite: fossil fragments and cement; 6 percent detrital quartz: medium to coarse, angular silt, and rare grains of fine sand; and 3 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Collophane nodules are made up of relict pellets on their edges and grade into structureless collophane in their centers. Organic matter is found throughout the rock but is practically lacking in nodules except for prominent concentrations in patches. Francolite occurs as cement in pellets. Quartz and muscovite are less abundant in nodules than pelletal area.	0. 5
15D4-----	Claystone, silty, medium-hard, brownish-black (10YR 2/1), thin-bedded. Similar petrographically to 15D2 except that this rock is composed of 50 percent illite; 25 percent detrital quartz; 10 percent carbonate; 5 percent collophane; and the remainder organic matter and muscovite.	2. 2
15D3-----	Phosphorite, argillaceous, medium-pelletal to finely nodular, medium-hard, dark-gray ( <i>N</i> 4/0), thick-bedded.	0. 5
15D2-----	Claystone, medium-hard, brownish-gray (10YR 3/1), thin-bedded. Consists of 70 percent illite: cryptocrystalline, shows mass extinction parallel to bedding; 10 percent collophane: dark-brown, very fine to fine, elongate, well-rounded, medium well sorted pellets; 10 percent carbonate: microcrystalline grains up to $\frac{1}{4}$ mm in diameter; 5 percent detrital quartz: medium to coarse, angular silt; and 2 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Stratification of rock is shown by laminae containing varying proportions of illite, carbonate, and collophane. The more carbonatic laminae are lighter in color.	1. 1
15D1-----	Phosphorite, sandy, medium to coarsely pelletal and finely to coarsely nodular, fine quartz sand, medium-hard, brownish-black (10YR 2/1), fissile.	0. 5

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
Unit C of the Phosphoria formation:		
15C22-----	Sandstone, calcareous, phosphatic, hard, medium-gray (N 7/0), massive, contains chert inclusions. Consists of 60 percent detrital quartz: medium, subrounded, well-sorted sand; 20 percent calcite: coarsely crystalline cement; 20 percent collophane and francolite: medium, well-rounded, well-sorted sand and fossil fragments; and traces of detrital grains of chert, chalcedony spherulites, glauconite, and sphene. Calcite cement gives rock poikiloblastic texture. Near top of unit phosphatic fragments become larger than quartz grains, reaching 1 mm in diameter. Rock is homogeneous.	11. 5
15C21-----	Chert, calcareous, hard, yellowish-gray (10YR 7/1), massive. Consists of 45 percent chalcedony: micro-crystalline grains up to $\frac{1}{4}$ mm in diameter, spherulites up to $\frac{1}{16}$ mm in diameter common, sponge spicules common; 40 percent calcite: 20 percent as euhedral rhombs up to $\frac{1}{8}$ mm in diameter and 20 percent as anhedral, coarsely crystalline calcite; 10 percent detrital quartz: very fine, subangular, well-sorted sand; 5 percent collophane: very fine, well-rounded, elongate, well-sorted sand; and less than 1 percent glauconite: very fine, well-rounded, well-sorted sand and rare fragments up to 1 mm in diameter. Anhedral calcite occurs as patches in rock and euhedral calcite as rhombs in chert. Quartz, collophane, and glauconite are evenly scattered throughout rock.	12. 4
15C20b-----	Phosphorite, calcareous, very finely to very coarsely oolitic and organic, and coarsely nodular, hard, light brownish gray (10YR 6/1). Contains grains of glauconite.	0. 5
15C20a-----	Carbonate rock, phosphatic, finely pelletal, medium-hard, yellowish-gray (10YR 7/1).	1. 0
15C19-----	Limestone, phosphatic, hard, yellowish-gray (2.5YR 8/2), massive. Consists of 70 percent calcite: 30 percent as coarsely crystalline fossil fragments and 40 percent is medium crystalline matrix; 20 percent collophane: fine to medium, well-rounded, well-sorted pellets and angular fragments of collophane, in part replaced echinoid spines(?) up to 2 mm long; 5 percent detrital quartz: fine to medium, subrounded, well-sorted sand; less than 1 percent glauconite: fine to medium sand; and less than 1 percent chert: fine to medium sand. Sparry calcite and calcite spherulites line voids. Collophane fills holes in bryozoa. Rock is heterogeneous.	13. 3
15C18-----	Dolomite, medium-hard, yellowish-gray (10YR 7/1), massive. Rock is similar petrographically to 15C17.	4. 8

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
15C17-----	Dolomite, medium-hard, light brownish gray (10YR 5/1), bedding indeterminate. Consists of 95 percent dolomite: microcrystalline grains up to $\frac{1}{64}$ mm in diameter; 5 percent detrital quartz: very fine, subrounded, well-sorted sand; and traces of hematite: euhedral grains up to $\frac{1}{32}$ mm in diameter pseudomorphous after pyrite. Rock is homogeneous.	2.0
15C16-----	Dolomite, medium-hard, light brownish gray (10YR 6/1), thin-bedded.	1.6
15C15-----	Dolomite, argillaceous, sandy, soft, light-brown (7.5YR 6/4), indeterminate bedding. Rock is petrographically similar to 15C13, except for different proportions of quartz, dolomite, and illite. Also rock is heterogeneous, in that sand occurs in lenses.	2.9
15C14-----	Dolomite, argillaceous, soft, weak yellowish-orange (2.5YR 8/2).	1.2
15C13-----	Sandstone, calcareous, medium-hard, yellowish-gray (10YR 7/1), indeterminate bedding. Consists of 60 percent detrital quartz: very fine to medium, angular to well-rounded, poorly sorted sand; 30 percent calcite: microcrystalline, anhedral grains up to $\frac{1}{64}$ mm. in diameter; 10 percent illite: mass extinction effect; traces of detrital grains of muscovite, calcite, chert, sphene, and tourmaline; and less than 1 percent hematite: euhedral grains up to $\frac{1}{16}$ mm in diameter, pseudomorphous after pyrite. Illite is distributed through calcite cement. Rock has homogeneous texture.	3.8
15C12-----	Sandstone, dolomitic, contains scattered white chert inclusions, hard, very pale brown (10YR 7/2), indeterminate bedding. Dolomitic sandstone is petrographically similar to 15C11. Chert inclusions are composed of spherulitic, microcrystalline chalcedony.	2.9
15C11-----	Sandstone, dolomitic, hard, very pale brown (10YR 7/2), massive. Consists of 70 percent sand and 30 percent dolomite, otherwise petrographically similar to 15C10. Also contains a few scattered grains of collophane equivalent to the quartz grains in size.	1.9
15C10-----	Dolomite, sandy, hard, yellowish-gray (10YR 8/1), indeterminate bedding. Consists of 80 percent dolomite: microcrystalline, anhedral grains up to $\frac{1}{64}$ mm in diameter; 20 percent detrital quartz: very fine, well-sorted, angular sand; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; and less than 1 percent hematite: grains up to $\frac{1}{16}$ mm in diameter, pseudomorphous after pyrite. Muscovite grains are oriented parallel to bedding. Quartz and muscovite are scattered almost evenly throughout the rock, but a slight vertical variation is apparent. Hematite is somewhat more abundant in the more sandy laminae.	3.3

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
15C9-----	Sandstone, cherty, calcareous, hard, yellowish-gray (10YR 7/1), massive. Consists of 60 percent detrital quartz: very fine to medium, subangular to rounded, poorly sorted sand; 20 percent calcite: microcrystalline grains up to $\frac{1}{64}$ mm in diameter; 20 percent chalcedony: well-rounded fragments up to 2 mm in diameter; less than 1 percent collophane: fine to medium, well-rounded sand; less than 1 percent hematite, grains up to $\frac{1}{32}$ mm in diameter, pseudomorphous after pyrite; and traces of detrital grains of tourmaline, sphene, feldspar and muscovite. Rock has a heterogeneous texture. Calcite occurs as cement. Chert fragments are scattered throughout the rock.	1. 1
15C8-----	Dolomite, cherty, hard, light brownish gray (10YR 5/1), indeterminate bedding. Consists of 70 percent dolomite; euhedral to subhedral grains up to $\frac{1}{16}$ mm in diameter and anhedral grains down to $\frac{1}{64}$ mm in diameter; 30 percent chalcedony: cryptocrystalline matrix occurring in patches, sponge spicules common; and less than 1 percent detrital quartz: very fine, angular, well-sorted sand. The larger grains of dolomite are more common near voids in rock. Rock is homogeneous.	2. 2
15C7-----	Chert, spherulitic, hard, very pale brown (10YR 7/3) and white (N 9/0), massive. Consists of 100 percent chalcedony, of which 50 percent is spherulites up to $\frac{1}{4}$ mm in diameter and 50 percent is microcrystalline grains up to $\frac{1}{64}$ mm in diameter. Contains 5.0 feet by 1.0 foot limestone concretion 2.8 feet above base of unit.	10. 8
15C6-----	Chert, nodular, hard, medium-gray (N 5/0).	1. 2
15C5-----	Chert, spherulitic, hard, white (N 9/0), thick-bedded. Similar petrographically to bed 15B14.	0. 4
15C4b-----	Mudstone, cherty, nodular, hard, pale-brown (10YR 5/3).	0. 4
15C4a-----	Chert, hard, light brownish gray (10YR 5/1), thin-bedded.	0. 2
15C3-----	Carbonate rock, hard, light brownish gray (10YR 5/1), thick-bedded. Contains chert nodules near base.	0. 7
15C2-----	Chert, hard, medium-gray (N 5/0), thin-bedded, laminated. Consists of 95 percent chalcedony: most as microcrystalline grains up to $\frac{1}{16}$ mm in diameter, some spherulitic, and the rest cryptocrystalline; 5 percent detrital quartz: fine, subrounded, well-sorted sand; less than 1 percent collophane and francolite: fossil fragments and rounded grains up to $\frac{1}{4}$ mm in diameter. Stratification of rock is shown by laminae of light-colored microcrystalline and dark-colored cryptocrystalline chert.	0. 8
15C1-----	Chert, hard, medium-gray (N 5/0), thin-bedded.	1. 3



TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. bed	Description	Thickness (feet)
Unit B of the Phosphoria formation:		
15B17-----	Mudstone, soft, light brownish gray (7.5YR 5/6), fissile. Contains ellipsoidal chert nodules. The centers of some of the chert nodules contain pyrite.	1.7
15B16-----	Chert, hard, medium-gray (N 5/0), thin-bedded. Consists of 90 percent chalcedony: microcrystalline grains up to $\frac{1}{4}$ mm in diameter, much of which is possibly sponge spicules; 10 percent detrital quartz: very fine, angular, well-sorted sand; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; less than 1 percent collophane and francolite: fossil fragments and rounded grains up to $\frac{1}{4}$ mm in diameter. Rock is homogeneous.	0.7
15B15-----	Mudstone, soft, pale greenish brown, fissile.	0.5
15B14-----	Chert, spherulitic, hard, white (N 9/0), massive. Consists of 99 percent chalcedony and quartz: 50 percent as spherulites of quartz up to 2 mm in diameter and 49 percent as microcrystalline chalcedony matrix with grains up to $\frac{1}{16}$ mm in diameter; 1 percent calcite: coarsely crystalline patches; and less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Spherulites resemble crude uniaxial positive crosses under crossed nicols.	1.3
15B13-----	Dolomite, cherty, hard, brownish-gray (10YR 4/1), thick-bedded. Consists of 70 percent dolomite: microcrystalline, euhedral to subhedral grains up to $\frac{1}{4}$ mm in diameter; 25 percent chalcedony: spicules up to $\frac{1}{4}$ mm long and $\frac{1}{16}$ mm wide; 5 percent detrital quartz: very fine, angular, well-sorted sand; and less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Stratification of rock is shown by orientation of sponge spicules parallel to bedding and laminae containing varying amounts of quartz sand.	1.7
15B12-----	Chert, sandy, hard, pale-brown (2.5YR 6/2), thin-bedded. Consists of 75 percent chalcedony: 60 percent as spicules up to $\frac{1}{8}$ mm long and $\frac{1}{32}$ mm wide, and 15 percent as cryptocrystalline matrix; 20 percent detrital quartz: very fine, angular, well-sorted sand; 5 percent calcite: anhedral to subhedral grains up to $\frac{1}{16}$ mm in diameter and irregular patches of calcite up to $\frac{1}{4}$ mm in diameter; and less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Stratification of rock is shown by sponge spicules oriented parallel to the bedding, and laminae that contain various amounts of quartz sand.	1.0
15B11-----	Dolomite, cherty, silty, hard, medium-gray (N 5/0), thin-bedded. Consists of 60 percent dolomite: microcrystalline, euhedral grains up to $\frac{1}{256}$ mm in diameter; 20 percent chalcedony: microcrystalline, anhedral	1.0

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
	grains up to $\frac{1}{128}$ mm in diameter; 20 percent detrital quartz: very coarse, angular, well-sorted silt; less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter; traces of collophane: very coarse, subangular, well-sorted silt; and traces of detrital grains of tourmaline and sphene. Stratification of rock is shown by laminae composed of various proportions of dolomite, chert, and quartz. Dolomite gives rock a granular texture.	
15B10-----	Carbonate rock, cherty, hard, dark-gray (N 4/0), thick-bedded.	0.9
15B9-----	Mudstone, medium-hard, pale-brown (2.5YR 5/2), fissile. Contains a few laminae of organic phosphorite.	1.7
15B8-----	Dolomite, argillaceous, medium-hard, pale-brown (2.5YR 5/2), fissile. Consists of 70 percent dolomite: microcrystalline, less than $\frac{1}{128}$ mm in diameter; 5 percent detrital quartz: coarse, angular silt; 20 percent illite: microcrystalline, gives mass extinction effect; and 5 percent hematite: euhedral grains up to $\frac{1}{32}$ mm in diameter, pseudomorphous after pyrite. Rock is homogeneous. Quartz, illite, and hematite are disseminated throughout the rock.	1.0
15B7-----	Mudstone, medium-hard, pale-brown (2.5YR 6/2), fissile.	1.5
15B6-----	Dolomite, medium-hard, grayish-brown (2.5YR 4/2), fissile. Consists of 99 percent dolomite: microcrystalline, anhedral grains up to $\frac{1}{32}$ mm in diameter; and 1 percent detrital quartz: very coarse, angular, well-sorted silt. Rock is homogeneous with a mosaic texture.	0.6
15B5-----	Dolomite, argillaceous, medium-hard, grayish-brown (2.5YR 4/2), fissile. Contains films of glauconite.	0.6
15B4-----	Siltstone, calcareous, hard, light yellowish brown (2.5YR 6/4) at base to yellowish gray (2.5YR 7/1) at top, massive. Consists of 50 percent detrital quartz: coarse to very coarse, angular silt; 40 percent calcite: coarse-grained cement; 10 percent glauconite: microcrystalline, shows mass extinction that is length slow parallel to bedding; traces of hematite, anhedral grains up to $\frac{1}{16}$ mm in diameter, and a few grains pseudomorphous after pyrite; and less than 1 percent muscovite: flakes up to $\frac{1}{16}$ mm in diameter. Stratification of rock is shown by laminae of siltstone containing glauconite and siltstone containing hematite. Glauconite and hematite do not occur together in rock. Calcite cement gives rock a poikiloblastic texture.	2.2
15B3-----	Phosphorite, medium-hard, brownish-gray (10YR 4/1), thin-bedded. Consists of 65 percent francolite: medium to very coarse, well-grounded, ellipsoidal pellets; 30 percent calcite: coarse-grained fracture	0.9

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
	fillings; 5 percent glauconite: cryptocrystalline, shows mass extinction, length slow parallel to bedding; and less than 1 percent detrital quartz: very fine, subrounded, well-sorted sand. Francolite pellets show mass extinction, length fast parallel to bedding; pellets distorted by compaction. Glauconite occurs as thin seams in rock, mostly as matrix, and is draped around francolite grains. Quartz occurs almost exclusively in matrix. Rock in general is homogeneous.	
15B2-----	Limestone, siliceous, hard, light brownish gray, thick-bedded. Consists of 60 percent calcite: coarsely crystalline, twinned crystals up to 4 mm in diameter; and 40 percent quartz: 20 percent as euhedral crystals up to 1 mm in diameter and 20 percent as anhedral grains from $\frac{1}{128}$ to $\frac{1}{2}$ mm in diameter. Calcite occurs in some quartz areas as a matte of unoriented rods up to $\frac{1}{4}$ mm long and $\frac{1}{6}$ mm wide, large areas of which are in crystallographic continuity. Quartz euhedra occur in coarsely crystalline calcite. Granular quartz and calcite exhibit a mosaic texture.	0.5
15B1-----	Phosphorite, calcareous, medium-hard, brownish-gray (10YR 4/1), thick-bedded. Consists of 80 percent collophane and francolite: light-brown to colorless, fine to very coarse, well-rounded, ellipsoidal to spherical oolites and fine-grained pisolites; 20 percent calcite: cement, poikiloblastic texture; less than 1 percent detrital quartz: fine to medium, subangular sand; and less than 1 percent muscovite: flakes up to $\frac{1}{64}$ mm in diameter. Concentric rings in oolites are formed by alternating layers of collophane and francolite; most francolite is slightly lighter in color and contains few muscovite inclusions; francolite rings give negative uniaxial cross. Oolites interfere with one another, caused in part by solution and in part by compaction, as shown by truncation of oolite rings and contortion of rings. They are oriented with long diameter parallel to bedding. Muscovite is included in oolites. Sand grains occur almost wholly in matrix.	2.7
Unit A of the Phosphoria formation:		
15A4-----	Chert, veined with calcite, hard, brownish-gray (10YR 4/1), thick-bedded. A bed of phosphorite occurs 0.3 feet from base. Consists of 75 percent chaledony: spherulites up to $\frac{1}{16}$ mm in diameter, and relict sponge spicules which form slightly more coarsely crystalline chaledony than the microcrystalline chert matrix; 5 percent detrital quartz: fine, medium well rounded, well-sorted sand; less than 1 percent collophane: irregularly shaped pellets up to 2 mm in diameter;	1.3

TABLE 2.—*Stratigraphic and petrographic description of the strata of the Phosphoria formation at Flat Creek, Wyoming—Continued*

No. of bed	Description	Thickness (feet)
	less than 1 percent francolite: brachiopod shell fragments, which show rounding and some overgrowths of collophane, up to 1 mm in diameter; 20 percent calcite: larger areas of clear, coarsely crystalline and brown, finely crystalline calcite. Chert at the boundaries of the calcite has a crystalline rim oriented with the <i>c</i> axis of the quartz at right angles to the boundary.	
15A3-----	Dolomite, cherty, hard, light brownish gray (10YR 6/1), massive. Consists of 80 percent dolomite: euhedral crystals up to $\frac{1}{16}$ mm in diameter; 20 percent chalcedony: microcrystalline matrix and sponge spicules; 1 percent detrital quartz: very fine to fine, subrounded, well-sorted sand; and less than 1 percent collophane: very fine, well-rounded, well-sorted sand and fossil fragments. Rock is homogeneous.	1.0
15A2-----	Chert, sandy, hard, medium-gray (N 5/0), massive, brecciated. Consists of 80 percent chalcedony: spherulites up to $\frac{1}{8}$ mm in diameter, microcrystalline matrix; 20 percent detrital quartz: fine, subangular, well-sorted sand with overgrowths of clear quartz; and traces of detrital grains of tourmaline and muscovite. Brecciated fragments of clear spherulitic chert in a brown, sandy, spherulitic chert matrix. Some overgrowths of detrital quartz grains in clear breccia fragments are irregular and spongy in texture.	1.0
15A1-----	Dolomite, sandy, hard, pale-brown (10YR 6/2), massive. Consists of 75 percent dolomite: microcrystalline, anhedral grains less than $\frac{1}{4}$ mm in diameter; 5 percent calcite: coarsely crystalline fossils; 20 percent detrital quartz: fine to medium, subrounded, well-sorted, etched sand; and traces of detrital grains of orthoclase, sphene, plagioclase, microcline, and chert. Dolomite has a mosaic texture. Many fossil molds lined with sparry dolomite crystals. Sand grains evenly distributed throughout rock.	1.5
Tensleep sandstone (upper part only):		
15T1-----	Sandstone, hard, very pale brown (10YR 7/3), massive. Consists of 95 percent detrital quartz: fine to medium, subrounded, well-sorted sand; less than 3 percent calcite; euhedral crystals up to $\frac{1}{16}$ mm in diameter; and traces of detrital grains of tourmaline, plagioclase, orthoclase, microcline and sphene. Quartz grains show crystallographic continuous overgrowths of quartz giving rock a mosaic texture.	25.8

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# INDEX

	Page
<b>A</b>	
Acidity of ocean water.....	147-148
relation to deposition.....	148-152
Acknowledgments.....	109
Age.....	106
Anhydrite.....	139, 151
association in chemical cycle.....	140, 147
deposition.....	149
Apatite, compound nodules and pellets.....	119
concentration.....	122
diagenetic recrystallization.....	123
euhedral.....	123-124
Apatite casts.....	118-119
Apatite grains, nuclei.....	117, 118
Apatite sand grains.....	119
Areal variation, lower and upper cycles.....	143
Areal zoning, relation to upwelling currents..	148,
transgression.....	151-152, 154
<i>Aulosteges</i> faunule.....	152
.....	116
<b>B</b>	
Baldwin Creek, Wyo.....	116
Basins of deposition.....	153-154
Bear Creek, Idaho, organic phosphorite.....	126-127
Beaverhead County, Mont.....	114
Bedded chert.....	119-120
Biogenic minerals, preservation.....	149
Brachiopod shells, phosphatic.....	119
Brazer Canyon, Utah.....	114
Bryozoans, apatite casts.....	119
Buck Creek, Wyo., carbonate concretions....	127
Burroughs Creek, Wyo., unit <i>C</i> .....	130
<b>C</b>	
Calcite geodes, Minnekahta formation.....	115
Calcite-phosphorite ratio.....	148
Calcium carbonate, precipitation.....	148
Carbonate environment.....	153
Carbonate fluorapatite.....	116
Carbonate rock.....	106, 120, 121, 140
facies.....	115
precipitation.....	151
sandstone facies, western Wyoming.....	112
tongues.....	115
unit <i>C</i> .....	129, 130
unit <i>E</i> .....	134, 135-136
Centennial Range, Mont.....	113
Chert.....	106, 119-120, 121, 140
bedded.....	137, 140
concretionary and nodular.....	137-140
facies.....	145-146
chert-limestone.....	146
chert-phosphorite-mudstone.....	112
solution.....	123
tubular.....	119, 137, 140
unit <i>C</i> .....	129, 130-131, 132
unit <i>E</i> .....	132, 134, 135-136, 137
Chert environment.....	152
Chugwater formation, Owl Creek Mountains,	
Wyo.....	110
<i>Claraia</i> zone, Dinwoody formation.....	134
Clastic materials, source.....	147, 154
unit <i>C</i> .....	129
unit <i>E</i> .....	136-137
Clastic rocks, association with chemical cycle..	140
Collophane.....	116, 118, 121, 124
Conclusions.....	154-155
Concretionary chert.....	119
unit <i>C</i> .....	122
Cordilleran miogeosyncline.....	106, 153, 154
Cordilleran shelf.....	154
Correlation.....	112
phosphorites.....	112-113
with Phosphoria of other areas.....	113-116
Cottonwood Creek, Wyo., unit <i>C</i> .....	132
Cross-bedded rocks.....	122
<b>D</b>	
Deposition, diagenetic.....	123
Depositional cycles, distribution of rocks...	140-141
areal variation.....	143
relation to facies change.....	146, 152
relation to physical-chemical environ-	
ment.....	150-152
Depositional environments, physical chemis-	
try.....	147-150
Diagenesis.....	123-124
Dinwoody formation.....	111, 132, 134
Dolomite, anhydritic, Lakeridge 1 well, Wyo-	
ming.....	132
dark.....	121, 124, 133
<b>E</b>	
Embar formation.....	110
Embar group, Maverick Springs anticline,	
Wyoming.....	111
Erosion surface, pre-Phosphoria.....	124
Ervay tongue of Phosphoria formation.....	116, 153
Euhedral apatite.....	119
Eustatic changes of sea level.....	153-154
Evaporite facies.....	151
<b>F</b>	
Fall Creek, Idaho, carbonate rock and chert..	132
miogeosynclinal rocks.....	116
organic phosphorite.....	127
sandstones.....	121
stratigraphic and petrographic descrip-	
tions.....	155-168
Facies changes.....	106, 143-146, 154
relation to cycle of deposition.....	146
relation to tectonic movement.....	153-154
relation to time horizons.....	152

	Page		Page
Facies relations, comparison with cyclic rock sequence.....	141-146	Mudstone-chert facies.....	144-145, 152
Field work.....	107	Muscovite, in quartz silt.....	121
Fish remains, phosphatic.....	119		
Flat Creek, Wyo., platform rocks.....	116	N	
pre-Phosphoria erosion surface.....	124	Nodular chert, unit <i>C</i> .....	131
sandstone.....	121	Nodular phosphorite suite.....	139
stratigraphic and petrographic descriptions.....	169-178	Nomenclature, review.....	109-112
Forelle limestone.....	115, 116, 153		
Fossils, phosphatic.....	118-119, 132, 140	O	
Francolite.....	117, 118, 124	Oolitic phosphorites.....	118
		Organic matter, precipitation.....	149
G		Organic phosphorites.....	118-119, 134
General Petroleum Co., Lakeridge 1 well.....	109	Orogeny, Cretaceous and Tertiary.....	106
Glauconite.....	118, 121, 134, 138, 140, 148-149, 151	Owl Creek Mountains, Wyo.....	110
Glendo shale.....	115		
Globular chert.....	120	P	
Greenalite, deposition.....	149	Paleogeographic setting.....	146-147
Gros Ventre, Wyo., pre-Phosphoria erosion surface.....	124	Park City formation.....	110, 111
Gros Ventre Range, Wyo.....	110	Pelletal phosphorites.....	117-119
		Petrographic description.....	116-121
H		Phosphate, diagenetic deposition.....	123
<i>Hustedtia</i> faunule.....	116	Phosphoria formation.....	111
		correlation with Phosphoria of other areas.....	113, 116
I		Fall Creek, Idaho, phosphatic shale member, description.....	160-166
Iron minerals, relation to chemical cycle.....	140	Rex member, description.....	155-159
relation to physical-chemical environment.....	148-149	Flat Creek, Wyo., unit <i>A</i> , description.....	177-178
unit <i>B</i> .....	127	unit <i>B</i> , description.....	175-177
		unit <i>C</i> , description.....	172-174
K		unit <i>D</i> , description.....	170-171
Key beds, correlation.....	112-113	unit <i>E</i> , description.....	169-170
King, R. H., correlations, Little Popo Agie River, Wyo. to Baldwin Creek, Wyo.....	116	lithologic character.....	113
		paleogeographic setting.....	146-147
L		phosphatic shale member.....	111, 112
Lakeridge 1 well, Wyoming.....	132, 140	stratigraphic and petrographic description.....	155-178
Laminations.....	122	thickness.....	113
Lateral relations, Phosphoria formation.....	141-146	type section, Phosphoria Gulch, Idaho.....	110
comparison of units <i>B</i> and <i>C</i> with <i>D</i> and <i>E</i> .....	143	units <i>A</i> to <i>E</i> , basal contacts.....	124, 125, 128, 132, 134
comparison of units <i>B</i> and <i>D</i> .....	141-142	composition.....	125,
comparison of units <i>C</i> and <i>E</i> .....	142-143	126, 129-132, 133-134, 135-137	
Limestone, light.....	121	facies.....	112, 125, 127, 132, 134, 134-135, 137
<i>Lingula</i> zone, Dinwoody formation.....	134	phosphate content.....	126
Lithologic character, Phosphoria formation.....	113	transgressive and regressive relations.....	152
Little Popo Agie River, Wyo., section.....	115, 116	unit <i>D</i> .....	132, 133, 134
		upper contacts.....	125, 129, 132, 134
M		vertical distribution.....	127
Madison Range, Mont.....	114	units <i>B</i> and <i>D</i> , lateral relations.....	141-142
Marienberg Alps, laminated dolomite.....	124	units <i>C</i> and <i>E</i> .....	144-145
Maverick Springs anticline, Wyoming.....	111	upper shale member.....	111
Methods of study.....	107	Phosphoria rocks, environments of deposition.....	150-152
Middle Piney Lake, Wyo., unit <i>C</i> .....	122	Phosphorite.....	106, 121, 126-127
Mineral stability fields.....	149	transgressive and regressive relations.....	147-148
Minnekahta limestone, calcite geodes.....	115	Phosphorite environment.....	152-153
correlatives.....	116	Phosphorite, facies.....	144, 148
Migeosyncline, Cordilleran.....	106, 116	precipitation.....	147, 148
Mudstone.....	106, 121, 132, 140	Phosphorites, oolitic and pisolitic.....	118-140
associations.....	122	organic.....	118-119, 140, 151
transgressive and regressive relations.....	152	origin.....	147
unit <i>D</i> .....	132, 133, 135	petrographic description.....	116-117
		Phosphoria sea, depth of water.....	146-147

	Page		Page
Physical-chemical environments, cyclic		Sediment, rate of deposition.....	147
changes.....	150-151	stable and unstable shelf.....	154
distribution.....	150-152	Siderite deposition.....	148
relation to type of sediment.....	122, 155	Silica deposition.....	123, 149
Physical chemistry of environments of depo-		acidity control.....	151
sition.....	147-150	Siltstone, Dinwoody formation.....	134
Pisolithic phosphorites.....	118	Solution, diagenetic.....	123
Platform rocks, Flat Creek, Wyo. section.....	116	Spherulites, chert.....	120
Precipitation from ocean water, physical-		Sponge spicules, apatite casts.....	118-119
chemical conditions.....	147, 148, 151	concentration.....	122
Pulsations of transgression and regression....	152-153	Stable shelf.....	154
Pyrites.....	120, 121, 134, 140, 148, 151	Stratigraphic nomenclature.....	109-112
<b>Q</b>		Stratigraphic relations.....	138-146
Quadrant quartzite.....	110	Stratigraphic units, petrographic description	
Quartz overgrowths.....	120	and areal variation.....	124-125
<b>R</b>		Stratigraphy, regional.....	109, 113-116
Rod bed facies.....	106, 115, 154	<b>T</b>	
Red bed phosphorite suite.....	139	Tectonic movements, Phosphoria time.....	154
Red bed-carbonate rock-evaporite facies, cen-		Tectonic provinces.....	154
tral Wyoming.....	112	Tensleep sandstone, Flat Creek, Wyo.,	
Red beds.....	111, 139	description.....	178
deposition.....	151	Teton formation.....	110
Red Creek, Wyo., unit <i>C</i> .....	130	Thickness of Phosphoria formation.....	113
Redox potential, ocean water.....	147, 148	unit <i>E</i> .....	134
relation to deposition.....	148-152	Thickness relations.....	141-142, 143
Regression.....	152-153	Time horizons.....	152
tectonic control.....	153	Tosi Creek, Wyo., unit <i>C</i> .....	130
Rex member.....	110, 115	Transgression.....	152-154
correlation with unit <i>C</i> .....	11, 114, 155	Trench <i>H</i> , Idaho, organic phosphorite.....	127
description.....	155-159	Tubular concretions, chert.....	119, 137
Rox Peak, Utah.....	110	<b>U</b>	
Rock sequence, cyclical.....	140-141	Unstable shelf.....	154
relation to physical-chemical environment....	151	Upper Coal Measures.....	110
unit <i>C</i> .....	132	Upper shale member. <i>See under</i> Phosphoria	
unit <i>E</i> .....	138	formation.	
Rock suites, Phosphoria formation.....	138-139	Upwelling currents, influence on areal zon-	
<b>S</b>		ing.....	148, 151-152, 154
Salinity of ocean water.....	147, 151	<b>W</b>	
Sand grains, apatite.....	119	Weber quartzite.....	110
Sandstone.....	106, 121, 122	Wells Canyon, Idaho.....	110
association in chemical cycle.....	122, 140	Wells formation, correlation.....	114
unit <i>C</i> .....	129, 130, 131	Fall Creek, Idaho, description.....	166-168
unit <i>E</i> .....	134, 135, 137	Wind River Range, Wyo.....	110, 115, 132
		Woodside shale.....	110