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Douglas McKay, *Secretary*

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*By* EARLE R. CRESSMAN

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*Prepared as part of the program of the Department of the Interior for the Missouri River basin and of work done on behalf of the U. S. Atomic Energy Commission. The report is published with the permission of the Commission*

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# A CONTRIBUTION TO ECONOMIC GEOLOGY

## PHYSICAL STRATIGRAPHY OF THE PHOSPHORIA FORMATION IN PART OF SOUTHWESTERN MONTANA

By Earle R. Cressman


### ABSTRACT

In much of southwestern Montana the Phosphoria formation of Permian age has been divided by previous workers into five units, tentatively designated as units *A* to *E* in ascending order.

Unit *A* consists of dolomite and quartz sandstone. It is underlain by the Quadrant formation of Pennsylvanian age.

Unit *B* consists of phosphate rock and carbonaceous mudstone. Immediately west of Lima, Mont., the unit is 30 feet thick, but 70 miles to the north and east it disappears.

A few miles east of Lima unit *C* is nearly 300 feet thick, but it thins to the east, north, and west. Near Lima bedded chert constitutes the lower third and dolomite the upper two-thirds of the unit. The dolomite grades westward into dolimitic sandstone, and both chert and dolomite thin eastward as sand becomes more prominent.

Unit *D* consists of phosphate rock and carbonaceous mudstone. Near Lima the unit thins from 80 feet to 5 feet or less in the Gravelly and Madison Ranges.

Unit *E*, which consists largely of standstone and bedded chert, is 100 to 130 feet thick over much of the area. Facies changes between chert and sandstone are common and abrupt. The chert, in part, intertongues with or grades into mudstone on the extreme west and south parts of the region discussed.

Facies changes occur within units, but in most of the area there is little lateral gradation between units. Sand was derived from both east and west, and the silt and clay may have had a western source. Facies changes from sandstone to chert are thought to have resulted from the sorting of siliceous organic remains from detrital quartz sand.


## INTRODUCTION

### PURPOSE AND SCOPE OF THE REPORT

The Permian Phosphoria formation of the central and northern Rocky Mountains constitutes one of the world's largest reserves of phosphate. As part of a detailed investigation of the Phosphoria, members of the U. S. Geological Survey have measured 50 sections at 33 different localities in the part of southwestern Montana discussed in this report (fig. 1). The phosphatic units have been

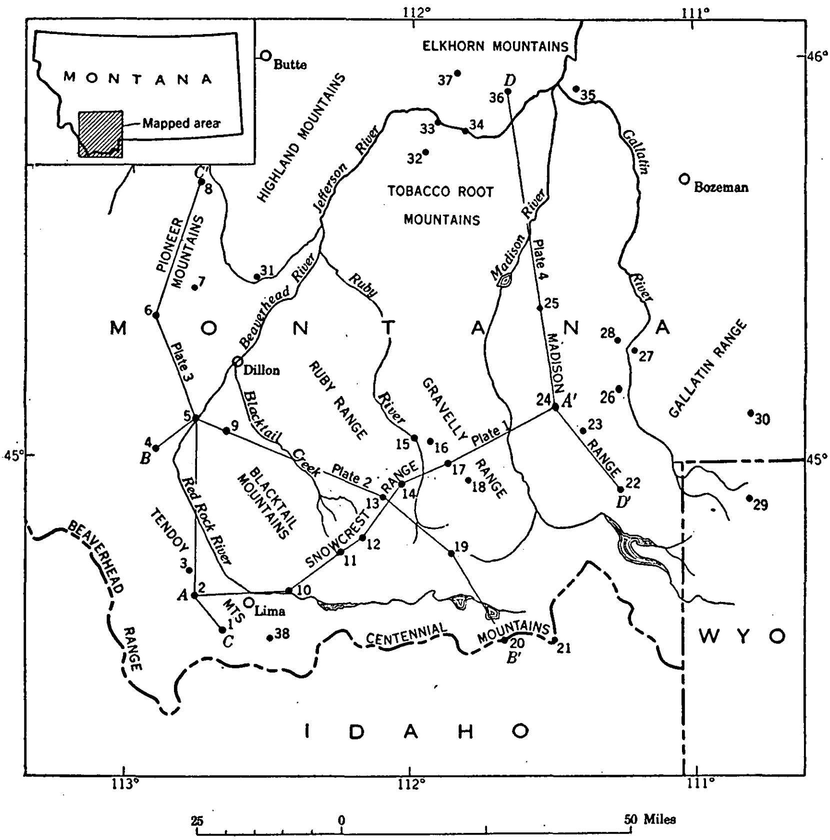


FIGURE 1.—Index map of southwestern Montana showing the location of measures stratigraphic sections and the lines of stratigraphic sections illustrated in plates 1–4.

sampled at every locality and the samples analyzed for $P_2O_5$ and acid insoluble material, and all units have been sampled at several sections. Abstracts of the sections and the analytical data have been published (Swanson and others, 1953*a*, *b*; Klepper and others, 1953; Cressman and others, 1953; Peterson and others, 1954). Field descriptions of closely spaced hand specimens from 10 of the localities have been checked by microscopic examination, and 240 thin sections from 12 localities have been examined somewhat cursorily.

In addition to the stratigraphic sections described as part of the present program, several measured sections published by Condit, Finch, and Pardee (1928) have been utilized.

## ACKNOWLEDGMENTS

Although the author took part in the measurement or examination of sections at 18 of the 33 localities discussed in this report, many other geologists have participated in gathering the data, particularly R. W. Swanson, W. R. Lowell, F. S. Honkala, M. R. Klepper, and

J. A. Peterson. Swanson is especially familiar with the Phosphoria formation in Montana and his many suggestions are gratefully acknowledged. Discussions with T. M. Cheney, R. P. Sheldon, R. A. Gulbrandsen, and L. D. Carswell, all members of the Geological Survey who are studying other parts of the western phosphate field, have helped clarify many of the concepts presented. V. E. McKelvey organized the program of which this work is a part and has critically reviewed the manuscript.

The investigation has been conducted as part of the Department of the Interior program for the Missouri River basin and has been supported partly by the Division of Raw Materials of the U. S. Atomic Energy Commission.

## STRATIGRAPHY

### NOMENCLATURE AND REGIONAL CORRELATION

The type locality of the Phosphoria formation is at Phosphoria Gulch, near Georgetown in southeastern Idaho (Richards and Mansfield 1912, p. 684–689). The formation in that region is divided into two members: a lower phosphatic shale member, which consists of about 180 feet of phosphatic mudstone, mudstone, and phosphate rock; and an upper member, the Rex chert, which consists of about 240 feet of bedded chert. Cherty mudstone that contains some thin phosphatic beds occurs at the top of the formation and locally is distinct enough to be considered a third member (McKelvey, 1949, p. 272). The Phosphoria formation at the type locality is underlain by the Wells formation, largely of Pennsylvanian age but possibly in part of Permian age (Williams, 1953, p. 39), and is overlain by the Dinwoody formation of early Triassic age (Newell and Kummel, 1942).

Recent work by Sheldon (McKelvey and others, 1953*a*) has shown that northeastward from the type locality the phosphatic shale member thins, the Rex chert member becomes largely carbonate rock and sandstone, and the uppermost phosphatic, cherty mudstone thickens to a distinct upper phosphatic shale member. In much of western Wyoming the upper phosphatic shale member is overlain by a chert, carbonate rock, and sandstone member that has not been recognized in southeastern Idaho. Beds of carbonate rock between the Tensleep sandstone and the lower phosphatic shale member are included in the Phosphoria formation in western Wyoming, where the formation consists of five members, two phosphatic and three nonphosphatic. In central Wyoming the Phosphoria intertongues with red beds and evaporites (see particularly Thomas, 1934).

The name Phosphoria was first extended to Montana by Stone and Bonine (1914, p. 375), who applied it in the Elliston region to an interval of sandstone and shale, 80 feet thick, which contains a thin bed of phosphate rock at the base. Equivalent strata in Montana previously had been either included as part of the Quadrant quartzite of Pennsylvanian age (Peale, 1893, p. 39–43; Iddings and Weed, 1894; Emmons and Calkins, 1913, p. 71–74) or grouped with overlying Triassic rocks as the Teton formation (Hague and others, 1899, p. 34).

In most of southwestern Montana the Phosphoria formation is underlain by the Quadrant quartzite of Pennsylvanian age and overlain by the Dinwoody formation of Early Triassic age. In the northern end of the Tobacco Root Mountains and the southern end of the Elkhorn Mountains, the Phosphoria was truncated by post-Permian erosion and is unconformably overlain by Jurassic rocks of the Ellis group.

In much of southwestern Montana the Phosphoria has been divided into five members (Butler and Chesterman;[1] Klepper and others;[2] Klepper, 1950, p. 61). These are, in ascending order, a basal quartz sandstone-dolomite member (unit *A*), a thin lower phosphatic shale member (unit *B*), a middle sandstone-dolomite-chert member (unit *C*), an upper phosphatic shale member (unit *D*), and a chert-quartz sandstone member (unit *E*). The lower sandstone, limestone, and chert member of Sloss and Moritz (1951, p. 2167) includes units *A*, *B*, and *C* of this paper.

The lowest horizon in the Phosphoria formation that can now be correlated over southwestern Montana is the base of unit *B*; therefore, strata below unit *B* have not been considered in this report.

The Phosphoria formation exclusive of unit *A* is nearly 500 feet thick near Lima. It thins northward and eastward; in the vicinity of Butte, Bozeman, and the west boundary of Yellowstone Park, the formation is only about 100 feet thick (fig. 2).

On the basis of physical data, Sheldon[3] has been able to correlate major units of the Phosphoria in northwestern Wyoming with the Phosphoria of southeastern Idaho. Similarities between some of the Montana sections and sections in Wyoming described by Sheldon strongly suggest that unit *B* in Montana is the equivalent of the phosphatic shale member in southeastern Idaho and that unit *C* is the partial equivalent of the Rex chert. On the same basis, unit *D* is equivalent at least in part to the upper cherty mudstone that has been recognized at the top of the Rex chert member in southeastern Idaho. Beds equivalent to unit *E* either are not present in southeastern Idaho or are represented by part of the upper cherty mudstone.

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[1] Butler, A. P., Jr., and Chesterman, C. W., Investigation of trace elements in the Phosphoria formation in southwestern Montana, preliminary report (unpublished).

[2] Klepper, M. R., and others, Distribution and stratigraphy of the Phosphoria formation in southwestern Montana: Paper read at Northwest Science meeting, Spokane, Wash., December 1948.

[3] Sheldon, R. P., Physical stratigraphy of the Phosphoria formation in northwestern Wyoming: U. S. Geol. Survey Bull. 1027–(in press).

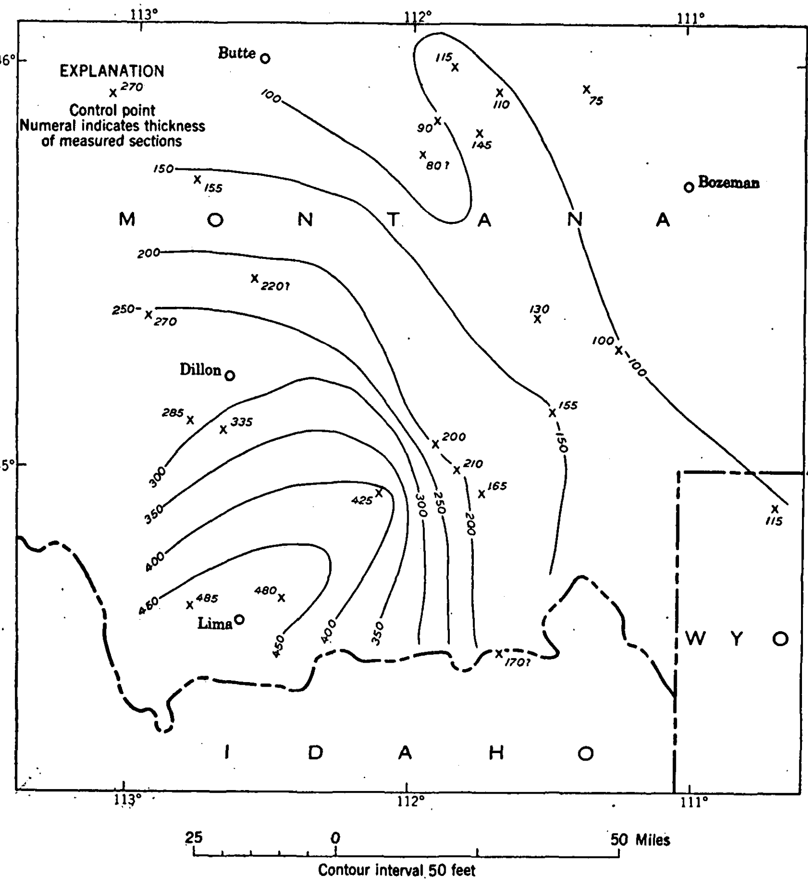


FIGURE 2.—Isopach map of the combined units *B*, *C*, *D*, and *E* of the Phosphoria formation.

Baker and Williams (1940, p. 624–625) have found in north-central Utah that the fauna of the Phosphoria formation is generally younger than that of the Kaibab limestone. If the lithologic correlation, suggested in this paper, between the Phosphoria in Montana and the type Phosphoria in Idaho is correct, and if the correlative lithologic units are also approximate time equivalents, then the Phosphoria in Montana, exclusive of unit *A*, is also probably post-Kaibab in age. Fusulinids of Wolfcamp age have been described from the Phosphoria near Three Forks, Mont., by Frenzel and Mundorff (1942), but were collected from beds in the lower part of the formation that are possibly equivalent to unit *A*.

The lithology and correlation of units *B*, *C*, *D*, and *E* are presented separately below. Some of the relationships discussed are illustrated by columnar sections (pls. 1–4) and in a fence diagram (pl. 5). The sedimentary rocks in the region have been extensively folded and faulted (Klepper, 1950; Lowell;[4] [5] Myers;[6] Swanson[7]), and there has been much crustal shortening, particularly in the Tendoy and Pioneer Mountains near the west side of the area. No attempt has been made in the illustrations to restore the sections to their relative preorogenic locations.

### UNIT *B*

*Thickness and distribution.*—Unit *B* of the Phosphoria formation is more than 25 feet thick just west of Lima (pls. 1, 5; fig. 3*A*). It thins progressively northward and eastward and is not identifiable beyond a radius of 70 miles north and east of Lima. The unit is absent at two places near the west end of Phosphoria exposures in the Centennial Mountain;[8] one area, of known extent, is too small to represent in figure 3, and the other, although of unknown extent, is thought to be small and is likewise not shown. These small areas may have been local topographic highs during the time in which unit *B* was deposited.[9]

Sheldon[10] has shown that the variability in thickness of the phosphate rock increases toward the edge of the shale units of the Phosphoria in Wyoming. Similarly, in a few places in the eastern and northern parts of the Montana area, there are large local variations in the thickness of unit *B*, although the information on the nature and extent of the variations is not sufficient to represent them in figure 3. In the Centennial Mountains the change in thickness of the unit from nearly 20 feet to complete disappearance within 1 or 2 miles is extreme,[11] but at the canyon of the Big Hole River (fig. 1, section 31) it thickens from 2.5 feet on the north side of the canyon to 6.5 feet at a locality 2 miles to the south. Although unit *B* is absent in the Madison Range, there is a 3-foot bed of phosphate rock at Quadrant Mountain, Wyo. (fig. 1, section 29), that is probably correlative with it.

The lithologic character of the bed that immediately underlies unit *B* is illustrated in figure 4. The sandstone in the southwest corner of the area that is separated from other units by a solid line is believed to be stratigraphically higher than the other rocks represented. East

[4] 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.

[5] Lowell, W. R., 1953, Geologic map and structure sections of the southwest quarter Willis quadrangle, Beaverhead County, Mont.: U. S. Geol. Survey Open File Report.

[6] Myers, W. B., 1952, Geology and mineral deposits of the northwest quarter Willis quadrangle and adjacent Brown's Lake area, Beaverhead County, Mont.: U. S. Geol. Survey Open File Report.

[7] Swanson, R. W., 1950, Geology of a part of the Virginia City and Eldridge quadrangles, Montana: U. S. Geol. Survey Open File Report.

[8] Honkala, F. S., 1953, Preliminary report on geology of Centennial Range, Mont.-Idaho, phosphate deposits: U. S. Geol. Survey Open File Report, pl. II.

[9] Honkala, F. S., idem, p. 14.

[10] Sheldon, R. P., op. cit.

[11] Honkala, F. S., op. cit., p. 10, pls. II and VI.

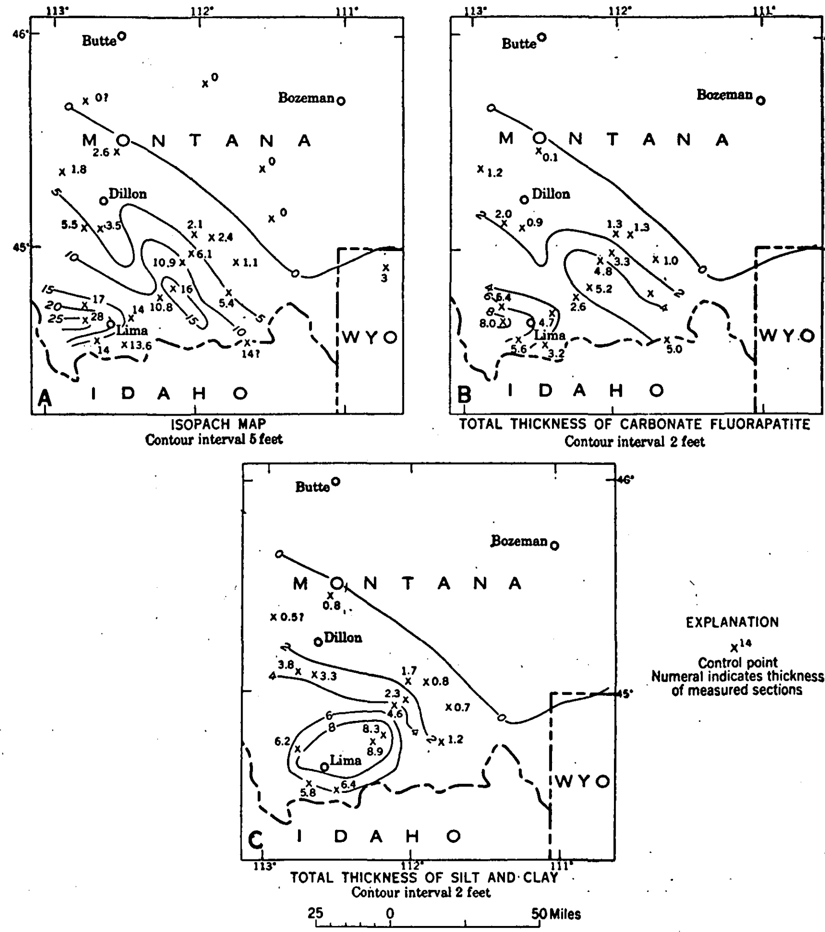


FIGURE 3.—Isopleth maps of unit *B* of the Phosphoria formation.

of the Ruby River unit *A* thins rapidly. The presence of conglomerate at the base of unit *B* in parts of the Gravelly Range (Swanson and others, 1953*b*, p. 17; Condit, 1918, p. 113) indicates that the contact of units *A* and *B* is disconformable east of the Ruby River where the rocks immediately underlying unit *B* are probably older than those to the west. Regionally, the meager evidence suggests that the basal bed of unit *B* oversteps the uppermost beds of unit *A* to a small degree and that unit *A* incorporates stratigraphically higher beds toward the southwest. It is not known whether the postulated overstep at the contact of units *A* and *B* is unique within the formation or whether similar relations might exist at other horizons in the Phosphoria.

*Lithologic character.*—Unit *B* consists mostly of dark-colored phosphate rock and mudstone. The phosphate rock is composed of cryptocrystalline carbonate-fluorapatite (Altschuler and Cisney, 1952),

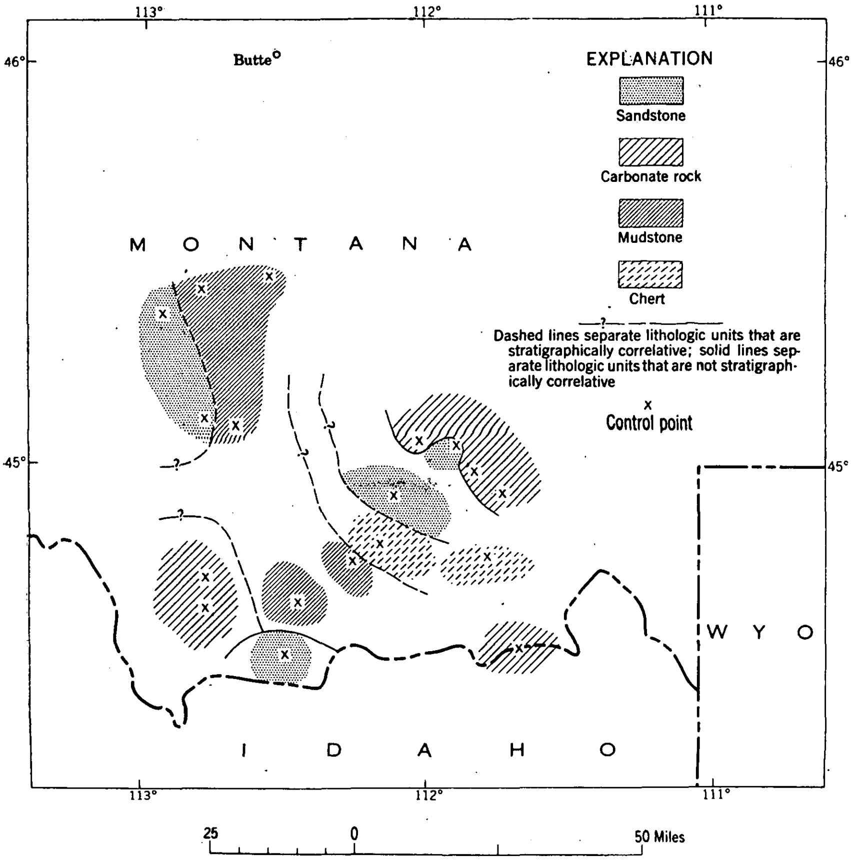


FIGURE 4.—Map showing lithologic constitution of the uppermost bed of unit *A* of the Phosphoria formation.

which occurs chiefly as structureless pellets that average 1/16 to 1/4 millimeter in diameter. The color of the phosphate rock ranges from black and brownish black to medium gray and light brown, largely depending on the degree of weathering. The pellets in the basal phosphate bed, averaging from 1/4 to 1 millimeter, are larger than those in the other phosphate beds. At several localities the basal bed contains small phosphatic nodules, and in most sections it contains abundant fish scales, bone fragments, phosphatic shell fragments, and oolites with well-defined concentric structure.

The mudstone is a mixture of unidentified clay minerals and very fine grained silt composed of quartz and muscovite. The color ranges from brownish black to weak yellowish orange, depending on the degree of weathering.

Mixtures of argillaceous and phosphatic material are common, forming argillaceous phosphate rock and phosphatic mudstone. Carbonaceous matter is present in most rocks of the unit in roughly estimated amounts of 5 or 10 percent.

In the north end of the Gravelly Range (fig. 1, sections 16 and 18), where unit *B* is thin, it contains phosphatic quartz sandstone and sandy phosphate rock. At Alpine Creek (fig. 1, section 18) the unit contains several thin beds of chert- and limestone-pebble conglomerate, in which the pebbles average about 20 millimeters in diameter.

*Regional relations.*—At Little Sheep Creek (fig. 1, section 1; pl. 3, section 1) at the south end of the Tendoy Mountains, unit *B* consists of a basal phosphate bed that constitutes about one-third of the member, an overlying mudstone that contains several thin beds of phosphate rock, and a thin (0.8 foot) uppermost bed of cherty phosphate rock. These features are of necessity somewhat generalized on the stratigraphic diagrams. The sequence can be followed 30 miles northeastward to the Snowcrest Range and 40 miles eastward to the Centennial Mountains (pls. 2, 3). The basal bed of the unit is continuous northeastward to the Gravelly Range. The correlation of the thick basal bed of phosphate rock in the Tendoy Mountains with the thin bed of phosphate rock that composes the *B* member in the sections just south of Dillon is tentative, but it is assumed that the thick basal phosphate bed is more likely to be continuous than the thinner beds of phosphate rock higher in the unit (pl. 3).

There are facies changes within unit *B* in the Gravelly Range and Centennial Mountains where the member is sandy and conglomeratic, but elsewhere the gross lithologic character of the unit is relatively constant.

The distribution of the total equivalent carbonate-fluorapatite (calculated as percent $P_2O_5 \times 2.6$) and the total silt and clay (total acid insoluble minus estimated sand and chert) is shown in figure 3. There are two maxima in the apatite distribution. The eastern maximum is caused largely by thickening of the basal phosphate bed; the western maximum is caused largely by the presence of thin beds of phosphate rock in the upper part of the unit. Comparison with a similar map of unit *B* in northwestern Wyoming[12] indicates that these two maxima are local irregularities and that the broad relation is one of apatite content increasing to the southwest. The map showing distribution of silt and clay has one maximum that overlaps in large part the two apatite maxima and bridges the low area between them.

### UNIT *C*

*Thickness and distribution.*—Unit *C* thins to the east, north, and west from a maximum thickness of about 300 feet just east of Lima (fig. 5*A*). The unit is about 50 feet thick at the easternmost and northernmost exposures of unit *B*. Where unit *B* is absent, the base of unit *C* probably can be located at the contact between gray phos-

[12] Sheldon, R. P., op. cit.

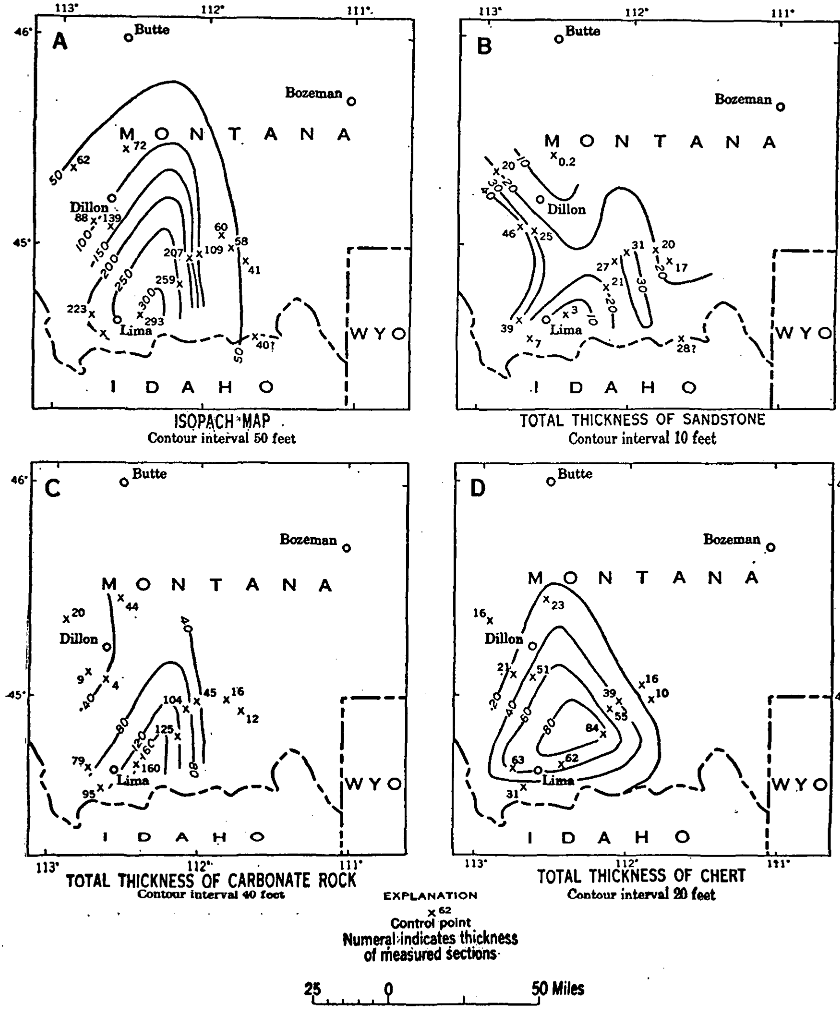


**Figure 5.—Isopleth maps of unit *C* of the Phosphoria formation.**

phatic sandstone and the underlying lighter nonphosphatic sandstone (Condit, 1918, p. 113).

Where unit *C* is more than 100 feet thick, it is composed dominantly of carbonate rock and bedded chert; where it is less than 100 feet thick, it is composed largely of quartz sandstone.

*Lithologic character.*—The carbonate rock of unit *C* is nearly all dolomite. The most notable exception is at Little Sheep Creek (fig. 1; pl. 3, section 1) where most of the carbonate rock in the upper half of the unit is limestone. Rocks equivalent to this limestone are dolomite in the Gravelly Range.

The dolomite ranges in color from medium and light gray to yellowish gray and pale brown. The dolomite beds mostly range from 0.3 to 0.8 foot in thickness, although there are some thicker beds.

Coquinoid limestone occurs in the middle of the unit at Little Sheep Creek (pl. 3, section 1), but most of the carbonate rock is dense and shows little evidence of clastic origin. Microscopically, most of the carbonate rock is composed of an extremely fine grained mosaic of anhedral dolomite grains that range from 5 to 25 microns in diameter.

Bedded chert composes the lower third of unit *C* over much of the area. It consists largely of microcrystalline quartz, which in most localities contains only a small admixture of detrital silicates. Siliceous sponge spicules are present at all localities and in all or nearly all chert beds, and some beds are composed almost entirely of these spicules. In the lower third of the unit most of the chert is in beds from 0.1 to 0.4 foot thick, but in several sections the chert beds are somewhat thicker near the contact between the bedded chert and the overlying dolomite. Unweathered chert is black to medium gray immediately overlying unit *B*, but in several sections it is lighter higher in the section. Weathered chert is mostly in shades of yellowish brown and yellowish orange.

The quartz sandstone of unit *C* contains small but conspicuous amounts of chert grains, carbonate-fluorapatite grains and bone fragments, and glauconite grains. No feldspar has been detected. The sand is mostly very fine and fine grained and is more poorly sorted than is sand in unit *E*. The sandstone ranges in color from brownish gray to light gray and in thickness of bedding from 0.2 foot to several feet.

Dolomitic quartz siltstone and silty dolomite occurs in the middle of unit *C* at Little Sheep Creek and Wadhams Spring (pl. 1, section 10; pl. 3, section 1). The silt is believed to be the finer grained equivalent of the sandstone at Big Sheep Canyon (pl. 1, section 2).

*Regional relations.*—Immediately east of Lima, where unit *C* is 300 feet thick, the lower third of the unit is bedded chert and the upper two-thirds is dolomite. From this point the unit thins to the north and east but retains about the same character as far as the 100-foot isopach (fig. 5*A*). East of the 100-foot isopach the unit is dominantly sandstone; the chert grades and interfingers eastward into sandstone, and the dolomite thins to a few small beds (pl. 1). North of the 100-foot isopach the chert apparently grades into dolomite (pls. 3, 5). Northeast of the 100-foot isopach the chert grades into sandstone and the dolomite either pinches out or grades abruptly into sandstone (pl. 2). West of Lima, the dolomite in the upper two-thirds of unit *C* grades into dolomitic sandstone and sandy dolomite, and the chert in part grades into or interfingers with mudstone (pl. 1).

A thin phosphatic bed in the lower third of unit *C* can be traced from the Tendoy Mountains north to Dillon (pl. 3, sections 1, 2, and 5), northeastward into the Snowcrest Range (pl. 1, sections 2, 10, and

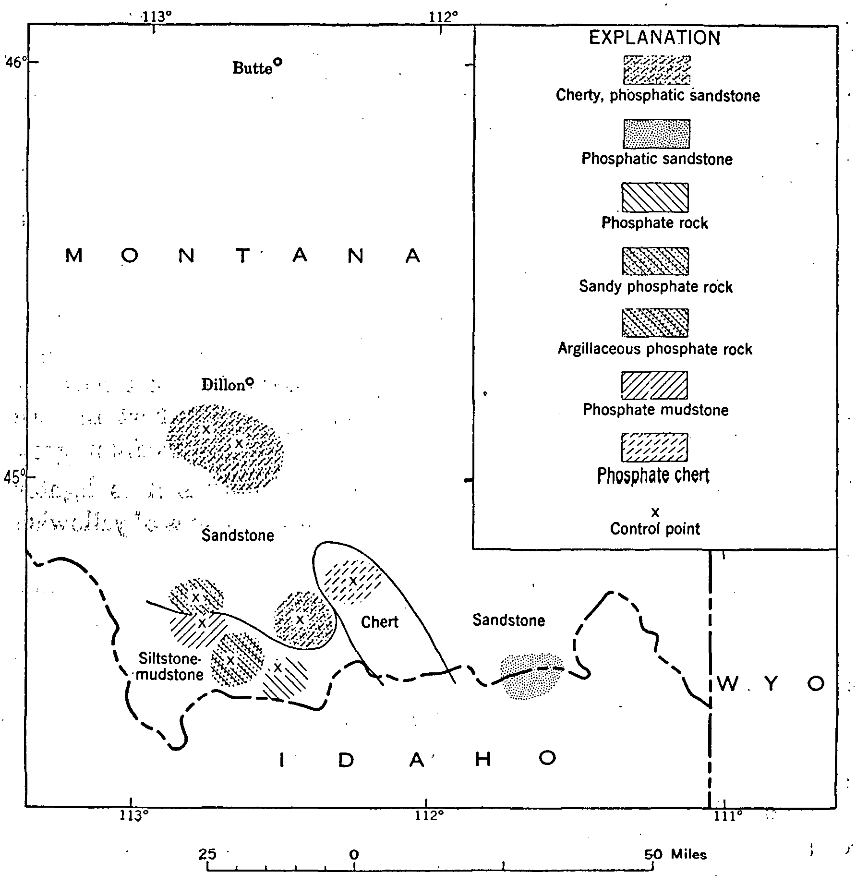


FIGURE 6.—Map showing lithologic constitution of the phosphatic bed in the lower third of unit *C* of the Phosphoria formation.

11), and east into the Centennial Mountains (pl. 2, section 20). The carbonate-fluorapatite content of the bed ranges from 15 percent (pl. 2, section 9) to more than 50 percent (fig. 1, section 3), and the rocks range from argillaceous, sandy, and cherty phosphate rock to slightly phosphatic chert and sandstone (fig. 6). The bed is 1 to 2 feet thick in most sections in the vicinity of Lima and in the Centennial Mountains, but at Big Sheep Canyon (pl. 1, section 2) it is 5 feet thick. Immediately south of Dillon the bed is more than 5 feet thick. In spite of the range in thickness, phosphate content, and gross lithologic character, the bed is, in all localities where it has been identified, a relatively thin unit that is considerably more phosphatic than the adjacent beds.

Two zones of dolomite containing nodules and interbeds of chert are present from Little Sheep Creek in the Tendoy Mountains (pl. 3, section 1) to Hogback Mountain in the Snowcrest Range (pl. 2, section 13). A sandstone bed occurs at the top of unit *C* over most of the area.

The distributions of total sand, carbonate rock, and chert in unit *C* are illustrated in figure 5. The similarity of the maps showing the thickness of carbonate rock and chert to the isopach map suggests that the accumulation of carbonate and chert was governed by the amount of subsidence of the depositional basin. The increase of sandstone to the west indicates that sand was derived in large part from that direction. Small amounts of sand must have been derived from the east as indicated by the eastern sand maximum and by the line of stratigraphic sections in plate 1.

## UNIT *D*

*Thickness and distribution.*—Unit *D* thins northward and eastward from a maximum of at least 80 feet just west of Lima (fig. 7*A*). Unit *D* in the Gravelly Range is only 5 or 10 feet thick. In the sections

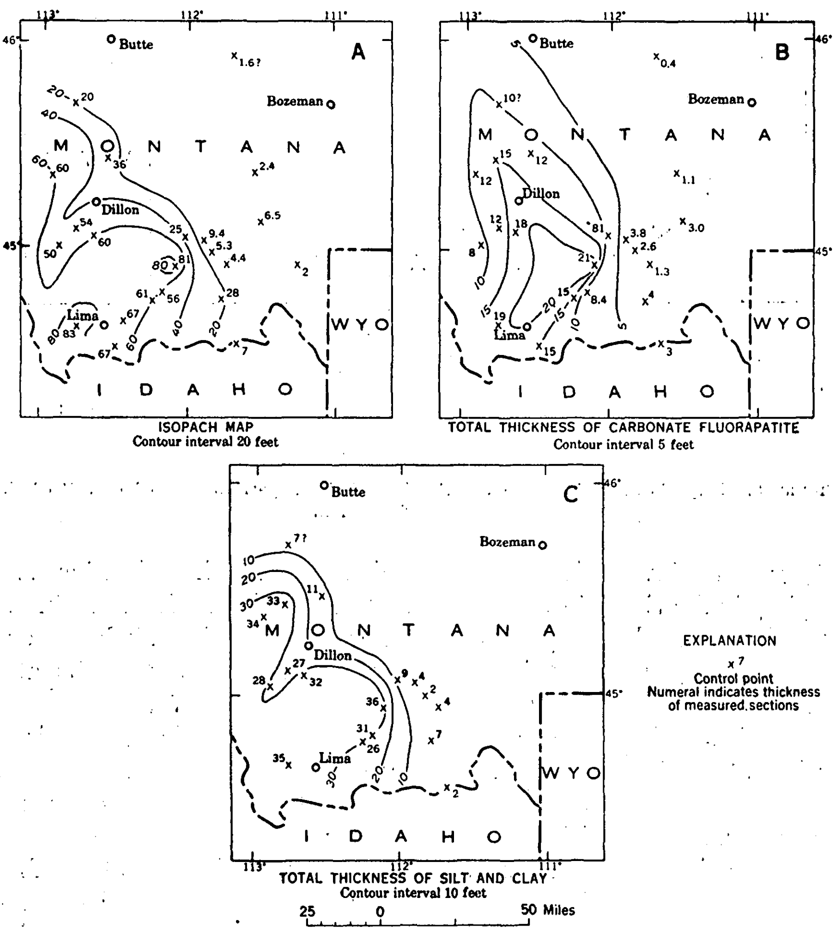


FIGURE 7.—Isopleth maps of unit *D* of the Phosphoria formation.

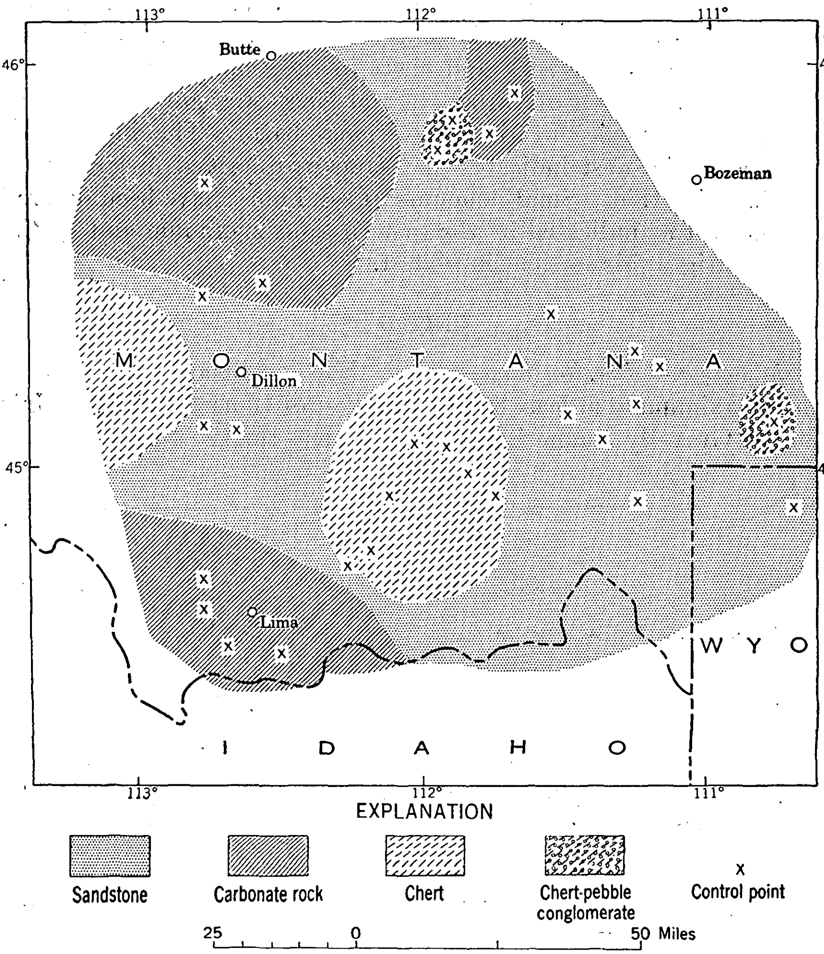


FIGURE 8.—Map showing lithologic constitution of the uppermost bed of unit *C* of the Phosphoria formation.

along the Jefferson River it is 3 feet thick or less. The unit thins most rapidly in the vicinity of the Ruby Valley. Eastward from the Snowcrest Range to the Ruby Range, the lower half of the unit lenses out and the upper half thins abruptly by loss of both carbonate-fluorapatite and fine detritus (pl. 1, sections 12 and 17).

The lithologic character of the bed immediately underlying unit *D* is illustrated in figure 8. A minor disconformity on the east and northeast margins of the area is suggested by chert-pebble conglomerate at several localities, but elsewhere there is little evidence for an unconformity at this horizon. Sandstone underlies the *D* member over most of the region and grades into carbonate rock to the southwest and probably to the northwest. The bedded chert that overlies the sandstone in two areas may have resulted from local postsandstone deposition, the incomplete stripping of a continuous bed of chert, or local facies change from the sand. The passing of conformable contacts at the center of the basin into unconformable contacts near the margins is to be expected and probably occurs throughout the formation.

*Lithologic character.*—Unit *D* is fairly similar to unit *B*. Many phosphate beds throughout the unit in the westernmost sections (fig. 1, sections 3, 4, and 6) contain 10 or 20 percent of carbonate-fluorapatite nodules in a matrix of structureless apatite pellets. The nodules range from 2 to 25 millimeters in diameter and are themselves composed of pellets. In sections just to the east (fig. 1, sections 5, 7, 8, 9, and 31), nodules are neither as common nor as distinct. Phosphate rock in the sections in the south-central part of the area (fig. 1, sections 10, 11, 12, 13, 14, and 38) are composed almost entirely of structureless apatite pellets that are about 1/16 to 1/4 millimeter in diameter. Phosphate rock composed of oolites and fossil fragments occurs at the base of unit *D* in the Gravelly Range, and most of the phosphate rock in the sections along the Jefferson River are oolitic and nodular. In summary, the phosphate rock in the western edge of the field is composed of compound nodules in a matrix of pellets, in the central area of structureless pellets, and in the eastern part of the area of oolitic, organic, and nodular phosphate rock. The phosphate nodules in the eastern part of the area are in a different matrix and are associated with different rocks than the nodules in the west; they are probably of a different origin. Other than in the Gravelly Range, where the basal phosphate bed is oolitic but higher beds are pellety, there is little stratigraphic difference in the type of phosphate rock in any one section, the variation being geographic rather than stratigraphic.

The mudstone of unit *D* is much like that of unit *B*. The organic matter may constitute as much as 20 or 25 percent of some beds, and some of the mudstone contains as much as 10 percent by weight of distillable oil (Swanson and others, 1953*a*, p. 23; Bowen, C. F., 1918). There is little obvious lateral variation in the character of the mudstone.

Dolomite, in beds averaging 0.4 to 1.0 foot thick, is present in unit *D* in many sections. The dolomite is brownish black and brownish gray; texturally it is a very fine grained anhedral mosaic. Fossils are rare in most of the dolomite beds. The dark color and small grain size of the dolomite makes its field identification difficult. Unit *D* has been sampled at most localities discussed in this report and analyzed for $P_2O_5$ and acid-insoluble content (acid-insoluble content represents that part of the sample not soluble in aqua regia and not ignitable at about 1000° C; see McKelvey and others, 1953*c*, p. 3). The part of the rock that is not in the carbonate-fluorapatite or acid-insoluble portions contains a great variety of elements, but in rocks that contain a negligible amount of organic matter, gypsum, and iron sulfides, oxides, and sulfates it consists mostly of carbonates. Unit *D*, however, contains so much carbonaceous material that the carbonate content cannot be deduced from the analyses.

There is some phosphatic sandstone in the upper part of unit *D* at Hogback Mountain (pl. 2, section 13), but it has not been identified at any other locality and its stratigraphic relations are not known.

In unit *D*, as in unit *B*, carbonate-fluorapatite, silt and clay, and dolomite combine to form intermediate rock types.

*Regional relations.*—The uppermost phosphate bed of unit *D* is continuous from just east of Lima to the eastern edge of the field, but it is not known whether or not it extends northward to the Dillon region and the Pioneer Mountains. The position of this bed, and thus of the contact of units *D* and *E*, at Big Sheep Canyon (pl. 1, section 2) is not certain, but there the contact between members has been placed at the contact between phosphatic and nonphosphatic mudstone. Other than the uppermost bed, individual beds in unit *D* cannot be correlated over the region. A bed-for-bed correlation of the unit has been made from the West Fork of Blacktail Creek to Hogback Mountain (fig. 1, sections 11 and 13), a distance of about 25 miles; and correlation in considerable detail is possible from Wadhams Spring (pl. 1, section 10) to Hogback Mountain, a distance of 35 miles. Several zones in unit *D* can be carried from the sections just south of Dillon to those in the Pioneer Mountains, a distance of about 30 miles. Unit *D* is very similar in the sections in the Gravelly and Madison Ranges, consisting of a thin lower phosphate bed, an overlying mudstone, and an uppermost bed of phosphate rock.

Figure 7 includes maps that show the total thickness of apatite and of silt and clay in unit *D*. Melrose (fig. 1, section 8), the only place in the area where phosphate rock is currently being mined from unit *D*, is located where the apatite content is only moderately high but the content of silt and clay is relatively low.

The previously mentioned difficulty of identifying carbonate rock in unit *D* makes it impossible on the basis of data available to determine any regional relationships in the areal distribution of carbonate rock. However, the small amount of acid-soluble material other than carbonate-fluorapatite at Sheep Creek, Sawtooth Peak, and Hogback Mountain (fig. 1, sections 9, 12, and 13) suggests that carbonate rock is least common where the phosphate content is highest.

### UNIT *E*

*Thickness and distribution.*—Over much of the area unit *E* is 100 to 130 feet thick; it is more nearly uniform in thickness than are the other units, although west of Lima it is 140 feet thick and it thins to 60 feet within 100 miles eastward. In the northern end of the Tobacco

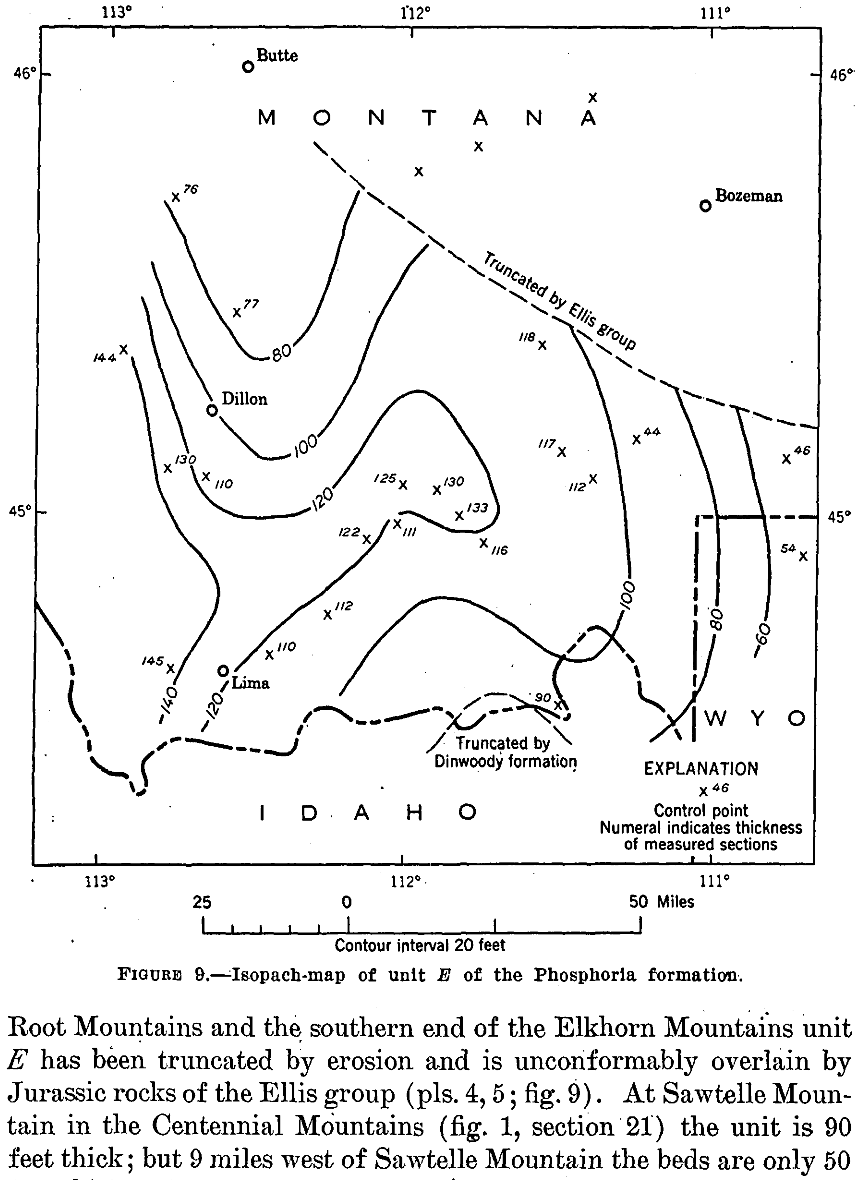


FIGURE 9.—Isopach-map of unit *E* of the Phosphoria formation.

Root Mountains and the southern end of the Elkhorn Mountains unit *E* has been truncated by erosion and is unconformably overlain by Jurassic rocks of the Ellis group (pls. 4, 5; fig. 9). At Sawtelle Mountain in the Centennial Mountains (fig. 1, section 21) the unit is 90 feet thick; but 9 miles west of Sawtelle Mountain the beds are only 50 feet thick and are overlain by mudstone similar to that of the basal Dinwoody formation (pl. 2, section 20). The change in thickness of the rocks of unit *E* in the Centennial Mountains may be due to a westward facies change from sandstone at Sawtelle Mountain to mudstone similar to that in the Dinwoody to the west, but no such abrupt change from sandstone to mudstone is evident elsewhere in the unit. It is possible that the thinness of the westernmost Centennial section may have resulted from stripping of the upper 50 feet of unit *E* during a pre-Dinwoody erosion interval.

*Lithologic character.*—Unit *E* is composed mostly of bedded chert and sandstone. Unweathered chert is dark and medium gray to grayish brown. Where the chert has been subjected to intensive weathering, many of the beds are dull and in lighter shades of yellowish brown and orange so that they megascopically resemble siltstone. Weathered chert is interbedded with unweathered chert in some sections (fig. 1, sections 9 and 11), suggesting some primary difference in composition that has not been detected in thin sections.

The thickness of bedding of the chert ranges from less than 0.01 foot to several feet. In the Gravelly Range, chert in the basal part of unit *E* is in beds about 0.1 foot thick. Higher in the sections the beds are also about 0.1 foot thick, but the bedding planes become less distinct; about 30 feet above the base of the member the chert is massive. Similar relations are evident in the Madison Range, but elsewhere no consistent stratigraphic variation in thickness of bedding is evident.

The chert is composed of microcrystalline quartz with small admixtures of silt and clay. Siliceous sponge spicules are present in every thin section of unit *E* chert that has been examined. Many spicules are nearly indistinguishable from the surrounding siliceous cement so that it is difficult to estimate the amount of spicules in a thin section, but a conservative estimate is that they make up at least 25 percent of the nondetrital quartz in nearly every specimen examined. A few samples of the chert are composed almost entirely of spicules. All samples of the chert that have been examined in thin section contain many small spicules of carbonate-fluorapatite. Many of these apatite spicules are hexactinal in form and thus represent either replacements of siliceous spicules or canal fillings of spicules, the siliceous part of which has been dissolved or rearranged. It is possible that much of the apparently inorganic microcrystalline quartz in the chert may have resulted from solution and redeposition of silica from spicules that are now represented by the apatite replacements or canal fillings. The solution and redeposition of silica from spicules is also suggested by the observation that enlarged axial canals of many siliceous spicules are filled with inorganic microcrystalline quartz.

The sandstone ranges in color from grayish brown to light brownish gray and very pale orange. The thickness of bedding is extremely variable. Sandstone near the top of unit *E* in the Gravelly Range is crossbedded, but no current bedding has been observed farther west. There are no ripple marks.

The sandstone is composed largely of subangular quartz grains averaging 0.08 to 0.18 millimeter in diameter. About 10 percent of the detrital grains are chert. Glauconite grains are present in most of the sandstone west of the Ruby River, and sandstone in the upper part of unit *E* in the Gravelly Range is glauconitic. The glauconite rarely forms more than about 5 percent of the rock.

The heavy detrital minerals make up only about 0.01 percent of unit *E* sandstone. They consist almost exclusively of zircon, tourmaline, and rutile, all of which are highly resistant to weathering. There are very minor amounts of garnet and apatite. The varietal complexity of the tourmaline, and to a lesser extent of the zircon, suggests an ultimate source that included sedimentary, metamorphic, and igneous rocks. However, the immediate source of most of the heavy minerals, and thus of the quartz sand, was probably older sedimentary formations, as is indicated by the predominance of subrounded tourmaline and zircon and the extreme varietal complexity of the subrounded tourmaline as compared to the relative varietal simplicity of the angular tourmaline.

Pyrite has been observed in a few unweathered specimens of sandstone. Pseudomorphs of limonite after pyrite have been observed in many thin sections, and the yellowish brown and orange color of the weathered sandstone is probably caused by iron oxides produced by the weathering of pyrite. Most of the sandstone is cemented by microcrystalline quartz, and there are siliceous sponge spicules in many beds. The sorting of the sandstone is excellent, contrasting with the rather poor sorting of much of the sandstone in unit *C*.

In the Gravelly Range, sandstone in the middle of unit *E* is light gray, contains little glauconite or pyrite, and is cemented largely by overgrowths on the quartz sand grains.

The upper and lower thirds of unit *E* at Big Sheep Canyon (pl. 1, section 2) are mudstone. There are a few beds of thin-bedded brownish gray mudstone in the lower part of unit *E* at the south end of the Gravelly Range, and much of the lower half of unit *E* in the Centennial Mountains is thin-bedded brown and brownish gray mudstone. The mudstone contains very fine grained quartz and muscovite silt in a clay matrix and differs from mudstone in unit *D* largely in being lighter in color. Part of unit *E* in the Tendoy Mountains consists of mixtures of silt and clay and microcrystalline quartz, which form cherty mudstone and argillaceous chert.

Some carbonate rock occurs near the top of unit *E* in the Gravelly Range and throughout the lower half of the member near Three Forks (fig. 1, section 36). Most of the carbonate rock in the Gravelly Range is a mixture of extremely fine grained calcite and dolomite, but a few beds contain large amounts of shell fragments.

A few thin beds of phosphate rock in the lower half of unit *E* in the northern Madison Range, the Gallatin Range, and near the Jefferson River may have resulted from the reworking of older phosphate beds of unit *D*.

Fossils other than sponge spicules are extremely rare in most of unit *E*; but the uppermost beds, in a number of sections at Alpine Creek, Hogback Mountain, West Fork of Blacktail Creek, and Sheep

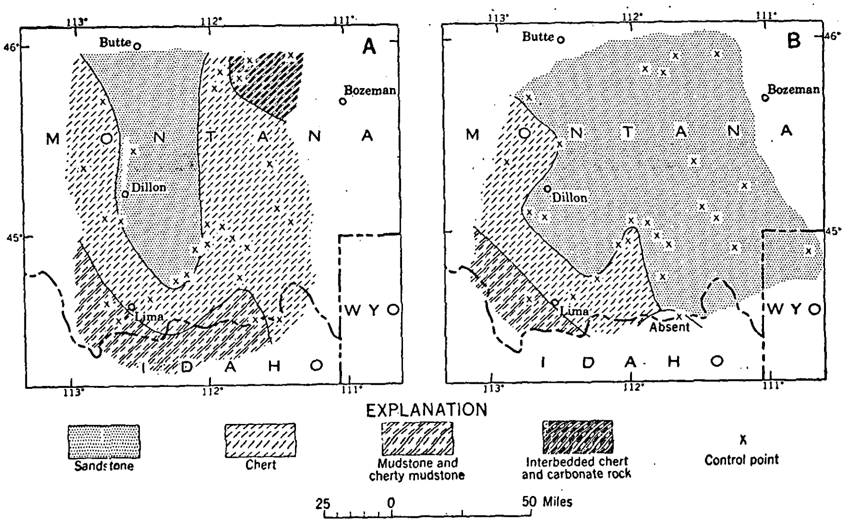


FIGURE 10.—Maps showing the distribution of facies of unit *E* of the Phosphoria formation. *A*, lower half of the unit. *B*, upper half of the unit.

Creek (fig. 1, sections 18, 13, 11, and 9), contain many brachiopod shells and fragments. A limestone composed largely of crinoid stem plates occurs at the top of unit *E* in Small Horn Canyon approximately a mile north of the Sheep Creek section (fig. 1, section 9).

*Regional relations.*—Unit *E* may be divided roughly into a lower and an upper half, each of which has a distinctive pattern of facies distribution. These are summarized in figure 10. Sand in the upper half of the unit was evidently derived from the northeast; the source of sand in the lower half of the unit appears to have been derived from the north, according to regional relations in this area, but its character is so similar to sand in the upper half of the unit that it may have been derived from the same source.

## THE PHOSPHORIA-DINWOODY CONTACT

In the northeastern part of the area, rocks of the Ellis group overlie truncated beds of unit *E*; in the Centennial Mountains, the upper half of unit *E* may have been stripped off before deposition of the Dinwoody formation; and at Shell Creek in the Madison Range the Dinwoody rests disconformably on the Phosphoria (Swanson, R. W., written communication, 1954). In most other localities, however, the Dinwoody formation overlies the Phosphoria with apparent conformity.

Over most of the region the lithologic change from Phosphoria to Dinwoody is abrupt; chert, carbonate-fluorapatite pellets, sponge spicules, and quartz sand all disappear at the top of unit *E*, and clay, which is present in only small amounts in unit *E*, forms a large part of the basal mudstone of the Dinwoody. However, in the sections near

Lima, which are nearer to the center of the basin of deposition, the transition from unit *E* to Dinwoody is more gradual. At Wadhams Spring (fig. 1, section 38) beds of unit *E* and the Dinwoody alternate near the top of unit *E*, and irregular quartz sandstone laminae in the basal beds of the Dinwoody formation are very similar to sandstone in the Phosphoria. Clay does not appear abruptly at the contact as it does in most of the region, but is present in the upper third of unit *E* and increases in amount toward the contact. In the Tendoy Mountains (fig. 1, section 2) the Phosphoria-Dinwoody contact is apparently within a sequence of mudstone. Although in most localities the grain size of the detrital quartz in the basal mudstone of the Dinwoody is considerably smaller than that of the detrital quartz in unit *E*, there is no obvious difference either in the varieties of quartz or in the species and varieties of heavy minerals between the two formations.

The change in gross lithologic constitution between unit *E* and the Dinwoody is apparently no more abrupt than the break between units within the Phosphoria formation. Nevertheless, the absence in the Dinwoody of sponge spicules, chert, glauconite, and phosphate pellets, constituents that occur throughout the Phosphoria, suggests that the change from unit *E* to Dinwoody was accompanied by a greater change in total environment than was any lithologic change within the phosphoria. Crossbedding at the top of unit E in the Gravelly Range, larger grain size of the uppermost sandstone of unit *E* in several sections, and the appearance of brachiopod shells in the uppermost beds of unit *E* all suggest shoaling of the Phosphoria sea toward the end of unit *E* deposition.

The abrupt lithologic break between the Phosphoria and Dinwoody formations and the indications of shoaling toward the end of unit *E* deposition suggest a hiatus between deposition of unit *E* and of the lower part of the Dinwoody formation. The length of any such interval of nondeposition and whether or not it was any longer than intervals of nondeposition within the Phosphoria must be evaluated by the paleontologist.

It frequently has been stated that the faunal break between the Phosphoria and Dinwoody formations is so great that it suggests a stratigraphic break of considerable magnitude (Mansfield, 1927, p. 188; Newell and Kummel, 1941, p. 205, and 1942, p. 938). Kummel has found lower Scythian ammonites and *Claraia* within 5 feet of the base of the Dinwoody formation in southwestern Montana (Kummel, 1954, p. 168), but the Phosphoria formation in Montana, and the upper two units in particular, can at present be dated as post-Kaibab only by means of a long-range lithologic correlation with beds in Utah, Idaho, and Wyoming (Baker and Williams, 1940, p. 624–625).

Therefore, the length of time represented by the break between the two formations remains unknown.

## FACIES RELATIONSHIPS

### TIME ZONATION

The recognition of time horizons is prerequisite to detailed analysis of lithologic facies and their paragenesis. Unfortunately, the study of the faunas collected by the Geological Survey from most of the sections mentioned in this report has not been completed. It is possible, moreover, that a faunal zonation of a thin formation of such contrasting lithologic facies will not result in a satisfactory time zonation.

If two adjacent lithologic facies are time equivalents, interfingering or intergradation of the facies should be expected. Other than in the Tendoy and Centennial Mountains there is no prominent interbedding or integradation in the Phosphoria between the phosphate rock-mudstone assemblage and the chert-sandstone-dolomite assemblage. Furthermore, the continuity of the same sequence of mudstone and phosphate rock in units *B* and *D* over a wide region suggests near contemporaneity of the individual zones. Finally, the uniform character of the phosphate rock within any one section of unit *D* indicates the persistence of uniform conditions at any one locality throughout the time in which unit *D* was deposited. All of these lines of evidence suggest that there has been no major transgression or regression in time by correlative rock units and thus that the unit contacts are approximate time horizons.

Evidence indicative of the migration of facies in time is the presence of mudstone and cherty mudstone in unit *E* and the base of unit *C* in the Tendoy Mountains and mudstone in unit *E* in the Centennial Mountains. Both of these localities are near the margins of the area.

Assuming, then, that the unit contacts are nearly time horizons over most of the region, a number of facies changes can be detected in the Phosphoria. These facies changes are listed in tables 1 and 2.

### SOURCE OF DETRITUS

The direction of transport of the sand and silt is summarized in figure 11. The source has been deduced mostly from the gross areal distribution of rock types but partly from change of grain size. Sand was derived from the east, west, and northwest, and probably from the north. Silt was derived from the west and northwest.

The source of the mudstone is not evident, and no direct evidence has been detected in units *B* or *D*. The fine-grained detritus in unit *E* (fig. 10) may have been derived from the west or it may have

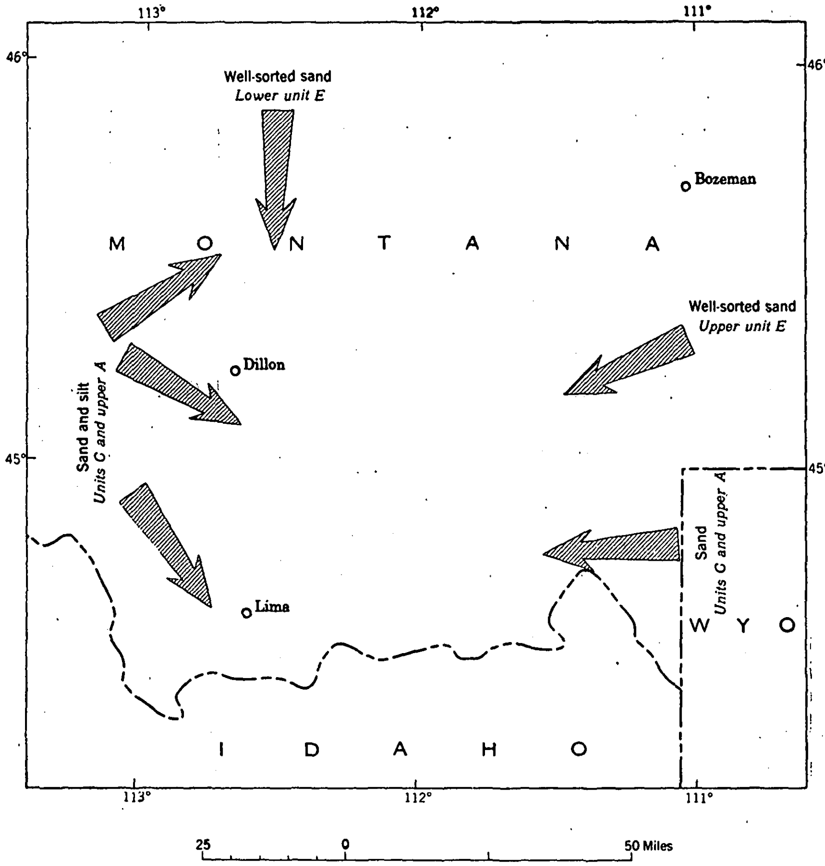


FIGURE 11.—Direction of transport of sand and silt in the Phosphoria formation.

been winnowed from sand on the east and deposited to the west after bypassing the area of chert deposition.

Sand that has been derived from the west grades eastward into dolomite (table 1, sequence III), siltstone (table 1, sequence IV), or mudstone (table 1, sequence VIII). Sand that has been derived from the north or northwest grades southward into chert (table 2, sequences IX and X), siltstone (table 2, sequence XI), or mudstone (table 2, sequence XII). Sand that has been derived from the east grades westward into chert (table 1, sequences I, V, VI, VII, and VIII) or dolomite (table 1, sequence III), but never directly into mudstone or siltstone, thus suggesting that silt and clay were derived from the west, northwest, and possibly the north, but not from the east. If the fine-grained detritus was derived from the west, the relations further suggest that little fine-grained silt and clay were available in the eastern source area but the western or northwestern source supplied detritus with a considerable range of grain size.

TABLE 1.—*East-west facies changes in the Phosphoria formation in southwestern Montana*

[Arrows indicate the direction of transport of silt and sand]

| *Sequence* | *West* | *Sequence of lithologic types* | *East* | *Position in section* | *Reference* |
|---|---|---|---|---|---|
| I | Mudstone and cherty mudstone. | Chert | ← Sandstone | Upper unit *E* | Fig. 10*B* |
| II | Nodular, pellety phosphate rock. | Pellety phosphate rock | Nodular, oolitic, fossiliferous phosphate rock. | Unit *D* | Text, p. 15 |
| III | Dolomitic sandstone → | Dolomite | ← Sandstone | Upper unit *C* | Pl. 1 |
| IV | Sandstone → | Dolomitic siltstone | Dolomite | Middle unit *C* | Pls. 1 and 6 |
| V | Mudstone | Chert | ← Sandstone | Phosphatic bed in unit *C* | Fig. 6 |
| VI | Chert and mudstone | Chert | ← Sandstone | Lower unit *C* | Pl. 1 |
| VII | Dolomite    Mudstone | Chert | ← Sandstone | Upper unit *A*, southern part of area. | Fig. 4 |
| VIII | Sandstone → Mudstone | Chert (?) | ← Sandstone(?) | Upper unit *A*, northern part of area. | Fig. 4 |

TABLE 2.—*North-south facies changes in the Phosphoria formation in southwestern Montana*

[Arrows indicate the direction of transport of silt and sand]

| *Sequence* | *South* | *Sequence of lithologic types* | *North* | *Position in section* | *Reference* |
|---|---|---|---|---|---|
| IX | Mudstone and chert | Chert | ← Sandstone | Lower unit *E* | Fig. 11*A* |
| X | Dolomite | Chert | ← Sandstone | Upper unit *C* | Pls. 2 and 5 |
| XI | ← Dolomitic siltstone | Sandstone → | Dolomite | Middle unit *C* | Pl. 3 |
| XII | Phosphatic mudstone | | ← Phosphatic sandstone | Phosphatic bed in lower unit *C*. | Fig. 6 |

The western source area was probably in north-central Idaho. The region now occupied by the Idaho batholith was a positive area during much of the Paleozoic era (Ross, 1934, p. 996–1000). Central Idaho supplied sediment to the east during Carboniferous time, and Ross (1934, p. 999) believes that the region remained positive during at least part of the Permian. The Paleozoic section in south-central Idaho contains thick argillaceous formations that in places have a total thickness of more than 5,000 feet (Ross, 1934, fig. 2). These are the Garden Creek phyllite of possible Cambrian age, the Lower Ordovician Ramshorn slate, and the Milligen formation of Mississippian age. These fine-grained sediments together with pre-Cambrian argillites of the same region would have been a more than adequate source for the mudstone in the Phosphoria formation.

Klemme,[13] working in an area approximately 30 miles north-northwest of Bozeman, has concluded from the study of pebbles from conglomerate in the Phosphoria that the shoreline of the eastern positive area was actively eroding the Madison limestone (Mississippian age), the Amsden formation (Pennsylvanian and Mississippian age), and the Quadrant formation (Pennsylvanian age), and it is probable that most of the sand in the Phosphoria was derived directly from the Quadrant. Eardley's paleogeologic map of the western United States at the close of the Permian (Eardley, 1949, p. 672) indicates that the eastern source area consisted largely of Mississippian and Pennsylvanian rocks with smaller more distant outcrop belts of lower Paleozoic and pre-Cambrian rocks. Although the Paleozoic sequence to the east includes some argillaceous units, particularly in the Big Snowy group of late Mississippian and Pennsylvanian(?) age, they are much thinner than the argillaceous Paleozoic rocks of south-central Idaho, and their belt of outcrop during Permian time was probably more distant from the site of Permian deposition than was the central Idaho positive area. Thus a western source for the Phosphoria mudstone is suggested by the facies relations and the paleogeography, but the evidence is not conclusive.

## BEDDED CHERT FACIES

Bedded chert is adjacent to sandstone in seven of the facies sequences in tables 1 and 2 (sequences I, V, VI, VII, VIII, IX, and X). In each sequence the chert is basinward from the sandstone. Although much of the sandstone contains chert cement, sandy chert is not common and the facies change from cherty sandstone to chert is abrupt at many places. The chert appears to have resulted in large part from the accumulation and partial diagenetic reorganization of sponge

[13] Klemme, D. H., The Geology of Sixteen Mile Creek Area, Montana: unpublished Ph. D. thesis, Princeton University.

spicules and other siliceous organic remains, and the facies relations between sandstone and chert probably resulted from the sorting of the siliceous organic remains from the quartz sand and the subsequent accumulation of the organic silica on the basinward side of the sand. The abruptness of the facies change probably reflects both the efficiency of the sorting and the uniform size of quartz sand that was supplied to the depositional basin.

### CARBONATE ROCK FACIES

Carbonate rock is interbedded to some extent with all other rock-types and is probably polygenetic. Dolomite that occurs as a geographically distinct facies is either immediately adjacent to sandstone (table 1, sequence III) or is separated from the sandstone by a bedded chert facies (table 2, sequence X). These facies relations indicate that most of the carbonate accumulated in deeper, less turbulent water than did sand and chert and that the original grain size was finer than sand size.

### PHOSPHATE ROCK FACIES

Most of the phosphate rock is intimately interbedded with carbonaceous mudstone and, as with the mudstone, probably accumulated in fairly deep, relatively quiet water poor in oxygen. The areal distribution of the types of phosphate rock in unit *D*—fossiliferous, nodular, oolitic phosphate rock on the east, pellety phosphate rock in the central part of the region, and nodular, pellety phosphate rock on the west—suggests that the fossiliferous, nodular, oolitic phosphate rock was deposited in shallower, more turbulent water than was the pellety rock. The sequence from east to west in unit *D* of fossiliferous, oolitic, nodular phosphate rock—pellety phosphate rock—nodular, pellety phosphate rock suggests that the nodular, pellety phosphate rock was deposited in deeper water than were the two more eastern facies, but deposition in deeper water in the western part of the area is difficult to reconcile with a western source for the mudstone.

### LATERAL SEQUENCE OF ROCK TYPES

Assuming that mudstone in unit *E* in the Tendoy and Centennial Mountains was deposited under about the same conditions as mudstone in units *B* and *D*, the sequence of facies in the Phosphoria formation from shoreward to seaward is as follows: Sandstone, chert, mudstone, interbedded pellety phosphate rock and mudstone, and interbedded nodular, pellety phosphate rock and mudstone. Carbonate rock is interbedded to some extent with all other lithologic types but for the most part occurs basinward from the sandstone. Fossiliferous, nodular, oolitic phosphate rock is associated with all other rock types with the exception of nodular, pellety phosphate rock. Nonglauconitic sandstone in unit *E* occurs for the most part on the eastern or shoreward margin of the area, but in several sections it is overlain by crossbedded fossiliferous, glauconitic sandstone that was apparently deposited in shallower water.

McKelvey (oral communication; and McKelvey and others, 1953*b*, table 1) has deduced the following shoreward to seaward sequence of facies in the Phosphoria formation from the gross lithologic constitution of sections in southeastern Idaho and western Wyoming: redbeds, sandstone, glauconitic sandstone, carbonate rock, chert, organic phosphorite, pisolitic phosphorite, pellety phosphorite, and mudstone. The sequence in Montana is generally similar to that in Idaho and Wyoming, but carbonate rock, fossiliferous phosphate rock, mudstone, and nonglauconitic sandstone do not seem to occupy definite positions in the Montana sequence.

### VERTICAL SEQUENCE OF ROCK TYPES

According to Sheldon,[14] the Phosphoria formation in northwestern Wyoming consists vertically of two cyclical rock sequences. Each cycle consists of an upward sequence of carbonate rock, tubular chert, nodular and concretionary chert, organic phosphorite, oolitic and nodular phosphorite, pellety phosphorite, oolitic and nodular phosphorite, bedded chert, nodular and concretionary chert, tubular chert, and carbonate rock. The cycles are incomplete, and generally one or more of the phases are not present, especially the phases from the lower carbonate rock to the lower organic phosphorite. Analogously in Montana, there is a similar twofold vertical repetition of rock types in the Phosphoria formation. The phosphatic mudstone-bedded chert-carbonate rock sequence that comprises units *B* and *C* is repeated in the phosphatic mudstone of unit *D* and the chert of unit *E*. The uppermost silty and sandy carbonate beds that are near the top of unit *E* at some localities complete the upper sequence.

### RELATIONSHIP OF FACIES TO DEPTH OF WATER

The rock types and their distribution have resulted from a number of complexly interrelated factors, such as the location, altitude, topography, climate, and drainage of each of the two source areas; the lithologic character of the rocks exposed in the source areas; the depth and submarine topography of the depositional basin; the nature of currents in the depositional basin; and the concentration of elements in the basin waters and in the inflowing marine and river water. It is difficult to determine what factors were the most important in the

[14] Sheldon, R. P., op. cit.

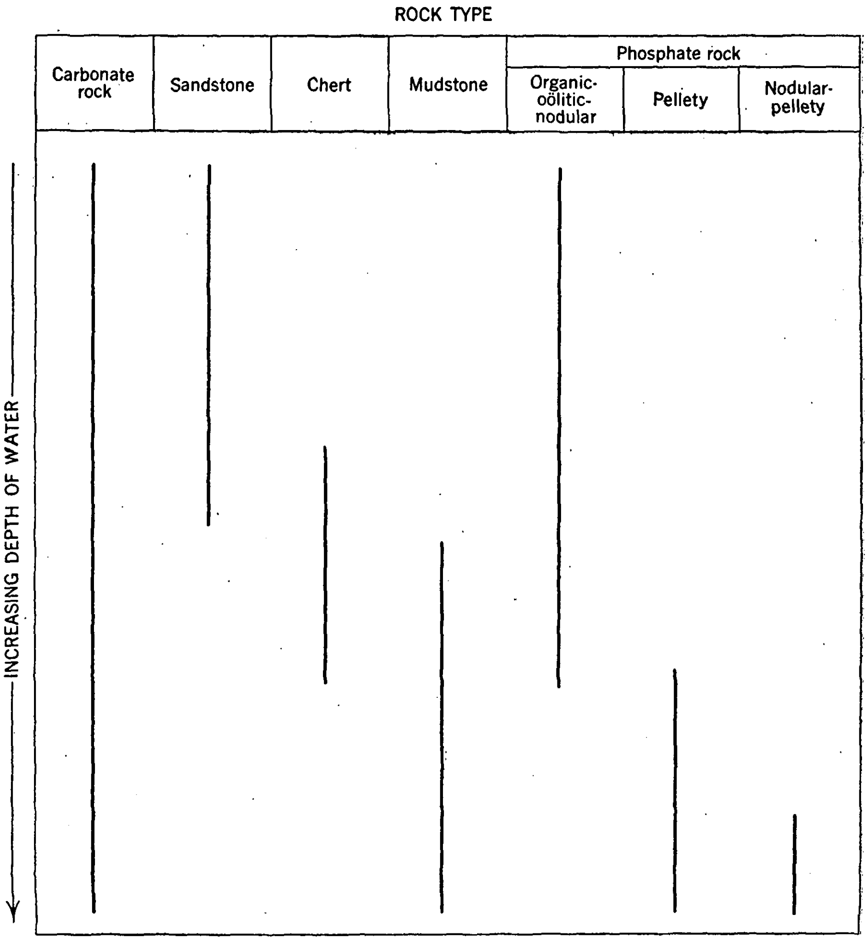


FIGURE 12.—Inferred relations between rock types in the Phosphoria formation in Montana and the relative depth of water in the depositional basin.

deposition of any one facies, and it is not known what changes in environment resulted in the vertical sequences of rock types. However, assuming that depth of water was the most important factor influencing turbulence, the relations illustrated in figure 12 between rock types and relative depth of water have been deduced from associations of gross lithologic units and the lateral sequence of facies. If the relations in figure 12 are correct, then the standstone and chert of units *C* and *E* probably were deposited in shallower water than were the mudstone and phosphate rock of units *B* and *D*. This, together with the absence over most of the region of clear evidence of the transgression of time horizons by unit contacts, suggests that the vertical sequences of rock types resulted from vertical tectonic movements that affected most of the region nearly simultaneously.

Sheldon [15] believes that the two vertical cycles of rock types in the Phosphoria of western Wyoming resulted from tectonic movements and thus presumably from changing depth of water. The tectonic changes led to transgression and regression of environments that were recorded there by transgressive and regressive facies.

It is evident, however, from the wide association of some rock types such as carbonate rock and fossiliferous phosphate rock and the interbedding of rock types that are usually deposited at different depths (for example, sandstone interbedded with mudstone and phosphate rock at Hogback Mountain) that relative depth of water was only one of a number of factors that determined the locus of deposition of the facies.

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